ENERGY HARVESTING FROM EXERCISE MACHINES: COMPARATIVE STUDY OF EHFEM PERFORMANCE WITH DC-DC CONVERTERS AND DISSIPATIVE OVERVOLTAGE PROTECTION CIRCUIT

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COMMITTEE MEMBERSHIP

TITLE:	Energy Harvesting from Exercise Machines: Comparative Study of EHFEM Performance with DC-DC Converters and Dissipative Overvoltage Protection Circuit
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ABSTRACT

Energy Harvesting from Exercise Machines: Comparative Study of EHFEM Performance with DC-DC Converters and Dissipative Overvoltage Protection Circuit

Cameron Kiddoo

Energy Harvesting from Exercise Machines (EHFEM) is an ongoing project pursuing alternate forms of sustainable energy for Cal Poly State University. The EHFEM project seeks to acquire user-generated DC power from exercise machines and sell that energy back to the local grid as AC power. The end goal of the EHFEM project aims to integrate a final design with existing elliptical fitness trainers for student and faculty use in Cal Poly’s Recreational Center. This report examines whether including the DC-DC converter in the EHFEM setup produces AC power to the electric grid more efficiently and consistently than an EHFEM system that excludes a DC-DC converter. The project integrates an overvoltage protection circuit, a DC-DC converter, and a DC-AC microinverter with an available elliptical trainer modified to include an energy converting circuit. The initial expectation was that a DC-DC converter would increase, when averaged over time, the overall energy conversion efficiency of the EHFEM system, and provide a stable voltage and current level for the microinverter to convert DC power into AC power. In actuality, while including a DC-DC converter in a test setup allows the EHFEM system to function with less frequent interruptions, this occurs at the cost of lower efficiency. Testing demonstrates the EHFEM project can convert user-generated DC power into usable AC electrical power. Retrofitting existing equipment with the EHFEM project can reduce Cal Poly’s energy cost.

ACKNOWLEDGMENTS

With great appreciation, I express my thanks to Dr. Braun for advising and allowing use of the core components and Precor elliptical trainer for testing. I would also like to thank Dr. Dolan for providing the Enphase M215 microinverter as well as test equipment and use of the lab bench in room 150. I also thank Dr. Taufik who, along with Dr. Braun and Dr. Dolan, taught and helped guide me through my university career.

The EHFEM project greatly appreciates Paul Grierson, who provided the Precor elliptical machine to Cal Poly's EE department [2]. I would also like to extend my thanks to Enphase Energy for providing an M190 microinverter to replace the M175 microinverter model and providing technical support when needed.

Furthermore, I am grateful for Laura Zamora for helping me test and acquire data for my project and her support as I continued to work on my report. Finally, I am grateful for my parents and family for their support throughout my entire educational career.

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CHAPTER 1: INTRODUCTION

Chapter 1 provides background on the significance of the EHFEM project while divulging what past projects and research accomplished. Doing so lays a basis for what this thesis explores.

1.1 Why we want EHFEM

The Energy Harvesting from Exercise Machines (EHFEM) project endeavors to bring alternate forms of sustainable energy to Cal Poly. The project strives for renewable energy sources by acquiring user-generated energy from exercise machines and sending that energy back to the local grid. The end goal of this project aims to integrate a final design with existing elliptical fitness trainers for use in Cal Poly's Recreational Center and reduce Cal Poly's energy costs.

1.2 What past research accomplished

The EHFEM project utilizes multiple components for converting user-generated DC power into power grid AC power. The project uses a Precor EFX 546i elliptical trainer with mechanical and electrical modifications to produce electricity and charge a car battery when in use. Lum et al. [1], demonstrate energy conversion with the elliptical using a Wilmore DC-DC converter and an Enphase M175 microinverter. Following their prototype, Lum and Yuen later acquire a Vicor Maxi DC-DC converter. This alternative converter, meant to replace the Wilmore DC-DC converter, has a wider input range than the Wilmore and has a small enough size to fit within the elliptical machine [1]. When testing with the elliptical, they reported that an EHFEM system with the Vicor DC-DC converter failed to produce AC power to the grid [1]. The Vicor converter sees a very low equivalent resistance with the M175 microinverter as the load, causing the Vicor's

overcurrent protection to prevent any input or output current [1]. Testers also experienced fluctuations in the elliptical trainer's pedal resistance as the energy harvesting kicked in and out [1]. Their results reveal a difficulty of maintaining an optimal user experience, and a need for future projects to construct a custom DC-DC converter for the project [1].

Other projects, designed DC-DC converters to adhere specifically to the parameters of the EHFEM project. Kou [2] proves a self-designed PWM-switching SEPIC topology provides a functional DC-DC converter design. However, the designed converter failed under testing despite including an LT4356-1 protection circuit [2]. Kou's results highlight a need for an external input voltage protection as well as a control mechanism for controlling DC-DC converter output current. Yoo and Chu [3] designed a Buck-Boost DC-DC converter for their senior project that costs less than Kou's and uses fewer components. Wong [4] developed a Buck Boost converter but with a superior power MOSFET. However, in the final phases of these two DC-DC converters, the reporters encounter operation errors possibly from malfunctioning MOSFETS or mishandling of the DC-DC converters [3, 4]. At the time of this report, the EHFEM project lacks a functioning custom DC-DC converter able to deliver the entire elliptical output voltage range to a microinverter.

Turner and Weiler [5] proposed an input protection system for use with Kou's DC-DC converter design. Their two-part input protection circuit protects the DC-DC converter from overvoltage conditions while also sensing and limiting the current the DC-DC converter outputs to the microinverter. Their efforts include extensive Precor elliptical trainer testing leading to the creation of a capacitive filtering/decoupling bank [5]. This capacitor bank helps filter out high frequency transients from the elliptical

trainer and allow the DC-DC converter to receive a more level DC voltage [5]. While their design functions and adheres to the specifications of Kou's DC-DC converter, Turner and Weiler note a major inefficiency issue where the circuit dissipates all power generated under maximum input conditions [5].

Concurrent with [3] and [4], Funsten et al. [6] developed an input protection system for the EHFEM project. We combined the capacitive filtering bank from [5] with a new overvoltage protection circuit to protect a DC-DC converter. This overvoltage protection design proves efficient and modifiable to protect other DC-DC converters from overvoltage conditions regardless of their maximum input voltage limit [6]. We also worked to implement a new current limiting circuit using the designs from Dr. Braun's 2012 sabbatical report. Unfortunately, the high current sense amplifier in the current limiter failed to work during final testing likely due to mishandling [6]. However, concurrent with testing in this report, Crivelli [7] resolved the issues of the high current sense amplifier and demonstrated the ability of the current limiter. Also concurrent with this report, Abshier and Xu [8] developed their own input protection system using a high power NMOS and PMOS to improve upon previous designs. While the voltage limiting circuit they developed successfully limits an input voltage, it has a couple flaws of its own. These flaws include the boost circuit requiring a charge up period of about forty seconds before any voltage limiting can occur, and the lack of a switching PMOS [8].

1.3 What this project accomplishes

The EHFEM power conversion project depends on the performance of its components. The performances of these components vary as the elliptical experiences different levels of user operation. We investigate EHFEM performance by conducting

efficiency testing on the individual components of the EHFEM project before combining components together and integrating with an energy generating elliptical trainer. After extensive testing, we produced significant results. This project reveals that while a system that excludes a DC-DC converter produces energy more efficiently than an EHFEM system that includes the DC-DC converter, including the DC-DC converter in the EHFEM project allows for a greater range of user operation.

Testing begins in Chapter 3 where we measure and compare the performance of available microinverters. Similar testing occurs in Chapter 4 with available DC-DC converters. Chapter 5 retests the overvoltage protection circuit (OVPC) designed previously for this thesis while improving the design for more reliable IGBT switching. Combination testing begins in Chapter 6, which tests the efficiency of a microinverter in connection with a DC-DC converter. Efficiency testing with the elliptical trainer begins in Chapter 7 and includes the OVPC and microinverters. Such testing measures a microinverter's efficiency when converting DC power the Precor elliptical generates into AC power. Chapter 7 also determines the operating range of the Precor elliptical. Chapter 8 follows similar testing as in Chapter 7, but includes connecting a DC-DC converter between the OVPC and microinverter. Doing so evaluates whether including a DC-DC converter improves the overall performance of the system. Chapter 8 also shows that using the OVPC as input protection for the Vicor DC-DC converter allows an EHFEM system with the Vicor to produce AC power to the grid. Finally, Chapter 9 concludes this thesis report and offers ideas for future projects. The following chapter provides background information on the Precor EFX-546i elliptical trainer.

CHAPTER 2: PRECOR EFX-546i ELLIPTICAL TRAINER

Chapter 2 introduces and provides background information on the Precor elliptical trainer available for EHFEM projects. This chapter addresses key components of the elliptical, and discloses the need for external circuitry to prevent a load connected to the elliptical's output from overload conditions.

The EHFEM project uses a Precor EFX-546i elliptical trainer. A team of students led by Rogan Guild modified the Precor elliptical trainer to generate DC power from an onboard 6-phase generator. Since the retrofit, the EHFEM project utilizes the elliptical trainer as the main source for DC power generation. When not used in an EHFEM setup, the DC power the Precor elliptical generates dissipates across a 10 Ω resistive load. In tests detailed in this report, the DC power becomes the input power for a DC-DC converter and/or microinverter. The Precor EFX-546i houses a 12-Volt battery in the lower front of the machine, which recharges as a user exercises [9]. When not used for power generation, the elliptical does not require an AC electrical connection [9].

Figure 2-1: Precor elliptical trainer used in the EHFEM project.

Figure 2-1 above shows the Precor elliptical machine used in the EHFEM project. The back end of the Precor elliptical houses the circuitry that converts user's mechanical energy into electrical energy. A tester must remove the protective housing for testing to occur. Figure 2-2 below shows the mechanical to electrical energy conversion circuit housed in the elliptical with the protective housing removed.

Figure 2-2: Precor Elliptical's energy harvesting unit. The unit converts a user's mechanical energy into electrical energy for harvesting.

Tests involving the Precor elliptical trainer require an overvoltage protection circuit (OVPC) to protect the elliptical's load—A DC-DC converter or microinverter—from overvoltage conditions. This overvoltage protection circuit utilizes an FGA180N33AT high power IGBT as a switch for diverting excess power from the elliptical's load through a diverting resistor. Testing with the Precor elliptical trainer also requires accessing the 10 Ω load within the protective housing. This load acts as a diverting resistor as part of the overvoltage protection circuit.

For instructions on removing the protective housing and preparing the Precor elliptical trainer for testing, see Appendix B.1. Appendix B.2 details delivering AC power from the main electrical grid to the testing room in Engineering East. The following chapter tests the efficiencies of the Enphase microinverters and compares findings with their respective datasheets.

CHAPTER 3: ENPHASE MICROINVERTERS: M175-24-240 AND M215-60-2LL-S25-IG

3.1 Introduction

The EHFEM project requires a microinverter to convert DC power into AC power and send the AC power to the electrical grid. This microinverter can receive DC power either from a DC-DC converter or from the output of the Precor elliptical trainer this project uses.

Past senior project and thesis reports make use of the M175 microinverter. Lum et al. test the M175 inverter with a Wilmore Model 1560 DC-DC converter [1]. Their report proves the inverter and DC-DC converter function in tandem and produce up to 70 W of AC power [1]. Kou's thesis report considers the M175 inverter's parameters when designing a DC-DC converter using SEPIC technology [2].

This testing phase characterizes how efficiently the M175 and M215 microinverters convert DC power into AC power. According to their datasheets, the M175 and M215 inverters have a peak power efficiency of 95% and 96.5% [10, 12]. Testing each inverter involves limiting the input current from the BK Precision Model 9153 high power DC source while varying the supplied DC voltage. Testing limits the supplied current because the microinverters maximize power production by receiving as much input current as possible when receiving less than 200 W of supplied power. The BK Precision source supplies and measures the DC input voltage and current while a GWINSTEK GPM-8212 power meter measures each inverter's AC output power.

The following sections detail results and troubleshooting options when performing microinverter efficiency testing. Figure 3-1 below depicts simple wiring

diagrams showing the connections between equipment and the AC bench. Appendix B.3 details the necessary equipment, setup instructions, and test protocols for microinverter efficiency testing.

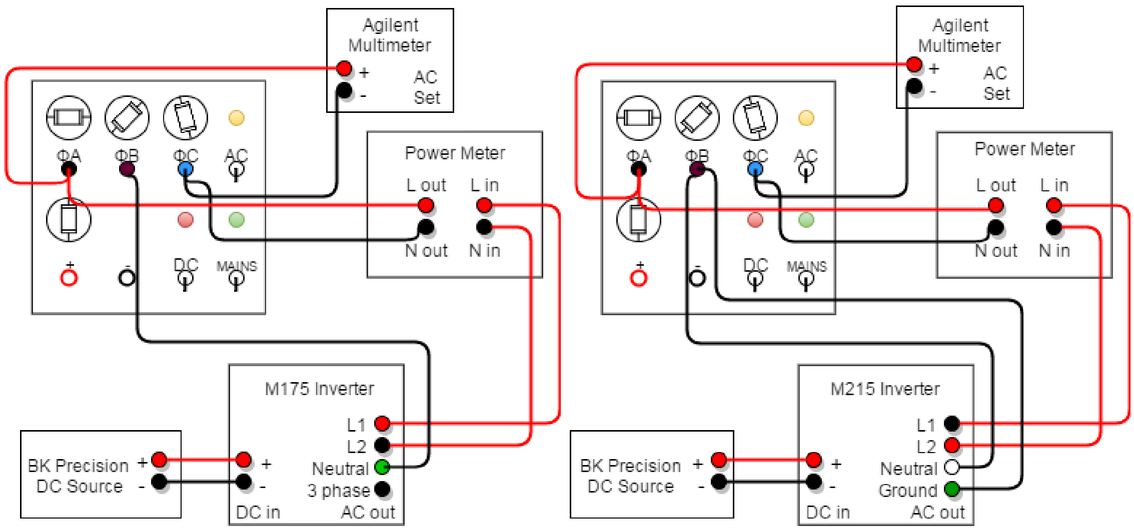


Figure 3-1: Wiring diagrams for testing the Enphase M175 microinverter (left) and M215 microinverter (right).

3.2 Testing the Enphase M175 and Enphase M215 Microinverters

3.2.1 Results of Enphase M175 Efficiency Testing

The M175 does not produce AC power until the BK Precision supplies the inverter with a minimum 32 V. Once producing AC power, the microinverter can continue to output AC power even if the input voltage decreases to a minimum of 25 V. We then record the input and output voltage, current, and power measurements over a range of voltages for various current limits. For the low current limit of 1.5 A, the input voltage and current tend to vary, leading the input power to vary by one watt to almost 20 watts for a given test level voltage. In the data tables, the low input power calculations consider the low input voltage measurement with the low input current measurement. However, acquiring these data points does not occur simultaneously, because the BK Precision does not necessarily supply a low voltage the same moment when supplying a

low current. “Pin low” in Appendix A-1 data tables may calculate lower than the actual supplied minimum power to the microinverter. This explains the occurrences of some efficiency calculations exceeding 100%.

Meanwhile, efficiencies calculations relating high output power to high input power calculate below 85% and lower. While the output voltage, current, and power maintain relatively consistent measurements, the large variation in input power leads to efficiency calculations that deviate from the 92-94% efficiency range. Appendix A.1 contains the data table and scatter plot for a set input current of 1.5 A as well as the other efficiency tables for this test session.

When testing at other set current limits above 1.5 A, the input voltage and current remains stable for each test level voltage. Likewise, the power meter measures a constant output voltage, current and power. When the M175 inverter receives a DC input voltage within its operating range, the inverter produces AC power with an average efficiency of 93.0%. This efficiency differs from the one data sheet specification by 2.1%. Figure 3-2 and Figure 3-3 below depict scatter plots of the efficiency for set current limits across the M175’s operating range. The M175 inverter maintains a consistent efficiency across its operating voltage range. To view the full set of data collected for the M175 inverter, see Appendix A.1.

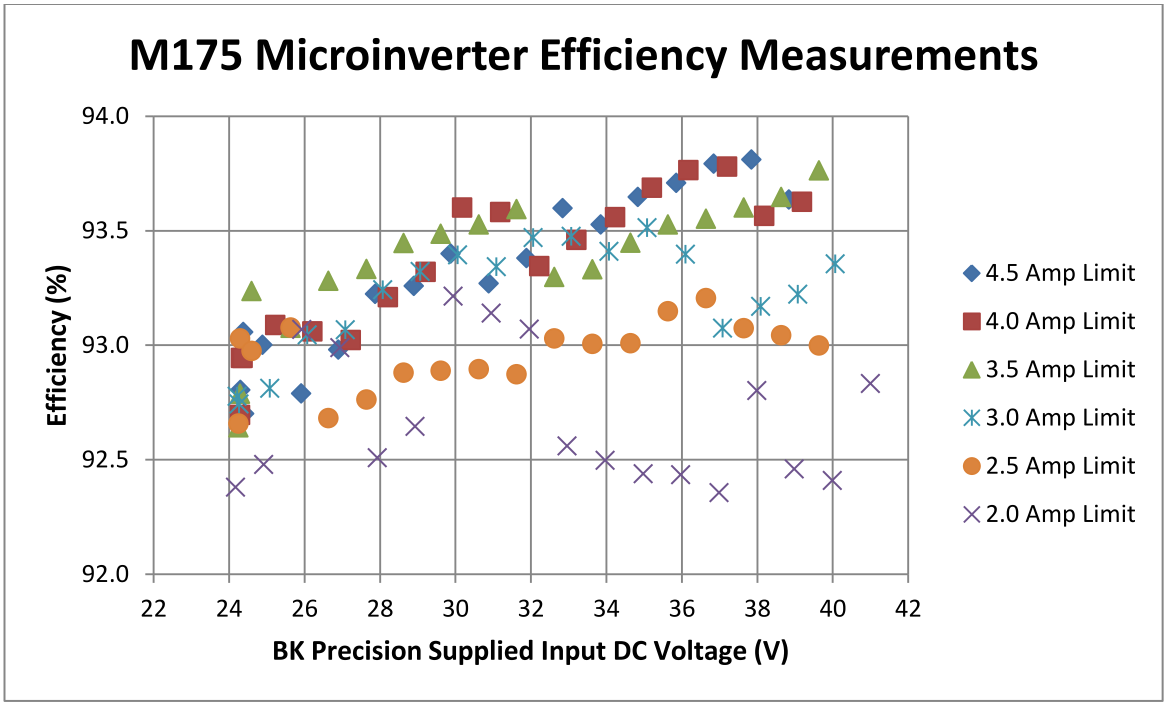


Figure 3-2: Scatter plot of the efficiency for set current limits of 2.0 A to 4.5 A across the M175's operating voltage range.

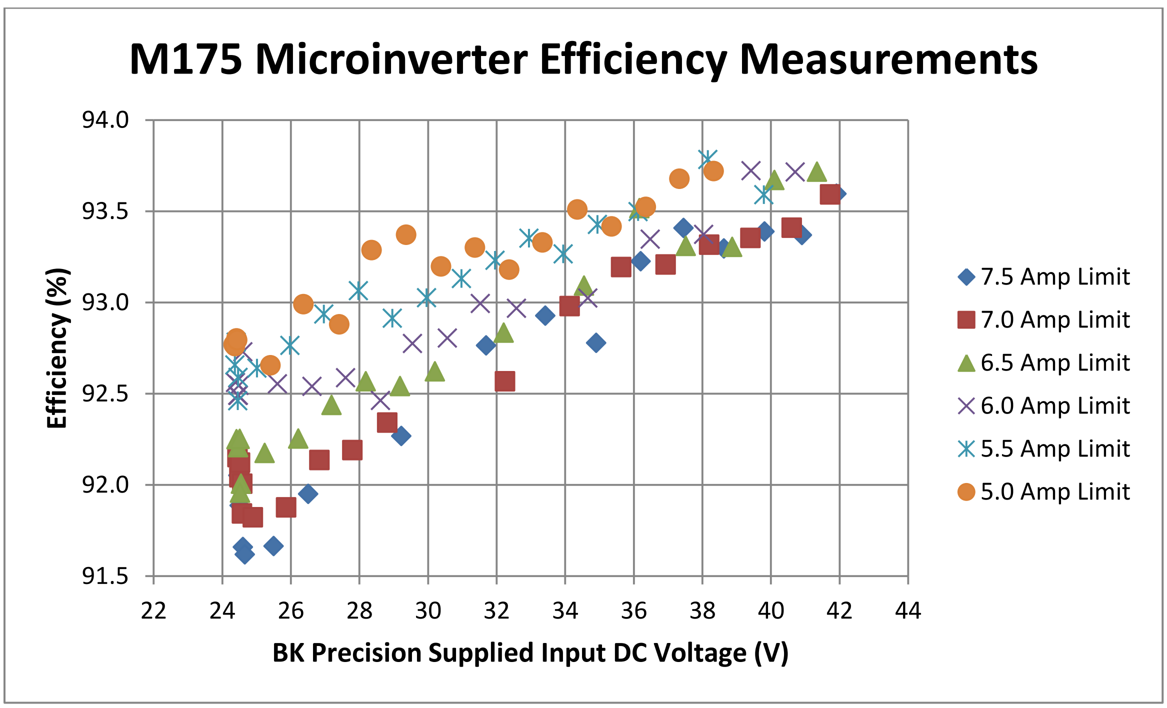


Figure 3-3: Scatter plot of the efficiency for set current limits of 5.0 A to 7.5 A across the M175's operating voltage range.

Note: Chapter 7 describes testing with the elliptical trainer, the Enphase M175 inverter, and an overvoltage protection circuit. Troubleshooting occurs after initial

testing, because the M175 inverter fails to produce AC power. Chapter 7.3.1 specifically details with attempting to clear a "Tripped GFI" condition in the M175 microinverter. Ultimately, we determine that the overvoltage protection circuit failed to protect the M175 inverter from overvoltage conditions, and no tripped GFI condition occurred.

3.2.2 Results of Enphase M215 Efficiency Testing

Appendix A.2 contains data tables for M215 efficiency testing. The tables that collect data from a DC input current limit of 0.5 A to 2.5 A contain three efficiency columns: Low, High, and AVG. The "Low-efficiency" column compares the lowest measured output power to the lowest supplied input power. The "High-efficiency" column compares the peak measured output power with the peak supplied input power, and the AVG column averages the two calculated efficiencies. For a set input current up to 2.5 A, the voltages and currents tend to vary at the M215's input and output for each test level voltage. Because of this, the M215 inverter has a calculated range of efficiencies for each test level voltage. While the overall efficiency averages to about 94.4%, some test level voltages have a "Low-efficiency" that calculates above 100%. An efficiency calculation above 100% occurs for a particular set level voltage when the power meter yields an output power that exceeds the product of the DC power source's supplied voltage and current. When testing with a DC input current limit set to 2.5 A or lower, the BK Precision DC source outputs a fluctuating voltage and current. Often, the supplied current quickly drops to the minimum current reported in a table, then rises up to the maximum current allowed by the set limit. When the supplied input current drops to a measured minimum, the supplied voltage does not decrease to a minimum voltage as well. Rather, the supplied input voltage may increase to the maximum voltage reported in

a table when the input current drops. In the data tables, the low input power calculations consider the low input voltage measurement with the low input current measurement. However, acquiring these data points does not occur simultaneously, which explains the occurrences of some efficiency calculations exceeding 100%. Figure 3-4 and Figure 3-5 below show scatter plots of the average efficiency calculations across the microinverter's operating range for lower current limits.

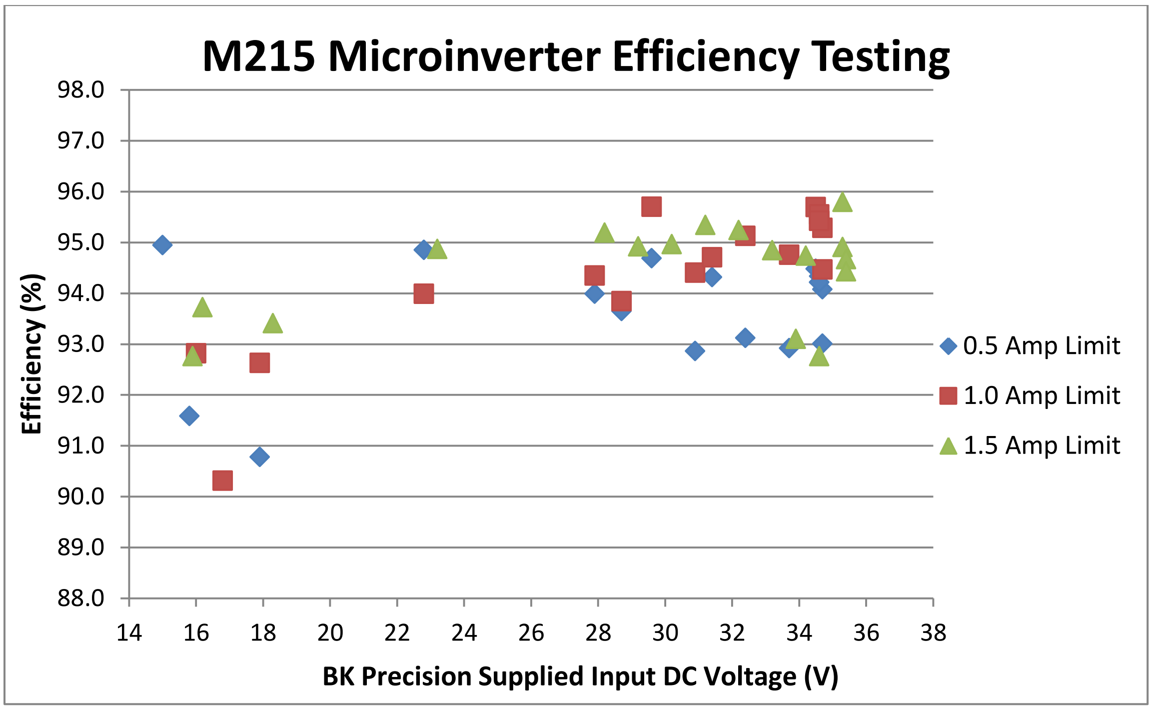


Figure 3-4: Efficiency scatter plot for set current limits of 0.5 A to 1.5 A across the M215's operating voltage range.

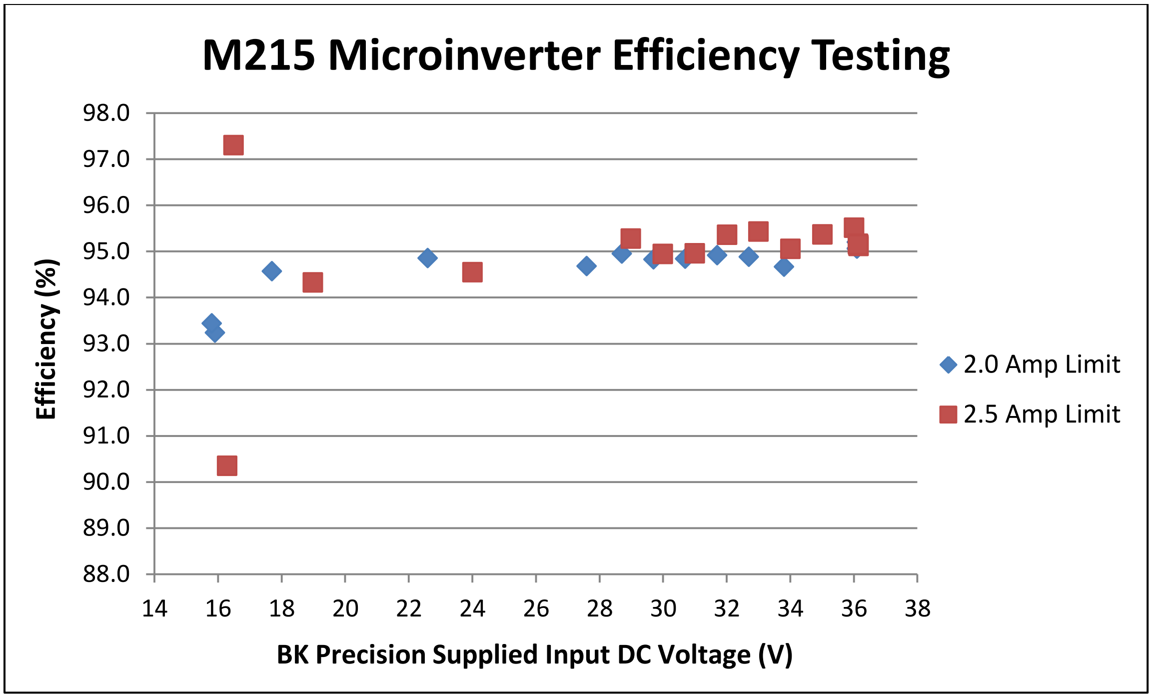


Figure 3-5: Efficiency scatter plot for set current limits of 2.0 A and 2.5 A across the M215's operating voltage range.

Variations in input and output voltages, currents, and powers cease for set current limits greater than 3.0 A. The M215 produces AC power at an efficiency of 94.6% across its operating voltage range for a set current limits of 3.0 A to 5.0 A. This varies from the ideal efficiency of 96.5 % by 2.0%. For a set current limit ranging from 5.5 A to 7.5 A, the M215 produces AC power with a 93.8% average efficiency across its operating range. Figure 3-6 and Figure 3-7 depict the scatter plots of the M215's efficiency measurements for these current limits over the inverter's operating range. The M215 inverter produces AC power most efficiently when supplying a DC input voltage greater than 26 V. See Appendix A.2 for the full set of data tables organizing recorded measurements and efficiency calculations.

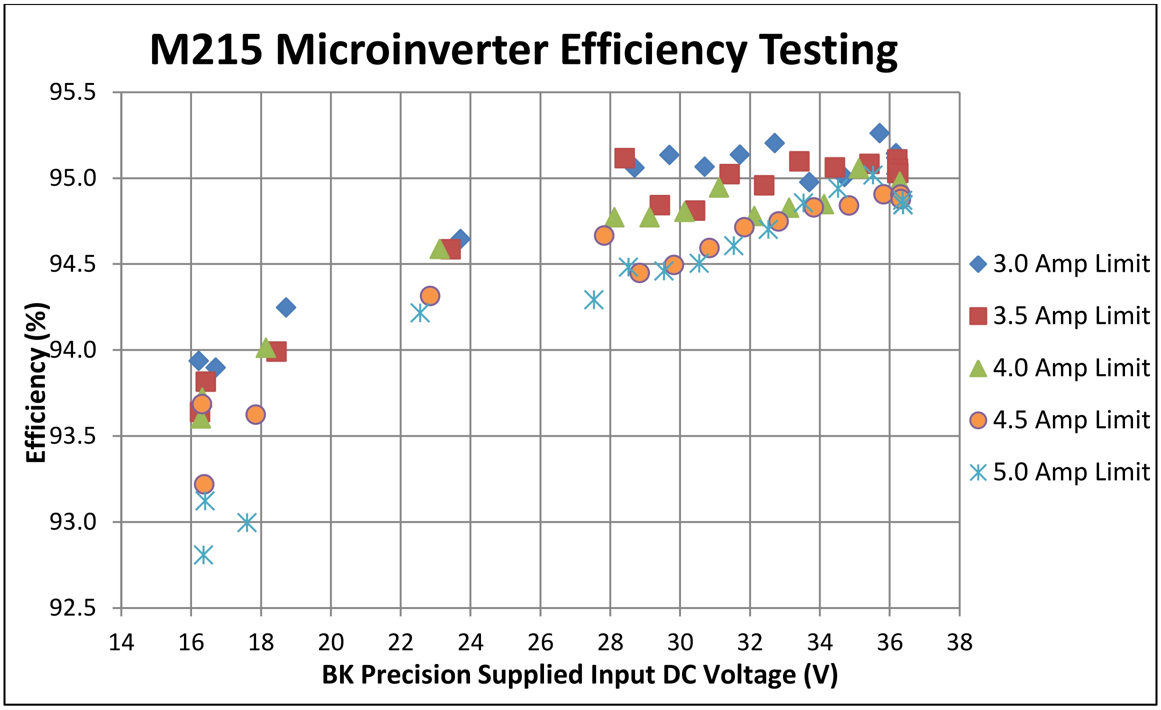


Figure 3-6: Scatter plot of the efficiency for set current limits of 3.0 A to 5.0 A across the M215's operating voltage range.

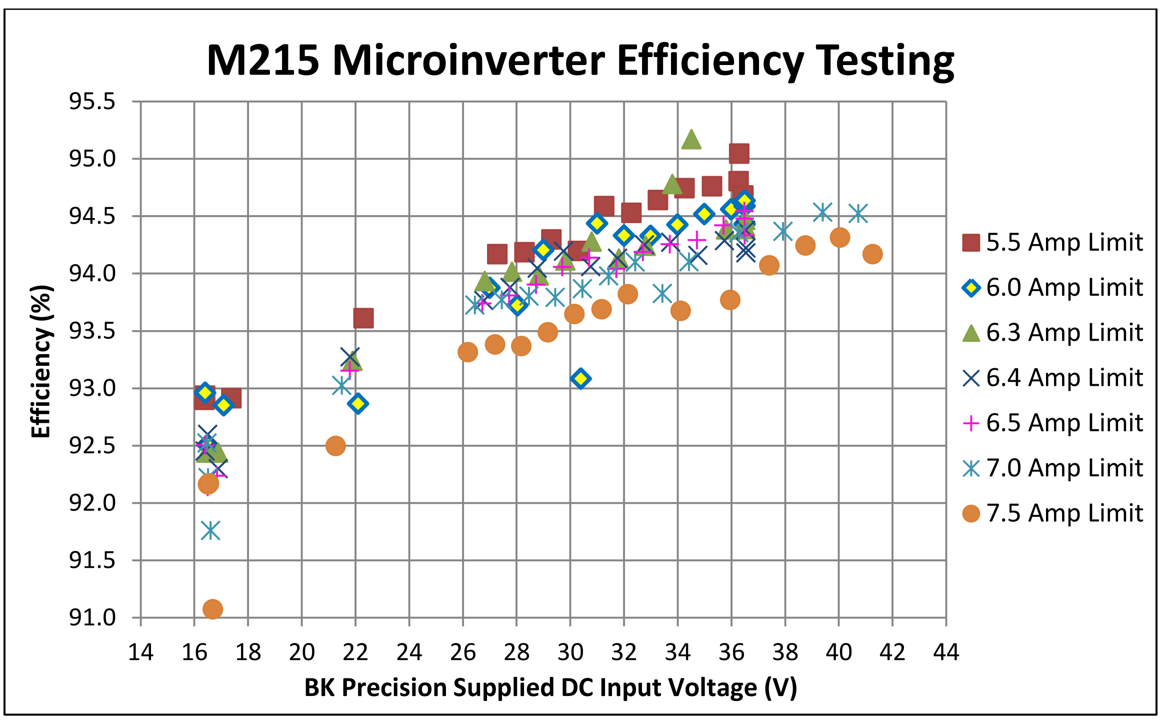


Figure 3-7: Scatter plot of the efficiency for set current limits of 5.5 A to 7.5 A across the M215's operating voltage range.

3.2.3 Troubleshooting the M215 Inverter

Over the course of testing involving the Enphase M215 microinverter, we encounter a couple issues that require troubleshooting the microinverter. The issues we encounter include the M215 failing to produce power, as well as the inverter registering a GFI Tripped condition. Both of these conditions require intervention before testing with the M215 can continue. When troubleshooting the M215, one may consult page 27 of Enphase's "Installer's Guide to Troubleshooting and Enphase System" wherein the guide details the different status LEDs and troubleshooting options if necessary [14].

The status LED on the M215 indicates whether the inverter functions properly. The microinverter LED flashes green about 90 seconds into startup [12]. Post startup, a flashing green LED indicates normal inverter operation that also receives messages from the Enphase Envoy [12]. An orange LED also indicates the inverter operates normally, but cannot communicate with the Envoy. Prior to troubleshooting, we did not have access to an Envoy and thus saw an orange LED for normal operation. The M215 indicates the need for troubleshooting when the status LED flashes red, or emits a solid red light. A flashing red LED indicates the inverter does not sense the utility grid, while a solid red LED indicates a tripped GFI condition [14]. The following subsections describe troubleshooting techniques used to fix the M215 microinverter.

3.2.3.1 Blinking Red LED

An Enphase M215 microinverter emitting a flashing red status LED indicates the microinverter fails to connect to the utility grid. Usually, this occurs when connected to a utility grid not within the voltage or frequency specifications [12]. A break in a wire connecting the microinverter's output to the grid may also cause this error.

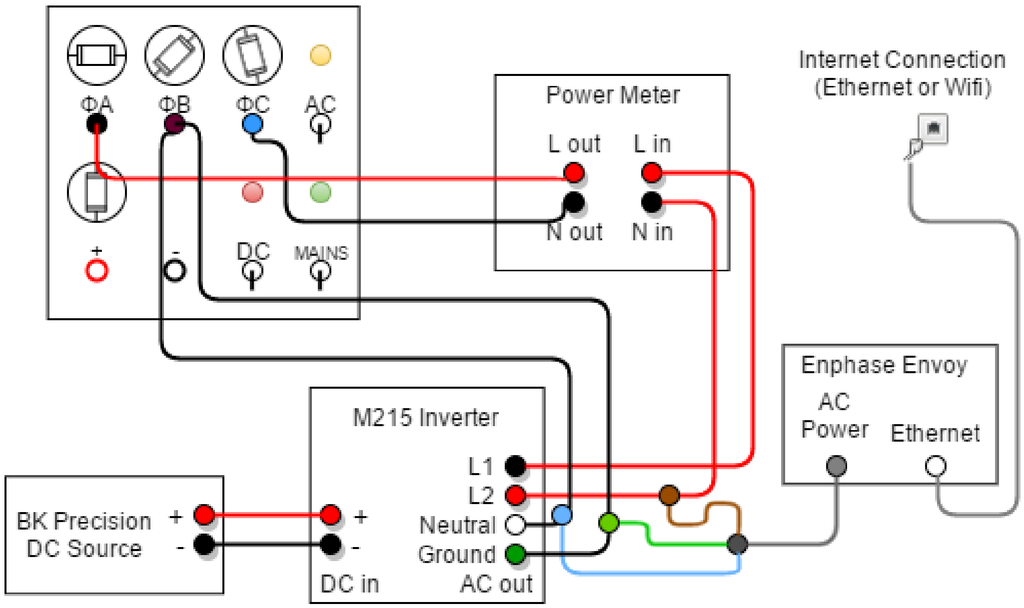


Figure 3-8: Wiring diagram showing a test setup for troubleshooting the Enphase M215 microinverter with an Enphase Envoy connected to the AC grid.

3.2.3.2 Solid Red LED

An M215 inverter emitting a solid red LED indicates a tripped GFI condition. Clearing a tripped GFI condition requires connecting an Enphase Envoy to the M215 inverter's AC output and establishing an internet connection [15]. Figure 3-8 above depicts a wiring diagram when troubleshooting the M215 microinverter with the Enphase Envoy. Once connected, the Envoy reports a tripped GFI condition, and a user can then clear the tripped GFI condition through the Envoy's interface [15]. The LED remains red until the condition clears. Enphase's "Installer's Guide to Troubleshooting and Enphase System" explains how to clear the condition [14]. The following procedure explains how to clear a tripped GFI condition on the M215 inverter.

1. First, connect the M215 inverter to a DC power source, the AC power grid, and an Enphase Envoy unit as shown in Figure 3-8 above. Energize the AC branch and let the DC source supply 35 V and 3 A. Wait for the LED on the inverter to light up red after the inverter completes startup.

2. To access the Envoys' interface, enter the Envoys displayed IP address (129.65.138.227) in the address bar of a web browser. This leads to the Envoy's home page.
3. Click on the Administration page.
4. In the menu on the left side of the screen, click on "Device Conditions and Controls".
5. Click on the serial number for the M215 inverter showing a "clear-gfi" control flag. Do NOT click on any of the boxes under "select" [14]
6. Check the box that says "clear" under "clear-gfi" and click the "send command" button [14]. Do NOT select any other flags unless recommended by Enphase [14]

Note: See Appendix C for pictures that correspond to the steps for clearing a tripped GFI condition.

After sending the command to clear the GFI, the M215 inverter should have a blinking green LED and generating AC power within five minutes. Sometimes, it may take longer for the condition to clear. If the condition does not clear after sending the command through the Envoy's interface, de-energize the AC branch, the power down the DC source, and try again. If the Envoy fails to clear a tripped GFI condition in the M215, contact Enphase Energy customer support [14].

After successfully characterizing the efficiencies of the M175 and M215 microinverters, we see that the Enphase M215 inverter tends to produce AC power more efficiently than the M175 model. The next chapter describes similar efficiency measurements on the DC-DC converters in the EHFEM project, and compares results with their respective data sheets.

CHAPTER 4: DC-DC CONVERTERS: VICOR V28A36T200BL2 AND CUI VHK200W-Q48-S28

4.1 Introduction

The EHFEM project utilizes a DC-DC converter to help provide a stable DC input voltage to the microinverter, which converts DC power into AC power [2]. The DC-DC converter receives a variable DC voltage from the output of the Precor EFX 546i elliptical trainer, which supplies power to the EHFEM system. The DC voltage the elliptical generates varies in magnitude depending on the user's running pace and the machine's resistance setting [9]. Integrating a DC-DC converter in the EHFEM system can ensure the DC voltage magnitude does not fall below the inverter's operating range. This can then allow the microinverter to convert DC power into AC power over greater ranges of elliptical machine resistance settings and user paces. When converting DC power into AC power, the microinverter converts power delivered at voltages within a maximum power point tracking (MPPT) range. The Enphase M175 microinverter and Enphase M215 microinverter have a peak power tracking voltage ranges of 25-40 V and 27-39 V [11, 13]. However, the voltage and current produced from the elliptical varies, and the elliptical may generate power at voltages outside a microinverter's MPPT range. Including a DC-DC converter allows for harvesting AC power from DC power delivered at voltages outside the microinverter's MPPT range. Including a DC-DC converter in the system, however, can lower the overall power efficiency of the EHFEM project.

Although we lack a DC-DC converter designed specifically for the EHFEM project, we have an off-the-shelf Vicor V28A36T200BL2 DC-DC Converter available for testing. In their senior project report, Lum et al. test and troubleshoot the Vicor DC-

DC converter [1]. They report the Vicor shuts down when receiving an input voltage exceeding 36 V, or when a microinverter draws a current greater than 5.56 A on the Vicor's output [1]. Despite this, the converter can still operate when testing with a Precor elliptical trainer, but under limited test conditions [1].

This chapter determines the efficiency of available DC-DC converters across their operating range. The ratio of the DC-DC converter's output power to supplied input power determines the efficiency. Available DC-DC converters include the Vicor DC-DC converter and a CUI VHK200W-Q48-S28 DC-DC Converter, another off-the-shelf DC-DC converter. This converter has a wider input voltage range of 18-75V and a greater maximum output current of 7.14 A [17]. According to their data sheets, the Vicor and CUI converters have typical efficiencies of 82.6% and 87% [17, 18]. Testing follows a similar process to testing the efficiencies of the Enphase M175 and M215 microinverters in Chapter 3. A BK Precision high power source supplies and measures DC input power while a power meter measures the DC output voltage, current, and power. Unlike testing the microinverters, the DC-DC converters in this chapter output DC power to a 10 Ω nominal resistive load. This resistor must dissipate as much as 200 W of power and not burn out. When testing, we use a C300KR10E 10 Ω resistor, which can dissipate up to 300 W of power.

Before efficiency testing on the DC-DC converters can begin, we must prepare each converter with external components as specified in their data sheets [17, 18]. The following sections detail preparations for testing the DC-DC converters and the results of their respective efficiency tests. While the Vicor has a maximum input voltage of 36 V, we test for an input voltage up to 28 V since this resides in the peak efficiency range.

4.2 Vicor V28A36T200BL2 DC-DC Converter

4.2.1 Preparing the Vicor DC-DC Converter for Testing

For basic operation, the DC-DC converter requires external fusing, grounding, and bypass capacitors [17]. Connect capacitors to the DC-DC converter as depicted in Figure 4-1 below.

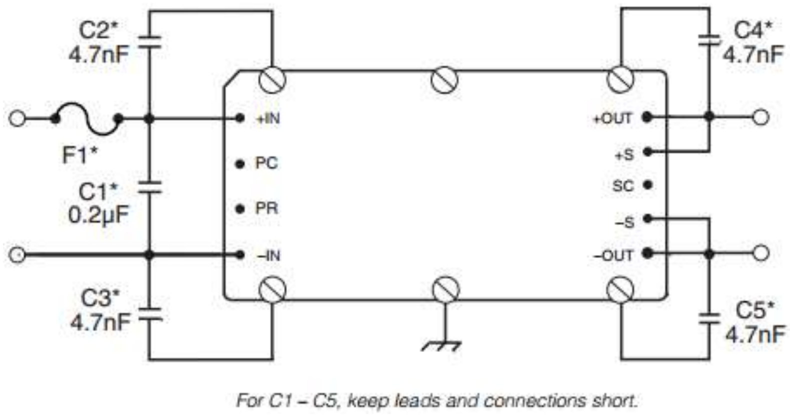


Figure 4-1: Basic module operation requires fusing, grounding, bypassing capacitors [17].

Several options exist for connecting the capacitors to the DC-DC converter, including soldering, wire wrapping, and using clips to maintain contact. Initial testing uses wire wrapping and alligator clips to connect the capacitors to the Vicor DC-DC converter. Figure 4-2 below shows how capacitor leads wrapped around the nodes of the Vicor DC-DC converter suffice as sufficient connections for initial testing. Alligator clip attachments from cables also help in securing connections. Note the use of electrical tape to secure capacitors leads to the converter's ground plane. The Vicor converter maintains this setup even in future tests that involve a microinverter, an overvoltage protection circuit, and an elliptical trainer. With the Vicor DC-DC converter prepared, efficiency testing can begin.

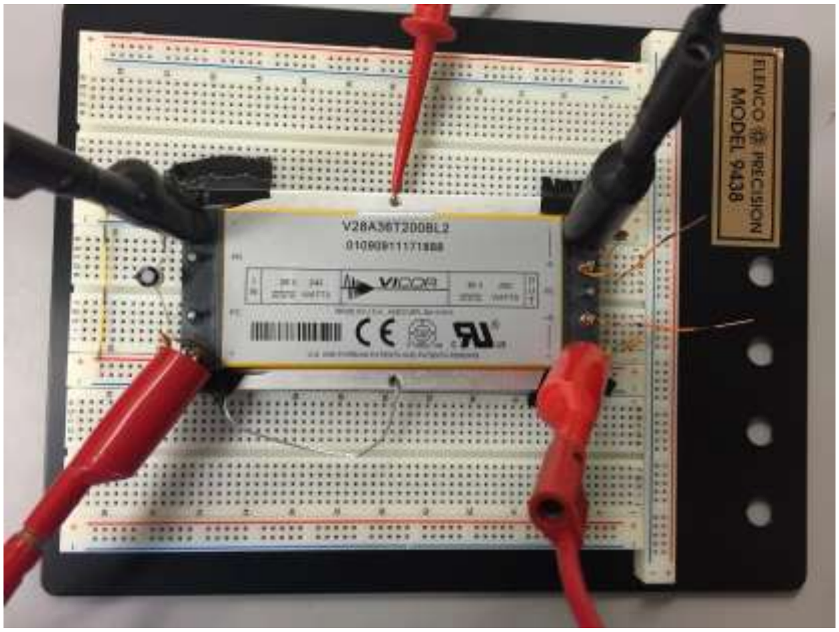


Figure 4-2: Picture of the Vicor V28A36T200BL2 DC-DC converter featuring a non-solder test setup. Secured to a breadboard, the Vicor has external grounding and bypass capacitors to allow basic operation. Red cables and alligator clips denote the positive terminals while black cables and alligator clips denote the negative terminals.

Figure 4-3 depicts a wiring diagram of the Vicor DC-DC converter connected to available test equipment. Refer to Appendix B.4 for a detailed test setup and procedure for testing the Vicor DC-DC converter's efficiency.

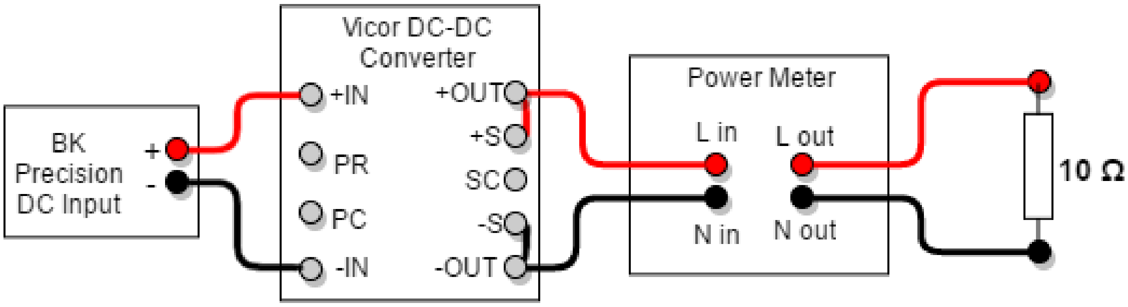


Figure 4-3: Wiring diagram for testing Vicor V28A36T200BL2 DC-DC converter with resistive load.

4.2.2 Results of Vicor DC-DC Converter Efficiency Testing

Table 4-1 below tabulates the data recorded for testing the efficiency of the Vicor DC-DC converter. With a 10 Ω resistive load connected at the output, the Vicor begins producing an output voltage when setting the input voltage to 10 V. At this voltage, the source supplies 1.61 A, and the Vicor outputs about 10.3 V and 1.04 A. Further

increasing the set input voltage on the DC source further increases the input current, output current, and output voltage. In addition, for a set voltage ranging from 12 V to 21 V the BK Precision supplies an actual voltage less than the set voltage level. These remain true until the BK Precision outputs 22 V. Setting the source voltage to output 22 V and beyond results in the Vicor DC-DC converter outputting an average of 35.4 V and 3.53 A. At this point, the Vicor produces a maximum output power of 125.1 W. Increasing the input voltage further beyond this point causes the input current to decrease. This occurs because the input power and converted output power remain relatively the same for the remaining input voltage settings. For a DC input voltage range of 22 V to 28 V, the Vicor receives an average of 156.5 W and outputs an average of 124.9 W leading to an average efficiency of 79.8%. This efficiency differs from the Vicor's typical efficiency of 82.6% by a 3.4% error [17]. Upon reflection, this lower efficiency arises due to incorrect means of measuring the output voltage with a power meter instead of a digital multimeter. Vicor efficiency exceeds 82.6% when the supplied input voltage equals 15.75 V. However, Vicor efficiency calculations also vary the most by 6.2% at this voltage. The Vicor receives a maximum input current of 7.10 A. At no point does the DC-DC converter receive an input current equal to the DC source's 7.5 A current limit. When the Vicor first outputs power at an input voltage of 10 V, the DC-DC converter emit a buzzing noise, which arises from the converter's internal switching. This buzzing continues until the input voltage equals 22.0 V, coincidentally when the power meter values cease fluctuating. Insufficient current from the BK Precision for voltages under 22 V leads to the converter making a buzzing noise.

Table 4-1: Vicor DC-DC Converter Efficiency Test Data

DC input current set to 7.5A													
Set	BK Precision (DC)			Power Meter (DC)						Efficiency			
Test Level (V)	Vin (V)	Iin (A)	Pin (W)	Vout low (V)	Vout high (V)	Iout low (mA)	Iout high (mA)	Pout low (W)	Pout high (W)	LOW (%)	HIGH (%)	AVG (%)
2	2.00	0.001	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	4.00	0.033	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	6.00	0.013	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	8.00	0.010	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	10.00	1.61	16.1	10.27	10.31	1.04	1.04	10.65	10.74	66.2	66.8	66.5
12	11.53	2.75	31.7	15.04	15.11	1.52	1.52	22.8	23.0	71.9	72.5	72.2
14	12.71	3.08	39.2	16.88	16.96	1.70	1.71	28.7	29.0	73.3	74.1	73.7
16	13.51	3.52	47.6	18.76	18.85	1.89	1.90	35.4	35.8	74.5	75.3	74.9
18	14.26	4.06	57.9	20.91	20.96	2.10	2.11	44.1	44.3	76.2	76.4	76.3
20	15.06	4.89	73.7	23.80	23.89	2.40	2.41	57.0	57.3	77.4	77.8	77.6
21	15.75	5.87	92.4	27.12	27.19	2.72	2.73	72.3	78.0	78.2	84.4	81.3
22	22.00	7.10	156.2	35.39	35.39	3.54	3.54	125.1	125.1	80.1	80.1	80.1
23	22.99	6.79	156.0	35.40	35.40	3.53	3.53	124.9	124.9	80.1	80.1	80.1
24	24.00	6.51	156.2	35.41	35.41	3.53	3.53	124.9	124.9	80.0	80.0	80.0
25	25.00	6.26	156.4	35.41	35.41	3.53	3.53	124.9	124.9	79.9	79.9	79.9
26	26.00	6.02	156.6	35.42	35.42	3.53	3.53	124.8	124.8	79.7	79.7	79.7
27	27.00	5.81	156.8	35.42	35.42	3.52	3.52	124.8	124.8	79.6	79.6	79.6
28	28.00	5.61	157.2	35.42	35.42	3.52	3.52	124.7	124.7	79.3	79.3	79.3

For set level voltages of 21 V and below, the converter fails to regulate the output to 36 V. This occurs due to insufficient current supplied by the BK Precision DC source. When testing, the BK Precision has a set current limit of 7.5 A as a precaution to prevent damaging the converter. For a supplied input voltage of 15 V, the DC source would have to supply about 10 A for the Vicor converter to regulate a 36 V output, which exceeds then supplied current limit. Because the Vicor converter has a 10 Ω resistive load, a 36 V output would cause 3.6 A of current to flow through the resistor leading to about 130 W of power dissipation. A power dissipation this great requires more power supplied to the converter. This in turn calls for a supplied current greater than the imposed limit for input voltages of 21 V or below. Changing the load can help to accurately characterize the Vicor's efficiency at lower input voltages. A resistive load of 20 Ω or greater would half

the output power dissipation, and thus requires half as much input current. An electronic load presents another option. Setting an electronic load to have a maximum load current of 1-2 A may mitigate the BK Precision from current limiting.

Figure 4-4 and Figure 4-5 plot the efficiency of the Vicor converter over the supplied input voltage and current range. Figure 4-4 shows the efficiency of the Vicor increases with an increasing supplied input voltage until the source supplies 24 V where a slight decrease occurs. The scatter plot shows the Vicor maintains a consistent efficiency for a supplied input voltage of 22-28 V. For supplied voltages below 16 V, Figure 4-4 plots lower efficiency calculations, because the Vicor DC-DC converter fails to output a constant voltage of 36 V. The scatter plot in Figure 4-5 shows the Vicor's efficiency increases with the supplied input current. The Vicor's efficiency varies least within the supplied input current range of 5.61-7.10 A. An outlier exists in both scatter plots of Figure 4-4 and Figure 4-5. This outlier corresponds to the set voltage level of 21 V on the DC source, which outputs an actual voltage and current of 15.75 V and 5.87 A. Both scatter plots include error bars to show variations in efficiency when they occur.

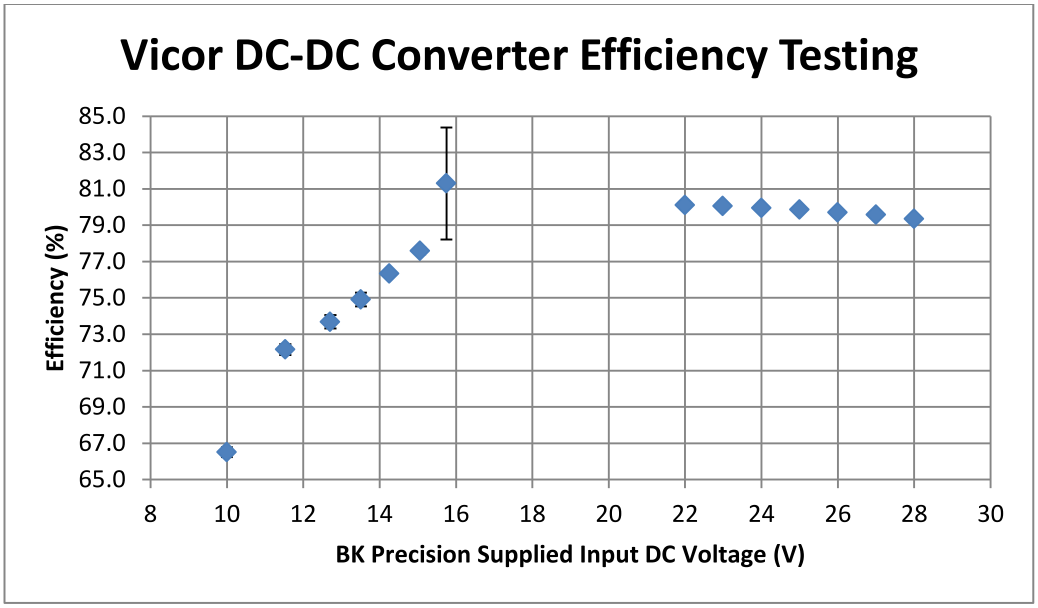


Figure 4-4: Scatter plot of Vicor DC-DC converter efficiency for a supplied input voltage range and 10 Ω load. Scatter plot includes error bars so show variation in input voltage and efficiency. The converter fails to regulate an output voltage of 36 V for supplied input voltages less than 22 V.

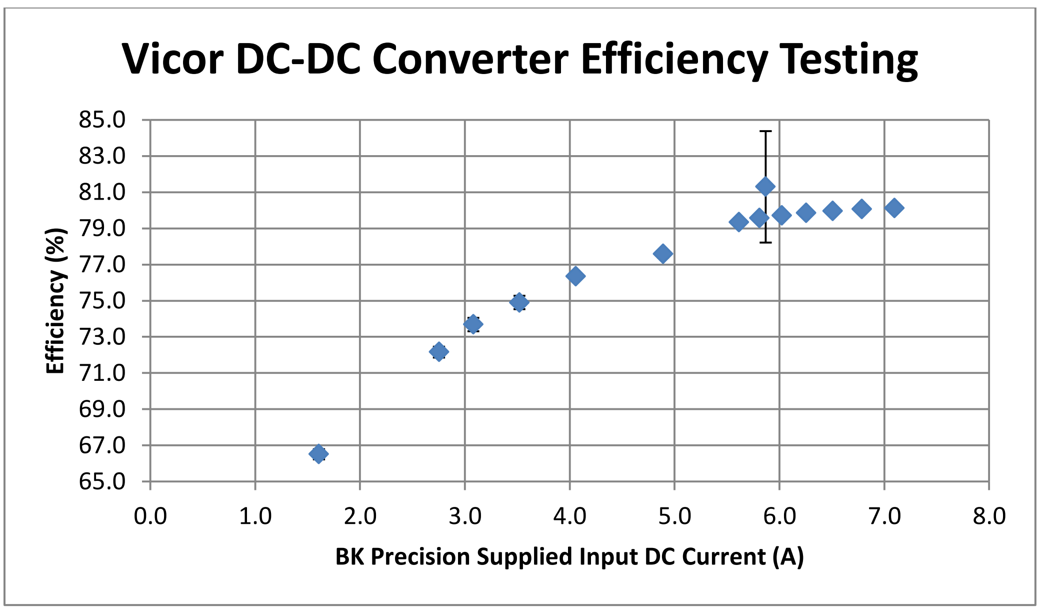


Figure 4-5: Scatter plot of Vicor DC-DC converter efficiency test for a supplied input current range and 10 Ω load. Scatter plot includes error bars so show variation in input voltage and efficiency.

Results of testing show the Vicor converter proves more effective at regulating a DC voltage for input voltages greater than 21 V. For the Vicor converter to output a constant 36 V means the converter's load must have a sufficient impedance to avoid

needing a high input current. Either that or the Vicor converter must have a power source that can consistently supply a voltage exceeding 22 V.

4.3 CUI VHK200W-Q48-S28 DC-DC Converter

4.3.1 Prepping the CUI DC-DC Converter for Testing

For basic operation, the DC-DC converter requires a 47 μF external input capacitor for filtering and a 100 μF external output capacitor to limit output ripple. The converter also needs a 12 μH external inductor to prevent large influxes of current from potentially damaging the converter [18]. The input capacitor should have a minimum voltage rating of 100 V, and the output capacitor should have a minimum voltage rating of 50 V. Connect the capacitors and inductor to the DC-DC converter as depicted in Figure 4-6 below. Use Philips screwdriver to secure the inductor and capacitor to the DC-DC converter. With the CUI DC-DC converter properly prepared, efficiency testing can begin.

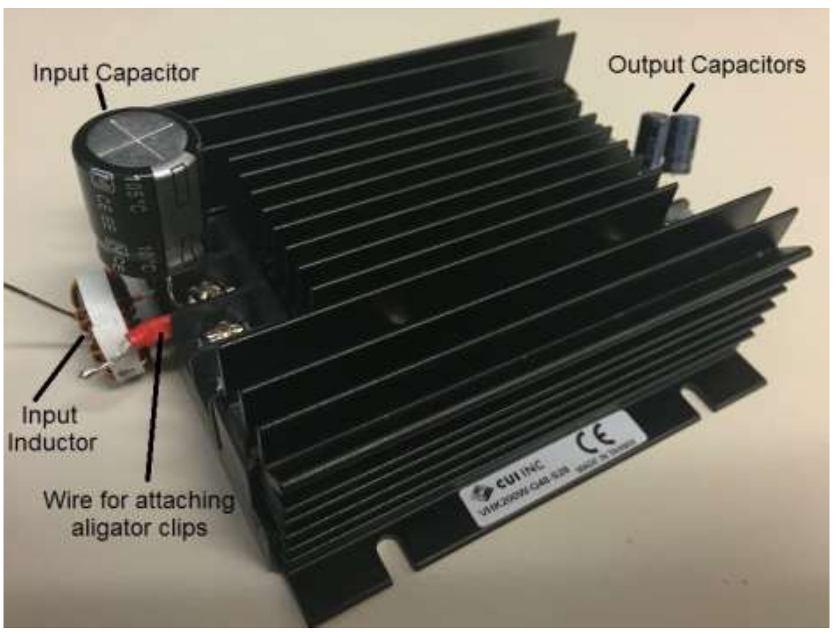


Figure 4-6; CUI DC-DC Converter with external inductor and capacitors attached.

Figure 4-7 shows a simple wiring diagram of the Vicor DC-DC converter connected to available test equipment. Refer to Appendix B.4 for a detailed test setup and procedure for testing the CUI DC-DC converter's efficiency.

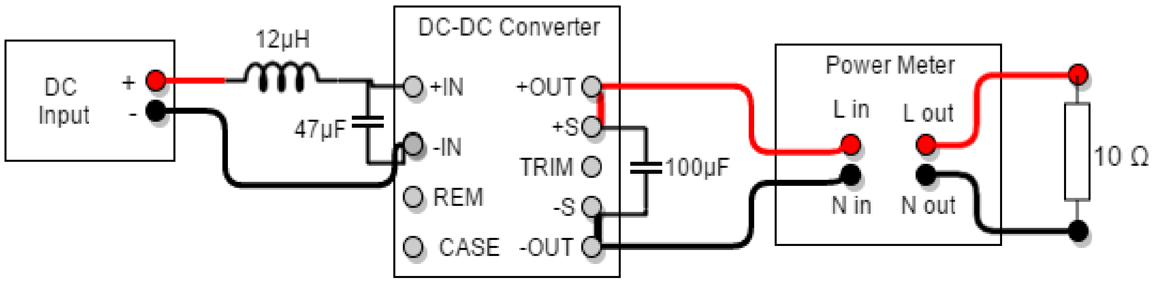


Figure 4-7: Wiring diagram for testing CUI VHK200W-Q48-S28 DC-DC converter with resistive load.

4.3.2 Results of CUI DC-DC Converter Efficiency Testing

Table 4-2 collects measurements for the CUI's efficiency testing. When supplying 26.01 V, the BK Precision DC source outputs 3.27 A for a total power of 85.13 W. Meanwhile, the power meter measures 27.34 V, 2.74 A, and 74.72 W. Unlike the Vicor DC-DC converter, as the supplied input voltage increases, the input current gradually decreases. As the input voltage increases, the output voltage, current, and power see little change.

Table 4-2: CUI DC-DC Converter Efficiency Test Data

DC input current set to 7.5A							
Test Level (V)	BK Precision DC Source (DC)			Electronic Load (DC)			Efficiency (%)
	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (A)	P_{out} (W)	
26	26.01	3.27	85.13	27.34	2.73	74.72	87.8
27	27.00	3.15	84.94	27.33	2.73	74.67	87.9
28	28.00	3.03	84.84	27.32	2.73	74.61	87.9
29	29.00	2.93	85.00	27.36	2.73	74.80	88.0
30	30.00	2.84	85.17	27.36	2.74	74.83	87.9
31	31.00	2.73	84.63	27.28	2.73	74.37	87.9
32	32.00	2.64	84.54	27.27	2.73	74.34	87.9
33	33.00	2.56	84.48	27.29	2.73	74.45	88.1
34	34.00	2.48	84.42	27.28	2.73	74.39	88.1
35	35.00	2.41	84.35	27.28	2.73	74.39	88.2
36	36.00	2.34	84.35	27.29	2.73	74.45	88.3
37	37.00	2.28	84.36	27.31	2.73	74.56	88.4
38	38.00	2.23	84.63	27.39	2.74	74.99	88.6
39	39.00	2.17	84.59	27.39	2.74	74.99	88.7
40	40.00	2.12	84.64	27.40	2.74	75.05	88.7
41	41.00	2.07	84.67	27.40	2.74	75.05	88.6
42	42.00	2.02	84.70	27.40	2.74	75.05	88.6
43	43.00	1.97	84.75	27.40	2.74	75.05	88.5
44	44.00	1.93	84.79	27.40	2.74	75.05	88.5
45	45.00	1.89	84.83	27.40	2.74	75.05	88.5
46	46.00	1.85	84.92	27.40	2.74	75.05	88.4
47	47.00	1.81	84.98	27.40	2.74	75.05	88.3
48	48.00	1.77	85.06	27.40	2.74	75.05	88.2
49	49.00	1.74	85.11	27.40	2.74	75.05	88.2
50	50.00	1.70	85.20	27.40	2.74	75.05	88.1
51	51.00	1.67	85.32	27.40	2.74	75.05	88.0
52	52.00	1.64	85.44	27.40	2.74	75.05	87.8
53	53.00	1.61	85.49	27.40	2.74	75.05	87.8
54	54.00	1.59	85.64	27.40	2.74	75.05	87.6
55	55.00	1.56	85.75	27.40	2.74	75.05	87.5
56	56.00	1.53	85.90	27.40	2.74	75.05	87.4
57	57.00	1.51	85.96	27.40	2.74	75.05	87.3
58	58.00	1.48	86.07	27.41	2.74	75.10	87.3
59	59.00	1.46	86.20	27.41	2.74	75.10	87.1
60	60.00	1.44	86.28	27.41	2.74	75.10	87.0
61	61.00	1.42	86.44	27.41	2.74	75.10	86.9

The CUI emits an audible high-pitched noise when supplied 26 V. The noise progressively decreases in pitch and volume as the input voltage increases. The noise sounds very faint when the input voltage reaches 39 V, and sounds less audible over ambient noise for input voltages greater than or equal to 43 V. The noise from the converter may arise from its internal components and switching within the DC-DC converter.

Figure 4-8 and Figure 4-9 show plots of the CUI DC-DC converter's efficiency over the supplied input voltage and current range. The efficiency of the CUI DC-DC converter tends to increase with the input voltage until 40 V where the efficiency follows a decreasing trend with an increasing voltage. This decreasing trend occurs because the input power increases slightly as the supplied input voltage continues to increase, but the CUI outputs a constant power. A similar pattern occurs when comparing the efficiency to the supplied input current. The CUI's efficiency increases with the input current, but starts to decrease after the supply current equals 2.17 A. Within this voltage range, the CUI has an average efficiency of 88.0%, exceeding the typical 87% efficiency in the data sheet by an error of 1.1% [18]. Unlike the efficiency plots of the Vicor converter, the efficiency plots for the CUI do not contain error bars or any prominent outliers.

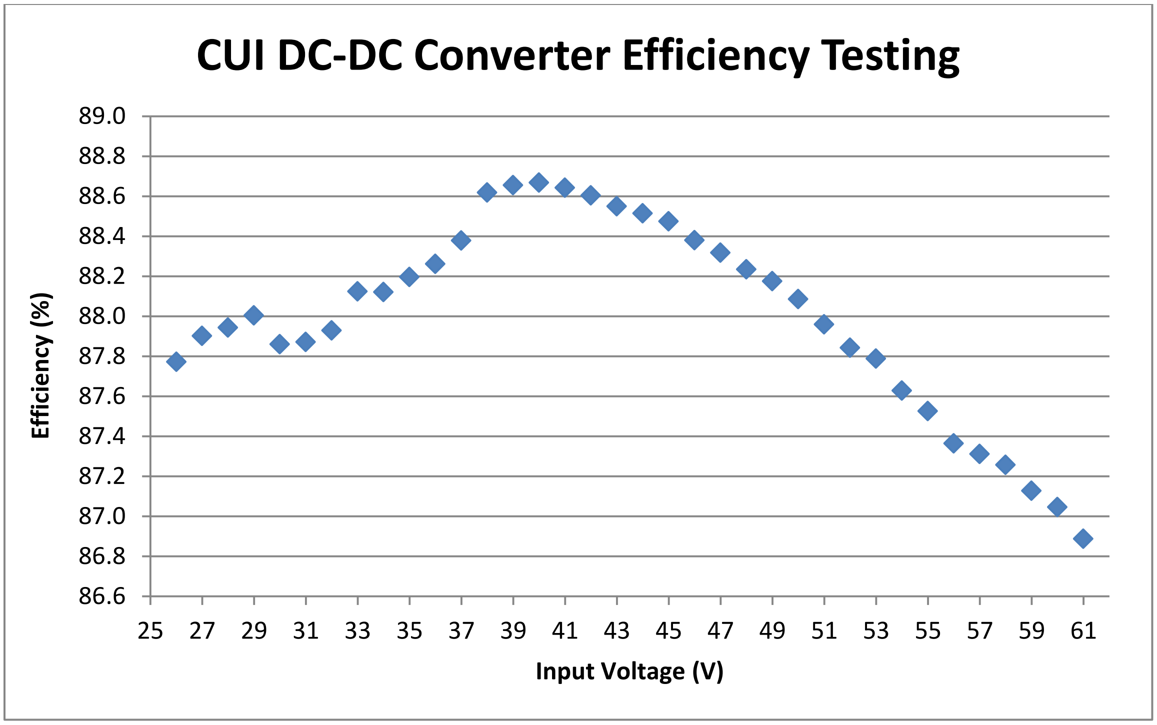


Figure 4-8: Scatter plot of CUI DC-DC converter efficiency \test for a supplied input voltage range and 10 Ω load.

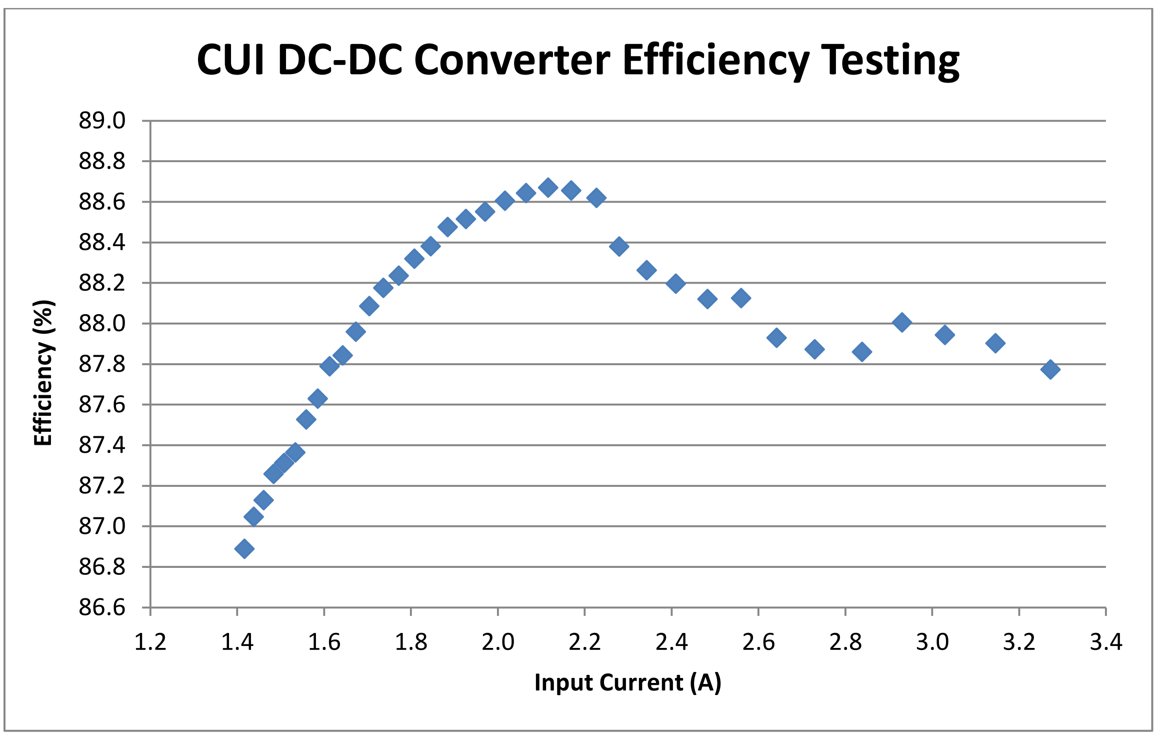


Figure 4-9: Scatter plot of CUI DC-DC converter efficiency test for a supplied input current range and 10 Ω load.

Note that Appendix A.3 contains a data table for a previous efficiency test on the CUI DC-DC converter for this report. That previous test session used a programmable electronic load set to 10 Ω instead of a resistive load. For supplied input voltages of 26-28 V, the CUI's efficiency calculates above 100%. Measurement errors induced by the power meter or power source may induce this error. Incorrectly measuring the CUI input and output voltages may also cause this error. Connecting digital multimeters directly to the contacts of the CUI to measure the input and output voltages instead of relying on the power meter and power supply would yield more accurate measurements and calculations. Table A-31 shows that when supplying 26 V, the BK Precision DC source outputs 2.81 A for 73.06 W of power. Meanwhile, the power meter measures 27.44 V, 2.75 A, and 75.3 W. Re-testing the CUI DC-DC converter's efficiency results with the data seen in this chapter.

The following chapter discusses the overvoltage protection circuit previously designed for this thesis [6]. In the chapter, we verify the overvoltage protection circuit still functions while modifying the circuit to improve IGBT switching time when diverting excess power from the load.

CHAPTER 5: OVERVOLTAGE PROTECTION CIRCUIT

5.1 Introduction

Prior chapters discuss efficiency tests on available DC-DC converters and DC-AC microinverters. Chapter 3 tests the Enphase M175 and Enphase M215 microinverters by supplying a DC source to each inverter and measuring their power outputs to the AC grid with a power meter. Similarly, Chapter 4 tests the CUI VHK200W-Q48-S28 and Vicor V28A36T200BL2 DC-DC converters by supplying DC power and measuring the power output to a resistive load. With a set maximum limit on the supplied current, a BK Precision high power DC source supplies an input voltage over the operating range of each converter or inverter. Individual testing of each component allows one to verify each one operates within their specified ranges, and observe a component's behavior when converting DC power. Testing reveals that the inverters tend to pull the maximum allowed current from the DC source rather than the supplied voltage. On the other hand, Table 4-1 and Table 4-2 show that the DC-DC converters tend to pull the maximum supplied voltage from the DC source and not the current limit. For each microinverter, the BK Precision supplies a DC voltage over each microinverter's operating range for multiple set current limits. Meanwhile, the DC-DC converters have a set supplied current limit of 7.5 A. Chapter 5 discusses the overvoltage protection circuit (OVPC), which protects from overvoltage conditions by diverting excess power from a load through a diverting branch. This chapter also details design modifications that improve the OVPC's response time.

The efficiency tests conducted in Chapter 3 and Chapter 4 operate optimistically compared to tests involving the Precor elliptical trainer, which occur starting in

Chapter 7. Efficiency testing in Chapter 3 and Chapter 4 uses a high power DC source to provide a constant voltage and flow of current. However, testing with a Precor elliptical trainer supplying power introduces some complications. Instead of supplying a constant DC power, the elliptical trainer outputs voltage and current levels that vary with user operation. In addition, the elliptical frequently outputs high frequency voltage transients that can damage components connected to the elliptical. For these reasons, we require overvoltage protection when conducting any testing involving the Precor elliptical trainer.

5.2 Revisiting Overvoltage Protection

This session retests the overvoltage protection circuit (OVPC) designed for this thesis [6]. After ensuring the OVPC previously designed still functions, we then modify the OVPC to protect each the DC-DC converter at their specific voltage threshold. According to the report, the OVPC diverts power when the input voltage surpasses 50.75 V and ceases when the input voltage falls below 45 V [6]. The diverted power dissipates through a 10 Ω resistor and an IGBT. The output of an LT1017 comparator controls the switching on the IGBT's gate. The comparator utilizes a feedback resistor for hysteresis [6]. This should allow the power diversion to persist until the input voltage decreases to about 45 V. A voltage divider scales down the input voltage to the LT1017's positive input terminal and compares it with a 3.3 V reference voltage. A microcontroller with a 3.3 V output pin could supply the reference if available. This report, however, uses second voltage divider circuit to supply a 3.3 V reference voltage by scaling down the voltage on the 12 V rail supplied from an external DC source. Lastly, a capacitive bank

connects between the input and ground to filter out high frequency transient responses induced by the elliptical.

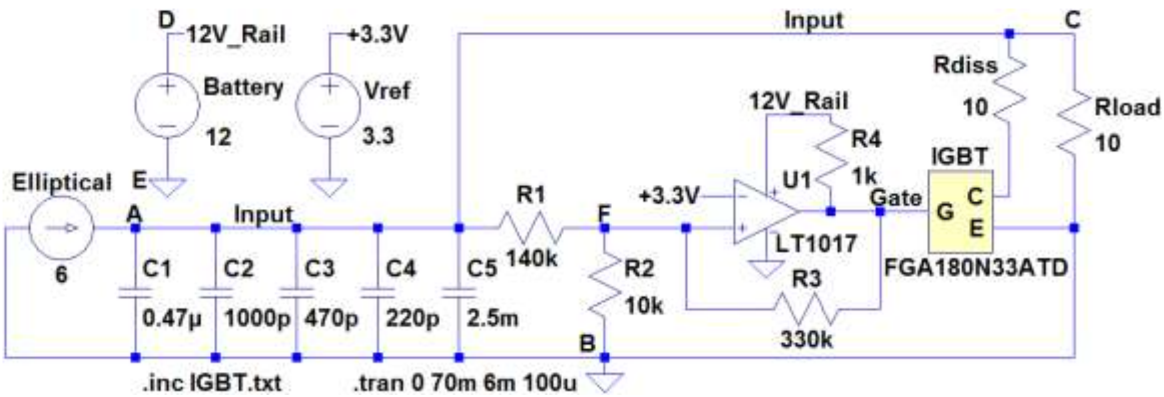


Figure 5-1: Circuit diagram of the overvoltage protection circuit designed for this thesis. On a breadboard, a 130 kΩ resistor and a 10 kΩ resistor make up the 140 kΩ resistance.

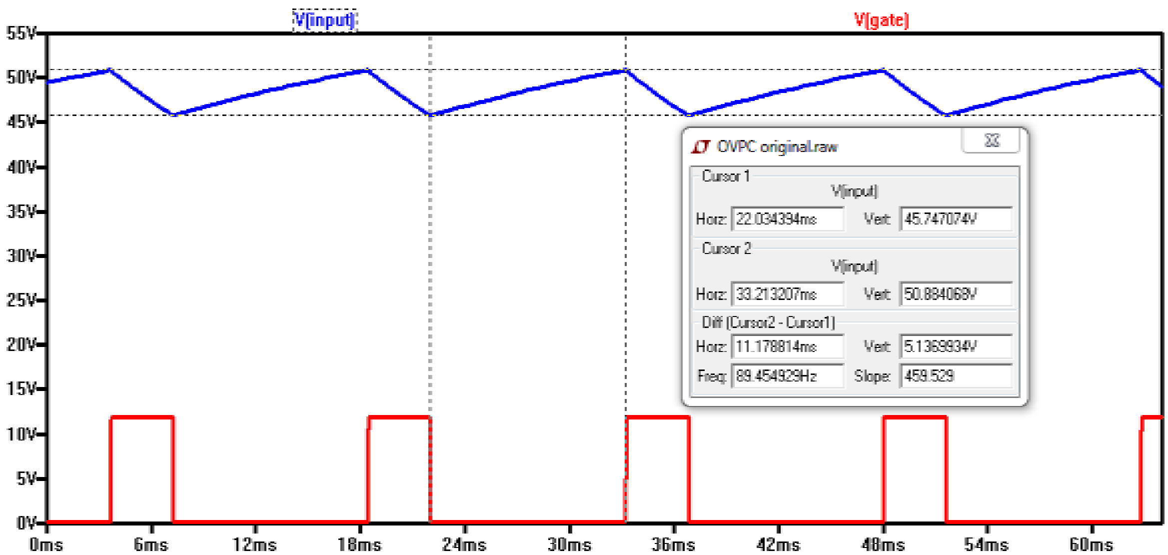


Figure 5-2: Simulation of the OVPC developed for this thesis. The simulation shows the OVPC divertspower through the IGBT when the input surpasses 50.8 V and ceases when the input voltage falls below 45.7 V.

Figure 5-1 depicts the circuit diagram of the described OVPC with a constant current source, and Figure 5-2 simulates the diagram. In conjunction with the capacitor bank, modeling the elliptical trainer with a constant current source should simulate an increasing voltage until the IGBT switches and diverts power. When diverting power, the capacitor bank should discharge and the input voltage should decrease until enough power dissipates and the IGBT switches off. The simulation in Figure 5-2 shows that the

OVPC diverts excess power when the input voltage surpasses 50.8 V and ceases diverting excess power when the input voltage decreases below 45.7 V. Testing should show the OVPC diverts and ceases diverting excess power at these voltage inputs. Once verifying the OVPC functions, we design and simulate new OVPCs in LTspice for the DC-DC converters. Then, we modify the OVPC previously designed to fit the parameters of the Vicor converter in section 5.2.2. In section 5.2.3, we construct another OVPC for the CUI converter using parts left over from the senior project. For this test session, we lack access to the Atmel ATSAM4SD32C microcontroller, and must supply a 3.3 V reference voltage by dividing down the 12 V rail.

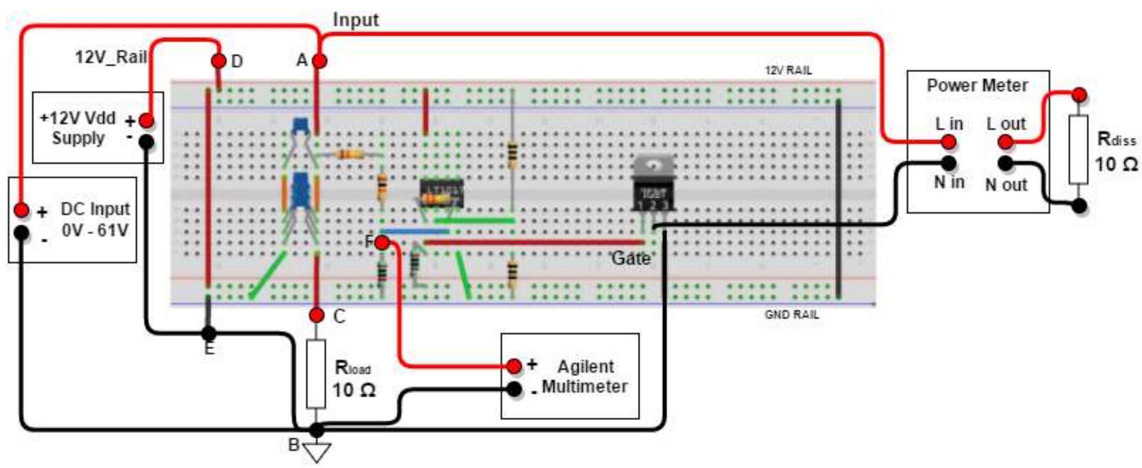


Figure 5-3: Wiring diagram of overvoltage protection circuit constructed on a bread-board and test equipment. This diagram exemplifies an improper way of connecting the OVPC to a 10 Ω load resistor. Over 4 A of current can flow across the load, and the small red and orange wires in the OVPC cannot handle that much current.

Figure 5-3 depicts a possible wiring diagram for the test session. Notice how the 10 Ω load resistor connects to the OVPC at node C. While functionally correct, this diagram represents an improper way of wiring the OVPC. A significant level of current exceeding 1 A flows through the 10 Ω load resistor. Connecting the load resistor at node C means amps of current passing through the OVPC and overheating or burning the small wires on the breadboard. The small wires on the breadboard can overheat and burn

if too much current passes. Paths of high current must flow through thicker wires. For these we use banana-to-banana cables and spade lug-to-banana cables supplied by the student project lab in Engineering East. The IGBT can handle a maximum average current of 180 A [19]. When connecting banana-to-banana cables to the IGBT, they must attach to the IGBT's terminals with alligator clips and not to wires that connect to the breadboard. Figure 5-4 below shows the proper wiring diagram. The figure shows the breadboard diagram of the OVPC, and the test equipment that connects. Refer to Appendix B.5 for a full list of necessary equipment along with test setup and procedure details.

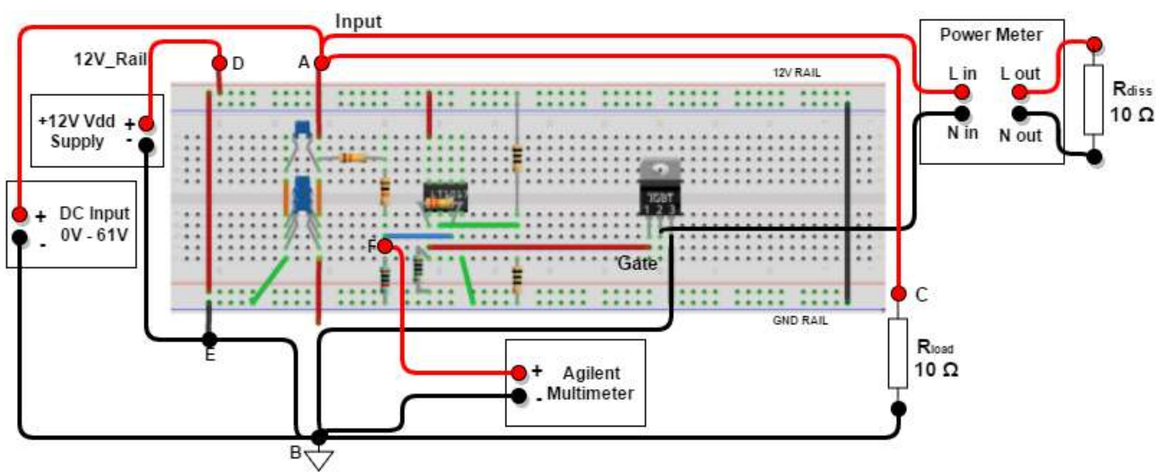


Figure 5-4: Wiring diagram of overvoltage protection circuit constructed on a breadboard and test equipment.

5.2.1 Results of Testing OVPC Designed for this Thesis

For a low DC input voltage, only the load resistor dissipates power. When the DC source increases to 50.5 V, the comparator output goes high, turning on the IGBT, and power flows through the diverting resistor. This causes power dissipation to split between the load and diverting resistors [6]. This test uses The BK Precision Model 9153, which has maximum output current and voltage ratings of 9 A and 60 V, but can supply up to 9.1 A and 61 V. Since this test uses a high power DC source and not an elliptical, the

IGBT does not necessarily divert the power flowing into the 10 Ω load resistor. Instead, the DC source sees a second circuit branch with a 10 Ω resistor and supplies additional power to it. As this happens, the power flowing through the load resistor does not decrease over time. During testing, power dissipated to the load only decreases when the output voltage from the DC source decreases.

Note that this method of testing does not mimic an exact setup with an elliptical. This setup simulates more of a stressed setup where both branches dissipate equal power rather than one side diverting power temporarily from the load branch. This lowers the load resistance seen by the source from 10 Ω to an effective 5 Ω and leads to dissipating more loss at the load side when the IGBT turns on. If not protected internally, the power supply may overload from trying to supply the required current to the branches, or brownout. When the OVPC diverts power, the output voltage from the DC source suddenly decreases. The moment the OVPC diverts, the DC source effectively tries to double the current it already outputs, but it has a maximum current output of 9.1 A. At an input of 50 V with the IGBT on, an ideal DC source would want to supply 10 A of current across two 10 Ω loads connected in parallel. Since the source caps out at 9.1 A, the supplied voltage drops to not violate Ohm’s law. This causes a brownout where the power supply experiences an unintentional drop in supplied voltage. For example, Table 5-1 shows that for a set voltage input of 51 V, the DC source supplies 47.48 V and 9.1 A.

The IGBT turns off, and the OVPC ceases diverting power when the input voltage decreases to 46.4 V. The hysteresis resistor (R3) allows the OVPC to cease power diversion once the input voltage decreases sufficiently. This turn-off voltage varies from

the 45 V value previously reported by 3.0% [6]. The turn-on voltage varies less at 0.5%. Some variation in threshold voltages may arise from using a voltage divider to supply a 3.3 V reference voltage rather than using a microcontroller as a source. Although this doesn't simulate an exact test setup with an elliptical, this test proved that the IGBT can turn on and off, and activate the diverting branch.

Table 5-1: Data collected when testing the existing overvoltage protection circuit. Rows highlighted yellow denote the BK Precision's set voltage level when the IGBT switches. A multimeter measures resistances of 19.5 Ω and 19.6 Ω from the load and dissipating resistors prior to testing.

Startup - Increasing Input Voltage; IGBT starts OFF

Set Volt Lv. (V)	BK Precision Input Source (DC) $V_{supplied}$ (V)	$I_{supplied}$ (A)	$P_{supplied}$ (W)	Agilent Multimeter (DC) LT1016 V+ (V)	LT1016 V^- (V)	Calculate (DC) (Load Resistor) $I(R_{load})$ (A)	$P(R_{load})$ (V)	Power Meter (DC) (Diverting Resistor) $I(R_{diss})$ (A)	$V(R_{diss})$ (V)	$P(R_{diss})$ (V)	Efficiency Load Only (%)	Load and Divert (%)
40	40.00	3.94	157.5	2.604	3.294	3.81	152.4	0	0	0	96.8	96.8
45	45.00	4.43	199.4	2.923	3.294	4.29	192.9	0	0	0	96.7	96.7
50	50.00	4.92	246.1	3.248	3.295	4.76	238.1	0	0	0	96.8	96.8
50.1	50.10	4.93	247.0	3.255	3.295	4.77	239.0	0	0	0	96.8	96.8
50.2	50.20	4.94	247.9	3.261	3.295	4.78	240.0	0	0	0	96.8	96.8
50.3	50.30	4.96	249.5	3.268	3.296	4.79	241.0	0	0	0	96.6	96.6
50.4	50.40	4.97	250.5	3.274	3.296	4.80	241.9	0	0	0	96.6	96.6
50.5	47.07	9.10	428.2	3.360	3.169	4.48	211.0	4.49	44.53	199.9	49.3	96.0
50.6	47.24	9.10	429.7	3.368	3.168	4.50	212.5	4.48	44.65	200.2	49.5	96.0
50.7	47.33	9.10	430.6	3.374	3.168	4.51	213.3	4.48	44.74	200.3	49.6	96.1
50.8	47.39	9.10	431.1	3.377	3.169	4.51	213.9	4.47	44.80	200.3	49.6	96.1
50.9	47.28	9.10	430.1	3.376	3.168	4.50	212.9	4.46	44.87	200.1	49.5	96.0
51	47.48	9.10	431.9	3.382	3.168	4.52	214.7	4.46	44.91	200.2	49.7	96.1
52	47.51	9.10	432.2	3.384	3.169	4.52	215.0	4.46	44.95	200.3	49.7	96.1
53	47.56	9.10	432.7	3.388	3.169	4.53	215.4	4.45	45.01	200.3	49.8	96.1
55	47.61	9.10	433.1	3.392	3.169	4.53	215.9	4.45	45.06	200.4	49.8	96.1
60	47.61	9.10	433.1	3.395	3.168	4.53	215.9	4.45	45.09	200.4	49.8	96.1

Shutdown - Decreasing Input Voltage; IGBT starts ON

Set Volt Lv. (V)	BK Precision Input Source (DC) $V_{supplied}$ (V)	$I_{supplied}$ (A)	$P_{supplied}$ (W)	Agilent Multimeter (DC) LT1016 V+ (V)	LT1016 V^- (V)	Calculate (DC) (Load Resistor) $I(R_{load})$ (A)	$P(R_{load})$ (V)	Power Meter (DC) (Diverting Resistor) $I(R_{diss})$ (A)	$V(R_{diss})$ (V)	$P(R_{diss})$ (V)	Efficiency Load Only (%)	Load and Divert (%)
53	47.71	9.10	434.0	3.396	3.169	4.54	216.8	4.44	45.13	200.40	49.9	96.1
52	47.72	9.10	434.1	3.398	3.168	4.54	216.9	4.44	45.13	200.40	50.0	96.1
51	47.72	9.10	434.1	3.398	3.168	4.54	216.9	4.44	45.13	200.40	50.0	96.1
50	47.72	9.10	434.1	3.398	3.169	4.54	216.9	4.44	45.12	200.40	50.0	96.1
49	47.73	9.10	434.2	3.398	3.168	4.55	217.0	4.44	45.13	200.40	50.0	96.1
48	47.73	9.10	434.2	3.398	3.169	4.55	217.0	4.44	45.13	200.30	50.0	96.1
47	47.00	9.00	423.0	3.351	3.169	4.48	210.4	4.42	44.38	195.90	49.7	96.0
46.9	46.90	8.96	420.0	3.345	3.169	4.47	209.5	4.38	44.32	194.00	49.9	96.1
46.8	46.80	8.93	418.0	3.339	3.170	4.46	208.6	4.36	44.21	192.70	49.9	96.0
46.7	46.70	8.91	416.1	3.332	3.170	4.45	207.7	4.35	44.11	192.00	49.9	96.0
46.6	46.60	8.89	414.3	3.326	3.170	4.44	206.8	4.34	44.03	191.30	49.9	96.1
46.5	46.50	8.89	413.4	3.320	3.170	4.43	205.9	4.35	43.93	190.00	49.8	95.8
46.4	46.40	4.56	211.7	3.014	3.293	4.42	205.0	0	0	0	96.8	96.8
46.3	46.30	4.60	213.0	3.014	3.293	4.41	204.2	0	0	0	95.9	95.9
46	46.00	4.52	207.9	2.988	3.293	4.38	201.5	0	0	0	96.9	96.9
45	45.00	4.42	199.0	2.923	3.293	4.29	192.9	0	0	0	96.9	96.9

Table 5-1 collects measurements from the DC supply, the multimeter, and power meter, for each set voltage level. The table also includes calculations for the load resistor's current, power, and the efficiency of the overvoltage protection circuit. Rows highlighted yellow denote the BK Precision's set voltage level when the IGBT switches on or off. Before the OVPC diverts excess power, 96.6% to 98.6% of the supplied power reaches the load resistor. Once the input voltage reaches 50.5 V, only 49.3% of the supplied power reaches the load resistor, which calculates to just above half the expected efficiency. If one factors in the power the diverting resistor dissipates at this voltage, then the OVCP has a total efficiency of 96.0 %. As the input voltage continues to increase, the efficiency improves, but only by as much as 0.5% for the load resistor.

Because this report utilizes two DC-DC converters for testing, both require an OVPC that fits its own operating range. This means the two separate overvoltage protection circuits have different resistor values for the voltage divider formed by R1 and R2. The next sections of this chapter detail modifying the OVPC's voltage divider and performing efficiency tests for the new overvoltage protection circuit.

5.2.2 Design and Testing of OVPC for Vicor DC-DC Converter

We modify the OVPC designed to protect the Vicor DC-DC converter. This Vicor OVPC uses resistors to form the voltage divider that creates the +3.3V reference voltage from the 12-Volt rail and measures 3.282 V. The Vicor OVPC uses different resistors for the R1 and R2 voltage divider. We select resistors for R1 and R2 so an input voltage of 26 V scales down to 3.3 V for the positive input of the LT1017 comparator. Manipulating the voltage divider equation in (5.1) with a target voltage of 3.3 V from a 26 V input yields the following ratio for resistor values:

$$3.3\text{V} = 26\text{V}\left(\frac{\text{R1}}{\text{R1+R2}}\right) \rightarrow \text{R1} = 6.879(\text{R2}) \quad (5.1)$$

When selecting the right resistors, these resistors should sum to a total resistance greater than 100 kΩ so the voltage divider draws less than a few milliamps of current from the supply. Modifying resistors R1 and R2 allow one to change the input voltage threshold when the OVPC diverts power through the IGBT. Table 5-2 below collects the nominal and measured resistance values for the two voltage dividers in the Vicor's OVPC. The table also includes the measured resistance values of the load and dissipating resistors.

Table 5-2: Collection of resistor values necessary for the Vicor's OVPC.

Vicor OVPC Resistors		
Label	Nominal	Measured
Ra	100 kΩ	98.25 kΩ
Rb	38.1* kΩ	37.15 kΩ
R1	150 kΩ	150.6 kΩ
R2	22 kΩ	22.96 kΩ
Rload	10 Ω	10.5 Ω
Rdiss	10 Ω	9.82 Ω
Measured Reference Voltage: 3.282 V *a 5.1 kΩ and 33 kΩ form the 38.1 kΩ resistance		

Figure 5-5 below shows a circuit diagram in LTspice of the OVPC designed for the Vicor DC-DC converter. The schematic includes the nominal resistor values for the resistors in Table 5-2. Figure 5-6 shows a simulation of the Vicor's OVPC with a constant current source. In conjunction with the capacitor bank, modeling the elliptical trainer with a constant current source should simulate an increasing voltage until the IGBT switches and diverts power. When diverting power, the input voltage should decrease until enough power dissipates and the IGBT switches off. The simulation shows the Vicor's OVPC diverts excess power when the input voltage exceeds 27.4 V and the

input voltage decreases. When the input voltage falls below 21.9 V, the IGBT shuts off, and the OVPC ceases diverting power through the IGBT.

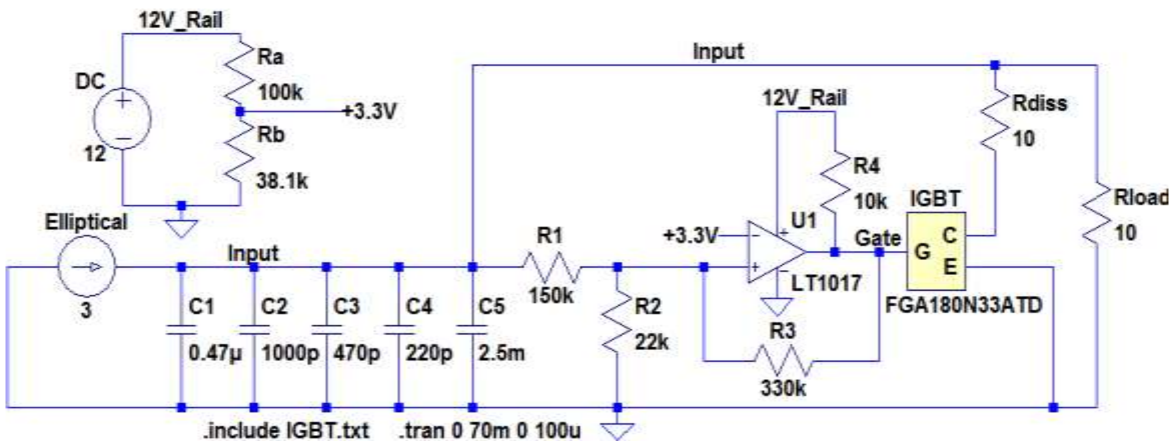


Figure 5-5: LTspice schematic for the OVPC designed for protecting the Vicor DC-DC converter from overvoltage conditions. This circuit represents the OVPC used for this test session. Final circuit designs include filter capacitors on the 12V_Rail node and +3.3V node, as well as a current driver.

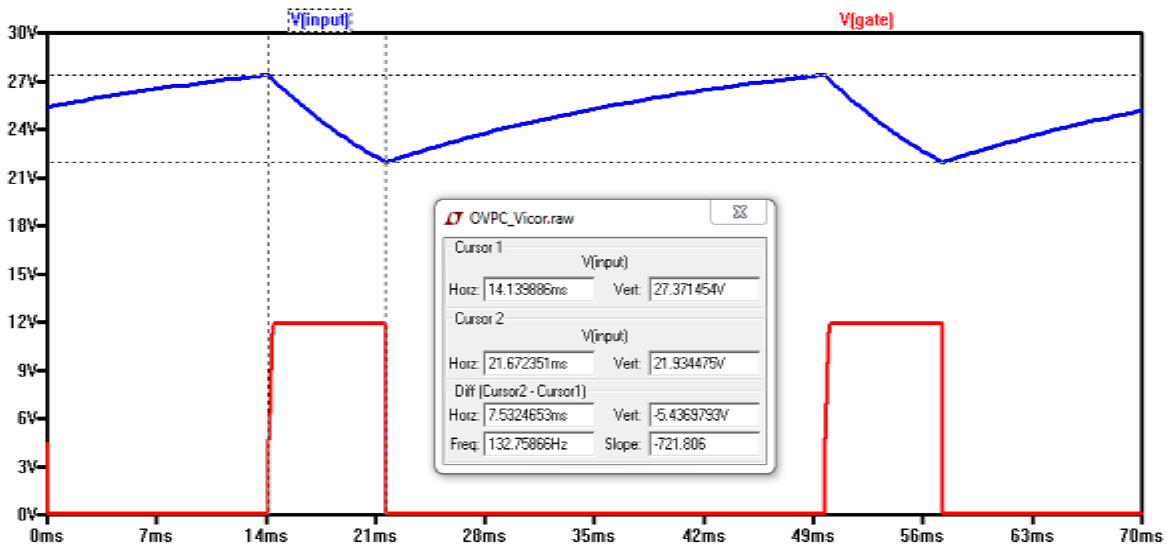


Figure 5-6: Simulation of the OVPC designed for protecting the Vicor DC-DC converter. Simulation shows the OVPC diverts power through the IGBT when the input surpasses 27.4 V and ceases when the input voltage falls below 21.9 V.

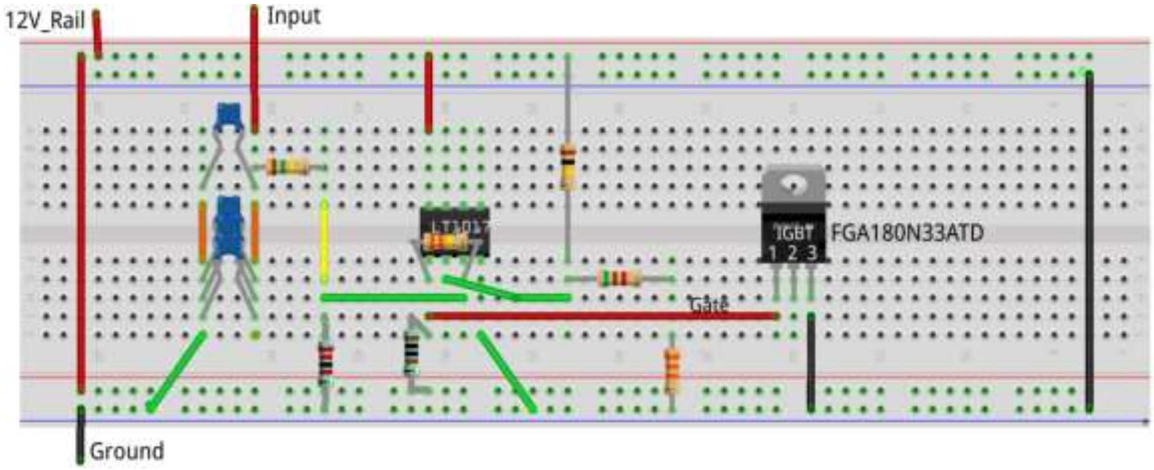


Figure 5-7: Breadboard diagram of the OVPC designed for the Vicor DC-DC converter.

Figure 5-7 depicts a breadboard diagram of the Vicor's OVPC. After acquiring the simulation in Figure 5-6, we test the Vicor OVPC using lab equipment. Testing follows the same procedure as outlined in Appendix B.5. Considering the wiring diagram of Figure 5-4, the OVPC in Figure 5-7 replaces the breadboard in the wiring diagram. Consult Appendix B.5 for details on connecting the Vicor's OVPC to lab equipment for testing. After setup, we test if the OVPC diverts power when the input voltage surpasses 27.4 V and ceases diversion when the voltage decreases past 21.9 V.

The OVPC dissipates power through the IGBT and diverting resistor once the input voltage equals 27.4 V as expected. Until then, only the load resistor dissipates power. When the IGBT switches on and diverts power, the source current supplied by the BK Precision almost doubles from 2.69 A to 5.26 A. The Vicor's OVPC does not cause the BK Precision to reach its supplied current limit, so the supplied voltage shows no sudden decrease. When the OVPC starts diverting power, the 330 kΩ hysteresis resistor causes the voltage on the V+ input of the LT1016 increases to 3.885 V. This causes the OVPC to have a lower voltage for ending power diversion than the voltage when power diversion begins. The OVPC ceases diverting power when decreasing the input voltage

down to 22.5 V. This turn-off voltage varies from the simulation by 3.1%. Before the IGBT turns off completely, the BK Precision's output current fluctuates for a couple seconds before settling at 2.27 A.

Table 5-3 collects measurements from the DC supply, the multimeter, and power meter for each set voltage level. Rows highlighted yellow denote the BK Precision's set voltage level when the IGBT switches on or off. Excel calculations yield the load resistor's current, power, and the efficiency of the overvoltage protection circuit. When calculating the current and power through the load resistor, we consider the measured resistance in favor of the nominal resistance. Before the OVPC diverts excess power, less than 97% of the supplied power reaches the load resistor. Once the input voltage equals 27.4 V, only 49.7% of the supplied power reaches the load resistor. The remaining power dissipates through the diverting resistor and IGBT branch. Considering both load power and dissipated power as power output yields a total efficiency of 95.4% when the IGBT turns on. The OVPC sees a noticeable change in efficiency by a 0.7% decrease when stepping up the supplied voltage to 40 V. The next section details constructing and testing an OVPC for the CUI DC-DC converter.

Table 5-3: Data collected from testing the overvoltage protection circuit designed for the Vicor DC-DC converter. Rows highlighted yellow denote the BK Precision's set voltage level when the IGBT switches on or off. A multimeter measures resistances of 19.5 Ω and 19.6 Ω from the load and dissipating resistors prior to testing.

Startup - Increasing Input Voltage; IGBT starts OFF

	BK Precision Input Source (DC)			Agilent Multimeter (DC)			Calculate (DC) (Load Resistor)		Power Meter (DC) (Diverting Resistor)			Efficiency	
Set Volt Lv. (V)	$V_{supplied}$ (V)	$I_{supplied}$ (A)	$P_{supplied}$ (W)	LT1017 V+ (V)	LT1017 V^- (V)	V_{gate} (V)	$I(R_{load})$ (A)	$P(R_{load})$ (V)	$I(R_{diss})$ (A)	$V(R_{diss})$ (V)	$P(R_{diss})$ (V)	Load Only (%)	Load and Divert (%)
25	25.00	2.46	61.45	2.991	3.276	0.143	2.38	59.5	0	0	0	96.9	96.9
26	26.00	2.56	66.48	3.110	3.279	0.143	2.48	64.4	0	0	0	96.8	96.8
27	27.00	2.66	71.69	3.229	3.279	0.143	2.57	69.4	0	0	0	96.9	96.9
27.1	27.10	2.67	72.22	3.242	3.279	0.143	2.58	69.9	0	0	0	96.8	96.8
27.2	27.20	2.68	72.76	3.254	3.279	0.143	2.59	70.5	0	0	0	96.8	96.8
27.3	27.30	2.69	73.30	3.266	3.279	0.143	2.60	71.0	0	0	0	96.8	96.8
27.4	27.40	5.26	144.10	3.885	3.281	11.95	2.61	71.5	2.58	25.52	65.8	49.6	95.3
27.5	27.50	5.27	144.95	3.896	3.28	11.94	2.62	72.0	2.59	25.63	66.3	49.7	95.4
27.6	27.60	5.29	145.95	3.908	3.28	11.94	2.63	72.5	2.95	25.72	66.7	49.7	95.4
27.7	27.70	5.31	147.00	3.920	3.28	11.94	2.64	73.1	2.60	25.82	67.1	49.7	95.4
27.8	27.80	5.32	147.98	3.932	3.28	11.94	2.65	73.6	2.61	25.91	67.5	49.7	95.4
27.9	27.90	5.34	149.01	3.943	3.28	11.94	2.66	74.1	2.62	26.02	68	49.7	95.4
28	28.00	5.36	150.00	3.955	3.28	11.94	2.67	74.7	2.63	26.13	68.6	49.8	95.5
29	29.00	5.55	160.95	4.073	3.28	11.94	2.76	80.1	2.72	27.06	73.6	49.8	95.5
30	30.00	5.74	172.26	4.192	3.28	11.94	2.86	85.7	2.81	28.02	78.7	49.8	95.4
35	35.00	6.71	234.78	4.783	3.28	11.94	3.33	116.7	3.29	32.80	107.7	49.7	95.6
40	40.00	7.77	310.80	5.373	3.28	11.94	3.81	152.4	3.76	37.59	141.4	49.0	94.5

Shutdown - Decreasing Input Voltage; IGBT starts ON

	BK Precision Input Source (DC)			Agilent Multimeter (DC)			Calculate (DC) (Load Resistor)		Power Meter (DC) (Diverting Resistor)			Efficiency	
Set Volt Lv. (V)	$V_{supplied}$ (V)	$I_{supplied}$ (A)	$P_{supplied}$ (W)	LT1017 V+ (V)	LT1017 V^- (V)	V_{gate} (V)	$I(R_{load})$ (A)	$P(R_{load})$ (V)	$I(R_{diss})$ (A)	$V(R_{diss})$ (V)	$P(R_{diss})$ (V)	Load Only (%)	Load and Divert (%)
35	35.00	6.78	237.30	4.782	3.280	11.94	3.33	116.67	3.27	32.78	107.2	49.2	94.3
30	30.00	5.81	174.33	4.191	3.280	11.94	2.86	85.71	2.80	28.00	78.4	49.2	94.1
25	25.00	4.84	121.00	3.600	3.280	11.94	2.38	59.52	2.32	23.20	53.9	49.2	93.7
24	24.00	4.63	111.12	3.482	3.280	11.94	2.29	54.86	2.23	22.26	49.6	49.4	94.0
23	23.00	4.44	102.05	3.364	3.280	11.94	2.19	50.38	2.14	21.31	45.5	49.4	94.0
22.9	22.90	4.42	101.20	3.352	3.280	11.94	2.18	49.94	2.13	21.22	45.1	49.4	93.9
22.8	22.80	4.40	100.34	3.340	3.280	11.94	2.17	49.51	2.12	21.14	44.8	49.3	94.0
22.7	22.70	4.38	99.47	3.328	3.280	11.94	2.16	49.08	2.11	21.03	44.4	49.3	94.0
22.6	22.60	4.36	98.60	3.316	3.280	11.94	2.15	48.64	2.10	20.93	43.9	49.3	93.9
22.5	22.50	2.27	51.10	2.692	3.277	0.144	2.14	48.21	0	0	0	94.4	94.4
22.4	22.40	2.26	50.56	2.680	3.277	0.144	2.13	47.79	0	0	0	94.5	94.5
22.3	22.30	2.23	49.77	2.668	3.277	0.144	2.12	47.36	0	0	0	95.2	95.2
22.2	22.20	2.22	49.33	2.657	3.277	0.144	2.11	46.94	0	0	0	95.2	95.2
22.1	22.10	2.21	48.89	2.645	3.277	0.144	2.10	46.52	0	0	0	95.2	95.2
22	22.00	2.20	48.44	2.633	3.277	0.144	2.10	46.10	0	0	0	95.2	95.2
21	21.00	2.10	44.16	2.513	3.277	0.144	2.00	42.00	0	0	0	95.1	95.1

5.2.3 Design and Testing of OVPC for CUI DC-DC Converter

Although the CUI DC-DC converter has an operating input range of 18-75 V, the BK Precision DC power source can only supply a maximum of 61 V. Testing in Chapter 4.3 shows the CUI DC-DC converter's power efficiency steadily decreases for input voltages exceeding 45 V. For these reasons, we select 57 V as an arbitrary maximum input voltage for the CUI DC-DC converter. This allows the OVPC to receive an input voltage for power diversion and test beyond that voltage.

A voltage dividing circuit establishes a +3.3V reference voltage from the 12-Volt rail using spare resistors. Likewise, a voltage divider to scales down a 57 V input to 3.3 V for the LT1017 comparator's positive input. Equations (5.2) and (5.3) manipulate the voltage divider equation to yield ratios for the resistors in each voltage divider. Resistors Ra and Rb refer to the resistors in the voltage divider for the 12-Volt rail, and resistors R1 and R2 correspond to the voltage divider at the input.

$$3.3\text{V} = 12\text{V}\left(\frac{\text{Ra}}{\text{Ra+Rb}}\right) \rightarrow \text{Ra} = 2.636(\text{Rb}) \tag{5.2}$$

$$3.3\text{V} = 57\text{V}\left(\frac{\text{R1}}{\text{R1+R2}}\right) \rightarrow \text{R1} = 16.576(\text{R2}) \tag{5.3}$$

We select resistors according to the above ratios and choose high value resistors to minimize current flow. The resistors in each voltage-dividing branch sum to hundreds of kiloohms so the voltage dividers draw less than one milliamp of current. Table 5-4 below collects the nominal and measured resistances for the two voltage dividers and the load and dissipating resistors.

Table 5-4: Collection of resistor values necessary for the CUI's OVPC.

CUI OVPC Resistors		
Label	Nominal (kΩ)	Measured (kΩ)
Ra	470 kΩ	468
Rb	180	197.7
R1	160	159.9
R2	10	9.97
Rload	20 Ω	19.5
Rdiss	20 Ω	19.6
Measured Reference Voltage: 3.287 V		

Figure 5-8 below shows an LTspice schematic of the OVPC designed for the CUI DC-DC converter. The circuit diagram includes the resistors in the above table. For a detailed explanation about modifying the OVPC design, see Chapter 5.3. The circuit diagram of Figure 5-8 also includes 20 Ω resistors for the load and dissipating resistors. This avoids the problem of BK Precision supplying its maximum supplied current when the OVPC diverts power and forcing the DC source to output less voltage. Figure 5-9 shows a simulation of the CUI's OVPC with a constant current source. In conjunction with the capacitor bank, modeling the elliptical trainer with a constant current source should simulate an increasing voltage until the IGBT switches and diverts power. When diverting power, the input voltage should then decrease until enough power dissipates and the IGBT switches off. The simulation shows the input voltage increases until 58.1 V when the IGBT turns on and diverts excess power. Power diversion ends when the input voltage falls below 52.3 V and shuts off the IGBT.

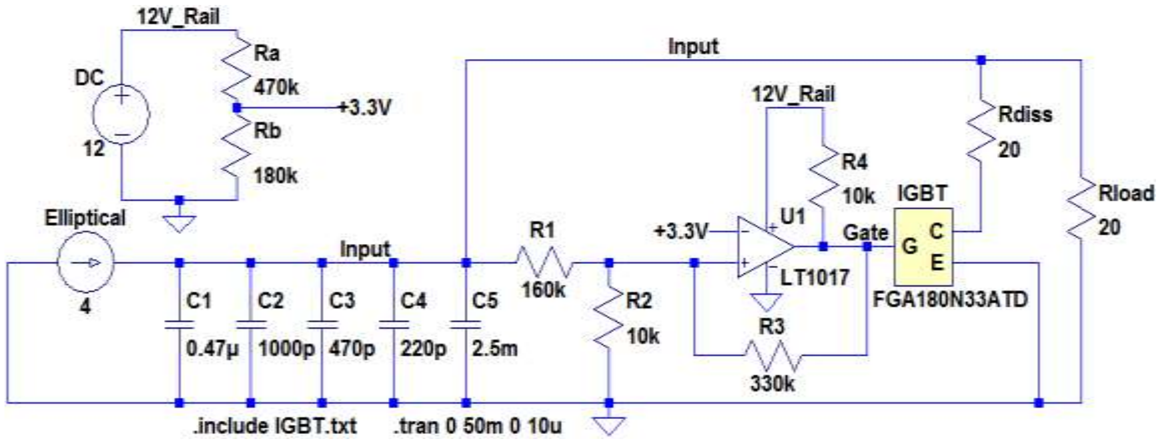


Figure 5-8: LTspice schematic for the OVPC designed for protecting the CUI DC-DC converter from overvoltage conditions. This circuit represents the OVPC used for this test session. Final circuit designs include filter capacitors on the 12V_Rail node and +3.3V node, as well as a current driver.

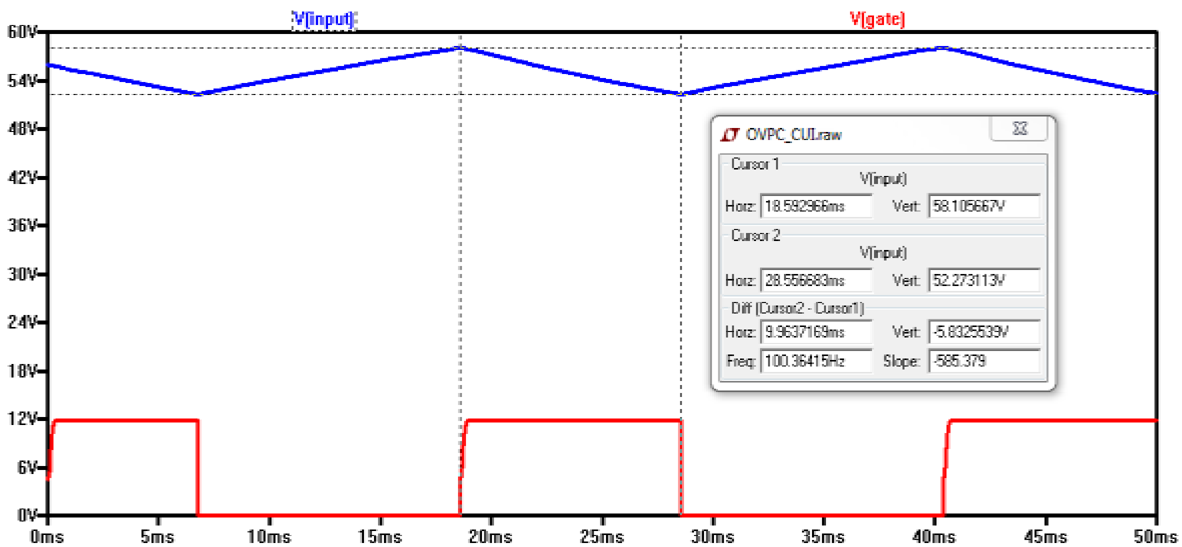


Figure 5-9: Simulation of the OVPC designed for protecting the CUI DC-DC converter. Simulation shows the OVPC diverts power through the IGBT when the input surpasses 58.1 V and ceases when the input voltage falls below 52.3 V.

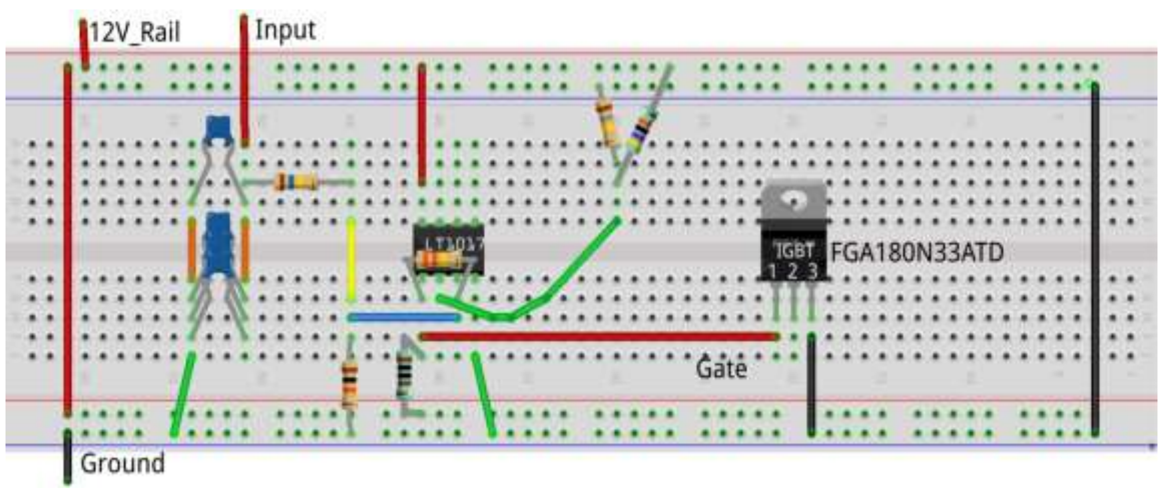


Figure 5-10: Breadboard diagram of the OVPC designed for the CUI DC-DC converter.

Figure 5-10 depicts a breadboard layout of the CUI's OVPC. After simulating, we test the CUI's OVPC by following the procedure in Appendix B.5. When setting up for testing, the OVPC in Figure 5-10 replaces the breadboard diagram in the wiring diagram of Figure 5-4. Consult the test procedure in Appendix B.5 for details on connecting the CUI's OVPC to lab equipment for testing. We then test to confirm the OVPC diverts power when the input voltage surpasses 58.1 V and ceases diversion when the voltage decreases past 52.3 V.

Testing shows the IGBT turns on and the OVPC diverts power when the input voltage equals 57.6 V, close to matching simulation. When the diverting resistor starts dissipating power, the current the BK Precision supplies almost doubles from 2.91 A to 5.74 A. Just like the Vicor's OVPC, the BK Precision does not reach its supplied current limit so the supplied voltage matches the set input voltage. Due to the hysteresis, when the OVPC diverts power the V+ input of the LT1017 increases to 3.602 V. This hysteresis allows for a turn-off voltage of 54.0 V when the OVPC ceases diverting power. When the input voltage decreases to 54.0 V, the BK Precision's output current briefly fluctuates before setting on 2.72 A.

Table 5-5 collects measurements for each test level from the BK Precision DC source, the multimeter, and power meter. As with prior OVPC data tables, the rows highlighted yellow denote the BK Precision's set voltage level when the IGBT switches on or off. Calculations for the load resistor's current, power, and the efficiency of the overvoltage protection circuit occur in Excel. When calculating the current and power through the load resistor, we consider the measured resistance in favor of the nominal resistance. The data shows that the load resistor dissipates as much as 99.4% of the

supplied DC power. Once diverting power, only 50.4% of supplied power reaches the load resistor and the rest diverts through the diverting resistor. When the OVPC ceases diverting power at 54.0 V, power efficiency increases to 99.7%. Compared to the OVPC designed for the Vicor DC-DC converter, the CUI's OVPC delivers power more efficiently to the load resistor.

Table 5-5: Data collected from testing overvoltage protection circuit designed for the CUI DC-DC converter. Rows highlighted yellow denote the DK Precision's set voltage level when the IGBT switches on or off. A multimeter measures resistances of 19.5 Ω and 19.6 Ω from the load and dissipating resistors prior to testing.

Startup - Increasing Input Voltage; IGBT starts OFF													
	BK Precision Input Source (DC)			Agilent Multimeter (DC)			Calculate (DC) (Load Resistor)		Power Meter (DC) (Diverting Resistor)			Efficiency	
Set Volt Lv. (V)	$V_{supplied}$ (V)	$I_{supplied}$ (A)	$P_{supplied}$ (W)	LT1016 V+ (V)	LT1016 V^{-} (V)	V_{gate} (V)	$I(R_{load})$ (A)	$P(R_{load})$ (V)	$I(R_{diss})$ (A)	$V(R_{diss})$ (V)	$P(R_{diss})$ (V)	Load Only (%)	Load and Divert (%)
50	50.00	2.54	127.05	2.848	3.279	0.119	2.51	125.6	0	0	0	98.9	98.9
55	55.00	2.80	153.73	3.135	3.279	0.119	2.76	152.0	0	0	0	98.9	98.9
56	56.00	2.84	159.26	3.193	3.279	0.119	2.81	157.6	0	0	0	98.9	98.9
57	57.00	2.89	164.96	3.250	3.279	0.119	2.86	163.3	0	0	0	99.0	99.0
57.1	57.10	2.89	165.25	3.256	3.279	0.119	2.87	163.8	0	0	0	99.1	99.1
57.2	57.20	2.90	165.71	3.262	3.279	0.119	2.87	164.4	0	0	0	99.2	99.2
57.3	57.30	2.90	166.17	3.268	3.279	0.119	2.88	165.0	0	0	0	99.3	99.3
57.4	57.40	2.90	166.63	3.274	3.279	0.119	2.88	165.6	0	0	0	99.4	99.4
57.5	57.50	2.91	167.15	3.280	3.280	0.119	2.89	166.1	0	0	0	99.4	99.4
57.6	57.60	5.74	330.80	3.602	3.280	11.96	2.89	166.7	2.84	55.44	157.3	50.4	98.0
57.7	57.70	5.75	331.49	3.608	3.280	11.96	2.90	167.3	2.84	55.52	157.0	50.5	97.8
57.8	57.80	5.75	332.35	3.614	3.280	11.96	2.90	167.9	2.84	55.62	158.0	50.5	98.1
57.9	57.90	5.76	333.33	3.620	3.280	11.96	2.91	168.5	2.84	55.70	158.3	50.5	98.0
58	58.00	5.76	334.31	3.626	3.280	11.96	2.91	169.0	2.84	55.81	158.6	50.6	98.0
59	59.00	5.86	345.68	3.683	3.280	11.96	2.96	174.9	2.89	56.78	164.1	50.6	98.1
60	60.00	5.96	357.36	3.740	3.280	11.96	3.02	180.9	2.94	57.78	169.8	50.6	98.1

Shutdown - Decreasing Input Voltage; IGBT starts ON													
	BK Precision Input Source (DC)			Agilent Multimeter (DC)			Calculate (DC) (Load Resistor)		Power Meter (DC) (Diverting Resistor)			Efficiency	
Set Volt Lv. (V)	$V_{supplied}$ (V)	$I_{supplied}$ (A)	$P_{supplied}$ (W)	LT1016 V+ (V)	LT1016 V^{-} (V)	V_{gate} (V)	$I(R_{load})$ (A)	$P(R_{load})$ (V)	$I(R_{diss})$ (A)	$V(R_{diss})$ (V)	$P(R_{diss})$ (V)	Load Only (%)	Load and Divert (%)
60	60.00	5.96	357.36	3.740	3.280	11.96	3.02	180.9	2.94	57.78	169.8	50.6	98.1
59	59.00	5.85	345.21	3.683	3.280	11.96	2.96	174.92	2.88	56.78	163.8	50.7	98.1
58	58.00	5.75	333.33	3.626	3.280	11.96	2.91	169.05	2.84	55.81	158.2	50.7	98.2
57	57.00	5.65	321.77	3.569	3.280	11.96	2.86	163.27	2.78	54.86	152.6	50.7	98.2
56	56.00	5.55	310.58	3.512	3.280	11.96	2.81	157.59	2.73	53.89	146.9	50.7	98.0
55	55.00	5.45	299.59	3.455	3.280	11.96	2.76	152.01	2.68	52.91	141.9	50.7	98.1
54.5	54.50	5.40	294.14	3.427	3.280	11.96	2.74	149.26	2.66	52.46	139.5	50.7	98.2
54.4	54.60	5.39	294.18	3.421	3.280	11.96	2.74	149.81	2.65	52.35	138.9	50.9	98.1
54.3	54.70	5.38	294.29	3.415	3.280	11.96	2.75	150.36	2.65	52.21	138.3	51.1	98.1
54.2	54.80	5.37	294.33	3.410	3.280	11.96	2.75	150.91	2.65	52.11	137.8	51.3	98.1
54.1	54.90	5.36	294.37	3.403	3.280	11.96	2.76	151.46	2.65	52.03	137.7	51.5	98.2
54	54.00	2.72	146.93	3.080	3.280	11.96	2.71	146.53	0	0	0	99.7	99.7
53	53.00	2.67	141.56	3.023	3.280	11.96	2.66	141.16	0	0	0	99.7	99.7
52	52.00	2.62	136.29	2.966	3.280	11.96	2.61	135.88	0	0	0	99.7	99.7
51	51.00	2.57	131.12	2.909	3.280	11.96	2.56	130.70	0	0	0	99.7	99.7
50	50.00	2.52	126.00	2.851	3.280	11.96	2.51	125.63	0	0	0	99.7	99.7

Prior to collecting the data in Table 5-5, we used 10 Ω nominal resistors for the load and dissipating resistors. When increasing the supplied voltage to 57.7 V, the BK Precision's output voltage and current would fluctuate and fail to maintain a constant output level. This occurs with 10 Ω loads connected because the DC source doubles its output current when the OVPC diverts power. At 57.7 V across two 10 Ω loads, the BK Precision attempts supplying 11.5 A, but the source has an output current limit of 9.1 A. Since the BK precision supplies a maximum 9.1 A, the supplied voltage decreases, which avoids violating Ohm's law. 9.1 A of current through two 10 Ω loads in parallel yields a potential of about 45.5 V. When the OVPC diverts power, the supplied voltage drops significantly below the turn-off voltage level, causing the IGBT to turn off. With 10 Ω resistors, we observe an endless cycle of the IGBT turning on and off. Removing the two 20 Ω resistors that form the 10 Ω load in the Precor elliptical and using those as the load and dissipating resistors remedies this problem. A similar phenomenon occurs when testing the original OVPC designed for this thesis. However, when the original OVPC diverts power, the input voltage does not decrease enough to fall below the turn-off voltage.

The next section in this chapter explores measuring the delay between the input voltage surpassing the turn-on voltage and the IGBT's gate response. In this section, we construct a new voltage divider for an OVPC meant to protecting the microinverters from overvoltage conditions. Further modifications and including a current driver in the OVPC design manage to improve the time delay and improve the signal stability on the IGBT's gate.

5.3 Measuring IGBT Delay and Improving OVPC Design

Prior to measuring the gate and collector delays of the OVPC, we attempt elliptical testing in Chapter 7 involving the OVPC and the Enphase M175 inverter. Initial testing in Chapter 7 has an OVPC to protect the inverter from overvoltage conditions. During this preliminary testing, we observed the input voltage and IGBT's collector voltage both decrease and settle from the 51 V threshold down to around 25 V. At no point does the input voltage rise back to 51 V after decreasing to 25 V. While the diverting resistor does not dissipate power, the system converts elliptical DC power into AC power and delivers that AC power to the electrical grid. However, testing the M175 inverter with a DC source and the AC lab bench a week later shows that the M175 no longer converts DC power to AC power. The inverter undergoes the startup process normally when supplied AC power but not when only supplied DC power. Troubleshooting in Chapter 7.2.1 confirms the OVPC did not provide adequate protection. An LTspice simulation shows the 47 nF and 10 µF capacitors on the IGBT's gate cause the OVPC to react too slowly when attempting to divert excess power. The OVPC used in that test session has capacitors between the IGBT's gate terminal and ground, because an oscilloscope reveals an unstable voltage signal on the IGBT's gate when testing the OVPC with a DC-DC converter. Inclusion of the capacitors allows for a stable IGBT gate voltage, but creates too long of a gate charge time to adequately protect a component from overvoltage conditions. In order to protect components from overvoltage conditions, we must procure a better means of charging the IGBT's gate to a stable voltage.

Note that for the next couple of sub-sections, until we drive the IGBT gate voltage with a current sink, we do not use a single shot trigger for acquiring waveforms. In the next section, we start with oscilloscope waveforms zoomed out and hit pause on the oscilloscopes after changing the supplied DC voltage from one potential to another. Then we zoom in to measure the delays. In section 5.3.4, we properly measure the gate and collector delays using a single-shot trigger. We also measure OVPC delays without gate capacitors and instead driven by a current sink.

5.3.1 IGBT Gate and Collector Delay Measurements for the M175 OVPC and the Vicor OVPC with Capacitors Connecting to the IGBT's Gate

Figure 5-11 below measures the IGBT gate and collector delays of the OVPC meant to protect the M175 microinverter from overvoltage conditions. We first measure the delays by using oscilloscope cursors to measure the time difference between the voltages increasing or decreasing on the IGBT terminals following a rising supplied input voltage. The BK Precision starts with an initial voltage of 0 V before supplying a set voltage of 55 V. Doing so measures a gate delay of 28 ms and a collector delay of 36 ms. Note that the voltage on the IGBT's gate does not rise to 12 V as expected. When setting the DC source to supply 55 V, the BK Precision also attempts to supply 11 A when the OVPC attempts diverting excess power. This occurs because two 10 Ω resistors both have a 55 V potential difference across their loads. However, the BK Precision can only supply a maximum of 9.1 A of current. Since the BK Precision can supply a maximum of 9.1 A, this causes the supplied voltage to drop to about 45 V, below the turn-off voltage threshold of 46.4 V as measured in Chapter 5.2.1. When this happens, the OVPC ceases diverting and causes the DC source to output only 5.5 A. Then the DC source returns to

attempting to output 55 V, which causes the cycle to repeat. The waveforms in Figure 5-11 have fluctuating voltage signals due to the current limitations of the BK Precision DC source.

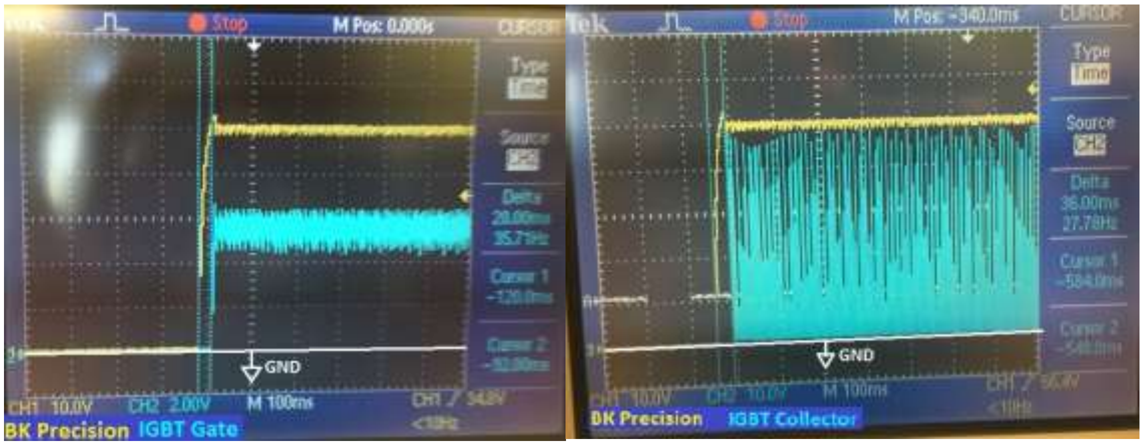


Figure 5-11: Oscilloscope capture of Input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Test measures the delays on IGBT terminals for the OVPC protecting the M175 inverter. Oscilloscope cursors measures gate delay of 28 ms and collector delay of 36 ms. Initial input voltage equals 0 V before rising to 55 V. Time scale: 100 ms/div.

Figure 5-12 measures the gate and collector delays of the OVPC used for the Vicor DC-DC converter. The OVPC protecting the Vicor should divert excess power when receiving an input voltage of 28 V. Similar to Figure 5-11, we measure the delays by using cursors to measure the time difference between the voltages rising on the IGBT terminals following a rising supplied input voltage. The BK Precision starts with an initial voltage of 0 V before supplying a set voltage of 30 V. Oscilloscopes measure a gate delay of 28 ms and a collector delay of 32 ms. These measurements show that a lower voltage threshold for power diversion has little to no impact on improving gate and collector delays. Testing shows the gate signal achieves a voltage of 12 V, and unlike the waveforms in Figure 5-11, fluctuations in gate, collector, and elliptical output voltages do not occur. Figure 5-12 has cleaner delay signals since the OVPC for the Vicor does not experience the same BK Precision source limitations.

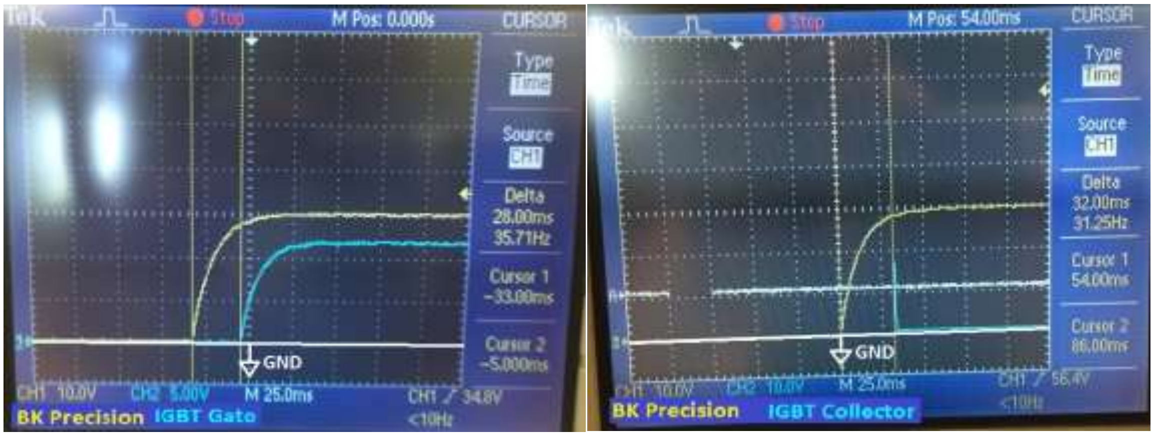


Figure 5-12: Single shot trigger of Input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Test measures the delays on IGBT terminals for the OVPC protecting the Vicor DC-DC converter. Oscilloscope cursors measures gate delay of 28 ms and collector delay of 32 ms. Initial input voltage equals 0 V and rises to 30 V. Time scale: 25 ms/div.

The gate and collector delays reveal a much slower OVPC response than desired. An ideal time delay should measure on the order of microseconds. The primary cause of this comes from the inclusion of the capacitors on the gate. Including capacitors on the gate help stabilize the IGBT's gate voltage gate, but increasing the delay on the OVPC can cause more harm than good. Equation (5.4) below allows for a theoretical calculation of the time taken to charge a capacitor.

$$\Delta t = \frac{\Delta V \times C}{I} \tag{5.4}$$

This same equation can yield the time required for the IGBT's gate to charge to 5 V. We assume the capacitance equals 10.047 µF, the sum of the two capacitors, and the LT1017's minimum output sink current equals 25 mA [20]. Equation (5.5) yields the following time delay:

$$\Delta t = \frac{5V \times 10.047\mu F}{25mA} = 0.002009 = \mathbf{2.01\ ms} \tag{5.5}$$

While this time delay does not equal the gate delay in Figure 5-11 or Figure 5-12, the time delay has the same order as those measured with the oscilloscopes. According to

its datasheet, the IGBT has an input capacitance of 3880 pF [19]. Using this capacitance in (5.6) results in a faster gate delay of 0.78 μs for an OVPC to divert excess power:

$$\Delta t = \frac{5V \times 3880pF}{25mA} = 7.76 \times 10^{-7} = \mathbf{0.78}\ \boldsymbol{\mu s} \tag{5.6}$$

Additionally, the way we initially measure the delay does not accurately reflect how the OVPC diverts power once the input voltage surpasses the threshold voltage. The next section of delay testing removes the capacitors from the IGBT's gate and measures the time delay when voltages achieve 50% of their target voltage.

5.3.2 IGBT Gate and Collector Delay Measurements without IGBT Gate Capacitors

After initial IGBT delay testing, we remove the 47 nF and 10 μF capacitors and retest the gate and collector response times. Delay testing uses two 20 Ω loads to avoid the problem of the BK Precision reaching its current limit when the M175 OVPC diverts power. Figure 5-13 measures the gate and collector delays of the OVPC designed for the M175 microinverter. This time, the oscilloscopes measure the time delays by placing cursors at the times where the voltage signals rise or fall to 50% of their target values. The gate delay measure 20.4 ms and the collector delays measures 21.8 ms.

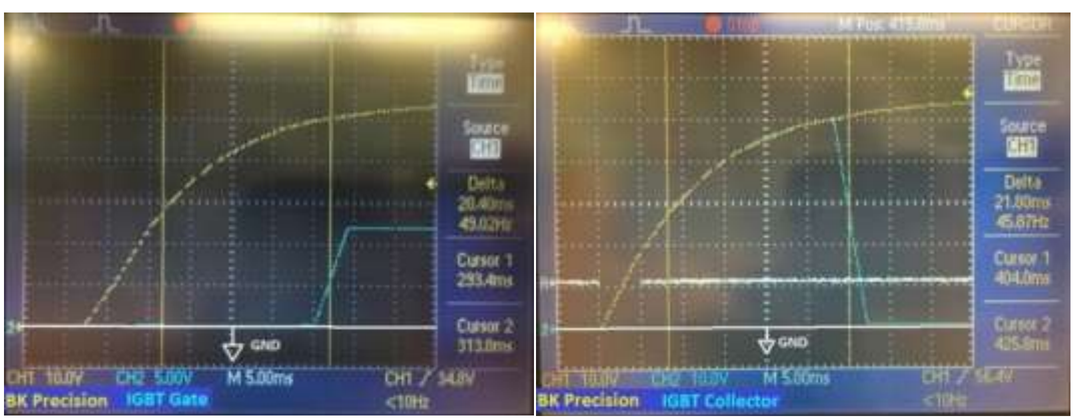


Figure 5-13: Oscilloscope capture of Input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Test measures the delays on IGBT terminals for the OVPC protecting the M175 OVPC. Oscilloscope cursors measures gate delay of 21.8 ms and collector delay of 20.4 ms. Initial input voltage equals 0 V and rises to 55 V. Time scale: 5 ms/div.

Figure 5-14 below shows oscilloscope capture with new gate and collector delay measurements for the OVPC meant to protect the Vicor DC-DC converter. As with the measurements in Figure 5-13, the oscilloscopes measure the time delays when the voltage signals reach their "**50 percent points**" [24]. Now the gate delay measures 21.8 ms and the collector delay measures 18.8 ms.

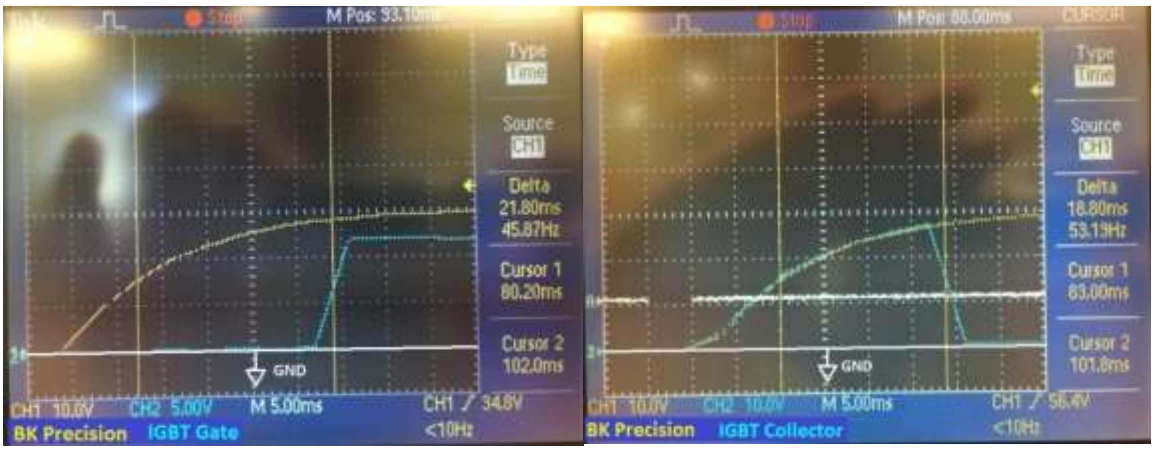


Figure 5-14: Oscilloscope capture of Input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Test measures the delays on IGBT terminals for the OVPC protecting the Vicor DC-DC converter. Oscilloscope cursors measures gate delay of 21.8 ms and collector delay of 18.8 ms. Initial input voltage equals 0 V before rising to 30 V. Time scale: 5 ms/div.

While the time delays have improved, the delays still measure on the order of milliseconds. When measuring the gate and collector delays for the Vicor's OVPC, the collector has a faster time delay than the gate. This seems odd because the collector should respond after the gate. However, the IGBT's gate only needs a typical voltage of 4.0 V to turn on, and the oscilloscope measures the time at which the voltage on the gate equals 6 V. We then attempt removing the 2.5 mF capacitor from the OVPC's capacitor bank, but this causes no change in the gate or collector delays.

We then conduct another method of measuring the gate and collector delays. The voltage output from the elliptical needs to surpass a particular threshold voltage in order to activate the OVPC. For the M175 OVPC, the comparator outputs a high voltage when

the input voltage surpasses 50.5 V and ceases diverting power when the input voltage drops below 46.4 V. For the Vicor OVPC, the comparator outputs a high voltage when the input voltage surpasses 27.4 V and ceases diverting power when the input voltage drops below 22.5 V. Proper delay measurements should have a starting point where the elliptical output voltage surpasses a particular threshold voltage. The gate delay can have an end time where the gate voltage reaches 5 V. Although the IGBT's data sheet claims the IGBT has a typical turn-on voltage of 4.0 V, we select 5 V to ensure IGBT activation. Meanwhile, a proper collector delay can still have an endpoint where the collector voltage drops to 50% of its voltage.

Figure 5-15 measures new gate and collector delays for the M175 microinverter using the method described in the paragraph above. The BK Precision DC source supplies an initial input voltage of 45 V before stepping up to 55 V. This results in a gate delay of 1.8 ms and a collector delay of 2.3 ms. Figure 5-16 measures new gate and collector delays for the Vicor DC-DC converter also using the new method. Unlike prior Vicor OVPC delay measurements, the set input voltage increases to 28 V, instead of 30 V, from an initial 0 V. This results in a gate delay of 2.2 ms and a collector delay of 3.9 ms.

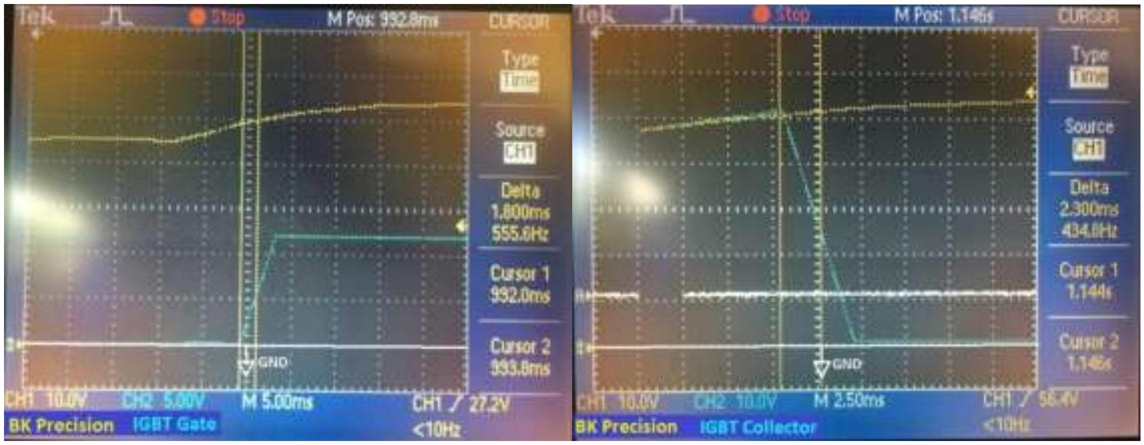


Figure 5-15: Oscilloscope capture of Input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Test measures the delays on IGBT terminals for the OVPC protecting the M175 inverter converter. Oscilloscope cursors measures gate delay of 1.8 ms and collector delay of 2.3 ms. Initial input voltage equals 45 V before rising to 55 V. Time scales: 5.0 ms/div on the left and 2.5 ms on the right.

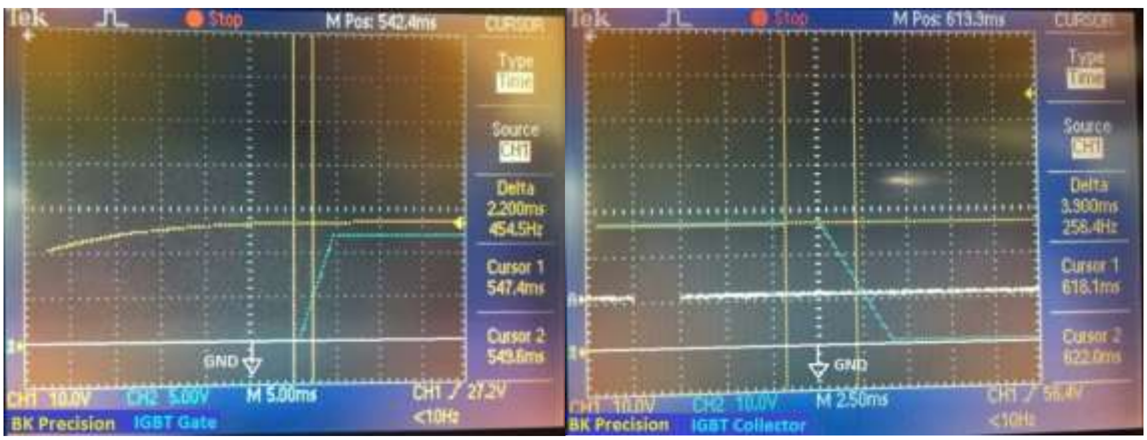


Figure 5-16: Oscilloscope capture of Input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Test measures the delays on IGBT terminals for the OVPC protecting the Vicor DC-DC converter. Oscilloscope cursors measures gate delay of 2.2 ms and collector delay of 3.9 ms. Initial input voltage equals 0 V before rising to 28 V. Time scales: 5.0 ms/div on the left and 2.5 ms on the right.

While the time delays further improve from the 20-30 ms times, the delays still exceed one millisecond. Furthermore, while we do not measure the time delays when the OVPC ceases diverting power, we observe the voltages on the gate and collector terminals fluctuate when the IGBT attempts to turn off. Figure 5-17 shows the voltage fluctuation when the OVPC ceases diverting power. Despite the oscillations, the voltage signals eventually settle to appropriate values after about six seconds.

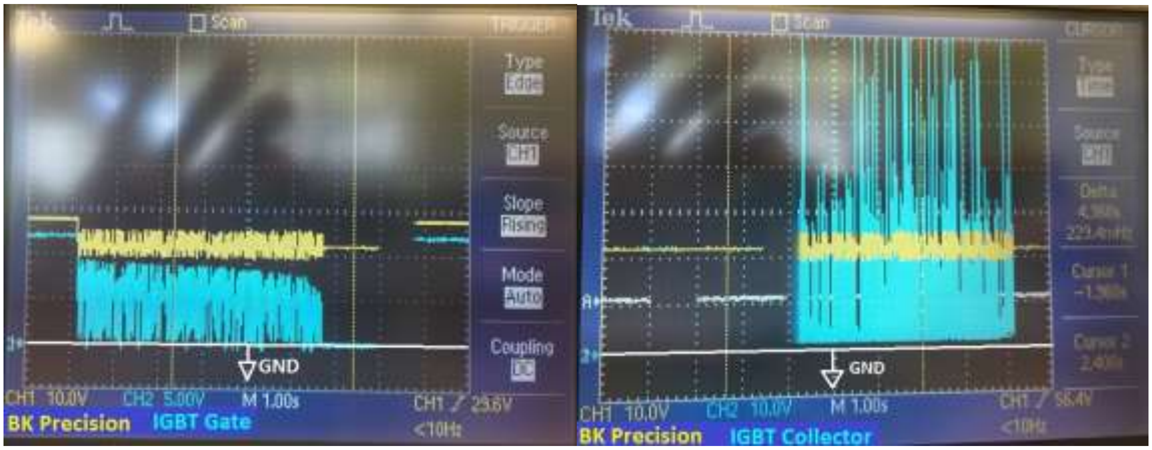


Figure 5-17: Oscilloscope captures of the input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). These scope captures show the gate and collector signals fluctuate when the OVPC attempts ceasing power diversion. The voltage signals settle after about six seconds. Time scale: 1.0 s/div.

While trying to improve the gate and collector delays for existing OVPCs, we design a new OVPC specifically for the M215 microinverter. This OVPC has a lower input voltage threshold than the M175 microinverter's OVPC for extra protection. The next section details designing the voltage divider for this OVPC and testing its gate and collector delays.

5.3.3 IGBT Gate and Collector Delay Measurements for New OVPC Designed for Protecting the M215 Microinverter

The M215 inverter has a lower maximum DC input of 48 V than the M175's 54 V maximum [11, 13]. This necessitates lowering the voltage threshold for power diversion. Additionally, the M175 and M215 microinverters have a peak power tracking range of 27-39 V and 25-40 V [11, 13]. Having the microinverters receive a maximum input voltage closer to their peak tracking ranges should improve efficiency. We decide to lower the threshold voltage for power diversion to 41 V and select appropriate resistor values for the voltage divider in the OVPC. The voltage divider must scale an input voltage of 41 V from the DC source down to 3.3 V for the positive input of the

comparator in the OVPC. Manipulating the voltage divider equation with a target voltage of 3.3 V from a 41 V input yields the ratio relating R1 to R2 in (5.7).

$$3.3\text{V} = 41\text{V}\left(\frac{\text{R2}}{\text{R1+R2}}\right) \rightarrow \text{R1} = 11.42(\text{R2}) \quad (5.7)$$

We select resistor values on the order of tens of kiloohms or higher so that the voltage divider does not draw more than a few milliamps of current from the 12-Volt supply. The selected resistors include:

R1a)	**Nominal:**	**100 kΩ**	**Measured:**	**99.6 kΩ**
R1b)	**Nominal:**	**10 kΩ**	**Measured:**	**9.82 kΩ**
R2)	**Nominal:**	**10 kΩ**	**Measured:**	**9.97 kΩ**

The new OVPC uses the voltage divider in the circuit labeled Figure 5-18 to lower the threshold voltage for power diversion. This allows the microinverters to receive a maximum input DC voltage further below their maximum operating limits. The circuit also includes filter capacitors to reduce possible source transients on the 12-Volt rail and the +3.3 V reference node. We intend to use this OVPC when conducting elliptical testing with either M175 or M215 microinverter, but without a DC-DC converter. See Chapter 7 for elliptical testing with the M215 microinverter sans DC-DC converter. The simulation in Figure 5-19 indicates this microinverter OVPC diverts excess power when the elliptical outputs 40.9 V and cease power diversion when the voltage decreases below 36.8 V. The following simulations and oscilloscope captures test for this new OVPC's gate and collector delays.

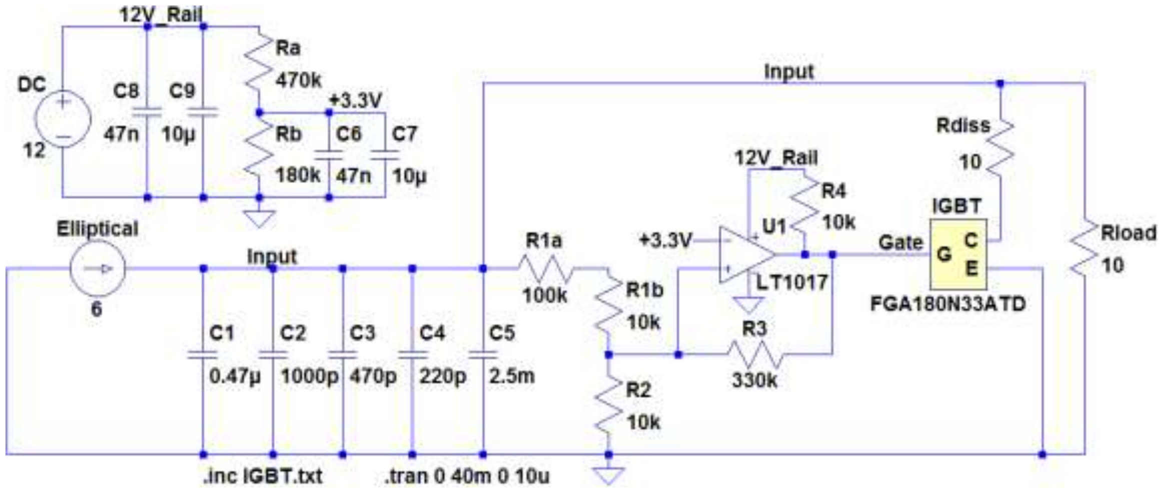


Figure 5-18: LTspice Schematic for the OVPC designed to limit the DC input voltage for the Enphase microinverters. The circuit represents a circuit setup for delay testing with a DC source and not testing with an elliptical.

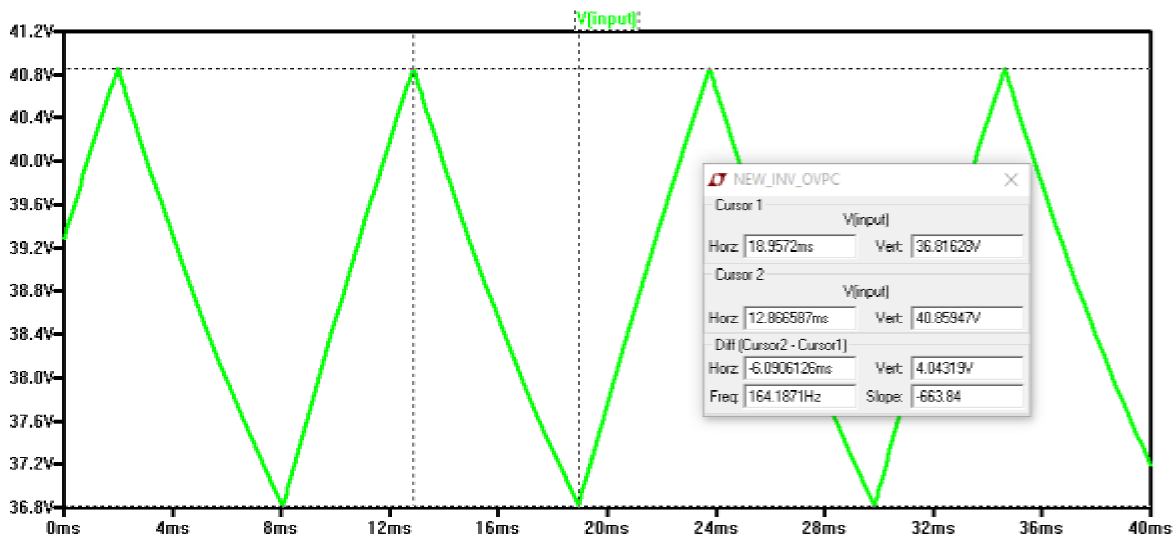


Figure 5-19: LTspice simulation of the new OVPC in Figure 5-17. Simulation assumes a 10 Ω, 300W resistor instead of an inverter for the load. The simulation shows this OVPC diverts excess power when the elliptical outputs 40.9 V and cease power diversion when the voltage decreases below 36.8 V.

For a simulation to reflect actual gate and collector delay testing, LTspice should simulate a step-up voltage to 44 V with an initial voltage of 38 V. Figure 5-20 and Figure 5-21 depict LTspice simulations of the gate delays. Figure 5-20 shows a gate delay of 14.53 µs between when the input voltage steps up to 44 V and when the collector voltage begins decreasing. Figure 5-20 shows an extended gate delay of 81.4 µs between the input voltage increasing and the IGBT gate voltage equaling 4.0 V, the

typical turn-on voltage [19]. Figure 5-22 shows a collector delay of 16.58 μs. However, delays in the low milliseconds when measuring these delays with test equipment.

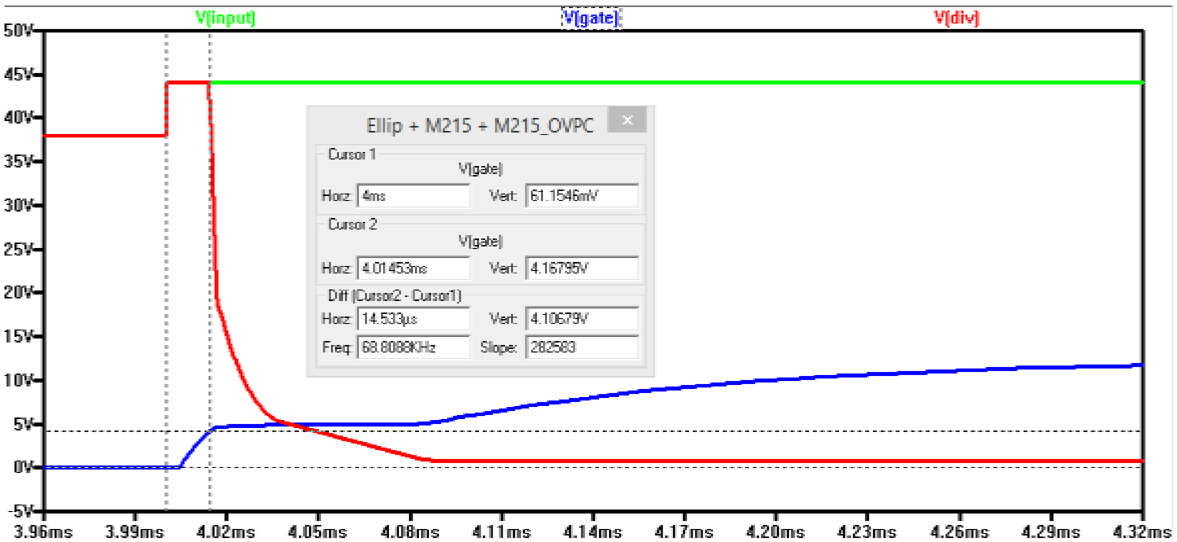


Figure 5-20: LTspice simulation measuring a gate delay of 14.53 μs for the new microinverter OVPC.

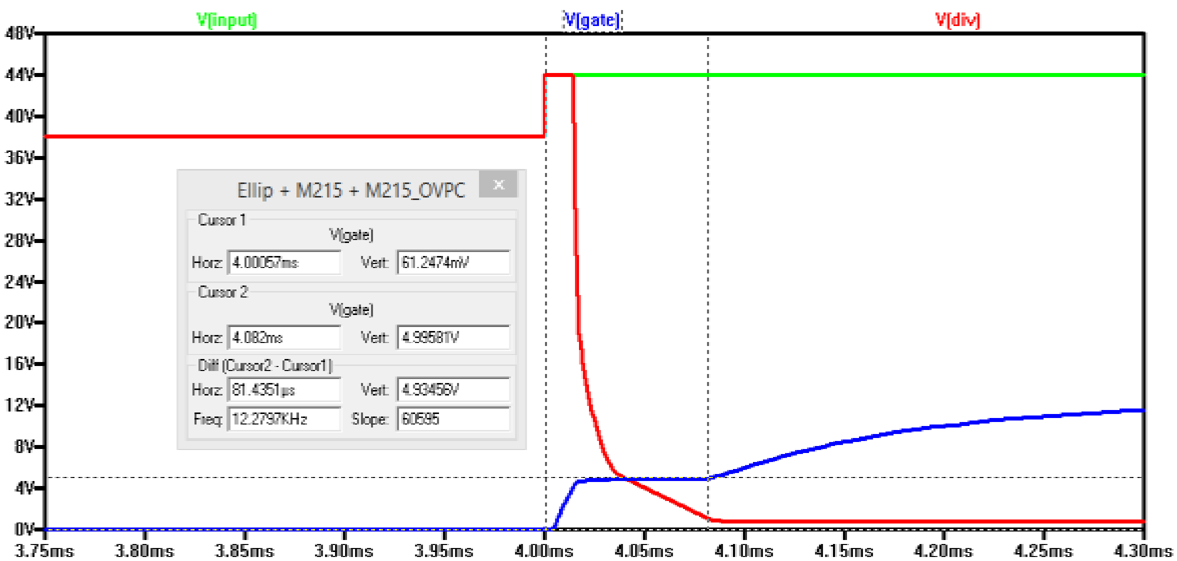


Figure 5-21: LTspice simulation measuring a gate delay of 81.4 μs for the new microinverter OVPC.

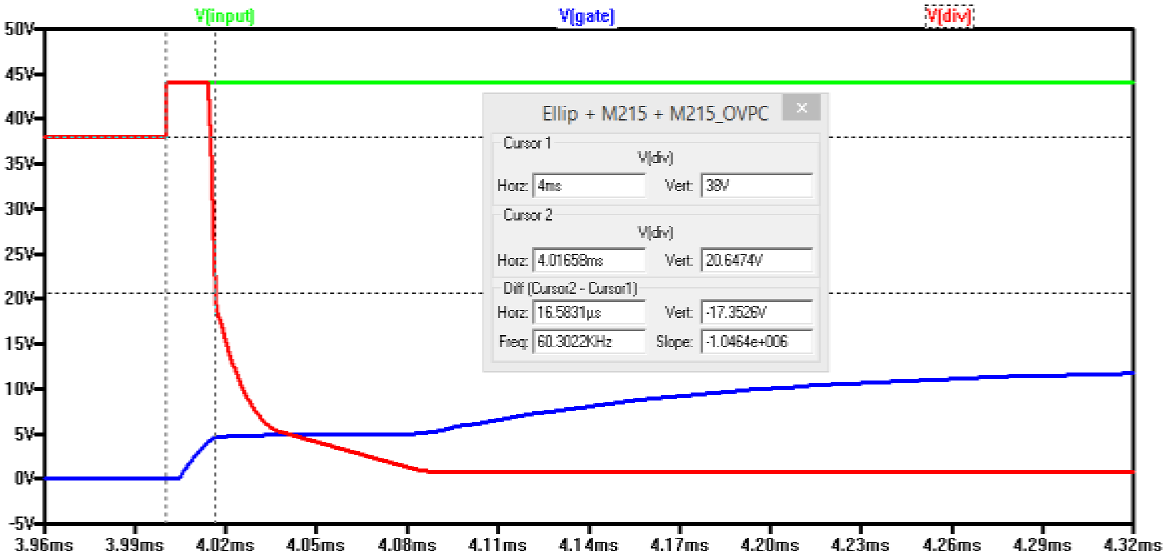


Figure 5-22: LTspice simulation measuring a gate delay of 16.58 µs for the new microinverter OVPC.

For delay testing, we supply the circuit with an initial input of 38 V then step up the voltage to 44 V. We then determine at which point the input reaches 41 V on the oscilloscope and set that as the starting point for the delay. To measure gate delay, we determine when the gate voltage surpasses 5 V, which sufficiently switches the IGBT on, and set that as the end point for gate delay. We measure the collector delay by setting the end point where the collector voltage drops to its 50 percent point. The oscilloscope captures in Figure 5-23 show gate and collector delay measurements, which bear resemblance to the delays in Figure 5-16. The gate delay measures 2.08 ms and the collector delay measures 2.2 ms, which measure slower than the simulated delays by three orders of magnitude.

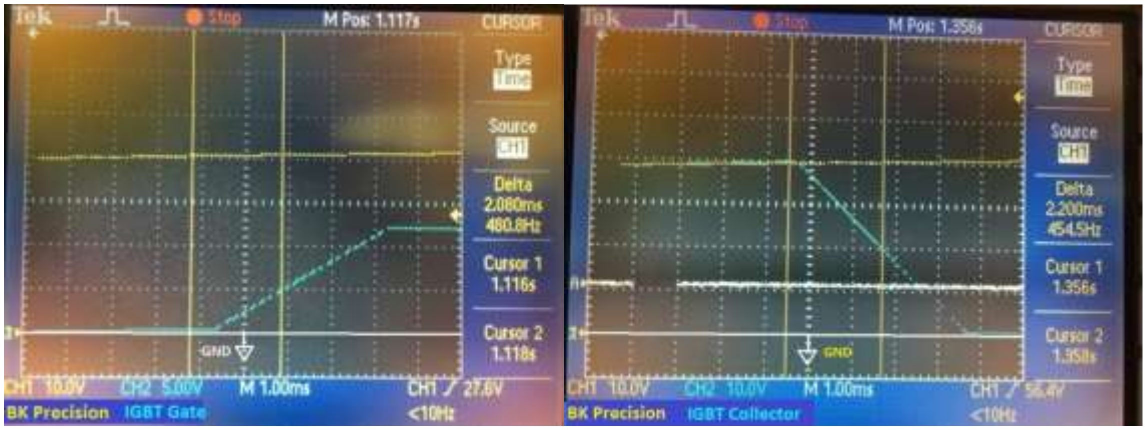


Figure 5-23: Oscilloscope capture of Input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Test measures the delays on IGBT terminals for the new OVPC protecting the M215 microinverter. Oscilloscope cursors measures gate delay of 2.08 ms and collector delay of 2.2 ms. Initial input voltage equals 38 V before rising to 44 V. Time scale: 1.0 ms.

We observe voltage fluctuation on the gate and collector when steadily increasing the supplied DC voltage. These fluctuations occur as the input voltage nears the voltage threshold to cause the OVPC to divert power. Therefore, it seems that at the threshold point, the comparator and IGBT gate struggle to settle on a voltage that works according to simulation. Adding capacitors to the gate removes the fluctuation, but causes the gate voltage to have a much longer delay. We then explore ways of improving the charge time on the IGBT's gate. The following section details implementing a current buffer between the comparator's output and IGBT's gate.

5.3.4 Measuring the IGBT Gate and Collector Delays of the New OVPC Design Featuring a Current Buffer

5.3.4.1 Driving the IGBT's gate with a Current Buffer

During previous delay testing, we encounter voltage oscillations around 4-6 volts when the voltage input nears the threshold to activate the comparator and IGBT. This oscillation eventually settles to 12 V when attempting to drive a high output. This causes a long delay between the input voltage surpassing the threshold voltage and the IGBT diverting excess power. To help drive current to the IGBT's gate, we add an NPN BJT

and resistor between the comparator's output and IGBT's gate. The BJT supplies the current, serving as the buffer, and the resistor offers a discharge path for excess current, serving as a current sink [25]. Figure 5-24 depicts the schematic of this in LTspice.

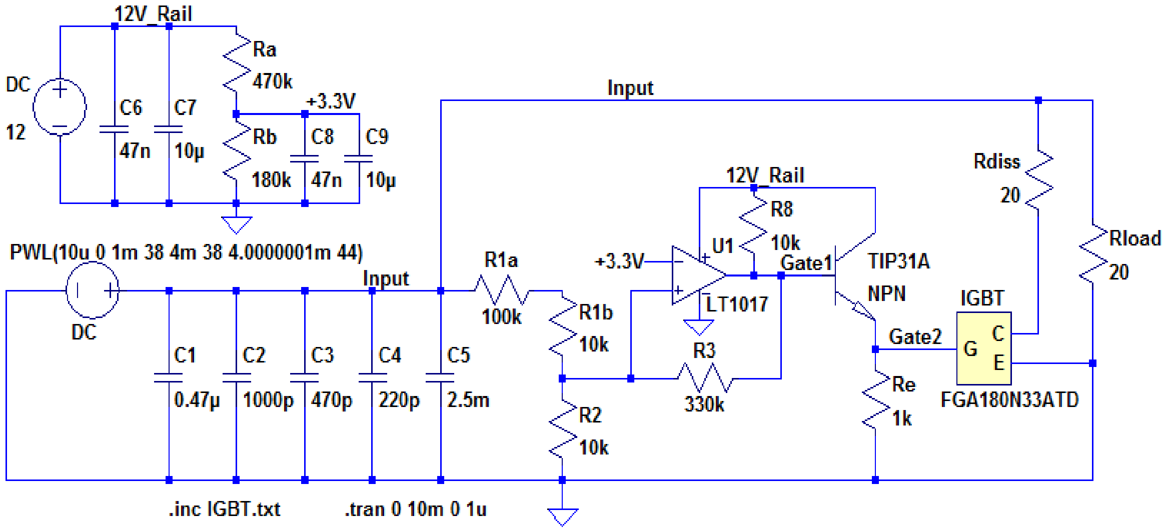


Figure 5-24: LTspice Schematic for the OVPC designed to limit the DC input voltage for the Enphase microinverters. LTspice schematic improves upon prior design by including a BJT to help drive current to the IGBT's gate.

Previous OVPC testing sees voltage instability at the IGBT's gate when the input voltage nears the threshold voltage to divert excess power. This specifically occurs when increasing the input voltage in steps of 0.5 V and approaching the voltage threshold. Voltage instability occurs less when setting the BK Precision to output a voltage exceeding the threshold by a few volts. When replicating the same test with a current-driven OVPC, we observe no occurrence of voltage instability. Instead, we observe a clean signal of a voltage rising from 0 V to 12 V at the IGBT's gate. When simulating the circuit in LTspice, the IGBT gate voltage maximizes at 10.7 V instead of 12 V. When testing on a lab bench we observe a gate voltage closer to 10 V. The differences in the BJT used in simulation vs. the one used in testing cause this difference. We use only a basic NPN for modeling in LTspice, but use a TIP31A power BJT when implementing the current buffer on the breadboard-constructed OVPC.

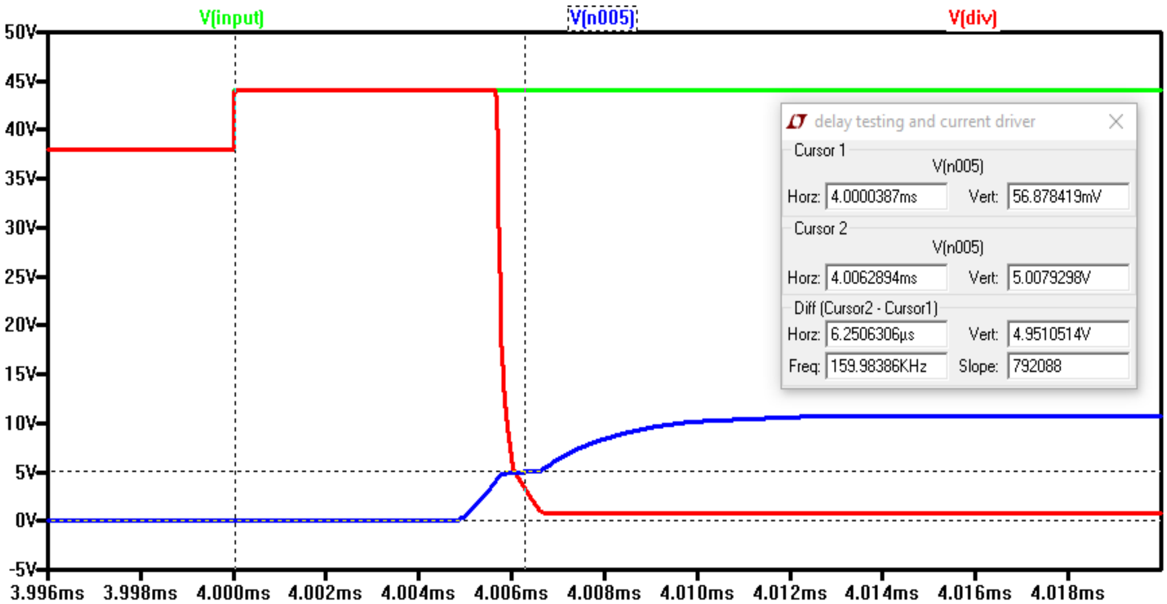


Figure 5-25: LTspice simulation measuring a gate delay of 6.25 µs when including a current driver.

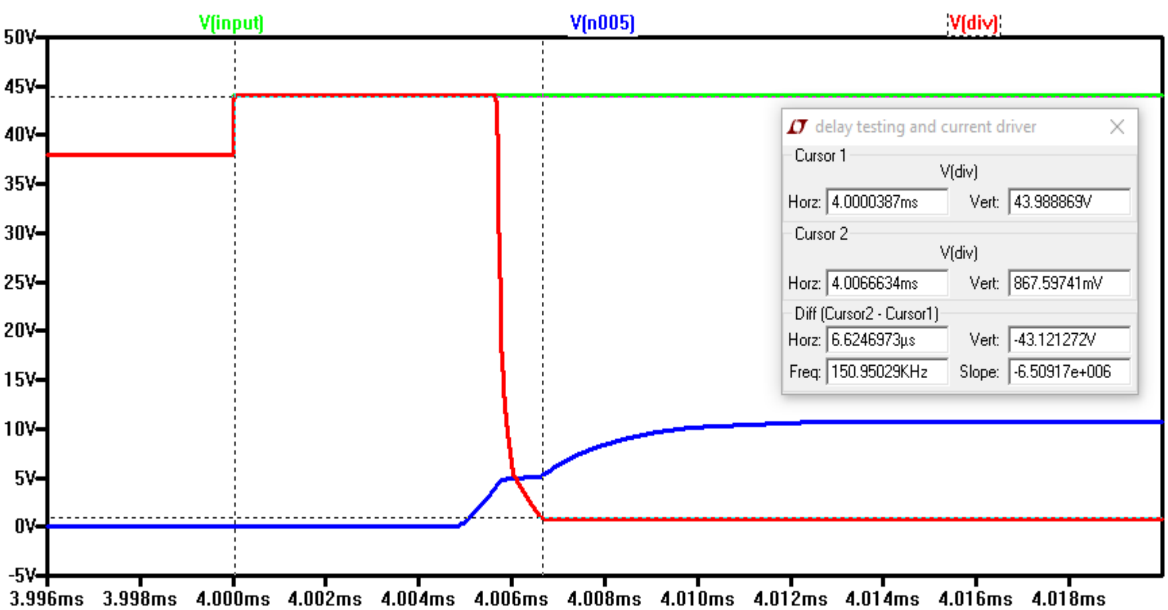


Figure 5-26: LTspice simulation measuring a collector delay of 6.62 µs when including a current driver.

Simulating the OVPC with a current buffer shows further improvement in the gate and collector time delays. Figure 5-25 above simulates the gate voltage taking 6.25 µs to charge to 5 V. Figure 5-26 simulates the collector voltage requiring 6.62 µs to reduce from 45 V to less than one volt. Both of these delay times improve upon the simulations without the current driver. Figure 5-27 shows an updated breadboard diagram of the

OVPC designed for protecting microinverters. The circuit includes a current driver and filter capacitors to reduce transients on the 12-Volt rail and the +3.3 V reference. The next section seeks to measure the gate and collector delays properly with an oscilloscope.

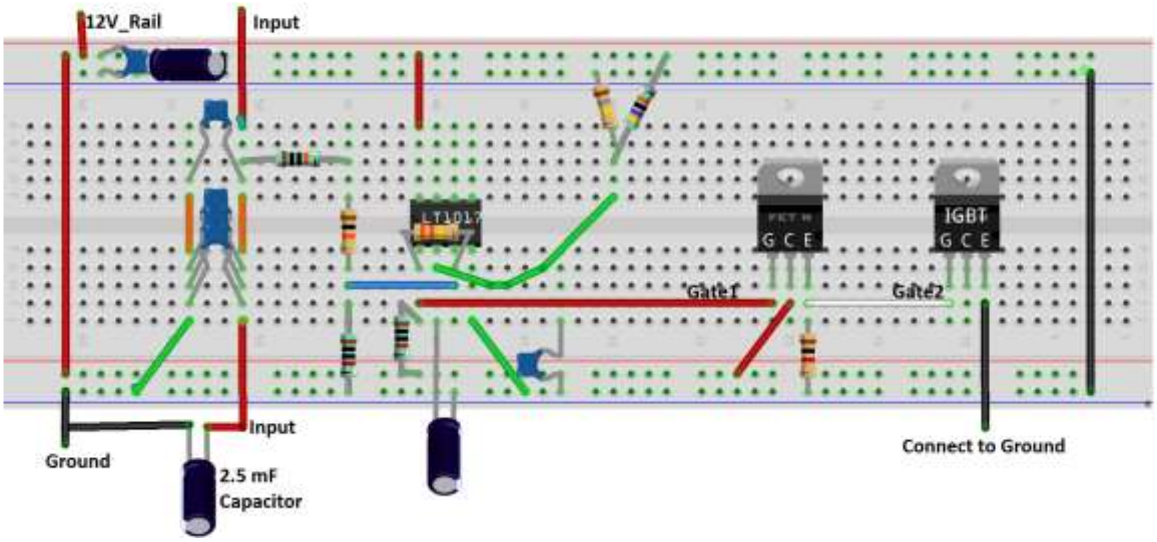


Figure 5-27: Breadboard diagram of the new OVPC designed for protecting the micro-inverters from overvoltage conditions. The circuit includes the new current driver between the output of the LT1017 comparator and IGBT's gate terminal. This bread-board diagram also includes filter capacitors on the 12-Volt rail and +3.3 V reference.

5.3.4.2 Properly Measuring the IGBT's Gate and Collector Delays

After setting up an oscilloscope to acquire a scope capture from a rising edge trigger, we acquire accurate delay measurements. The oscilloscopes trigger on the rising edge of the gate signal when acquiring the gate delay. Figure 5-28 shows a wiring diagram of this test session. Oscilloscope 1 measures the input voltage and gate signal of the TIP31A BJT. Oscilloscope 2 measures the input voltage and gate signal of the FGA180N33ATD IGBT. We initially set the BK Precision to output 0 V before setting the output voltage to supply 61 V. Testing uses the 20 Ω resistors from the elliptical as the load and diverting resistors. This ensures against reaching the BK Precision's 9.1 A current limit when the OVPC diverts power.

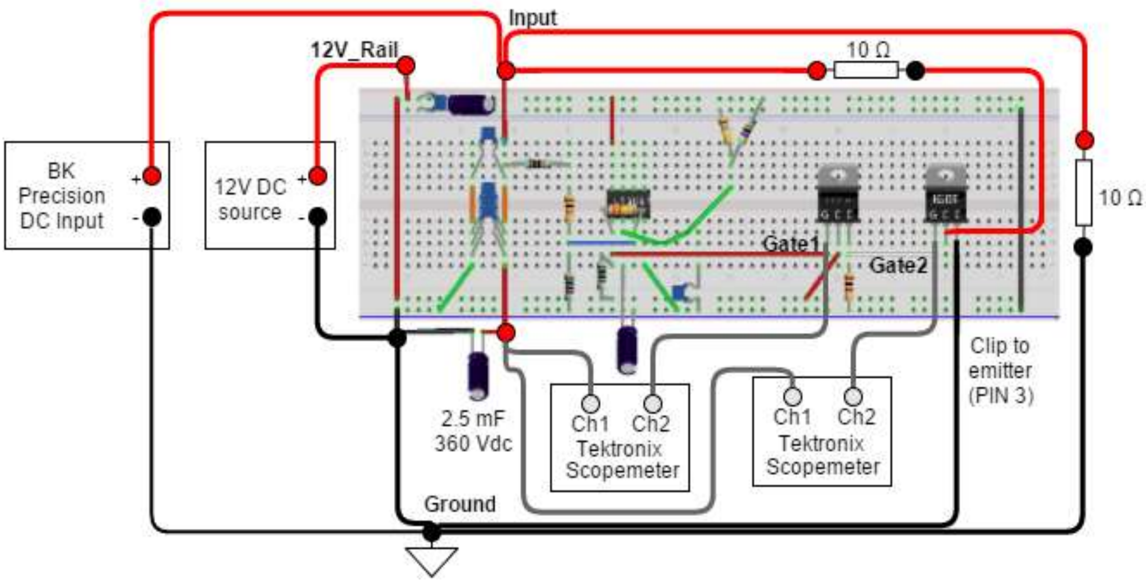


Figure 5-28: Wiring diagram for OVPC delay testing session. OVPC pictured protects the Enphase M215 microinverter

Figure 5-29 shows the BJT's gate delay and Figure 5-30 depicts a new IGBT gate delay measurement. The OVPC diverts power when the input voltage surpasses 40.6 V. However, the oscilloscope cursors cannot measure with precision to 40.6 V due to resolution limitations. The Tektronix oscilloscopes only display voltage measurements in increments of 0.4 V. For this reason, 40.8 V becomes the target input voltage for power diversion. Once the oscilloscopes acquire single shot-scope captures, we determine when the rising input signal measures 40.8 V and use that time as the starting point for delay measurements. We set the start of the gate voltage rising as the endpoint in this oscilloscope capture. These appear in the left images in both Figure 5-29 and Figure 5-30. The right oscilloscope captures in Figure 5-29 and Figure 5-30 measure the time difference between the start of the gate voltage rising and the time when the gate rises to 50 percent of its maximum voltage. Summing the time in both measurements yields the total gate delay for both BJT and IGBT. The scope captures at a time resolution of 50 µs per division show a BJT gate delay of 146.0 µs and an IGBT gate delay of 222.0 µs.

Adding on the times from the 2.5 µs per division captures brings the total BJT gate delay to 147.6 µs and the total IGBT gate delay to 223.2 µs. These delay measurements error on high end of total delay times due to the time leading up to the gate voltages beginning to rise. That said these delay times demonstrate that an OVPC with a current driver has a fast enough response time to protect other components from voltage overload.

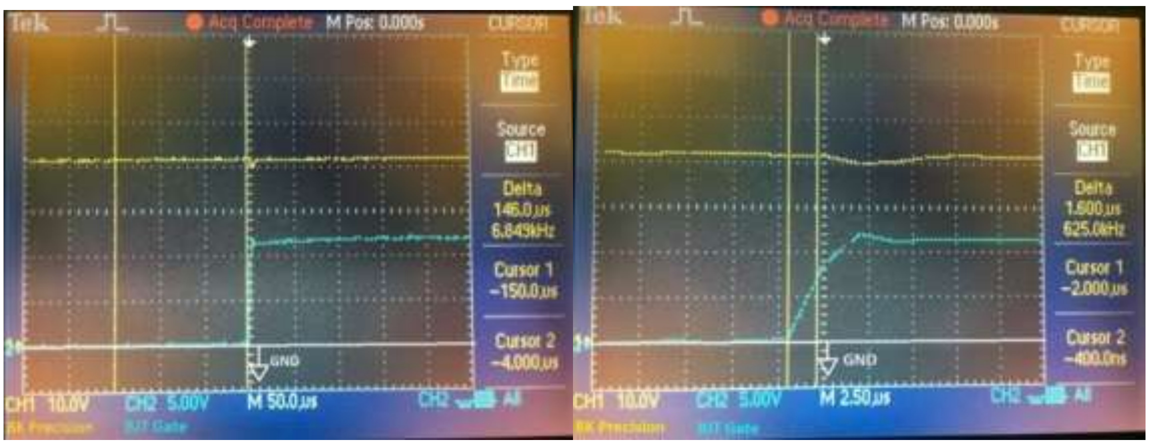


Figure 5-29: Oscilloscope captures measure the BJT's gate delay. Summing the times in both pictures yields a total delay of 147.6 µs. The yellow signal represents the DC supplied input voltage while the blue signal represents the IGBT's gate voltage.

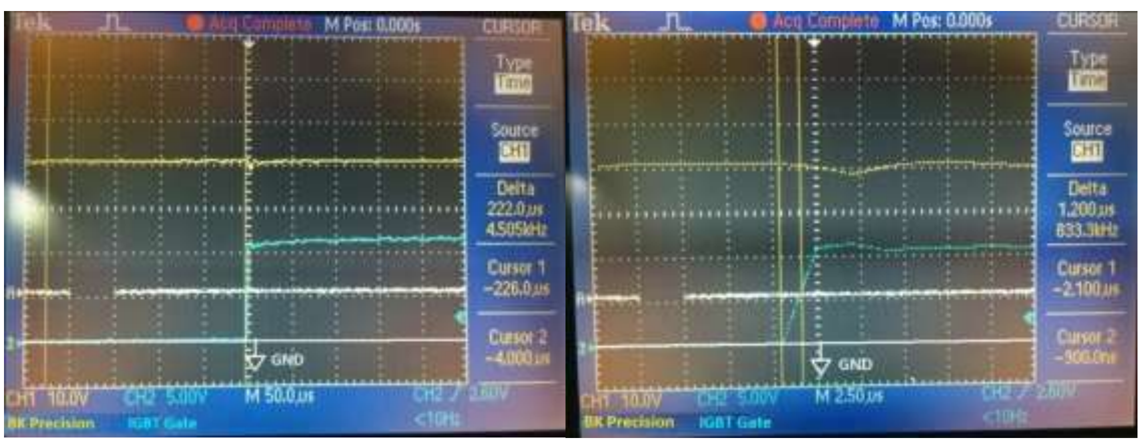


Figure 5-30: Oscilloscope captures measure the IGBT's gate delay. Summing the times in both pictures yields a total delay of 223.2 µs. The yellow signal represents the DC supplied input voltage while the blue signal represents the IGBT's gate voltage.

Figure 5-31 shows single shot triggers on the rising edges of the BJT's gate voltage and IGBT's gate voltage. The waveforms of the BJT and IGBT gate voltages resemble the simulations seen in Figure 5-25 and Figure 5-26. The oscilloscopes measure

a total BJT gate rise time of 1.14 µs and a total IGBT gate rise time of 1.20 µs. Figure 5-32 follows with fall time measurements on the BJT's and IGBT's gate. These fall times measure longer than their respective rising time measurements. The oscilloscope cursors measure a total BJT gate falling time of 1.64 µs and a total IGBT gate falling time of 25.2 µs.

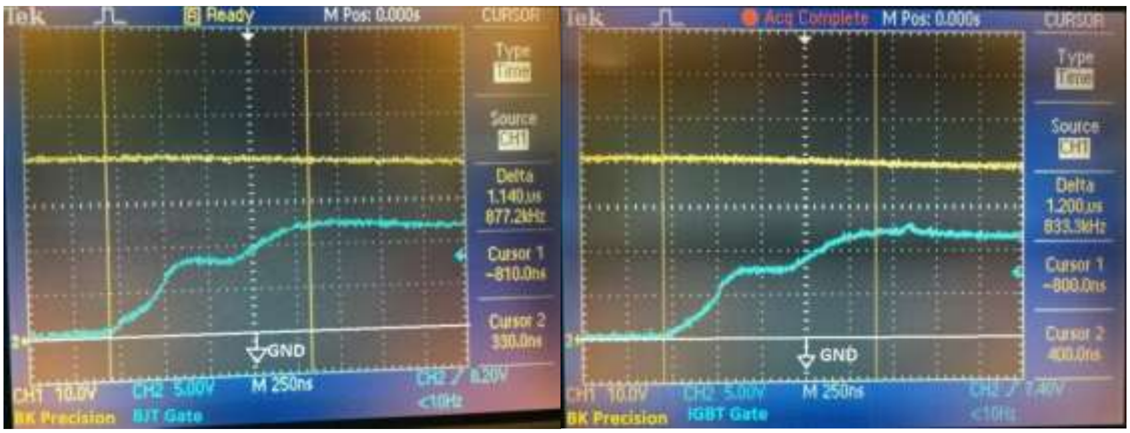


Figure 5-31: Single shot scope captures measuring rise times of the two gate voltages. The left image measures a BJT gate rise time of 1.14 µs and the right image measures an IGBT rise time of 1.20 µs. The yellow signal represents the DC supplied input voltage. The blue signal represents the IGBT's gate voltage.

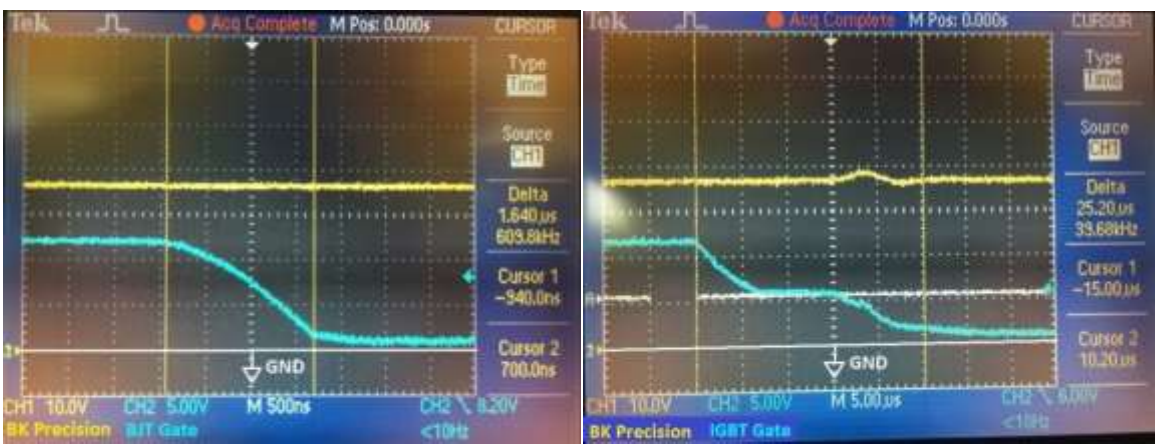


Figure 5-32: Single shot scope captures measuring falling times of the two gate voltages. The left image measures a BJT gate fall time of 1.64 µs and the right image measures an IGBT rise time of 25.2 µs. The yellow signal represents the DC supplied input voltage. The blue signal represents the IGBT's gate voltage.

Next, we measure the delay between the IGBT's gate and IGBT's collector. Using one Tektronix oscilloscope, channel 1 probes the IGBT's gate and channel 2 probes the IGBT's collector. The oscilloscopes have a resolution of 250 ns per division. Figure 5-33

shows oscilloscope captures measuring the collector's delay response. The left image measures a time difference of 330 ns between the start of the gate signal rising and the time at which the collector signal reaches its 50 percent point. The right image measures a time of 1.04 µs for the collector signal to reach its minimum value once the gate signal begins rising.

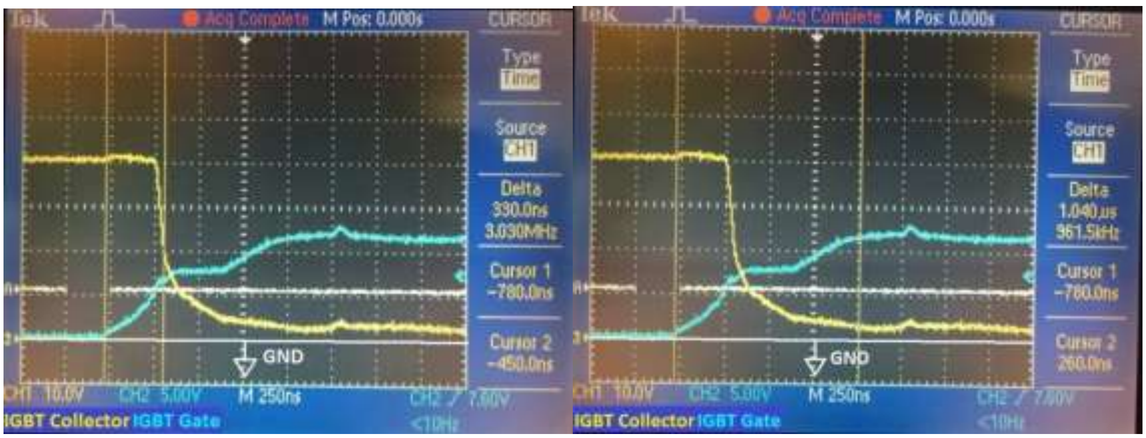


Figure 5-33: Single shot scope captures measuring collector response times for the IGBT. The left image measures the time difference between the gate signal rising and when the collector signals reaches its 50 percent point (330 ns). The right image measures the difference between the gate signal rising and when the collector signal reaches its minimum value (1.04 µs). The yellow signal represents the IGBT's collector voltage, while the blue signal represents the IGBT's gate voltage.

This proves that including a current driver between the LT1017's output and IGBT's gate improves the OVPC's response. Including a current driver eliminates voltage fluctuation on the IGBT's gate signal, which leads to the OVPC having a faster response time when diverting power. When properly using a single shot trigger on the rising edge of the gate voltage, the oscilloscopes capture waveforms that reflect the waveforms simulated in LTspice. BJT and IGBT gate delay times measure on the order of microseconds with the longest delay measuring 223.2 µs. The IGBT gate also has a rise time of 1.20 µs and a falling time of 25.2 µs due to the stability provided by the current-driving BJT. The IGBT's collector voltage descends to a minimum value 1.04 µs after the gate voltage begins rising, which shows the IGBT's collector responds quickly.

The OVPCs designed for the Vicor and CUI DC-DC converters now have a current driver as well. The following section summarizes the final designs of the OVPCs used for elliptical testing in the following chapters.

5.4 Final Designs Used for Elliptical Testing

This section of Chapter 5 summarizes the final designs for the overvoltage protection circuits. In total, there exist three different OVPCs meant to protect a DC-DC converter or microinverter from overvoltage conditions. Figure 5-34 depicts the circuit diagram of the OVPC protecting the M215 microinverter during elliptical testing in Chapter 7. Likewise, Figure 5-35 represents the CUI's OVPC, and Figure 5-36 depicts the Vicor's OVPC when conducting full system testing in Chapter 8.

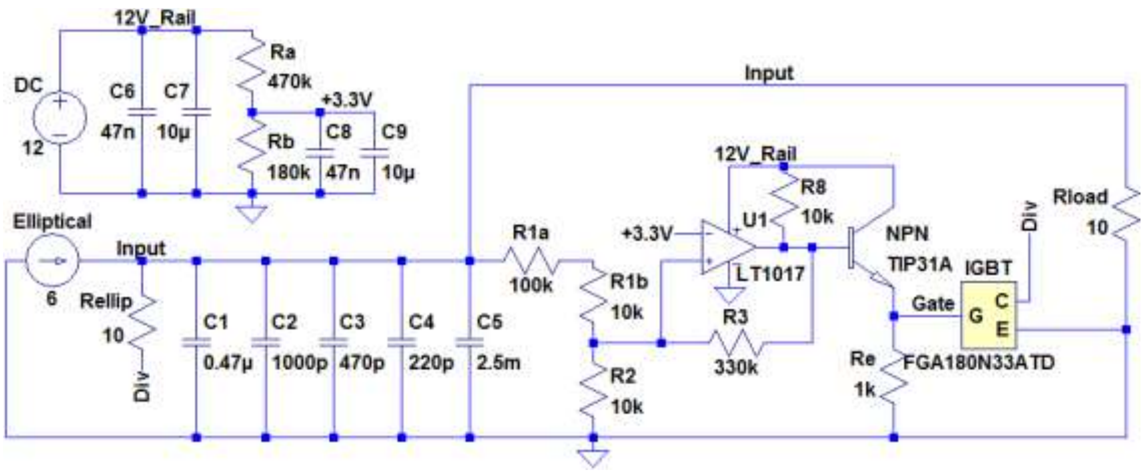


Figure 5-34: LTspice diagram of OVPC designed to protect the Enphase M215-60-2LL-S22 microinverter from overvoltage conditions. This OVPC may protect other microinverters from overvoltage conditions depending on their operating ranges.

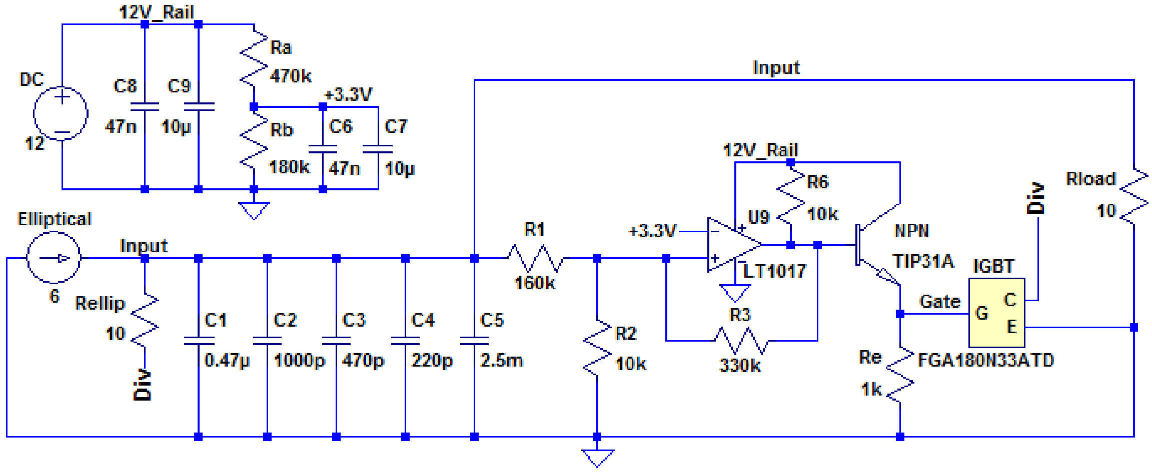


Figure 5-35: LTspice diagram of OVPC designed to protect the CUI VHK200W-Q48-S28 DC-DC Converter from overvoltage conditions.

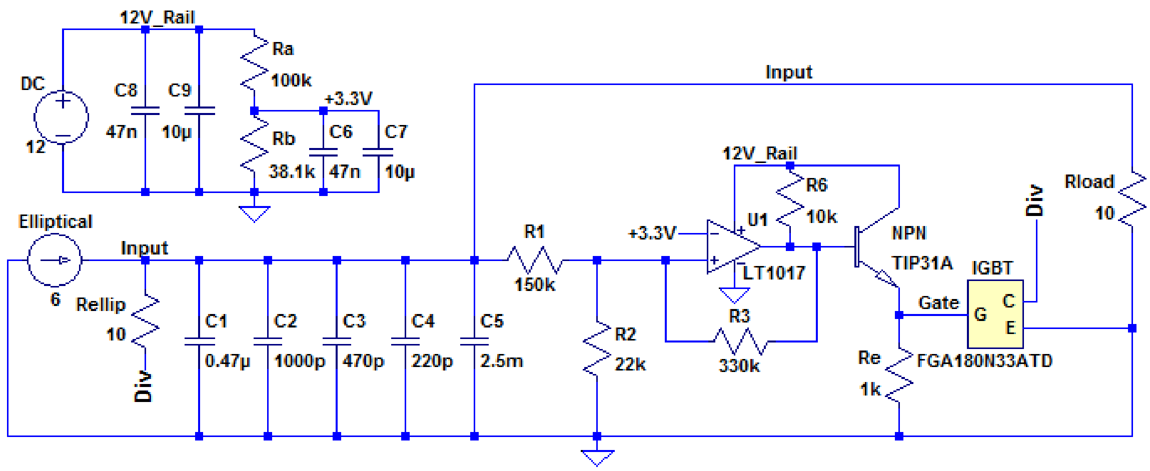


Figure 5-36: LTspice diagram of OVPC designed to protect the Vicor V28A36T200BL2 Maxi DC-DC converter from overvoltage conditions.

The three OVPCs share a very similar design on a circuit level. Differences between the three OVPCs manifest with different resistor values for R1, R2, R4, and R5. These resistors form the voltage dividers between the input node and ground, and the voltage divider between the 12-Volt rail and ground. All three OVPCS have different resistor values for R1 and R2 as each OVPC diverts excess power at different voltage thresholds. Figure 5-34 and Figure 5-35 share the same resistor values for R4 and R5, since the two OVPCs in the figures share the same breadboard. To switch between the inverter-only and CUI OVPCs means swapping resistors R1 and R2.

The following chapter combines available DC-DC converters with available Enphase microinverters and measures the efficiency of each combination over various test level voltages.

CHAPTER 6: DC-DC CONVERTER AND MICROINVERTER COMBINATION TESTING

6.1 Introduction

Previous chapters in this report characterize the efficiency of available microinverters and DC-DC converters. This chapter pairs each DC-DC converter with each Enphase microinverter and determines the AC power production efficiency of each combination across the DC-DC converter's operating range. The main components this chapter tests include the Enphase M175 and M215 microinverters, the Vicor DC-DC converter, and the CUI DC-DC converter.

When conducting efficiency tests in Chapter 4, the DC-DC converters have external passive components necessary for basic operation. The Vicor DC-DC converter has external bypass capacitive filtering while the CUI DC-DC converter has external capacitive filtering and an external inductor. Chapter 4.2.1 and Chapter 4.3.1 detail how to prepare the two DC-DC converters for testing.

Testing in this chapter requires the use of a sense resistor to measure the current flowing between the positive output of the DC-DC converter and the positive input of the microinverter. When testing, an Agilent multimeter measures the voltage drop across the sense resistor, and dividing the measured voltage by the measured resistance yields the DC-DC converter output current. Measuring the sense resistor's low resistance requires using four banana-to-grabber cables for a four-terminal sensing measurement. When set to reading low resistance measurements, the Agilent multimeter should measure the resistance. For this phase of testing, we measure a sense resistance of **0.0102 Ω** or

10.2 mΩ, and use this sense resistor across the following four converter-inverter combinations.

Appendix B.6 contains detailed setup procedures and test protocols for the following subchapters. Each test protocol includes a wiring diagram to illustrate how the converters and microinverters connect with each other to test equipment.

6.2 Vicor DC-DC Converter and M175 Microinverter Efficiency Testing

Table 6-1 tabulates data for testing the Vicor DC-DC converter and M175 inverter. We begin collecting data for a set input voltage of 10 V, because testing in Chapter 4.2 shows the Vicor DC-DC converter requires a minimum input of 10 V to output a voltage. Due to the BK Precision supplying a range of values, Table 6-1 includes columns for the minimum and maximum supplied input values. Similarly, the power meter often measures a range of AC output measurements, so Table 6-1 records the minimum and maximum output measurements. Each efficiency calculation compares an AC output power measurement with its respective supplied DC power calculation. For example, "MAX Efficiency" compares the ratio of the maximum output power to the maximum supplied power.

Between setting the BK Precision to supply 10 V to 13 V, the power meter measures about 0.5 W of AC power. Over this same set voltage range, the Vicor DC-DC converter outputs a DC voltage ranging from 12.39-24.88 V. The M175 inverter has a minimum startup voltage of 32 V, according to initial efficiency testing in Chapter 3. Only when setting the supplied input voltage to 18 V does the Fluke multimeter measure the Vicor output a maximum voltage of 32.84 V. At this set input voltage, the power meter measures a maximum of 4.97 W of AC power. Power meter measurements so far

show that the M175 inverter attempts producing AC power. However, the M175 can only manage producing a couple watts or less due to the insufficient DC input voltage from the Vicor DC-DC converter. Across the test voltage range of 13 V to 18 V, the BK Precision supplies an actual DC input voltage to the Vicor less than the set voltage. Within this test voltage range, the supplied DC current increases with the supplied DC voltage.

Once setting the BK Precision to supply 19 V, the DC source outputs a voltage equal to the set voltage, and the input current decreases to 0.88 A. The Vicor outputs a constant 36 V, and the M175 outputs a maximum AC current and power of 141.1 mA and 18.48 W. The maximum, minimum, and average efficiency calculations all improve as well. From a maximum input voltage of 19 V to 26 V, the minimum power measurements yield higher efficiency calculations than maximum power measurements. The low power efficiency calculations range from 67% to 80%, and the high power efficiency calculations range from 34.1% to 39.5%. There exist wide efficiency variations at multiple given biases. Such efficiency variations occur at biases with greater variation in calculated input power than the measured output power. For example, at a set test level voltage of 25 V the power meter measures a maximum output power of 18.79 W and a minimum output power of 12.79 W. Meanwhile, at this bias, the input power calculations supplied by the DC source range from 16.99 W to 51.0 W. When acquiring data, recording the minimum supplied voltage and current values do not occur simultaneously. The minimum and maximum powers do not represent an accurate instantaneous power over lengthy periods of recording data, and this leads to the wide efficiency variations at given biases.

Table 6-1: Collected data from Efficiency testing Vicor DC-DC converter and M175 inverter.

Efficiency Testing with Vicor V28A36T200BL2 DC-DC Converter and Enphase M175 Inverter

Set Test Level (V)	BK precision DC Source (DC)						Fluke MM (DC)		Agilent MM (DC)		
	V_{in} MIN (V)	V_{in} MAX (V)	I_{in} MIN (A)	I_{in} MAX (A)	P_{in} MIN (W)	P_{in} MAX (W)	$V_{DC\text{-}DC}$ MIN (V)	$V_{DC\text{-}DC}$ MAX (V)	V_{sense} MIN (mV)	V_{sense} MAX (mV)	V_{sense} AVG (mV)
10	9.99	10.00	0.21	0.21	2.10	2.11	12.39	12.40	0.05	0.05	0.05
11	10.99	11.00	0.36	0.36	3.97	3.99	16.97	16.97	0.01	0.04	0.04
12	11.95	11.98	0.49	0.50	5.90	5.99	20.20	20.44	-0.01	0.09	0.03
13	12.74	12.76	0.68	0.68	8.61	8.68	24.64	24.88	0.00	0.07	0.03
14	13.19	13.37	0.83	0.83	10.88	11.10	27.08	27.36	0.11	0.18	0.14
15	13.51	13.55	1.00	1.01	13.48	13.71	28.16	30.56	0.17	0.52	0.27
16	14.05	14.16	1.08	1.11	15.20	15.65	28.04	31.24	0.35	0.97	0.50
17	14.59	14.91	1.15	1.17	16.79	17.40	27.40	31.60	0.58	1.73	1.05
18	15.31	15.63	1.22	1.26	18.74	19.69	28.80	32.84	0.81	2.06	1.34
19	18.98	19.00	0.88	2.67	16.70	50.73	36.00	36.04	0.72	10.48	4.78
20	19.99	20.00	0.77	2.45	15.39	49.00	36.04	36.08	0.70	10.52	4.79
21	20.98	21.00	0.84	2.27	17.62	47.67	36.04	36.06	0.69	10.65	4.67
22	21.99	22.00	0.75	2.24	16.49	49.28	36.06	36.06	0.69	10.56	4.62
23	22.98	23.00	0.83	2.19	19.07	50.37	36.06	36.06	0.69	10.45	4.64
24	23.98	24.00	0.74	2.08	17.75	49.92	36.06	36.06	0.67	10.46	4.58
25	24.98	25.00	0.68	2.04	16.99	51.00	36.06	36.07	10.40	12.79	11.38
26	25.98	26.00	0.63	1.58	16.37	41.08	36.07	36.07	10.34	11.49	10.68
27	26.99	27.00	0.47	2.49	12.69	67.23	34.01	36.07	0.11	11.11	2.82
28	19.26	28.00	0.48	2.62	9.24	73.36	34.49	36.07	0.11	11.46	2.69

Set Test Level (V)	Calculate M215 Input I and P (DC)					Power Meter (AC)						Efficiency		
	I_{sense} MIN (A)	I_{sense} MAX (A)	I_{sense} AVG (A)	$P_{DC\text{-}DC}$ MIN (W)	$P_{DC\text{-}DC}$ MAX (W)	V_{out} MIN (V)	V_{out} MAX (V)	I_{out} MIN (mA)	I_{out} MAX (mA)	P_{out} MIN (W)	P_{out} MAX (W)	LOW (%)	HIGH (%)	AVG (%)
10	0.01	0.005	0.005	0.06	0.06	230.3	230.8	53.5	53.6	0.52	0.53	24.8	25.1	25.0
11	0.00	0.004	0.004	0.02	0.07	230.8	231.0	53.6	53.7	0.52	0.53	13.1	13.3	13.2
12	0.00	0.010	0.003	-0.01	0.20	230.8	230.9	53.6	53.7	0.52	0.53	8.8	8.8	8.8
13	0.00	0.007	0.003	0.01	0.17	230.7	231.3	53.7	53.8	0.52	0.52	6.0	6.0	6.0
14	0.01	0.018	0.015	0.31	0.49	231.2	231.3	53.6	53.7	0.19	0.20	1.7	1.8	1.8
15	0.02	0.053	0.028	0.49	1.62	229.7	231.1	53.4	57.1	0.07	0.92	0.5	6.7	3.6
16	0.04	0.10	0.05	0.99	3.12	230.6	231.0	53.6	60.5	0.00	2.06	0.0	13.2	6.6
17	0.06	0.18	0.11	1.64	5.63	230.5	231.2	56.6	63.5	0.68	3.43	4.0	19.7	11.9
18	0.08	0.21	0.14	2.39	6.96	230.4	230.9	60.4	78.2	2.07	4.97	11.0	25.2	18.1
19	0.07	1.08	0.49	2.65	38.81	230.1	231.5	108.3	141.1	13.17	18.48	78.9	36.4	57.6
20	0.07	1.08	0.49	2.57	39.02	230.5	231.2	106.1	140.9	12.32	18.44	80.0	37.6	58.8
21	0.07	1.09	0.48	2.56	39.47	231.5	232.3	106.2	143.2	12.87	18.85	73.0	39.5	56.3
22	0.07	1.09	0.47	2.54	39.14	230.1	230.5	104.4	143.2	12.02	18.76	72.9	38.1	55.5
23	0.07	1.07	0.48	2.57	38.74	230.5	231.0	106.1	142.7	12.78	18.71	67.0	37.1	52.1
24	0.07	1.07	0.47	2.48	38.76	230.7	231.0	106.6	131.9	12.87	17.02	72.5	34.1	53.3
25	1.07	1.32	1.17	38.53	47.44	230.3	231.0	106.1	143.2	12.79	18.79	75.3	36.8	56.1
26	1.06	1.18	1.10	38.35	42.61	230.8	231.5	104.2	117.2	11.96	14.68	73.1	35.7	54.4
27	0.01	1.14	0.29	0.38	41.19	230.4	230.8	0.0	135.9	2.12	20.80	16.7	30.9	23.8
28	0.01	1.18	0.28	0.39	42.49	230.0	230.8	0.0	89.8	1.54	15.36	16.7	20.9	18.8

The scatter plot in Figure 6-1 plots the average efficiency over the recorded maximum supplied input voltage at each set input voltage. The chart plots the average efficiency points since the minimum and maximum efficiency calculations consider a non-instantaneous input power. Lines from the plot points represent a possible efficiency range for each supplied maximum input voltage in accordance to Table 6-1.The jump in 18.1% average efficiency to 57.6% shows the Vicor transitioning to producing a constant 36 V and sufficiently powering the M175 inverter. The Vicor-M175 combination has an average efficiency of 48.7% across a supplied maximum input voltage range of 19-28 V. The plot points for a maximum input voltage of 27 V and 28 V deviate from the trend set by previous points because of a significant decrease in the measured minimum AC power.

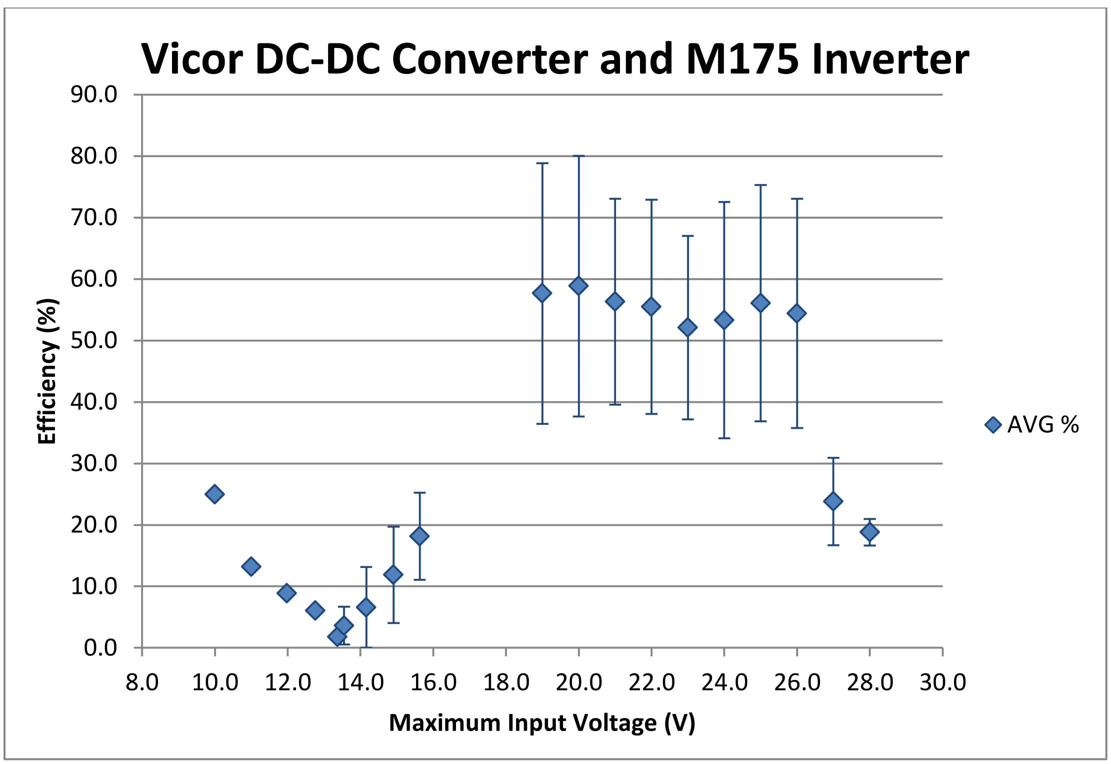


Figure 6-1: Vicor DC-DC Converter and Enphase M175 Inverter combination test efficiency plot when connected to the AC grid. Scatter plot includes calculated efficiencies from minimum, maximum, and average power measurements.

6.3 CUI DC-DC Converter and M175 Microinverter Efficiency Testing

Unfortunately, the combination of the CUI DC-DC converter and Enphase M175 microinverter fails to produce AC power to the grid. This occurs regardless of the input voltage or current the BK Precision supplies. The M175 microinverter has a minimum startup voltage of 32 V and the CUI DC-DC converter outputs a maximum 28 V. The CUI supplies an insufficient DC voltage to startup the M175, and so the inverter cannot produce AC power. Prior to ordering a DC-DC converter from CUI Inc., we consulted the M175 and M215 datasheets. The M215 data sheet lists a minimum startup voltage of 22 V [13], while the resources on the M175 inverter only list an peak power tracking voltage of 25-40 V [10, 11]. We realize the M175 microinverter has a minimum startup voltage of 32 V after conducting efficiency tests in Chapter 3.2. Unable to collect data for a CUI-M215 test combination, we move on.

6.4 Vicor DC-DC Converter and M215 Microinverter Efficiency Testing

Setting the BK precision to supply 22 V lets the CUI DC-DC converter output a constant 36 V to the M215 inverter as the inverter initializes. After the microinverter starts up, the supplied voltage drops to about 17 V and the output of the DC-DC converter averages about 23-24 V. This continues to provide enough DC voltage to power the M215 inverter, which produces up to 17.65 W of AC power. The M215 inverter ceases producing AC power when lowering the input voltage below 12 V. Table 6-2 tabulates data for testing the Vicor DC-DC converter and M215 inverter across the same set voltage level as Table 6-1. Table 6-2 also includes extra input and output columns for the minimum and maximum measurements and calculations. Similar to the Vicor-M175 test combination, each efficiency calculation compares an AC output

measurement with its respective supplied DC power calculation. For example, "MAX Efficiency" compares the ratio of the maximum output power of the maximum supplied power.

When setting the BK Precision to supply 10 V to 13 V, the DC source outputs a voltage equal to the setting. However, the Vicor DC-DC converter outputs a voltage fewer than 22 V and so the M215 microinverter fails to produce AC power. Setting the input voltage between 13 V and 15 V causes the M215 inverter to produce AC power, but no more than 4.91 W. Starting at a 13 V test voltage, the BK precision supplies an input voltage less than the set voltage level. When set to supply 28 V, the DC source outputs a maximum of 19.71 V. At no set test level does the Vicor DC-DC converter output a maximum of 36 V when paired with the M215 microinverter. From the set test levels of 16 V to 28 V, the M215 inverter increases in AC power production, and the minimum and maximum efficiency calculations increase compared to lower set test levels. The MIN efficiency calculations range from 40.9% to 59.5%, and the MAX efficiency calculations range from 46.5% to 61.3%.

Table 6-2: Collected data from Efficiency testing Vicor DC-DC converter and M215 inverter.

Efficiency Testing with Vicor V28A36T200BL2 DC-DC Converter and Enphase M215 Inverter											
Set Test Level (V)	BK precision DC Source (DC)						Fluke MM (DC)		Agilent MM (DC)		
	V_{in} MIN (V)	V_{in} MAX (V)	I_{in} MIN (A)	I_{in} MAX (A)	P_{in} MIN (W)	P_{in} MAX (W)	V_{DC-DC} MIN (V)	V_{DC-DC} MAX (V)	V_{sense} MIN (mV)	V_{sense} MAX (mV)	V_{sense} AVG (mV)
10	9.99	10.00	0.20	0.20	1.95	2.00	10.56	10.58	0.26	0.34	0.28
11	10.99	11.00	0.36	0.37	3.99	4.04	15.87	15.89	0.23	0.19	0.22
12	11.96	11.99	0.50	0.51	6.03	6.16	19.50	19.52	0.14	0.26	0.18
13	12.78	12.82	0.71	0.75	9.10	9.56	18.24	21.49	0.42	1.51	0.91
14	13.51	13.63	0.83	0.89	11.21	12.13	17.59	22.88	0.69	1.90	1.21
15	13.72	13.99	1.04	1.21	14.27	16.93	14.31	25.55	1.08	7.61	3.06
16	13.87	14.01	1.61	1.67	22.33	23.40	16.07	20.84	6.50	7.59	6.22
17	14.35	14.52	1.78	1.89	25.54	27.44	16.07	16.51	2.08	9.30	8.20
18	14.84	15.11	1.72	2.05	25.52	30.98	16.07	20.65	5.75	10.57	8.45
19	15.05	15.26	1.91	2.26	28.75	34.49	15.95	18.89	7.67	11.80	10.40
20	15.59	15.75	2.16	2.23	33.67	35.12	16.94	22.02	7.34	12.04	9.55
21	16.35	16.61	1.89	2.00	30.90	33.22	18.18	26.66	4.83	11.75	6.81
22	16.74	16.97	2.05	2.12	34.32	35.98	23.07	24.87	6.55	8.26	7.24
23	17.06	17.42	2.15	2.34	36.68	40.76	21.86	26.76	6.16	10.37	7.77
24	17.34	17.58	2.36	2.48	40.92	43.60	21.06	24.31	8.59	12.18	9.76
25	17.24	17.42	3.19	3.68	55.00	64.11	17.37	18.83	9.93	30.17	17.30
26	18.49	18.81	2.26	2.39	41.79	44.96	17.22	32.89	5.07	8.18	6.88
27	19.06	19.15	2.42	2.52	46.13	48.26	28.24	30.56	7.03	9.06	8.15
28	19.36	19.71	2.58	2.72	49.95	53.61	27.75	30.35	7.88	10.55	9.40

Set Test Level (V)	Calculate M215 Input I and P (DC)					Power Meter (AC)						Efficiency		
	I_{sense} MIN (A)	I_{sense} MAX (A)	I_{sense} AVG (A)	P_{DC-DC} MIN (W)	P_{DC-DC} MAX (W)	V_{out} MIN (V)	V_{out} MAX (V)	I_{out} MIN (mA)	I_{out} MAX (mA)	P_{out} MIN (W)	P_{out} MAX (W)	MIN (%)	MAX (%)	AVG (%)
10	0.03	0.035	0.029	0.28	0.37	231.3	231.5	66.0	66.1	0.0	0.0	0.0	0.0	0.0
11	0.02	0.020	0.022	0.37	0.31	231.4	231.6	66.1	66.2	0.0	0.0	0.0	0.0	0.0
12	0.01	0.026	0.018	0.28	0.52	231.4	231.5	66.1	66.2	0.0	0.0	0.0	0.0	0.0
13	0.04	0.16	0.094	0.78	3.34	231.5	231.6	70.5	78.4	0.94	1.94	10.3	20.3	15.3
14	0.07	0.20	0.12	1.25	4.47	232.9	233.1	71.0	75.2	1.94	2.93	17.3	24.2	20.7
15	0.11	0.78	0.31	1.59	19.98	232.9	231.6	75.3	94.7	1.96	4.91	13.7	29.0	21.4
16	0.67	0.78	0.64	10.73	16.26	232.4	235.1	107.8	108.6	10.81	10.97	48.4	46.9	47.6
17	0.21	0.96	0.84	3.43	15.78	230.4	230.5	121.3	122.4	13.08	13.27	51.2	48.4	49.8
18	0.59	1.09	0.87	9.50	22.43	230.8	231.0	121.4	133.2	13.55	15.39	53.1	49.7	51.4
19	0.79	1.21	1.07	12.57	22.92	230.6	230.8	120.8	135.7	14.35	17.34	49.9	50.3	50.1
20	0.75	1.24	0.98	12.77	27.26	230.4	232.5	125.1	143.3	14.86	16.68	44.1	47.5	45.8
21	0.50	1.21	0.70	9.02	32.20	231.0	232.5	118.4	136.0	12.65	15.45	40.9	46.5	43.7
22	0.67	0.85	0.74	15.54	21.11	231.5	233.1	141.3	149.8	16.37	17.65	47.7	49.1	48.4
23	0.63	1.07	0.80	13.84	28.54	229.7	234.1	141.4	158.8	15.56	20.66	42.4	50.7	46.6
24	0.88	1.25	1.00	18.59	30.43	232.2	234.5	154.8	173.6	20.67	25.05	50.5	57.5	54.0
25	1.02	3.10	1.78	17.73	58.40	232.4	233.0	204.0	228.0	32.70	39.30	59.5	61.3	60.4
26	0.52	0.84	0.71	8.97	27.64	230.1	232.3	172.0	206.4	16.90	22.30	40.4	49.6	45.0
27	0.72	0.93	0.84	20.40	28.47	231.4	231.8	166.6	206.2	20.20	25.60	43.8	53.0	48.4
28	0.81	1.08	0.97	22.48	32.91	231.4	237.5	198.2	237.5	24.40	29.10	48.9	54.3	51.6

Figure 6-2 plots the efficiency calculations with respect to the maximum supplied input voltage for each test level voltage. Lines from the plot points represent the efficiency range for each supplied maximum input voltage in accordance to Table 6-2. The scatter plot shows the Vicor-M215 test combination fails to output power for the first three test points due to the 0% efficiency calculation. The next three plot points show an efficiency improvement as the M215 inverter begins producing AC power. For a maximum supplied voltage ranging from 14.01 V to 19.71 V, the Vicor-M215 test combination shows further improvement in power efficiency. The Vicor-M215 combination has a calculated average efficiency of 49.4% across a maximum DC input voltage range of 13.87-19.36 V. This calculated average efficiency exceeds that of the Vicor-M175 test combination by a mere 0.7%. In addition, the Vicor-M215 efficiency calculations in Figure 6-2 show less variation as evident by smaller error bars from the plot points. However, the Vicor-M175 combination has a wider input voltage range for converting DC power to AC power.

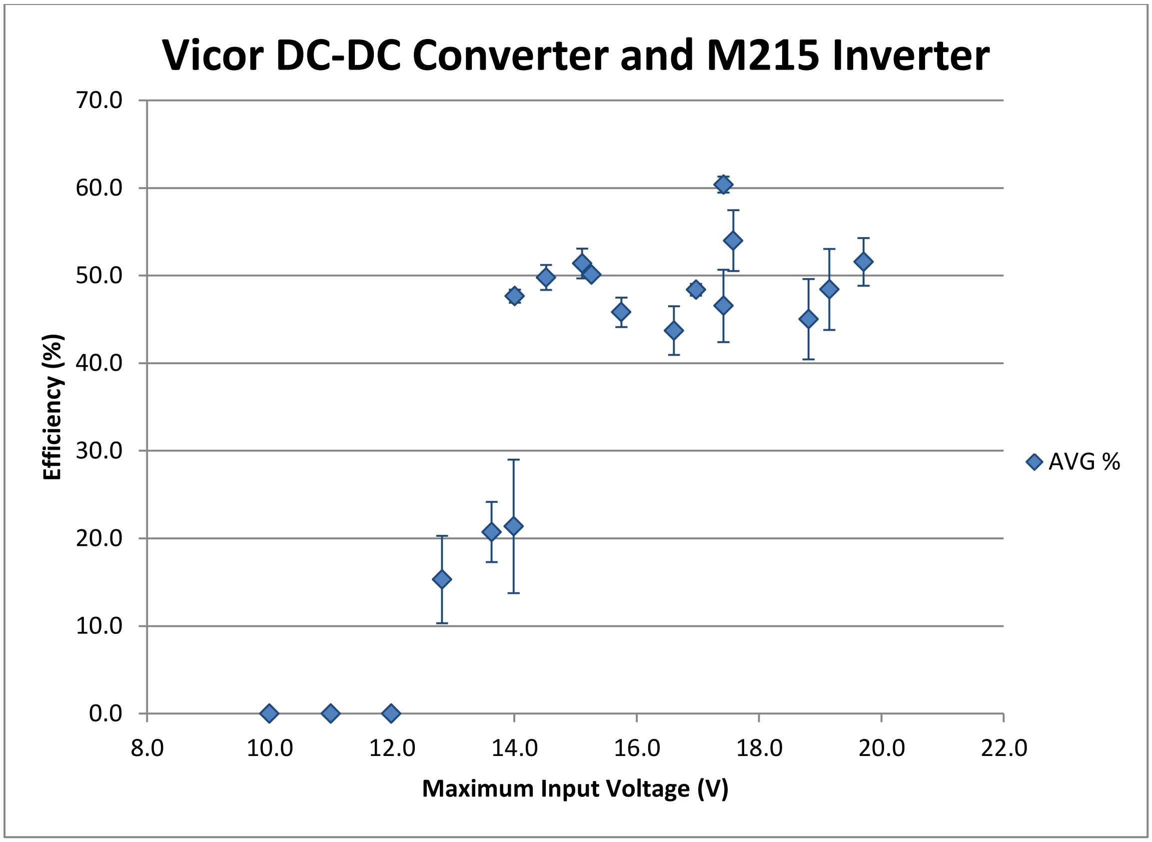


Figure 6-2: Vicor DC-DC Converter and Enphase M215 Inverter combination test efficiency plot when connected to the AC grid. Scatter plot includes calculated fficiencies from minimum, maximum, and average power measurements.

6.5 CUI DC-DC Converter and M215 Microinverter Efficiency Testing

When setting the BK Precision to supply 36 V, the CUI DC-DC converter outputs a constant 27.9 V. The inverter LED blinks orange after a couple minutes, indicating the M215 finishes startup. Then the CUI DC-DC converter tends to output a voltage between 19 V and 22 V. Table 6-3 and Table 6-4 tabulate data for testing the CUI DC-DC converter and M215 inverter combination across test level voltages ranging from 26 V to 61 V. For all set test level voltages, the BK Precision supplies a maximum input voltage equal to its set input voltage. In addition, the combination of the CUI DC-DC converter and M215 microinverter produce AC power for all voltage test levels. For tests up to a

28 V test level, the CUI DC-DC converter outputs a maximum voltage less than 27.9 V, and the M215 outputs a maximum AC power of about 3.9 W.

Starting at set supplied voltage of 29 V, the CUI DC-DC converter outputs a maximum of 27.93 V. Instead of a maintaining a constant output voltage however, the CUI's output voltage rises steadily from a 15.26 V minimum to the 27.93 V maximum before dropping back down to a minimum voltage and rising again. Meanwhile, the power meter measures about 2-5 W of AC power with occasional spikes into the 10's of watts and a maximum of 93.7 W. In addition, the BK Precision tends to supply the set voltage level of 29.0 V with 0.007 A of current. However, we observe the supplied voltage drop to a minimum of 26.1 V while simultaneously the input current spikes to a maximum of 1.88 A. Similar behavior continues when increasing the set voltage level, with the exception of the supplied input voltage decreasing significantly.

The power meter continues to measure a maximum AC power that exceeds 80 W until setting the DC source to supply 43 V. There occur multiple instances where the measured AC power exceeds the calculated maximum supplied power. This occurs because acquiring these data points does not occur simultaneously, meaning measuring the maximum output power doesn't occur at the exact same time when measuring the supplied voltage and current. This causes some errors where MAX efficiencies calculate above 100%. Similar to the previous tables in this chapter, "MAX Efficiency" compares the ratio of the maximum AC output power to the maximum supplied power to the system. "MAX Efficiency" does *not* compare the ratio of the maximum AC output power to the maximum power into the M215 inverter. Although the CUI DC-DC converter often outputs a low voltage after supplying 27.9 V, the voltage rises quickly enough so that the

M215 inverter does not turn off and require a restart. When setting the BK Precision to supply between 43 V and 61 V, the power meter measures a maximum AC power ranging from about 13-20 W. Consequently, the MAX efficiency calculates less than setting the BK Precision to supply to lower voltages, but less variation in efficiencies occurs.

For many of the tests, the Agilent multimeter measures a negative voltage across the sense resistor, which leads to a negative input power to the M215 microinverter. This negative voltage and power mean current back flows from the M215 inverter to the DC-DC converters output. The CUI DC-DC converter may cause this to occur because of the converter's output voltage dropping from its ideal 28 V output instead of maintaining a constant output.

Table 6-3: Part 1 of collected data from Efficiency testing CUI DC-DC converter and M215 inverter.

Efficiency Testing with CUI VHK200W-Q48-S28 DC-DC Converter and Enphase M215 Inverter											
Set	BK precision DC Source (DC)						Fluke MM (DC)		Agilent MM (DC)		
Test Level (V)	V_{in} MIN (V)	V_{in} MAX (V)	I_{in} MIN (A)	I_{in} MAX (A)	P_{in} MIN (W)	P_{in} MAX (W)	V_{DC-DC} MIN (V)	V_{DC-DC} MAX (V)	V_{sense} MIN (mV)	V_{sense} MAX (mV)	V_{sense} AVG (mV)
26	24.65	26.00	0.007	0.87	0.16	22.67	19.23	22.59	-12.07	19.97	16.00
27	24.84	27.00	0.007	1.14	0.17	30.81	20.14	22.93	-4.82	19.98	14.64
28	26.21	28.00	0.007	1.40	0.18	39.14	20.74	23.63	-7.87	34.28	14.12
29	26.10	29.00	0.007	1.88	0.18	54.52	15.26	27.93	-34.31	32.33	14.19
30	29.98	30.00	0.007	5.29	0.20	158.70	13.39	27.91	-17.18	38.50	13.38
31	28.86	31.00	0.007	6.74	0.20	208.94	19.20	27.90	-21.37	32.11	13.60
32	29.84	32.00	0.007	1.15	0.20	36.80	20.62	23.17	-4.21	47.66	14.62
33	30.52	33.00	0.007	1.91	0.22	63.03	16.42	27.92	-9.37	30.27	14.30
34	31.34	34.00	0.007	4.31	0.22	146.54	10.68	27.90	-5.41	30.39	14.05
35	34.91	35.00	0.007	5.46	0.25	191.10	16.50	27.93	-8.15	28.11	13.70
36	32.99	36.00	0.007	5.89	0.23	212.04	15.44	27.91	-4.00	27.40	13.90
37	30.62	37.00	0.007	5.14	0.22	190.18	8.85	27.90	0.37	28.71	13.80
38	37.99	38.00	0.007	6.05	0.27	229.90	8.86	27.90	-6.36	25.77	14.06
39	38.99	39.00	0.007	6.05	0.28	235.95	8.48	27.90	-6.39	26.82	13.67
40	39.99	40.04	0.007	2.52	0.29	100.90	8.46	27.92	-5.83	26.77	14.15
41	40.99	41.00	0.007	5.26	0.30	215.66	8.53	27.91	-32.34	26.18	13.78
42	41.98	42.00	0.007	1.66	0.31	69.72	9.33	27.90	5.07	33.15	13.94
43	42.99	43.00	0.007	2.38	0.31	102.34	9.78	27.90	-5.91	34.08	13.60
44	43.98	44.00	0.007	2.27	0.33	99.88	9.94	27.91	-31.26	33.87	13.64
45	44.99	45.00	0.008	1.15	0.34	51.75	7.01	27.90	-41.14	36.40	13.55
46	45.99	46.00	0.007	1.55	0.34	71.30	9.86	27.91	-16.12	37.83	13.70
47	46.99	47.00	0.008	1.13	0.35	53.11	7.75	27.91	-35.33	33.13	13.70
48	47.99	48.00	0.008	1.16	0.36	55.68	6.90	27.92	-40.41	39.53	13.05
49	48.99	49.00	0.008	1.09	0.37	53.41	10.46	27.92	-19.31	49.79	12.78
50	49.99	50.00	0.008	1.96	0.38	98.00	12.29	27.91	-24.14	30.86	13.23
51	50.99	51.00	0.008	1.85	0.39	94.35	7.92	27.91	-46.40	31.51	13.10
52	51.99	52.00	0.008	1.14	0.40	59.28	12.82	27.91	-13.29	27.16	13.36
53	52.99	53.00	0.008	1.02	0.41	54.06	12.07	27.91	-11.05	31.06	13.44
54	53.99	54.00	0.008	1.04	0.42	56.16	12.22	27.91	-55.63	32.32	13.36
55	54.99	55.00	0.008	1.14	0.43	62.70	10.56	27.91	-38.15	36.48	13.20
56	55.99	56.00	0.008	1.55	0.44	86.80	10.85	27.91	-54.24	44.60	12.80
57	56.99	57.00	0.008	1.43	0.45	81.51	9.38	27.92	-38.48	53.61	13.19
58	57.99	58.00	0.008	1.11	0.46	64.38	9.74	27.92	-36.66	43.30	13.05
59	58.99	59.00	0.008	1.15	0.47	67.85	8.58	27.90	-37.20	44.63	12.20
60	59.99	60.00	0.008	1.67	0.49	100.20	8.68	27.91	-34.44	47.80	12.30
61	60.99	61.00	0.008	1.19	0.49	72.59	8.41	27.90	-50.78	45.76	12.70

Table 6-4: Part 2 of collected data from Efficiency testing CUI DC-DC converter and M215 inverter.

Efficiency Testing with CUI VHK200W-Q48-S28 DC-DC Converter and Enphase M215 Inverter													
Set	Calculate M215 Input I and P (DC)					Power Meter (AC)						Efficiency	
Test Level (V)	I_{sense} MIN (A)	I_{sense} MAX (A)	I_{sense} AVG (A)	P_{DC-DC} MIN (W)	P_{DC-DC} MAX (W)	V_{out} MIN (V)	V_{out} MAX (V)	I_{out} MIN (mA)	I_{out} MAX (mA)	P_{out} MIN (W)	P_{out} MAX (W)	MIN (%)	MAX (%)
26	-1.24	2.05	1.64	-23.80	46.26	231.3	231.8	66.0	82.0	0.0	3.86	0.0	17.0
27	-0.49	2.05	1.50	-9.96	46.99	229.7	231.7	68.1	82.5	0.0	3.91	0.0	12.7
28	-0.81	3.52	1.45	-16.74	83.09	229.5	229.9	65.7	82.2	0.0	3.90	0.0	10.0
29	-3.52	3.32	1.46	-53.70	92.62	229.5	230.0	0.0	351.4	0.0	93.72	0.0	171.9
30	-1.76	3.95	1.37	-23.60	110.22	229.9	230.9	0.0	349.9	0.0	99.36	0.0	62.6
31	-2.19	3.29	1.39	-42.09	91.88	232.0	232.5	0.0	397.5	0.0	105.9	0.0	50.7
32	-0.43	4.89	1.50	-8.90	113.25	231.8	232.3	0.0	225.1	0.0	88.63	0.0	240.8
33	-0.96	3.10	1.47	-15.78	86.68	231.9	232.2	0.0	393.0	0.0	89.31	0.0	141.7
34	-0.55	3.12	1.44	-5.92	86.95	232.0	232.5	0.0	350.6	0.0	95.02	0.0	64.8
35	-0.84	2.88	1.41	-13.80	80.53	232.0	232.6	0.0	455.6	0.0	100.6	0.0	52.6
36	-0.41	2.81	1.43	-6.33	78.44	231.1	232.8	0.0	433.5	0.0	105.0	0.0	49.5
37	0.04	2.94	1.42	0.33	82.14	231.3	231.6	0.0	337.8	0.0	107.0	0.0	56.3
38	-0.65	2.64	1.44	-5.78	73.75	230.9	231.3	0.0	398.9	0.0	125.4	0.0	54.5
39	-0.66	2.75	1.40	-5.56	76.74	230.7	231.1	0.0	529.5	0.0	119.3	0.0	50.6
40	-0.60	2.75	1.45	-5.06	76.67	231.0	231.4	0.0	542.4	0.0	128.6	0.0	127.5
41	-3.32	2.69	1.41	-28.29	74.95	229.4	231.1	0.0	603.6	0.0	128.8	0.0	59.7
42	0.52	3.40	1.43	4.85	94.86	230.5	230.8	0.0	312.5	0.0	92.22	0.0	132.3
43	-0.61	3.50	1.39	-5.93	97.53	230.4	231.0	0.0	152.5	0.0	16.58	0.0	16.2
44	-3.21	3.47	1.40	-31.87	96.96	229.7	230.5	0.0	195.7	0.0	18.14	0.0	18.2
45	-4.22	3.73	1.39	-29.58	104.16	230.4	230.6	0.0	175.1	0.0	16.90	0.0	32.7
46	-1.65	3.88	1.41	-16.30	108.29	230.3	230.7	0.0	207.1	0.0	19.42	0.0	27.2
47	-3.62	3.40	1.41	-28.08	94.83	229.7	230.5	0.0	206.3	0.0	18.88	0.0	35.5
48	-4.14	4.05	1.34	-28.60	113.21	230.0	230.1	0.0	202.0	0.0	20.54	0.0	36.9
49	-1.98	5.11	1.31	-20.71	142.59	229.5	229.9	0.0	119.5	0.0	13.20	0.0	24.7
50	-2.48	3.16	1.36	-30.42	88.33	230.9	231.3	0.0	119.3	0.0	15.37	0.0	15.7
51	-4.76	3.23	1.34	-37.69	90.19	230.7	231.3	0.0	119.3	0.0	13.16	0.0	13.9
52	-1.36	2.79	1.37	-17.47	77.74	231.2	231.4	0.0	122.0	0.0	14.41	0.0	24.3
53	-1.13	3.19	1.38	-13.68	88.91	231.2	231.5	0.0	121.1	0.0	12.99	0.0	24.0
54	-5.71	3.32	1.37	-69.73	92.52	231.0	231.5	0.0	122.0	0.0	15.94	0.0	28.4
55	-3.91	3.74	1.35	-41.32	104.41	231.1	231.5	0.0	186.3	0.0	16.04	0.0	25.6
56	-5.56	4.57	1.31	-60.36	127.66	231.3	231.6	0.0	117.1	0.0	16.33	0.0	18.8
57	-3.95	5.50	1.35	-37.01	153.53	231.5	231.7	0.0	181.6	0.0	17.93	0.0	22.0
58	-3.76	4.44	1.34	-36.62	123.99	231.6	231.8	0.0	179.5	0.0	20.53	0.0	31.9
59	-3.82	4.58	1.25	-32.73	127.71	231.8	232.0	0.0	179.0	0.0	20.52	0.0	30.2
60	-3.53	4.90	1.26	-30.66	136.83	231.1	231.7	0.0	188.2	0.0	20.47	0.0	20.4
61	-5.21	4.69	1.30	-43.80	130.94	231.4	231.6	0.0	178.4	0.0	19.86	0.0	27.4

Figure 6-3 plots the MAX efficiency calculations with respect to the maximum input voltage for each test level voltage. The following plot and average maximum efficiency calculations exclude points with MAX efficiencies that exceed 100%. See Appendix A.4 for a similar scatter plot that includes efficiencies exceeding 100%. The plot shows that the system tends to convert DC power to AC power more efficiently in the voltage range of 30 V to 41 V. Within this range, the CUI-M215 combination functions with a maximum efficiency average of 55.7%. From a supplied voltage of 43 V to 61 V, the system has a maximum power efficiency that averages to 25%. Across the whole operating range, the combination of a CUI DC-DC converter and M215 inverter produce AC power to the grid with a maximum efficiency average of 32.7%. Compared to previous tests that utilize the Vicor DC-DC converter, the CUI-M215 combination converts DC power to AC power less efficiently on average across its operating range. However, unlike the prior tests with the Vicor DC-DC converter, testing with the CUI and M215 produces power to the grid across a much wider input voltage range.

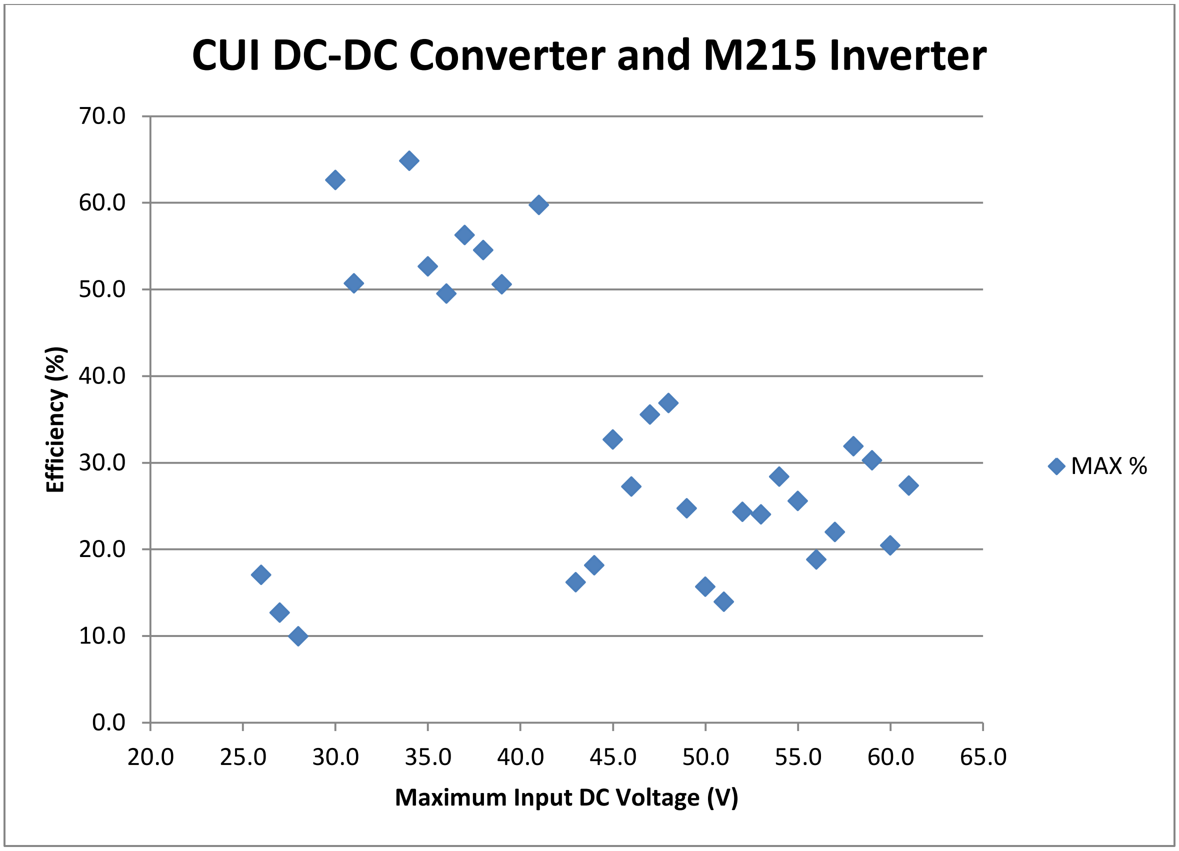


Figure 6-3: CUI DC-DC Converter and Enphase M215 Inverter test efficiency plot when connected to the AC grid. Scatter plot shows the maximum efficiency calculations from comparing output power to supplied input power.

The following chapter tests how efficiently and consistently the EHFEM system produces AC power to the electrical grid without including a DC-DC converter.

CHAPTER 7: PRECOR EFX 546i ELLIPTICAL TESTING WITHOUT A DC-DC CONVERTER

7.1 Introduction

Turner et al. previously conducted characterization testing with the Precor elliptical and determined the appropriate capacitors for the capacitive filter bank [5]. Additionally, Abshier et al. conducted characterization tests on the elliptical to determine how much voltage, current, and power the Precor elliptical produces under predetermined speeds and resistance level [8]. This test implements an overvoltage protection circuit (OVPC) with the Precor elliptical and a microinverter. The test measures weather the OVPC diverts excess power when the voltage output from the elliptical rises above an expected value. Prior OVPC tests included low power testing, which involved using load and dissipating resistors on the order of kiloohms [6]. High power testing also occurred, which uses the 10 Ω resistors rated for 300 W [6].

This round of testing seeks to determine how efficiently the EHFEM project can convert user-generated power into AC power without including a DC-DC converter. Testing involves connecting the Precor elliptical trainer a microinverter and an OVPC designed for the microinverter. The M175 inverter can handle a maximum DC input of **54 V** while the M215 inverter can handle a maximum DC input of **48 V**.

Collecting data requires one person running on the elliptical while another person records measurements. An oscilloscope probes the voltage generated from the Precor elliptical as well as the collector voltage of the IGBT. A multimeter and a small 0.010 Ω nominal sense resistor measure the elliptical-supplied input current to the M175 or M215 microinverter. The product of the probed elliptical voltage and current through the sense

resistor yields the power supplied to the Enphase microinverter. The IGBT's collector should have an equivalent voltage to the voltage generated from the elliptical until the OVPC activates the IGBT and diverts excess power. Measuring the voltage difference across the diverting resistor when the IGBT activates allows for power calculation through the diverting branch. A power meter measures the output power from the M175 or M215 microinverter to the AC grid.

7.2 Overvoltage Protection Circuit and M175 Inverter

In an effort to protect the M175 inverter, testing uses the same OVPC retested in Chapter 5.2. The OVPC should divert excess power when the elliptical generates above **50.5 V**, and cease diverting power if the voltage the drops below **46.4 V**. The OVPC does divert power, but not as expected. Instead of seeing an input voltage consistently increase and decrease due to the OVPC, the output voltage and collector voltage simultaneously decrease down and settle at a 25 V DC-level after surpassing 51 V. Despite this potential brownout, the M175 continues to generate power. However, after this test session, the M175 microinverter no longer seems to convert DC power into AC power when tested on its own despite doing so when testing with the elliptical earlier. This suggests a need for modifying the protective OVPC such as reducing the input voltage threshold of the OVPC. The OVPC protecting the Enphase microinverters should divert excess power at a voltage much lower than their maximum DC input.

Preliminary testing occurs to observe the behavior of the Precor elliptical with the M175 microinverter and its OVPC. The circuit diagram of Figure 7-1 contains a box representing the M175 inverter. Preliminary testing includes an OVPC with filter capacitors on the +3.3V reference voltage and the IGBT's gate, seen in Figure 7-1.

Including the capacitors on the +3.3V rail help filter out transients from the 12 V supply rail to the comparator. Having the capacitors on the IGBT's gate should help the voltage level maintain a level voltage when the IGBT switches. The tradeoff to this comes at a longer delay for the IGBT gate signal to charge enough to turn on and divert excess power from the microinverter. This caused a possible overvoltage condition in the microinverter leading to attempts to troubleshoot.

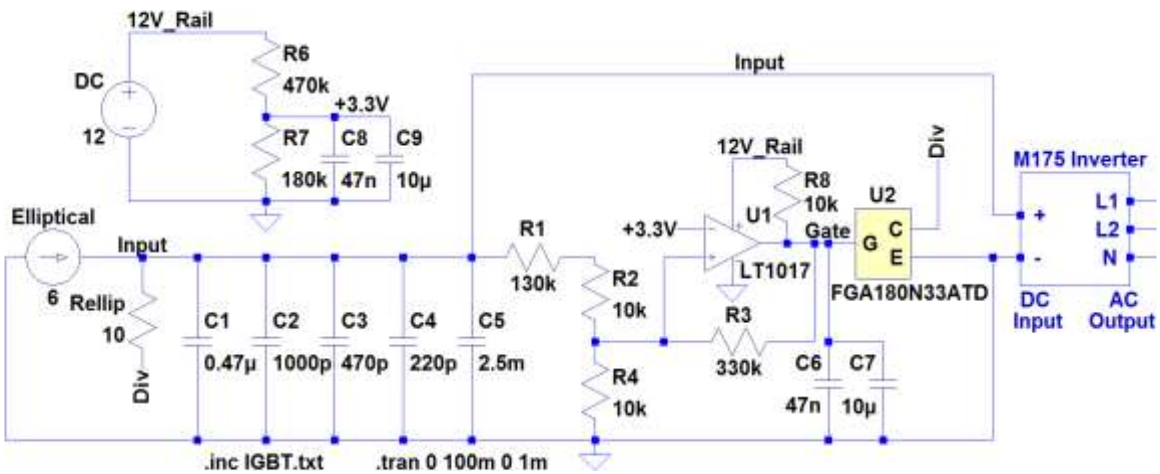


Figure 7-1: Circuit diagram showing Elliptical testing with an Enphase microinverter and an OVPC designed for the M175 Inverter. This modified OVPC uses the voltage divider from the CUI converters OVPC. Added capacitors (C6 and C7) either help filter any source transients to the +3.3V reference voltage, or help maintain a stable voltage signal on the IGBT's gate.

Chapter 5.3 details the changes and improvements made to the OVPC. Chapter 3.2.4.2 instructs how to clear the M215 inverter of a GFI error. For details concerning the necessary equipment as well as test protocols for testing in this chapter, refer to Appendix A.7.

7.2.1 Troubleshooting the Enphase M175 Inverter

Warning: ALWAYS de-energize the AC lab bench for performing any troubleshooting options with M175 inverter.

Troubleshooting the M175 begins by connecting it to the lab bench with an Enphase Envoy. The Envoy operates between the M175 and the Enphase Enlighten™

web-monitoring software accessible via the internet [15]. Figure 7-2 depicts a wiring diagram of the setup. The active (brown) wire connects to the inverter's L1 or L2 AC output while the neutral (blue) and earth ground (green) wires connect to the M175's neutral output. Connecting the Envoy to the internet allows for clearing a GFI condition in the microinverter through a web browser.

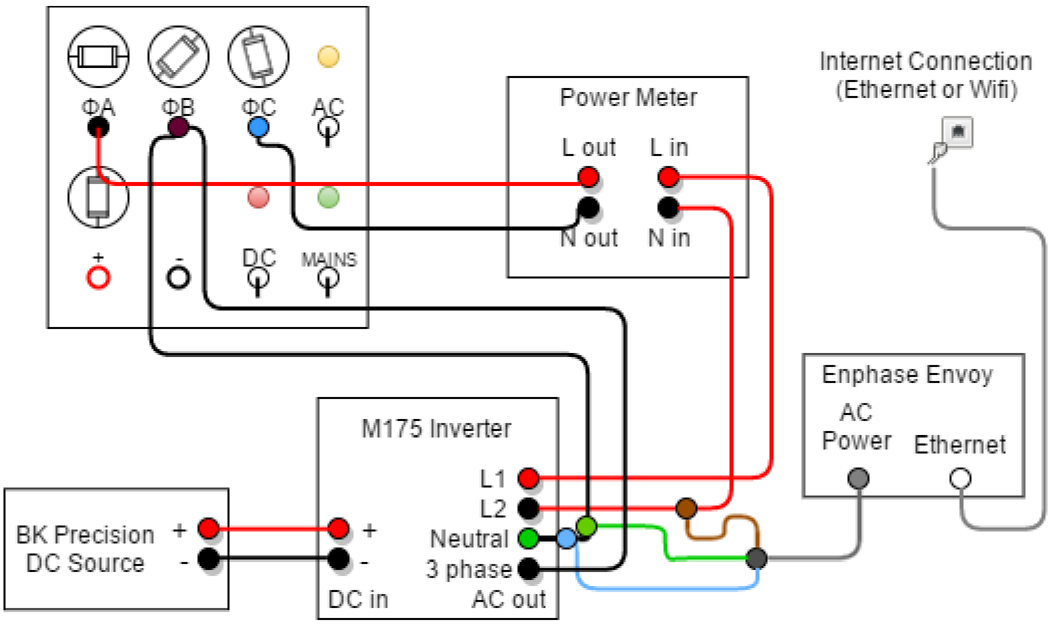
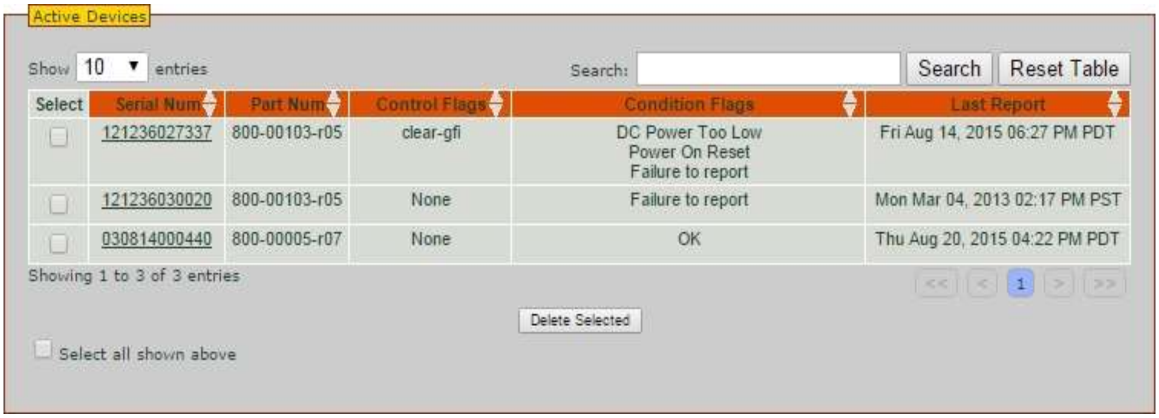


Figure 7-2: Wiring diagram showing a test setup for troubleshooting the M175 microinverter with an Enphase Envoy connected to the AC grid.

The BK Precision supplies DC power to the inverter while the M175 outputs AC power to the grid. A power meter measures the output power from the inverter. After connecting the Envoy to the system, supply AC power from the lab bench. Then, supply a DC source of 35 V with a 3.5 A current limit to the M175's input. When the Envoy powers up, the LCD screen displays the same IP address and a "+WEB" icon. Entering the displayed IP address into the web browser accesses the Envoy Administration page. Clicking on "Device Conditions and Controls" lists the M175's serial number with the other inverters. If the M175 isn't listed, pressing and holding the Envoy's scan button may allow the Envoy to detect the inverter.


Active Devices

Show 10 entries   Search: Search   Reset Table

Select	Serial Num	Part Num	Control Flags	Condition Flags	Last Report
☐	121236027337	800-00103-r05	clear-gfi	DC Power Too Low Power On Reset Failure to report	Fri Aug 14, 2015 06:27 PM PDT
☐	121236030020	800-00103-r05	None	Failure to report	Mon Mar 04, 2013 02:17 PM PST
☐	030814000440	800-00005-r07	None	OK	Thu Aug 20, 2015 04:22 PM PDT

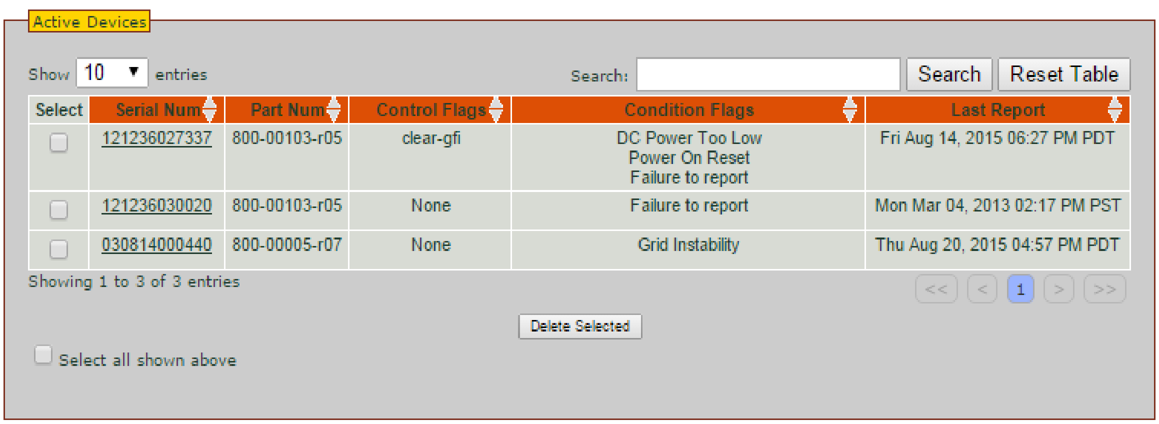
Showing 1 to 3 of 3 entries   << < 1 > >>

Delete Selected

Select all shown above

Figure 7-3: Listing of connected inverters including information on present control flags, conditions flags, and date of last report. The M175 inverter lists last with the Serial Number 030814000440.

Figure 7-3 lists the all inverters to have ever connected with the Envoy. The webpage displays the M175 inverter having an "OK" condition flag. Despite this, the M175 microinverter still fails to produce AC power.


Active Devices

Show 10 entries   Search: Search   Reset Table

Select	Serial Num	Part Num	Control Flags	Condition Flags	Last Report
☐	121236027337	800-00103-r05	clear-gfi	DC Power Too Low Power On Reset Failure to report	Fri Aug 14, 2015 06:27 PM PDT
☐	121236030020	800-00103-r05	None	Failure to report	Mon Mar 04, 2013 02:17 PM PST
☐	030814000440	800-00005-r07	None	Grid Instability	Thu Aug 20, 2015 04:57 PM PDT

Showing 1 to 3 of 3 entries   << < 1 > >>

Delete Selected

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Figure 7-4: Listing of connected inverters including information on present control flags, conditions flags, and date of last report. In this table, the M175 shows a "Grid Instability" condition flag.

In other cases the condition flag for the M175 reads "Grid Instability", seen in Figure 7-4, but measuring a line-to-neutral voltage of 116.0 Vac from the AC grid contradicts any grid instability. After calling Enphase tech support, an agent confirms the M175 has an internal failure, but unable to identify the exact cause without taking the inverter apart. The M175 inverter no longer functions. Finished with troubleshooting the M175, we turn to simulation.

7.2.2 Simulating Overvoltage Protection Circuit in LTspice

Figure 7-5 constructs a circuit diagram of the OVPC in LTspice to simulate a possible overvoltage condition. The simulation uses a 10 Ω resistive load in place of the M175 inverter. A 6 A ideal current source simulates a person running on the elliptical. Even though an actual runner may not produce a constant current of 6 A, simulating with a 6 A source allows the input voltage to surpass the threshold for power diversion. For example, if the simulation uses a 5 A source, then the input voltage settles at 50 V due to the 10 Ω load, which does not trigger the OVPC.

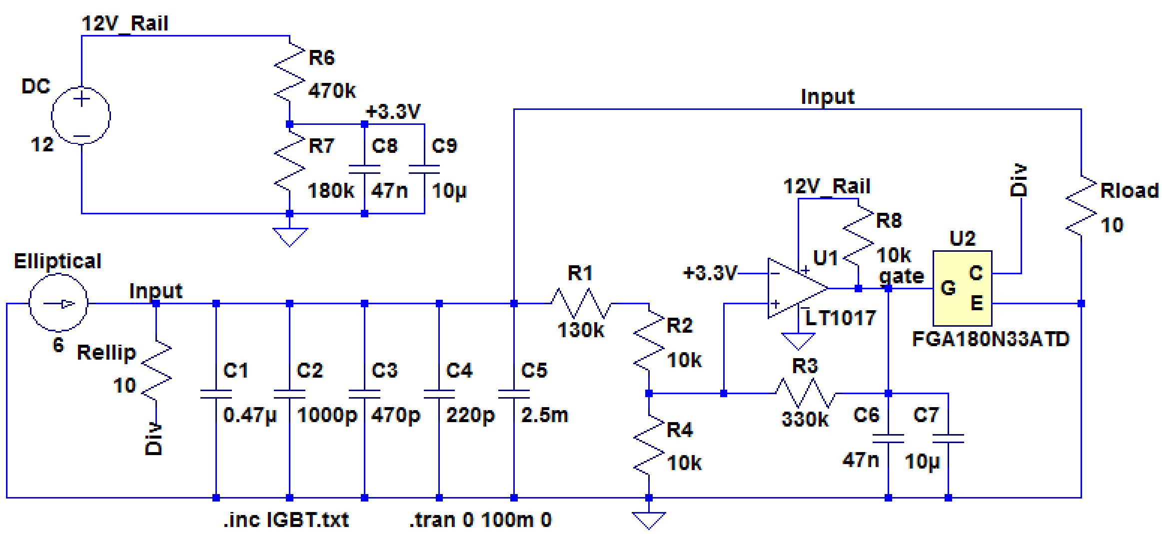

Figure 7-5: LTspice circuit diagram of the overvoltage protection circuit used when testing the Enphase M175 inverter with the Precor Elliptical. A 10 Ω, 300 W resistor replaces the M175 inverter as the load.

Figure 7-6 shows an LTspice simulation of the OVPC setup in Figure 7-5. The simulation shows the input voltage rise to a maximum of 57.9 V, then decrease to about 48 V and repeat. The voltage level on the gate begins charging when the input voltage reaches 50.5 V but only achieves a maximum of about 5 V. From the cursor measurements, the simulation shows it takes about 38.4 ms to charge the gate voltage high enough and turn on the IGBT. Having the 10 nF and 47 µF capacitors bridging the IGBT gate and ground creates too long of a delay for the IGBT to divert power from the

microinverter. This causes the input voltage to surpass the M175's maximum DC input of 54 V and overload the inverter.

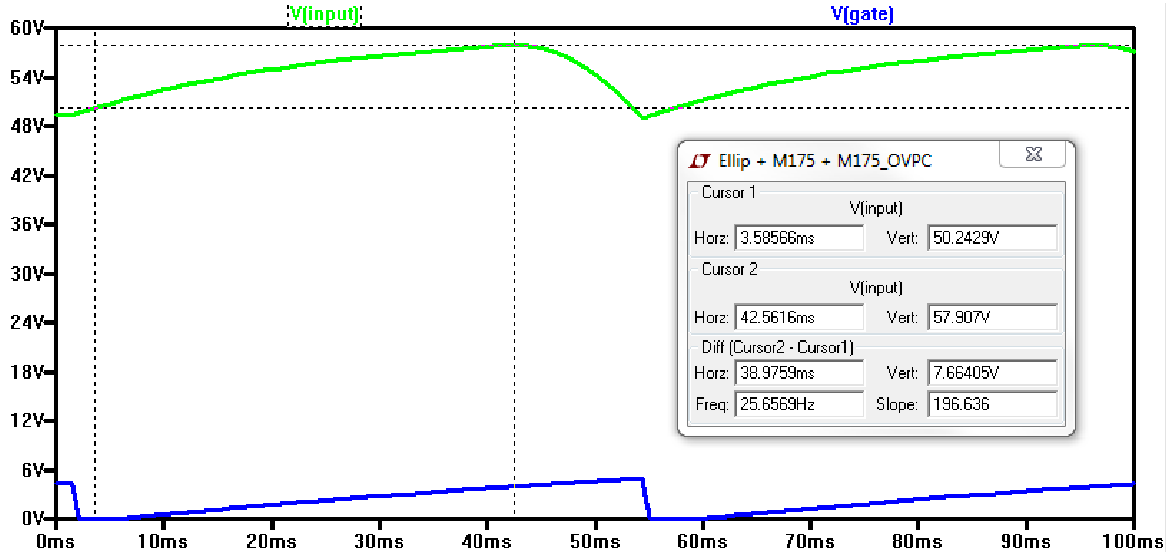

Figure 7-6: LTspice simulation of the OVPC used to protect the M175 Inverter. A 10 Ω 300 W resistor takes the place of the M175 inverter as the load.

With the M175 inverter out of commission, we set out to attempt elliptical testing with the M215 inverter and a new OVPC. Before testing, we modify an OVPC to better protect the M215 as well as troubleshoot the M215 to clear a GFI tripped condition. Chapter 5.3 explains improving the OVPC, and Chapter 3.2.4 covers troubleshooting the M215 microinverter.

7.3 Overvoltage Protection Circuit and M215 Inverter

After clearing a tripped GFI condition on the M215 microinverter, elliptical testing with the M215 and an improved OVPC begins. See Chapter 3.2.4 for a detailed report on how to set up the Envoy and clear a GFI condition on the Enphase M215. The improved OVPC contains a few differences from the OVPC used with the M175. In addition to the filter capacitors bridging the +3.3V rail, similar filter capacitors now also bridge the 12-Volt rail to ground for further source filtering. These capacitors have no effect on the IGBT gate's charge time. The OVPC also utilizes a current buffer

comprised of a TIP31A BJT and 1 kΩ resistor to help stabilize the voltage on the IGBT's gate. Chapter 5.3 further details the process of improving the IGBT switching and time delay on the OVPC.

Figure 7-7 shows the circuit diagram of the OVPC protecting the M215 with improvements to the OVPC included. The resistors in the circuit diagram's voltage divider correspond to the resistors selected in Chapter 5.3.3. For simulation, Figure 7-7 replaces the M215 microinverter with a 10 Ω resistive load; otherwise, LTspice cannot simulate the circuit. Figure 7-8 shows that the OVPC diverts power from the load resistor when the input voltage surpasses **40.8 V** and ceases power diversion when the input voltage decreases to **36.9 V**.

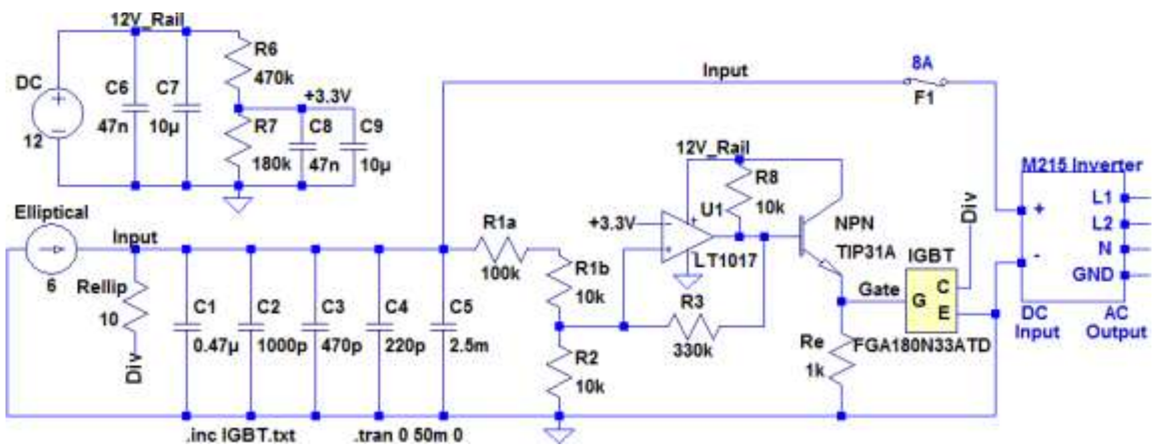

Figure 7-7: Circuit diagram showing elliptical testing with an Enphase M215 microinverter and an OVPC designed for the M215 Inverters

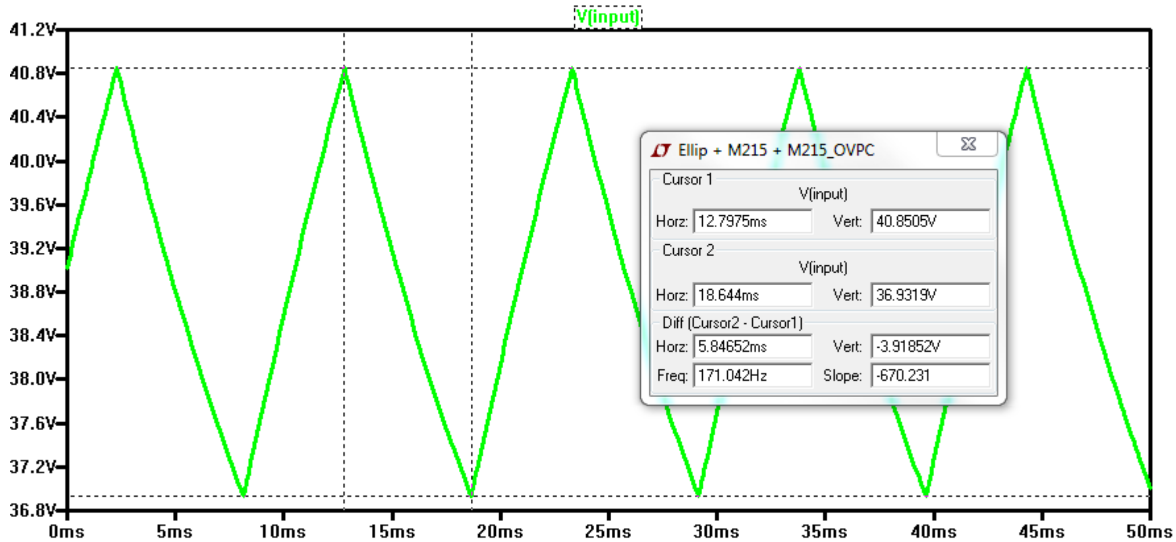

Figure 7-8: Simulation of the OVPC protecting the M215 inverter.
A 10 Ω resistive load takes the place of the M215 inverter.

Now expecting the OVPC to protect the M215 inverter adequately, we set up the lab bench in room 150 of Engineering East for testing. The wiring diagram in Figure 7-9 includes the updated OVPC for the M215 as well as isolated scopemeters to measure the input voltage and probe the IGBT collector voltage. For a detailed process on the setup procedure and test protocol, refer to Appendix B.7. Testing originally tried using oscilloscopes to measure the input and collector voltages, but for reasons detailed in the following section, these oscilloscopes proved non-ideal.

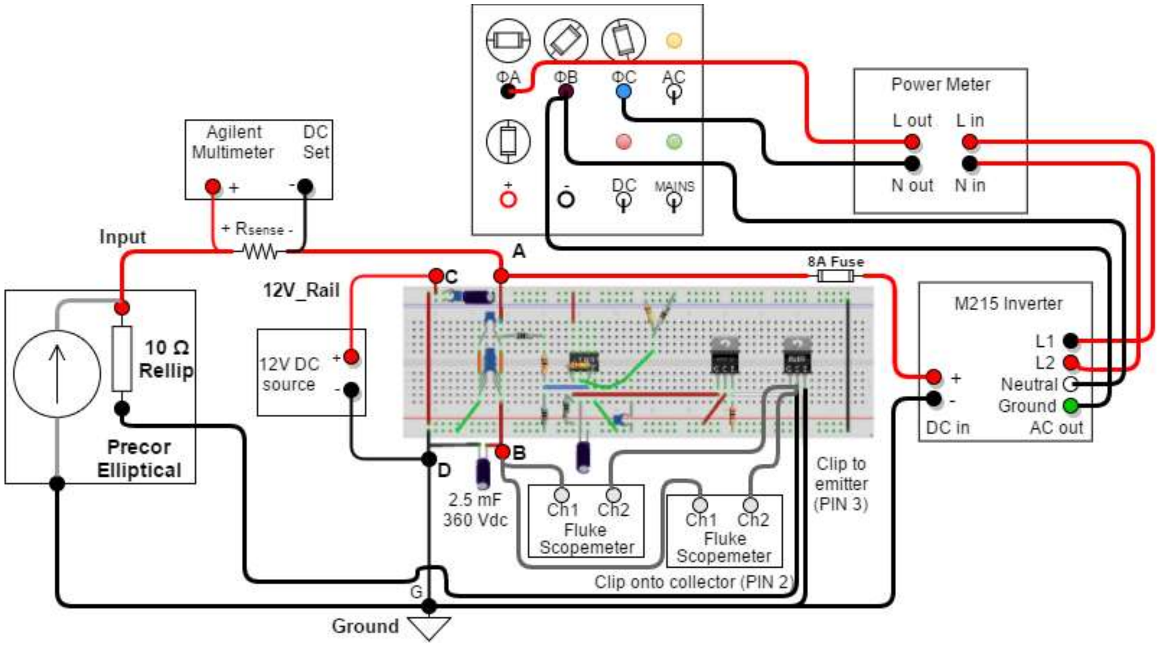

Figure 7-9: Wiring diagram for Precor elliptical, M215 inverter, and the Overvoltage Protection Circuit designed for the M215 inverter.

7.3.1 Connecting Scope Probe from Tektronix Oscilloscope Causes a GFI Tripped Condition in the M215 Microinverter

Before switching to using the Fluke 196C isolated scopemeters for this section, we tried collecting data with Tektronix oscilloscopes. With the elliptical in use, the input voltage builds up until it reaches 41.2 V, then decrease to 36.8 V before increasing again. Figure 7-10 below shows an oscilloscope capture of the input voltage and IGBT gate signals. The picture shows the elliptical output voltage decreases when the gate signal pulls to 12 V, and increases with a low gate signal. This shows that the OVPC functions similarly to the simulation in Figure 7-8.

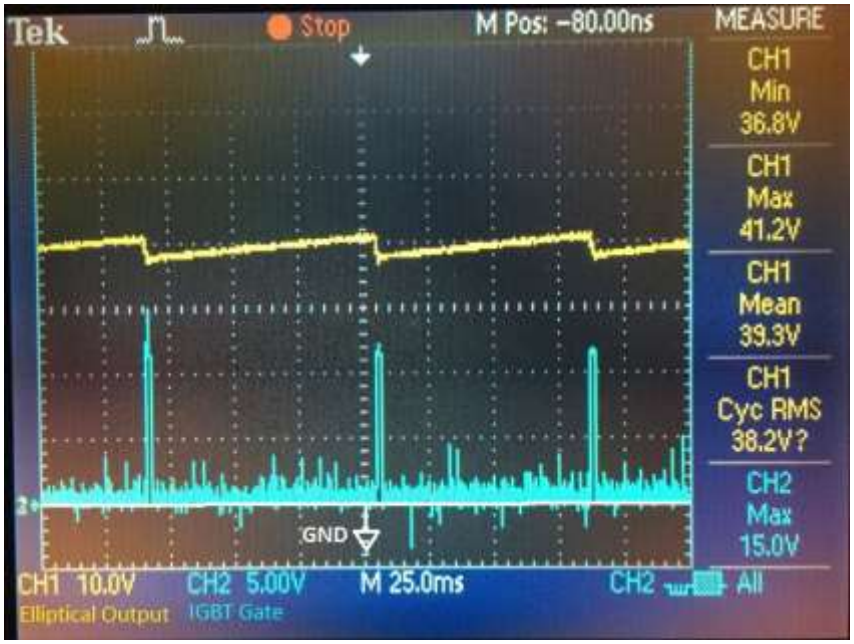

Figure 7-10: Oscilloscope capture of the Elliptical Output voltage (yellow) and the IGBT's gate signal (blue) while the M215 inverter undergoes its startup process. The oscilloscope capture shows the OVPC protecting the M215 functions according to expectations.

Although the OVPC meets expectations, we encounter an issue with the M215. After 90 seconds of running on the elliptical, the M215 LED blinks green 6 times, signaling the end of the startup phase. A few seconds later, the inverter's LED emits a constant red light, and fails to produce AC power. The red LED denotes a tripped GFI condition. We must clear the GFI condition by accessing the Envoy Administration page by entering the Envoys displayed IP address in a web browser. Chapter 3.2.4.2 explains how to clear a tripped GFI condition in the M215 inverter.

The M215 experiences a GFI tripped condition every time we attempt to connect the inverter to the OVPC when probed with a Tektronix oscilloscope. Specifically, a tripped GFI occurs when connecting any of the grounding clips of the Tektronix scope probes to the system's ground plain. Connecting a Tektronix oscilloscope introduces a ground level different from the microinverter's ground level. This occurs because the

Tektronix oscilloscopes have non-isolated ground connections. We cannot collect data for elliptical testing with the M215 inverter using the Tektronix oscilloscopes.

Unlike a setup that excludes a DC-DC converter, EHFEM testing with a DC-DC converter does not cause a tripped GFI condition when probing with Tektronix oscilloscopes. Chapter 8 of this report details elliptical testing with DC-DC converters and the M215 inverter.

7.3.2 Testing with Isolated Oscilloscopes

Connecting scope probes trips a GFI condition, because the Tektronix oscilloscopes have a non-isolated ground connection. A non-isolated oscilloscope references all measurements to earth-ground. Meanwhile the Precor elliptical, the M215 inverter, and the rest of the testing equipment all have isolated connections from earth-ground. The wiring diagram in Figure 7-9 shows the common ground between the elliptical, the inverter, and the OVPC at node G. This ground node does not connect to the same earth-ground connection as the non-isolated oscilloscopes. Bringing the two different ground levels into contact causes a GFI tripped condition.

Collecting data for elliptical testing without a DC-DC converter uses Fluke 196C 2-channel isolated portable scopemeters. These scopemeters have independently floating isolated inputs that allow for measuring OVPC voltage signals [21]. Replacing the oscilloscopes, the probes of the new scopemeters connect to the same locations as oscilloscope 2 depicted in Figure 7-9. Channel A of both probes measure the input voltage and channel B of both probes connect to the IGBT's collector. Testing also uses an 8 A fuse to protect against overcurrent from damaging the M215 inverter. We follow the same procedure as before of setting up for elliptical testing with the M215 inverter.

When conducting this test for a 100 SPM pace, we only had access to one of the Fluke 196C scopemeters. Unlike the Tektronix oscilloscopes, which displays up to five measurements at once, the Fluke 196C scopemeters only displays two. This limits the amount of data to collect in a timely manner without having to constantly change the measurement settings on the scopemeter. To compensate, the scopemeters measure only the elliptical voltage output (also the input voltage) and not measure the voltage on the IGBT's collector for each voltage test level. The Fluke 169C still probes the IGBT collector so we can observe if power diverts through the diverting resistor and IGBT.

Testing for a 150 SPM pace has access to both Fluke 169C scopemeters. One scopemeter displays the average voltage measurements, while the other uses cursors to measure the minimum and maximum points of the voltage waveform the elliptical generates. Cursors measure the minimum and maximum voltages because cursors display the measurement to one decimal point. Otherwise, the scopemeter rounds measurements to the nearest whole number when displaying the minimum and maximum voltages without cursors. As with testing at a 100 SPM pace, probing the IGBT's collector node shows if and when the IGBT diverts power. Due to display limitations, we do not record RMS voltages during this test session.

7.3.2.1 100 SPM Pace

We begin taking measurements once the M215 inverter produces power to the AC grid. The Fluke 169C scopemeter measures the average input voltage and the input voltage's peak-to-peak voltage. Using cursors after holding a scope capture, the Fluke measures the minimum and maximum voltage on the input signal. When calculating the dissipating power through the IGBT and elliptical's resistor, we assume the collector

voltage has an average voltage level of 1 V. Assuming a low average collector voltage when the IGBT diverts power simplifies measurement taking, because ringing occurs on the collector. This ringing also occurs in Chapter 8 during the full system tests that include a DC-DC converter. Figure 7-11 displays the occurring ringing on the IGBT's collector terminal, while the M215 produces power at a low resistance setting. The vertical cursors mask the amplitude of the peaks in the ringing, which deviate from the DC line by as much as 10 V. The frequency between the peaks in the ringing measures 31.64 kHz. This frequency matches measurements made when conducting full system testing with an elliptical resistance of 4 at a 150 SPM pace (see Figure A-11 of Appendix A.5). This frequency aligns with other frequency measurements regarding ringing that occurs in full system tests that include a DC-DC converter.

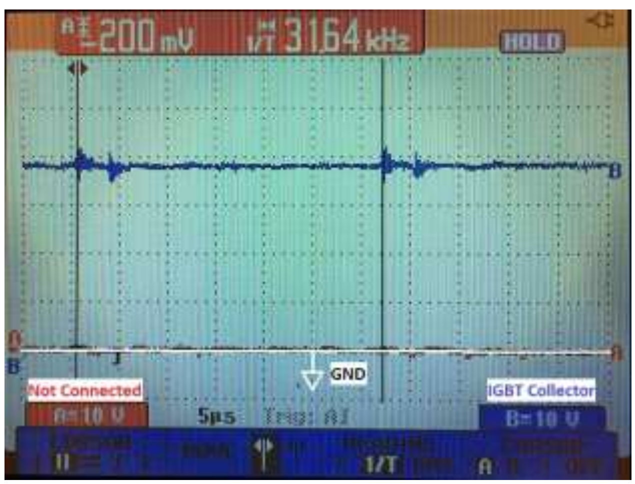

Figure 7-11: Scopemeter cursors measure the frequency between peaks of ringing oscillations on the IGBT. Elliptical Resistance = 2, Pace = 120 SPM.

While the elliptical powers up the inverter, the scopemeter displays a waveform that shows the OVPC diverting power when the input voltage reaches about 41 V. When the M215 starts up and produces AC power, the elliptical output voltage decreases and the OVPC stops diverting power. Figure 7-12 below shows the elliptical output voltage has an average of 35.7 V, a minimum voltage of 34.4 V, and a maximum voltage of

37.2 V. This occurs while running with an ERS of 2. Increasing the ERS to 4 and 6 produces similar elliptical output voltage waveforms. Table 7-1 shows that even though the input voltages for these resistance settings vary little, the voltage across the sense resistor increases with the ERS. This means the current into the inverter increases, thus increasing the input power. The efficiency at which the M215 converts DC power into AC power increases with the elliptical resistance. The average efficiency increases from about 69% at an ERS of 2 to just less than 90% at an ERS of 6. Appendix A.5 includes scopemeter captures of the input and collector voltages for ERS of 4 and 6.

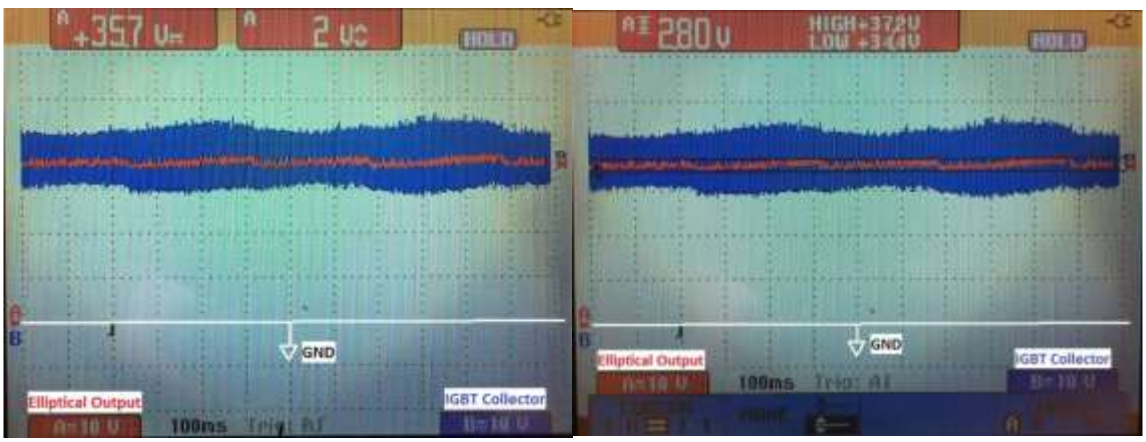

Figure 7-12: Waveform captures of the Elliptical Output (red) and IGBT Collector (blue) voltages using an isolated scopemeter. The left image displays the average electrical output voltage measurement. The right image displays the maximum and minimum voltage measurements via cursors. Elliptical Resistance Setting = 2, Pace = 100 SPM.

When increasing the ERS to 8, the elliptical output voltage drops to an average of 17.4 V as the M215 inverter generates AC power. The waveforms of Figure 7-13 show the decrease in average voltage while the variation in the minimum and maximum points increase. Although the scopemeter measures lower voltages than previous resistance settings, the elliptical supplies more input current to the M215 inverter. Looking at Table 7-1 in section 7.3.2.3, the average current through the sense resistor calculates to 2.09 A. While prior resistance settings have an average input voltage a little over twice as much, the average current generated while running at an ERS of 8 increases by a factor of

about 9.6 from a resistance setting of 6. Consequently, the average input power to the M215 increases by a factor of 4.7. Due to the lower input voltages, an occurrence of the OVPC diverting excess power still fails to occur.

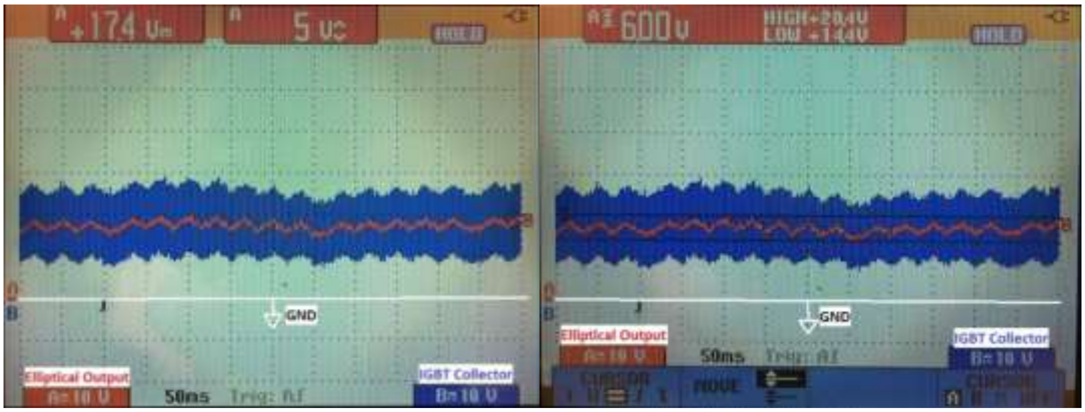

Figure 7-13: Waveform captures of the Elliptical Output (red) and IGBT Collector (blue) voltages using an isolated scopemeter. The left image displays the average electrical output voltage measurement. The right image displays the maximum and minimum voltage measurements via cursors. Elliptical Resistance Setting = 8, Pace = 100 SPM.

Increasing the ERS to 10 further decreases the average input voltage to 16.2 V. Shown in Figure 7-14 below, the input voltage also has a lower maximum, but a higher minimum due to the input voltage having a more DC-like waveform. As the ERS increases to 12 and 14, the average input voltage remains about the same, but the current continues to increase. Appendix A.5 includes scopemeter captures of the input and collector voltages for ERS of 12 and 14.

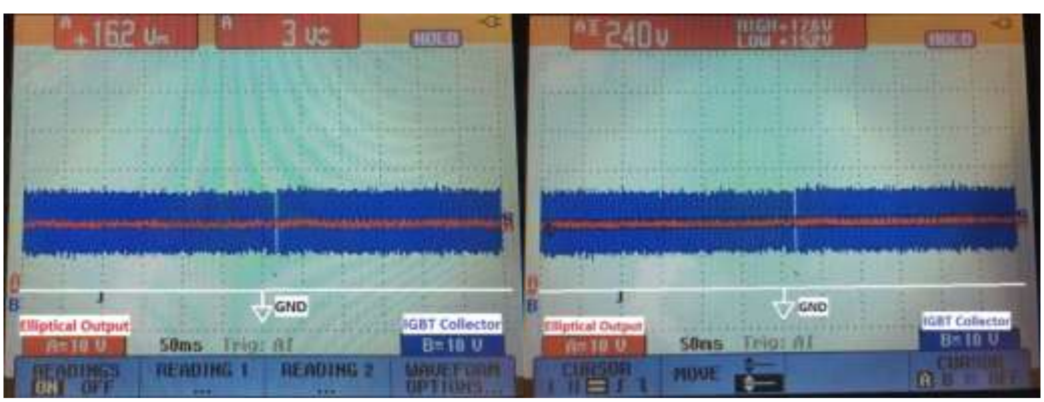

Figure 7-14: Waveform captures of the Elliptical Output (red) and IGBT Collector (blue) voltages using an isolated scopemeter. The left image displays the average electrical output voltage measurement. The right image displays the maximum and minimum voltage measurements via cursors. Elliptical Resistance Setting = 10, Pace = 100 SPM.

7.3.2.2 150 SPM Pace

Testing at a 150 SPM pace uses two scopemeters. One scopemeter measures the average voltage, while the other uses cursors to measure the minimum and maximum observed voltage. This helps speed up the data collecting process. As with 100 SPM testing, we assume the collector voltage has an average voltage level of 1 V due to transients on the collector. Appendix A.5 includes a scopemeter capture measuring a frequency of 31.64 kHz between peaks in the transients, which matches the frequency of similar transients measured at a 100 SPM pace in this chapter.

Figure 7-15 below depicts the elliptical output voltage when running at a 150 SPM pace with an ERS of 2. The elliptical outputs an average voltage of 23.5 V with cursors measuring a minimum voltage of 23.2 V and a maximum voltage of 26.0 V. Compared to a 100 SPM pace at this resistance setting, running at a 150 SPM pace produces less voltage but more current. Consequently, running at the faster pace also produces more input power to the M215 inverter than the slower pace.

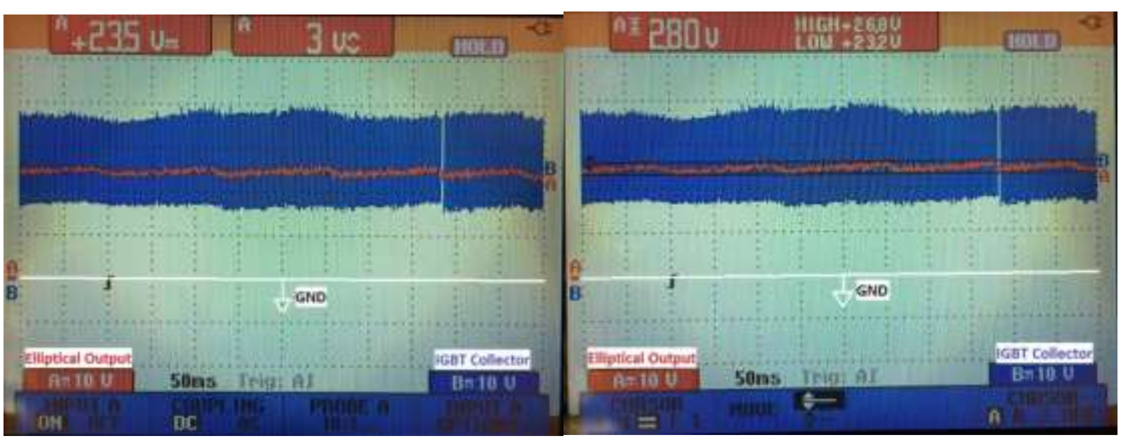

Figure 7-15: Waveform captures of the Elliptical Output (red) and IGBT Collector (blue) voltages using an isolated scopemeter. The left image displays the average electrical output voltage measurement. The right image displays the maximum and minimum voltage measurements via cursors. Elliptical Resistance Setting = 2, Pace = 150 SPM.

When increasing the ERS to 4 for a 150 SPM pace, the average input voltage decreases to 16.4 V as seen in Figure 7-16. A similar situation of the input voltage

decreasing occurs for a 100 SPM pace, but at an ERS of 8. Although the input voltage decreases, the input current to the M215 increases. When increasing the ERS to 6, 8, and beyond, the input voltage remains relatively the same, but the input current continues to increase. As with collecting data for a 100 SPM pace, the input power to the M215 increases with the ERS. Additionally, the efficiency at which the M215 converts DC power into AC power increases with the elliptical resistance. The average efficiency increases from about 57% at an ERS of 2 to just less than 87% at an ERS of 6. Appendix A.5 includes a scopemeter capture of the input and collector voltages for an ERS of 6. The capture bears resemblance to the one in Figure 7-16, but has a higher average input voltage.

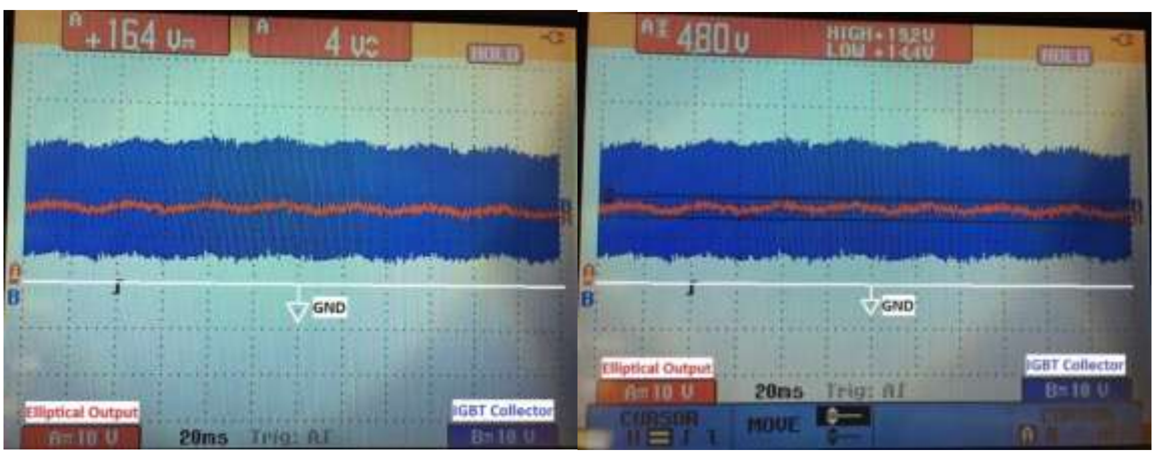

Figure 7-16: Waveform captures of the Elliptical Output (red) and IGBT Collector (blue) voltages using an isolated scopemeter. The left image displays the average electrical output voltage measurement. The right image displays the maximum and minimum voltage measurements via cursors. Elliptical Resistance Setting = 4, Pace = 150 SPM.

Although the elliptical output voltage maintains a similar voltage with an increasing resistance beyond an ERS of 4, a noticeable change to the collector waveform occurs when increasing the resistance to 8. Shown in Figure 7-17, the scopemeter reveals instances of the minimum collector voltage falling below the ground potential. This suggests occurrences of the OVPC diverting power through the IGBT despite only having

a maximum input voltage of 18.4 V. We explore this by decreasing the time scale on one of the scopemeters with the elliptical still in use.

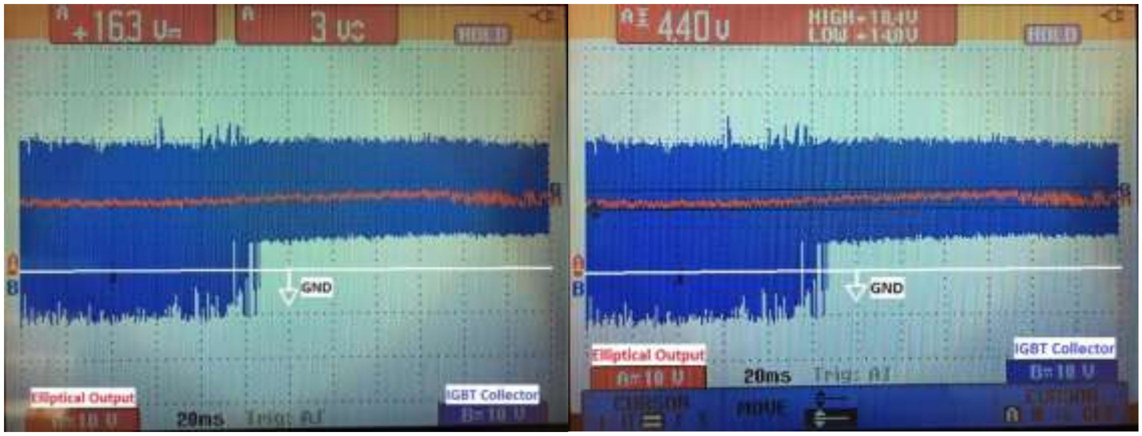

Figure 7-17: Waveform captures of the Elliptical Output (red) and IGBT Collector (blue) voltages using an isolated scopemeter. The left image displays the average electrical output voltage measurement. The right image displays the maximum and minimum voltage measurements via cursors. Elliptical Resistance Setting = 8, Pace = 150 SPM.

Decreasing the time scale on the scopemeter reveals that the collector voltage does drop to a potential that averages about 800 mV above ground. Figure 7-18 shows a frequent drop in the collector voltage from a 17.2 V DC level. The duration of the power diversion last for only about 50 µs, and the frequency between the IGBT diverting power measures 5.2 kHz. This phenomenon of the collector’s DC level dropping to around 800 mV also occurs for resistance settings of 10 and 12. Appendix A.5 includes the scopemeter captures of the elliptical output and collector voltages for these settings.

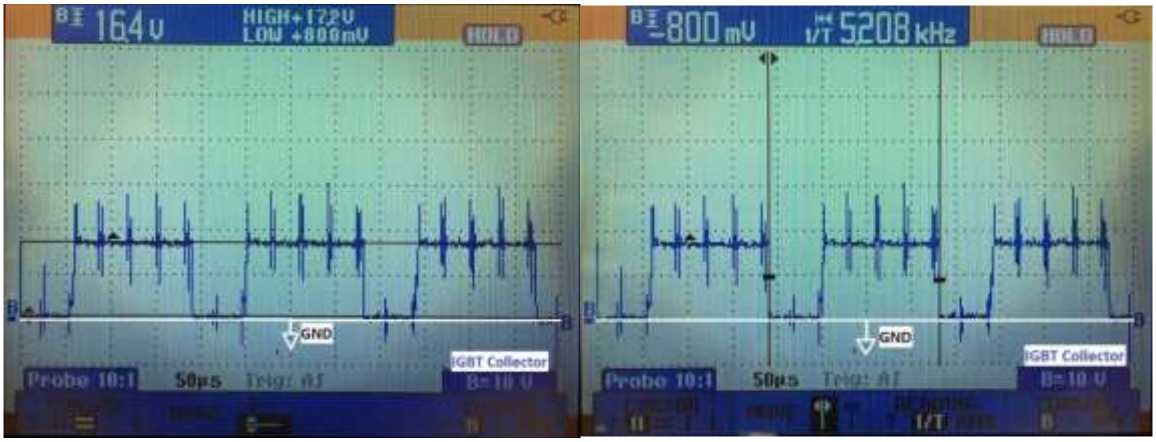

Figure 7-18: Scopemeter capture of the IGBT's collector terminal showing that power diverts through the IGBT. The left image shows the DC level of the waveform frequently drops from a 17.2 V level to about 800 mV. The right image measures a 5.2 kHz frequency between the IGBT switching on. Elliptical Resistance Setting = 8, Pace = 150 SPM.

7.3.2.3 Data Tables and Efficiency Plots

Table 7-1 and Table 7-2 show that as the ERS increases so do the average input current and power. However, the average input voltage tends to decrease. The maximum power point tracking in the M215 inverter causes this phenomenon. Prior efficiency testing in Chapter 3.2 shows that the M215 tends to pull the maximum available current from the source when producing power to the grid. When increasing the elliptical's resistance, the input power increases, and the inverter pulls more current to maximize output power. The inverter pulling more current causes the input voltage to decrease. The decrease in average input voltage ends at 16.2 V, which exceeds the inverter's minimum operating voltage by 0.2 V.

We calculate the efficiency for each resistance setting by dividing the AC output power by the DC input power to the M215 inverter. The product of the calculated currents through the sense resistor with their respective input voltages determines the input power. Multiplying the minimum input voltage with the minimum sense resistor current yields the minimum input power. The same goes for the maximum power and

average power, but the products of the max measurements and average measurements yields these values. Calculating the input power in this manner leads to efficiency calculations resulting above 100% for and ERS of 6 and 8. This also leads to “minimum” efficiency calculations yielding higher values than their “maximum” efficiency counterparts for each ERS. Referring to Table 7-1 and Table 7-2, the “MIN” efficiency calculations do not mean the lowest efficiency. The “MIN” efficiency compares the minimum output power to the minimum input power. Likewise, the “MAX” efficiency compares the maximum output power to the maximum input power. Note that recording the data points from the scopemeter and power meter does not happen simultaneously. The minimum and maximum powers do not represent an accurate instantaneous power over lengthy periods of recording data, and this leads to the wide efficiency variations at given biases.

Table 7-1: Data collected from elliptical testing with Enphase M215 microinverter and an OVPC. Fields highlighted yellow represent recorded measurements. Average pace of runner = 100 SPM. Diverting resistor measures 9.85 Ω.

Elliptical Testing with Enphase M215 Inverter and Overvoltage Protection Circuit														
Elliptical	Scopemeter Channel 1 (DC)					OVPC Diverting - Calculate (DC)						Agilent Multimeter (DC)		
Restance Setting (ERS)	V_{IN} MIN (V)	V_{IN} PEAK (V)	V_{IN} AVG (V)	V_{IN} RMS (V)	Does OVPC Divert?	I_{divert} MIN (A)	I_{divert} MAX (A)	I_{divert} AVG (A)	P_{divert} MIN (W)	P_{divert} MAX (W)	P_{divert} AVG (W)	V_{sense} MIN (mV)	V_{sense} MAX (mV)	V_{sense} AVG (mV)
2	34.4	37.2	35.7		NO	0	0	0	0	0	0	0.41	0.90	0.68
4	34.4	37.2	35.1		NO	0	0	0	0	0	0	0.79	1.67	1.25
6	34.0	37.6	35.6		NO	0	0	0	0	0	0	1.353	2.96	2.12
8	14.4	20.4	17.4		NO	0	0	0	0	0	0	18.55	24.40	20.40
10	15.2	17.6	16.2		NO	0	0	0	0	0	0	25.32	37.60	30.40
12	14.4	19.2	16.4		NO	0	0	0	0	0	0	40.22	46.90	44.10
14	14.4	20.0	16.2		NO	0	0	0	0	0	0	44.00	59.50	52.40
16														
18														
20														

Elliptical	M215 Input Current & Power - Calculate (DC)						M215 Output - Power Meter (AC)							Efficiency		
Restance Setting (ERS)	I_{sense} MIN (A)	I_{sense} MAX (A)	I_{sense} AVG (A)	P_{in} MIN (A)	P_{in} MAX (A)	P_{in} AVG (A)	V_{out} MIN (V)	V_{out} MAX (V)	I_{out} MIN (mA)	I_{out} MAX (mA)	P_{out} MIN (W)	P_{out} MAX (W)	P_{out} AVG (W)	MIN (%)	MAX (%)	AVG (%)
2	0.04	0.09	0.07	1.44	3.43	2.47	231.0	231.2	71.5	79.6	0.98	2.41	1.695	67.9	70.3	68.6
4	0.08	0.17	0.13	2.77	6.39	4.50	231.2	231.1	81.5	97.2	2.64	4.99	3.815	95.3	78.1	84.8
6	0.14	0.30	0.22	4.72	11.41	7.74	231.1	231.3	99.9	124.1	5.27	8.61	6.94	111.7	75.4	89.7
8	1.90	2.50	2.09	27.40	51.05	36.41	231.0	231.3	206.3	233.2	31.1	40.2	35.65	113.5	78.7	97.9
10	2.60	3.86	3.12	39.47	67.87	50.51	231.2	231.6	181.2	159.6	33.8	56.9	45.35	85.6	83.8	89.8
12	4.13	4.81	4.52	59.40	92.36	74.18	230.8	230.9	239.4	345.1	51.8	77.2	64.5	87.2	83.6	87.0
14	4.51	6.10	5.37	64.98	122.05	87.06	231.1	231.5	0.0	385.2	52.0	83.2	67.6	80.0	68.2	77.6
16																
18																
20																

Table 7-2: Data collected from elliptical testing with Enphase M215 microinverter and an OVPC. Average pace of runner = 100 SPM. Fields highlighted yellow represent recorded measurements. Diverting resistor measures 9.85 Ω.

Elliptical Testing with Enphase M215 Inverter and Overvoltage Protection Circuit																	
Elliptical	Scopemeter Channel 1 (DC)					OVPC Diverting - Calculate (DC)						Agilent Multimeter (DC)					
Restance Setting (ERS)	V_{IN} MIN (V)	V_{IN} PEAK (V)	V_{IN} AVG (V)	V_{IN} RMS (V)	Does OVPC Divert?	I_{divert} MIN (A)	I_{divert} MAX (A)	I_{divert} AVG (A)	P_{divert} MIN (W)	P_{divert} MAX (W)	P_{divert} AVG (W)	V_{sense} MIN (mV)	V_{sense} MAX (mV)	V_{sense} AVG (mV)			
2	23.2	26.0	23.5		NO	0	0	0	0	0	0	1.376	2.14	1.72			
4	14.4	19.2	16.4		NO	0	0	0	0	0	0	4.16	7.23	5.30			
6	14.4	21.2	17.8		YES	1.4	2.1	1.7	18.2	41.4	28.7	16.15	22.62	19.96			
8	14.0	18.4	16.3		YES	1.3	1.8	1.6	17.2	30.7	23.8	25.97	32.20	30.10			
10	14.0	20.4	16.4		YES	1.3	2.0	1.6	17.2	38.2	24.1	37.70	42.90	40.70			
12	14.0	20.0	16.5		YES	1.3	1.9	1.6	17.2	36.6	24.4	48.90	54.50	53.20			
14																	
16																	
18																	
20																	
Elliptical	M215 Input Current & Power - Calculate (DC)						M215 Output - Power Meter (AC)							Efficiency			
Restance Setting (ERS)	I_{sense} MIN (A)	I_{sense} MAX (A)	I_{sense} AVG (A)	P_{in} MIN (A)	P_{in} MAX (A)	P_{in} AVG (A)	V_{out} MIN (V)	V_{out} MAX (V)	I_{out} MIN (mA)	I_{out} MAX (mA)	P_{out} MIN (W)	P_{out} MAX (W)	P_{out} AVG (W)	MIN (%)	MAX (%)	AVG (%)	
2	0.14	0.22	0.18	3.27	5.71	4.15	231.1	231.2	65.4	87.2	0.04	4.67	2.4	1.2	81.8	56.8	
4	0.43	0.74	0.54	6.14	14.24	8.91	231.1	231.5	102.1	119.9	5.6	8.33	7.0	91.1	58.5	78.1	
6	1.66	2.32	2.05	23.85	49.18	36.44	230.7	231.2	192.2	220.3	29.4	33.9	31.7	123.3	68.9	86.9	
8	2.66	3.30	3.09	37.29	60.77	50.32	231.1	232.2	200.7	226.9	42.6	49.4	46.0	114.2	81.3	91.4	
10	3.87	4.40	4.17	54.13	89.76	68.46	231.4	231.4	266.3	307.3	58.8	68.8	63.8	108.6	76.6	93.2	
12	5.02	5.59	5.46	70.22	111.79	90.03	231.3	231.4	356.1	385.7	77.7	87.1	82.4	110.7	77.9	91.5	
14																	
16																	
18																	
20																	

Starting at a resistance level of 14 for a 100 SPM pace, the power meter fails to display a reading for the minimum output current to the grid. Instead of displaying a number, the power meter displays dashed lines. In addition, the power meter displays an absurdly large output power. Figure 7-19 shows a picture of the power meter displaying a maximum AC power of 834.6 W while the measurement for the output current changes between displaying a measurement and dashed lines. However, Table 7-1 lists 83.2 W; the previous observed maximum power before observing dashed lines. Despite this, the system continues to generate power, but only for a bit. While running, the runner notices the elliptical turn off while in use and quickly turn back on. Doing so resets the elliptical's resistance setting back down to 1, which causes the elliptical to not output power. While still able to acquire output data for this resistance setting, we retry running at a 100 SPM pace to see if this issue persists. The person running continues to experience instances of the elliptical turning off and back on again and resetting the resistance setting. The same problem of the elliptical resetting while in use also occurs when running at a 150 SPM pace with an ERS greater than 12.

Figure 7-19: Power meter reading showing 834.6 W of maximum output power in error. Meanwhile the display for measured AC current transitions between displaying a numerical value to dashed lines.

We attempt to collect data for higher resistance settings at both paces, but fail to do so. At a 100 SPM pace, we start by setting the elliptical resistance to 2 and running at 100 SPM to power up the M215 inverter. Once the M215 outputs AC power, the runner then increases the resistance setting to 16. Shortly after setting the elliptical's resistance to 16, the power meter displays a maximum output power above 800 W and the elliptical resets again just as described above. We cannot collect data for resistance settings above 14 for a 100 SPM pace. Despite the absurdly high output power reading, no components show any signs of damage. With a 150 SPM pace, we try collecting data for an ERS of 14, but experience the same problem of the elliptical resetting. The M215 microinverter causes the Precor elliptical to reset. When increasing the ERS of the elliptical, the elliptical produces more power. However, because the M215 microinverter maximizes power conversion by pulling more current, this causes the elliptical output voltage to drop below the microinverter's minimum operating voltage.

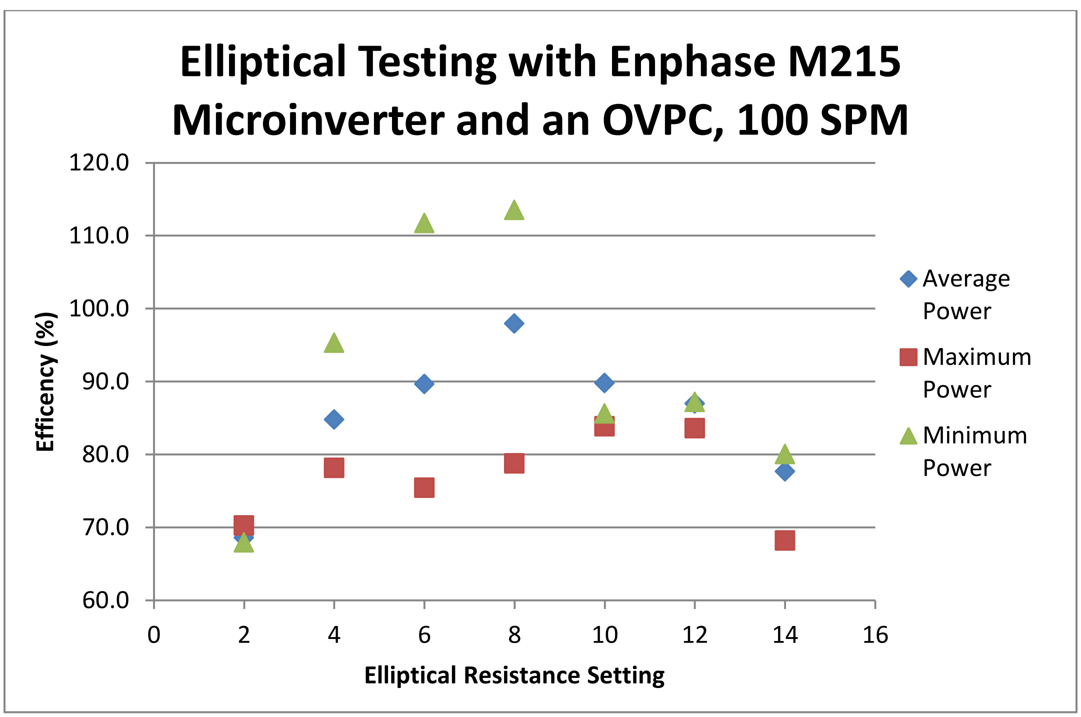

Figure 7-20: Efficiency plots for Elliptical testing at a 100 SPM pace with an Enphase M215 Microinverter with overvoltage protection.

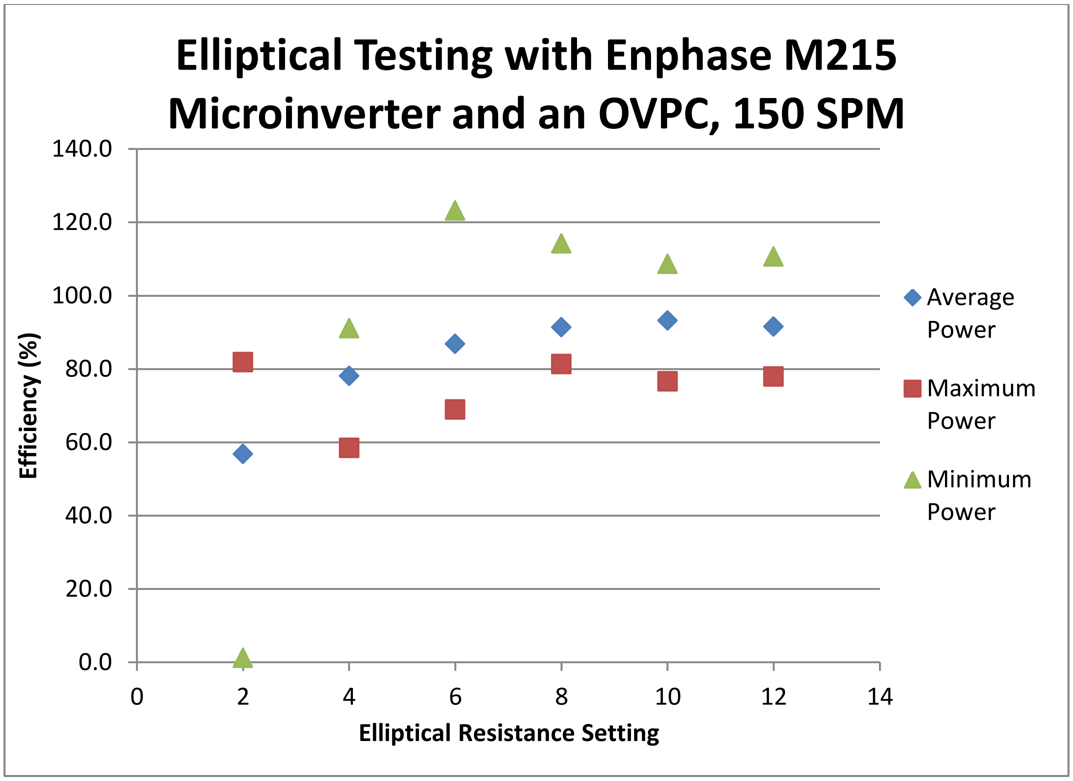

Figure 7-21: Efficiency plots for Elliptical testing at a 150 SPM pace with an Enphase M215 Microinverter with overvoltage protection.

Figure 7-20 and Figure 7-21 plot the efficiency calculations for elliptical testing with an Enphase M215 Microinverter with overvoltage protection. Figure 7-21 shows efficiencies for a 100 SPM. The average power efficiency shows an increasing trend with the ERS until setting the ERS to 8. When increasing the ERS beyond 8, the average power efficiency declines from 97.9% efficiency to 77.6% efficiency. The maximum power efficiency shows the least variation between the three efficiency columns with efficiencies ranging from 68.2% to 83.8%. Figure 7-21 plots efficiencies for a 150 SPM pace. At this pace, the average power efficiency increases with the ERS until peaking at 93.2% efficiency for an ERS of 10. The efficiency decreases slightly to 91.5% when increasing the ERS to 12. Again, the maximum power efficiency varies the least. The efficiency calculations for the maximum power efficiency range from 58.5% to 91.8%.

Meanwhile the minimum power efficiency plot shows the most variation due to the efficiency calculation of 1.2% for an ERS of 2.

Compared to data collected in the following chapter, data collected in Chapter 7 show the EHFEM project generates power to the AC grid more efficiently when excluding a DC-DC converter from the setup. However, without a DC-DC converter, the microinverter pulls too much current from the elliptical at higher ERSs and causes the elliptical's output voltage to drop below the microinverter's minimum operating voltage. Thus, without a DC-DC converter, the system has a limited range of elliptical resistance settings for given speeds in which the system produces AC power without resetting. Adding in a DC-DC converter can also further limit the operating range, which we discover in the following chapter.

The following chapter conducts full system testing with the Precor elliptical trainer and compares results with data collected in this chapter. While testing in Chapter 7 does not include a DC-DC converter, Chapter 8 uses the CUI and Vicor DC-DC converters in separate test sessions with the Enphase M215 inverter. Chapter 8 also makes use the OVPCs designed in Chapter 5 to protect each DC-DC converter.

CHAPTER 8: FULL SYSTEM EHFEM TESTING

8.1 Introduction

Chapter 7 tests how efficiently elliptical-generated power could convert into AC power with just an inverter and an overvoltage protection circuit (OVPC). When testing just the M215 inverter and an OVPC we discover that probing the OVPC with the Tektronix oscilloscope trips the M215 inverter's GFI sensor, which shuts down the inverter and requires maintenance. The Tektronix oscilloscopes trip the microinverter's GFI sensor, because the oscilloscopes have non-isolated ground connections. This leads to acquiring a couple Fluke 196C isolated scopemeters, which avoid tripping a GFI flag in the M215 microinverter. With the scopemeters, we successfully acquire efficiency data for elliptical testing using the M215 microinverter while excluding a DC-DC converter.

This test session determines how efficiently the EHFEM project can convert elliptical-generated power into AC power when excluding only the current limiter. Full system testing normally includes the Precor elliptical, an overvoltage protection circuit, DC-DC converter, current limiter, and microinverter. The current limiter functions by regulating the DC-DC converter's output current so as not to overload the microinverter with too much current [6]. However, testing in this chapter excludes the current limiter. The datasheet for the CUI VHX200W-Q48-S28 claims to have a maximum output current of 7.14 A, while the datasheet for the Vicor V28A36T200BL2 claims a maximum load current of 5.56 A [17, 18]. The datasheet for the M215 inverter lists a maximum DC short circuit current of 15 A, more than twice the maximum output current of the CUI [13]. The current limiter also requires a microcontroller with a pre-written code compiled and loaded onto the microcontroller, which would not compile. For these reasons, we

exclude the current limiter while testing with the M215 inverter. Meanwhile, the M175 inverter's data sheet lists a maximum DC short circuit current of 10 A and a maximum input current of 8 A, which also exceed the maximum load currents of the DC-DC converters [11]. Despite high current ratings for the microinverters, elliptical tests involving the M175 or M215 should use fuses or a current limiter as a precaution.

8.2 Full System Testing with CUI DC-DC Converter and M215 Inverter

Full system testing begins with the CUI DC-DC converter and the M215 inverter. Prior testing on the OVPC designed for the CUI converter demonstrates power diversion when the input voltage surpasses 57.6 V and ceases diverting power when the voltage reduces to 54 V. We begin data collection with the elliptical at a low resistance setting of 2 and increase the resistance by 2 for each data set until the elliptical reaches its maximum resistance (20). We plan to collect data of a user running on the elliptical at a pace of 100 strides per minute (SPM) and 150 SPM.

Figure 8-1 shows a circuit diagram, and Figure 8-2 depicts a wiring diagram of the following test. We expect to see the OVPC limit the input voltage, also known as the elliptical output voltage, into the CUI converter. The M215 microinverter should then convert the CUI's 28 V DC output into AC power, and send the AC power to the electrical grid. Refer to Appendix B.8 for details about the necessary equipment and steps for setting up and conducting the test.

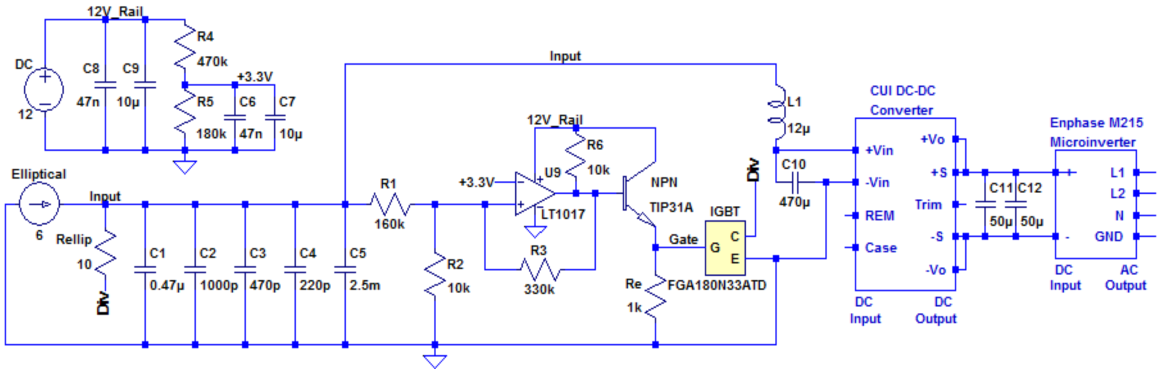

Figure 8-1: Circuit Diagram of a full system test involving the Precor elliptical machine, CUI DC-DC converter, and Enphase M215 microinverter.

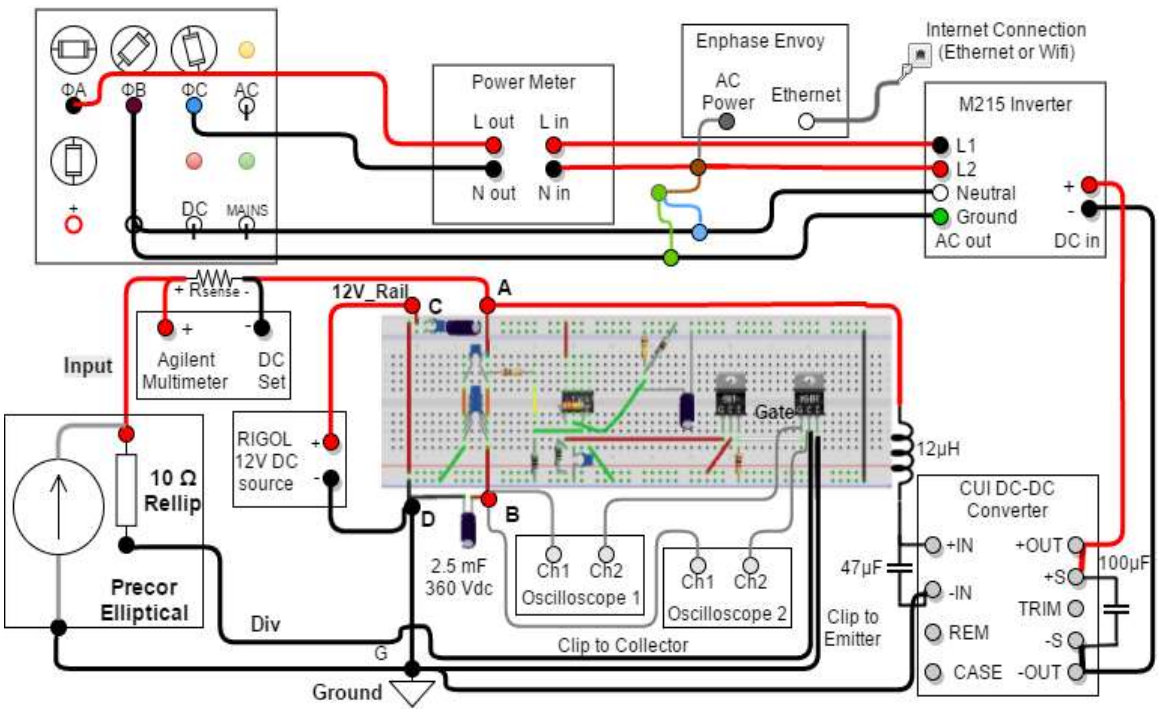

Figure 8-2: Wiring Diagram of a full system test including the Precor elliptical, CUI DC-DC converter, and Enphase M215 inverter.

8.2.1 100 SPM Pace: Initial Test

Testing begins with one person running on the elliptical with an elliptical resistance set to level 2 at a constant pace of 100 SPM, while another person prepares to collect data. After about 90 seconds, the M215 inverter's LED blinks green, and the power meter measures a couple watts. When ready to collect data, simultaneously press the "STOP" buttons on both oscilloscopes to view the input voltage on the OVPC. Then

press the “MinMax” button on the multimeter, followed by pressing the “Max” button on the power meter. We then record the MIN, MAX, MEAN, and RMS voltages for the elliptical output voltage, and the IGBT’s collector voltage from the oscilloscopes. This brief period of time allows the multimeter to acquire minimum and maximum voltages across the sense resistor, and for the power meter to acquire maximum AC output values. We record the maximum values for the output AC voltage, current, and power, and then press the “Min” button on the power meter. While the power meter looks for the lowest values of AC generation, we record the maximum voltage across the sense resistor. We then press the “MinMax” button to record the minimum voltage, and press the button again to record the average voltage across the sense resistor. We then record minimum values for AC voltage, current and power generation. This concludes data collection for one resistance setting, and the elliptical’s user increases the elliptical’s resistance by 2. Before moving on to collect more data, we take pictures of the oscilloscope captures. We then press the “RUN” buttons on both oscilloscopes, and hold the “MinMax” button on the multimeter so it resets the measured minimum and maximum values. We then repeat the same process of collecting data.

Maintaining a constant speed of 100 SPM, while not difficult for a short time, proves strenuous after about a minute on the elliptical. We then question the feasibility of running on the elliptical at 150 SPM at the highest resistance settings long enough to collect accurate data. Collecting data proves a slow process. It takes the data recorder about two minutes between resistance levels to record all measurements. In this time, the runner burns about 30-40 calories according to the elliptical’s counter.

After collecting a set of test data the test session concludes with a tired runner stepping down from the elliptical. We note the low maximum AC power output measured for ERSs of 16 and 18, and discuss the option of re-measuring the two rows of data. About two minutes pass before the shutting down the AC power from the lab bench and turning off the DC source supplying the 12-Volt rail on the OVPC.

We later look to retest for resistance settings of 16 and 18. The power output at these levels equaled 1.95 W, which deviates from a rising trend of AC power generation of power above 10 W. For this reason, we felt it necessary to retest for these resistance levels and see if the inverter would generate more power. After resupplying power to the AC branch as well as the 12-Volt rail, the Enphase M215 inverter has to undergo its startup process. The elliptical user runs at a pace of 100 SPM and sets the resistance setting to 6 on the elliptical. After about 90 seconds, the power meter measures a few watts of AC power generation, and the oscilloscopes display the typical waveforms. The runner then increases the ERS to 16 and runs for a period before achieving a constant pace of 100 SPM.

The person recording data simultaneously presses the “STOP” buttons on the oscilloscope, and then presses the “MinMax” button on the multimeter, followed by the “Max” button on the power meter. A few seconds later, the power meter measures zero watts of power generation and the oscilloscopes display atypical waveforms. Now when operating the elliptical, the oscilloscopes only shows transient voltage spikes and no rise in the DC level of the signal. Since the system no longer produces a sufficient voltage to the input of the DC-DC converter, the inverter can no longer produce AC power. This

confirms that a component in the system had ceased functioning properly and troubleshooting occurs.

8.2.1.1 Exploring the Causes of Failure in the System

First, we inspect the OVPC by disconnecting the DC-DC converter but leaving the elliptical connected. Running on the elliptical, we set a pace of 100 SPM with a resistance setting of 2. Both oscilloscopes display the typical sawtooth-like waveform generating from the elliptical machine. Oscilloscope 1 shows the voltage on the IGBT's gate change periodically from 0 V to 12 V. The OVPC still functions properly.

Next, we investigate the CUI DC-DC converter. After disconnecting the converter's output from the M215 inverter, we connect the BK Precision DC source to the CUI's input and use the Agilent multimeter to measure the open circuit voltage at the CUI's output. With the source set to supply 30 V and a 3 A current limit to the CUI, we expect the converter to produce an output voltage close to 28 V. Instead, we notice the DC source instead supplies about 0.5 V and the full 3 A on the input of the converter while the multimeter shows the DC-DC converter outputs less than 1 mV. These signs indicate that the DC-DC converter has a short on the input and cannot function. A continuity check with a multimeter probing the +Vin and –Vin terminals of the DC-DC converter also confirms a short.

To ensure the M215 inverter still functions properly, we reconnect the BK Precision DC source to the inverter's input and supply a 30 V source and a 5 A current limiter. After a 90 second startup period, the inverter's LED flashes green every two seconds indicating proper function.

It seems possible that shutting down the AC power and DC source supplying the 12 V rail before leaving for lunch may have created a overloading surge of current through the CUI converter. The possibility arises from the 2.5 mF capacitor requiring significantly more time to completely discharge than other capacitors in the filtering bank. The capacitor bank and voltage divider circuit in Figure 8-1 have equivalent capacitances and resistances of 2.50 mF and 170 kΩ. This gives an RC time constant of 425 seconds. Equation (8.1) yields the relationship for calculating the capacitor voltage as it discharges. V_s represents the source voltage or starting voltage of the capacitor while V_c represents the capacitor's voltage as it discharges over time.

$$V_c = V_s exp\left[{}^{-t}/_{RC}\right] \qquad (8.1)$$

Calculating for a capacitor bank discharging 60 V down to 0.5 V takes 2034 seconds, or 34 minutes. However, this assumes that the CUI does not pull any voltage from the input and discharge the capacitor more quickly. Usually, the CUI powers down at 16 V, and the input voltage decreases from the maximum generated voltage when powering the elliptical (close to 60 V) to 16 V within a few seconds. It takes about 7.4 minutes for the capacitor bank to discharge from 16 V to 0.5 V. This calculates about 5 minutes longer than we had waited before shutting down the AC power and 12-Volt DC source. As the capacitors discharge, the power flows from the capacitor bank through the voltage divider used to scale down the input voltage in the OVPC. However, shutting down the AC branch or the 12-Volt DC source while the capacitors retain a charge should not damage the DC-DC converter. The power path for the OVPC's capacitor back to discharge through the voltage divider remains uninterrupted.

In addition, the CUI DC-DC converter ceased working while a user operated the elliptical. A signal present on the CUI DC-DC Converter input terminals must have caused it to fail short circuit. When testing with the Vicor DC-DC converter and M215 inverter, discussed further in this report, we measure a maximum of 3.46 A of input current flowing into the Vicor. Yet somehow while testing, we managed to break an input fuse rated for 5 A during two separate instances. From this observation, the CUI DC-DC converter may have also experienced high frequency transient spikes that the multimeter and sense resistor failed to measure, and caused the CUI to fail short circuit protection.

Perhaps the issue of the CUI failing short circuit protection associates with the M215 inverter's maximum power point tracking (MPPT). If the inverter's input voltage drops below the 16 V limit due to the inverter's MPPT, then the inverter stops accepting current. At this point, no current can flow from the DC-DC converter to the inverter, but current still flows into the CUI. The power present at the DC-DC converter input terminals must have another path to flow or else damage the converter. If the input voltage activates the OVPC, then power at the CUI's input terminals can flow through the 10 Ω diverting resistor. However, once the diverting resistor dissipates enough power to drop the input voltage low enough to turn off the power diverting IGBT, the remaining power must dissipate through the 170 kΩ formed by the series connected voltage divider. In the case of testing, the input voltage increases once the OVPC stops diverting. Once that voltage rises above the voltage threshold, the cycle repeats.

The following tries simulating in LTspice if a significant current spike occurs across the sense resistor when powering down the 12-Volt DC source shortly after stepping down from the elliptical. To accomplish this, a 35 Ω load replaces the CUI as

the load while the 47 µF capacitor and 12 µH inductor remain in the circuit. A single pulse current source of 3.7 A with a rise time of 10 seconds and fall time of 20 seconds represents a runner increasing speed, maintaining a pace, and decelerating to a stop. A 12 V pulse signal with a one-second fall time represents turning off the source that supplies the OVPC's 12-Volt rail. Figure 8-3 below depicts the circuit diagram for simulation. The diagram also includes the 0.010 Ω sense resistor. When simulating, the 12-Volt source should shut down when the input voltage equals 16 V. If a spike in current occurs as the 12-Volt source shuts down, then this can indicate too much input current overloading the CUI.

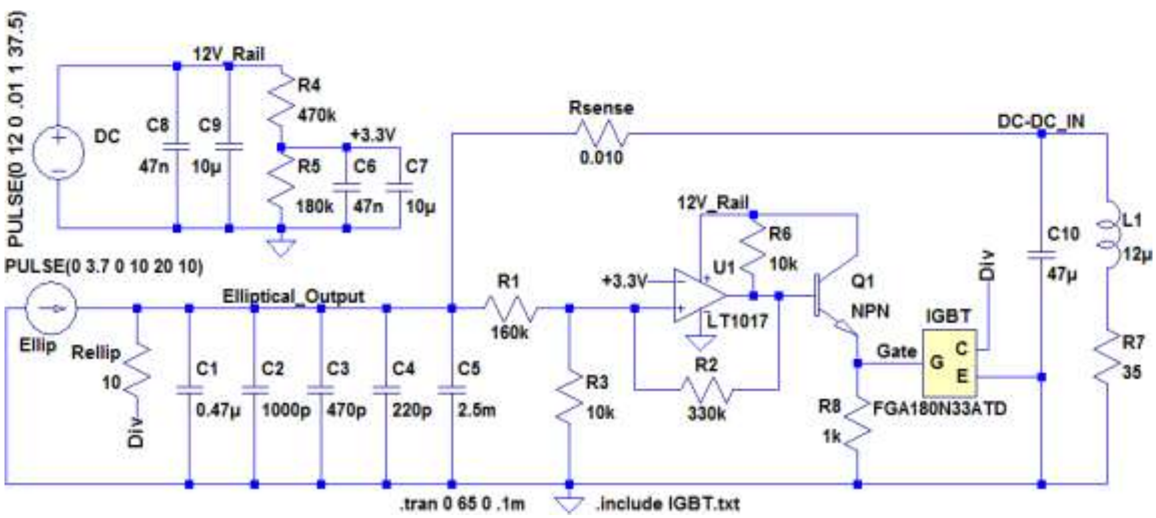

Figure 8-3: Circuit diagram of an OVPC with inductor-resistor load to simulate the CUI as the load. The pulsed sources intend to simulate a runner on the elliptical and shutting down the 12 V source. This setup attempts to generate a high current spike across the sense resistor.

Figure 8-4 shows the simulation of the above diagram. The input current increases and plateaus at 3.7 A as expected. As this happens, the input voltage increases until reaching 58 V where the voltage then fluctuates between 58 V and 52 V due to the IGBT diverting excess power. After 20 seconds, the current from the elliptical decreases but the input voltage continues to fluctuate until the current decreases to about 1.65 A wherein it then decreases. The waveform "V(Elliptical_Output,DC-DC_IN)" represents the voltage

drop across the sense resistor while "-I(Rsense)" depicts the current flowing from the input to the load through the sense resistor. Through trial and error, the following manages to simulate the 12-Volt source shutting down when the input voltage nears 16 V. The measurement box in the simulation shows an input voltage of 16.2 V as the 12-Volt source shuts down, and an instance of a current spike through the sense resistor does not occur. Instead, the waveform representing the current through the sense resistor continues to decrease.

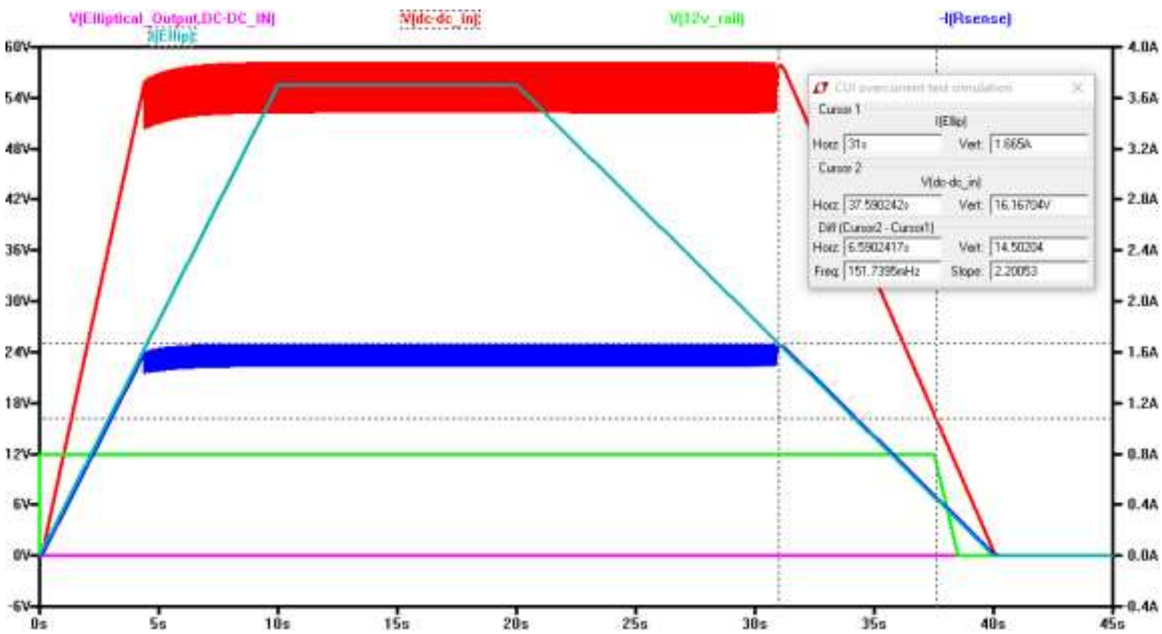

Figure 8-4: Simulation of the circuit diagram in Figure 8-3 attempting to generate a high current spike across the sense resistor. When the 12-Volt source shuts down while the input voltage equals 16 V, an instance of a high current spike does not occur. Maximum Time step = 100 ns.

With the CUI DC-DC converter out of commission, we order another CUI VHK200W-Q48-S25 DC-DC converter from Digi-Key to replace the broken converter. We still plan to perform full system testing with a CUI converter at a 150 SPM pace. We also plan another trial of the 100 SPM pace in hopes of measuring more watts of AC power generating from the M215 inverter, as well as acquire photos of oscilloscope captures. Since the CUI failed during testing, we include protective fuses at the input and

output of the DC-DC converter in later tests. The following subsections detail testing results with a new CUI at a 100 SPM pace and attempting to collect data for a 150 SPM pace. Beyond that, this thesis reports results for full system testing with the Vicor converter and M215 inverter.

8.2.2 100 SPM Pace: Second Test

The second trial of elliptical testing with the CUI and M215 includes two 8 A fuses to provide the CUI's input and output with overcurrent protection. Unlike the previous trial, this trial also uses a Fluke portable multimeter to measure the DC-DC converter's minimum and maximum voltage outputs. Figure 8-5 shows the placement of the fuses in a circuit diagram, and Figure 8-6 shows the fuses and multimeter in a wiring diagram.

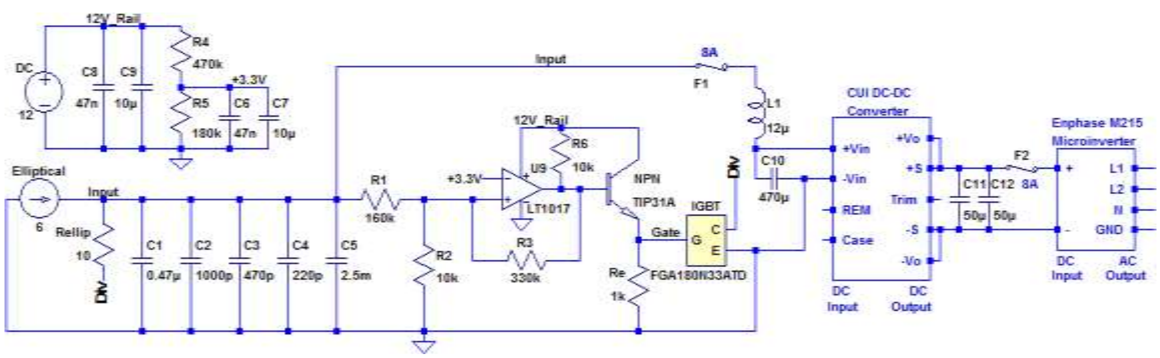

Figure 8-5: Circuit Diagram for elliptical test session involving Precor elliptical machine, a new CUI DC-DC converter, and Enphase M215 microinverter. This schematic includes protective fuses at the DC-DC converter's input and output.

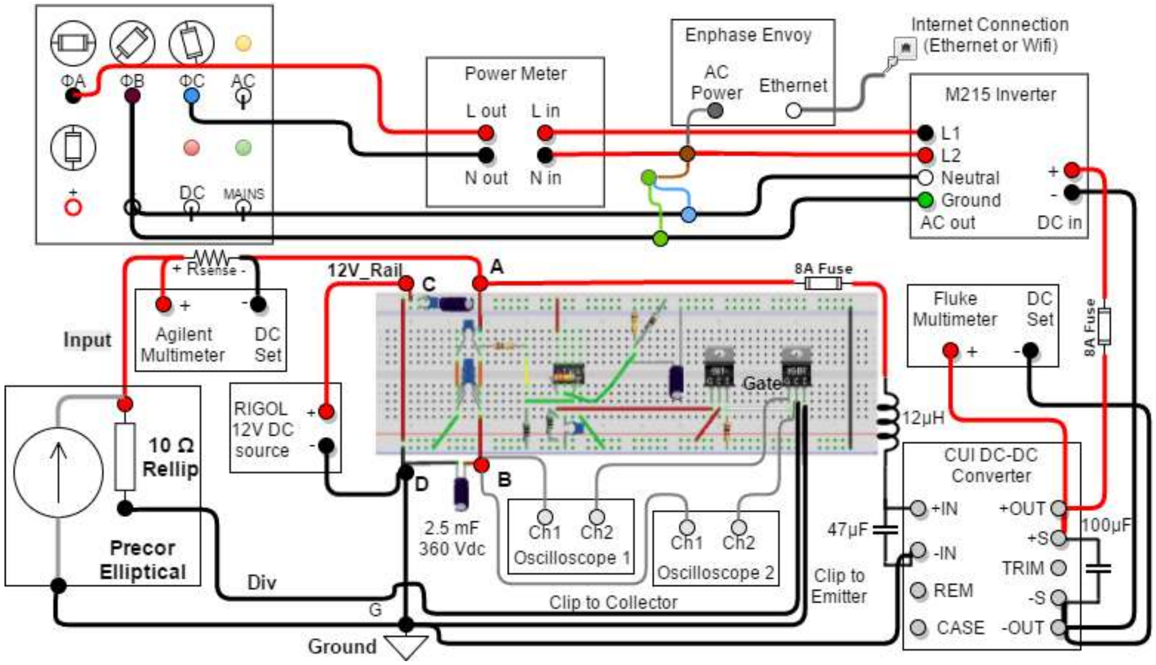

Figure 8-6: Wiring Diagram for elliptical test session involving Precor elliptical machine, a new CUI DC-DC converter, and Enphase M215 microinverter. This diagram includes protective fuses at the DC-DC converter's input and output.

When conducting a second round of elliptical testing with the CUI converter and M215 inverter, we take pictures of the waveforms on the Tektronix oscilloscope. Figure 8-7 shows the elliptical output voltage along with the voltages on the IGBT's gate and collector when running with the resistance set to 2. The elliptical output voltage of Figure 8-7 shows a waveform not seen during other test sessions. Rather than showing a DC-like or sawtooth-like waveform, the waveform appears irregular. In the oscilloscope captures, there appear multiple instances of the input voltage decreasing, but only one instance of the OVPC actively diverting excess power. During the first trial of this test setup at a 100 SPM pace, we did not observe an instance of the OVPC diverting power. In the one instance where the OVPC diverts in the second attempt, the circuit ceases diverting excess power at a voltage not equal to the minimum input voltage in the capture. Connecting the CUI DC-DC converter influences the behavior of the elliptical output voltage. Without the DC-DC converter, the input voltage for this resistance setting

appears DC-like with little fluctuation as seen in Figure 7-12 in Chapter 7.3.2.1. Including the CUI in the test setup allows the elliptical output voltage to increase and activate the OVPC. At the same time, the CUI tries to convert DC power at a maximum efficiency, and accomplishes this by decreasing the input voltage if it means pulling more current from the elliptical.

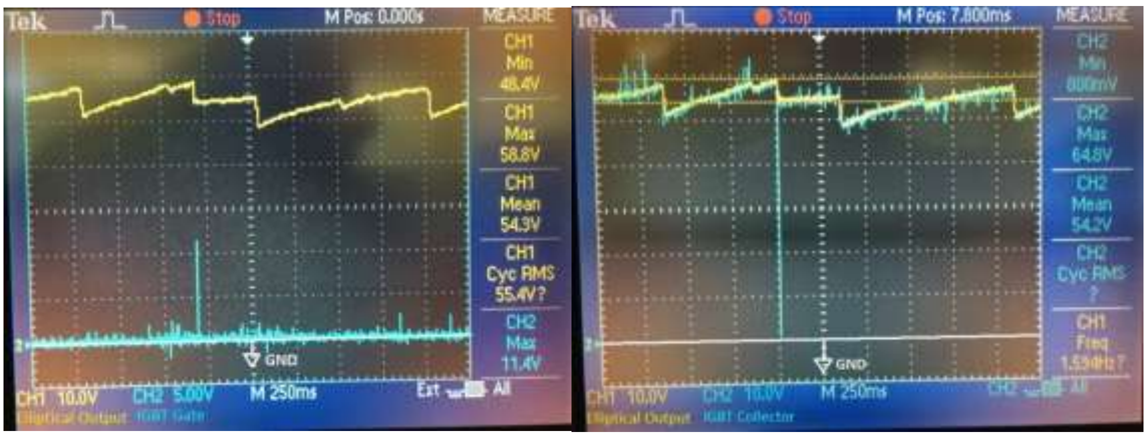

Figure 8-7: Oscilloscope capture of input voltage (yellow), IGBT gate voltage (blue, left), and IGBTcollector voltage (blue, right). Elliptical Resistance Setting= 2, 100 SPM

Figure 8-8 shows the same oscilloscope capture as the right image in Figure 8-7, but with cursor measurements. These cursors measure the input voltages when the OVPC diverts power (59.2 V) and ceases diverting power (54.0 V). When calculating the minimum and maximum power the OVPC diverts from the DC-DC converter, we use the voltage measurements in Figure 8-8.

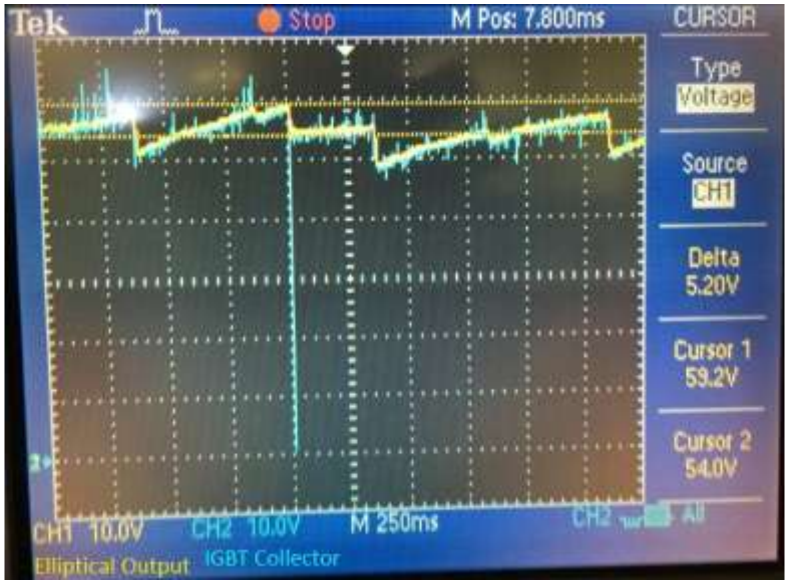

Figure 8-8: Oscilloscope capture of input voltage (yellow), IGBT collector voltage (blue). Elliptical Resistance = 2, 100 SPM

After recording measurements for an ERS of 2, we increase the setting to 4. At this setting, the waveform of the input voltage appears sawtooth-like, as shown in Figure 8-9. However, at this setting, the elliptical outputs a lower voltage potential, preventing the OVPC from diverting excess power. Although the input voltage decreases when increasing the ERS from 2 to 4, the current to the DC-DC converter increases. Despite the increase in current, the maximum power to the CUI input actually decreases, but M215-produced AC power still increases. Interestingly, even though the OVPC does not divert excess power at an ERS of 2 or 4, the Agilent multimeter still measures negative values for the minimum voltages measured across the sense resistor. Among other differences the report mentions later in Chapter 8.4.2, the previous trial at 100 SPM measures positive minimum voltages for resistance settings of 2 and 4.

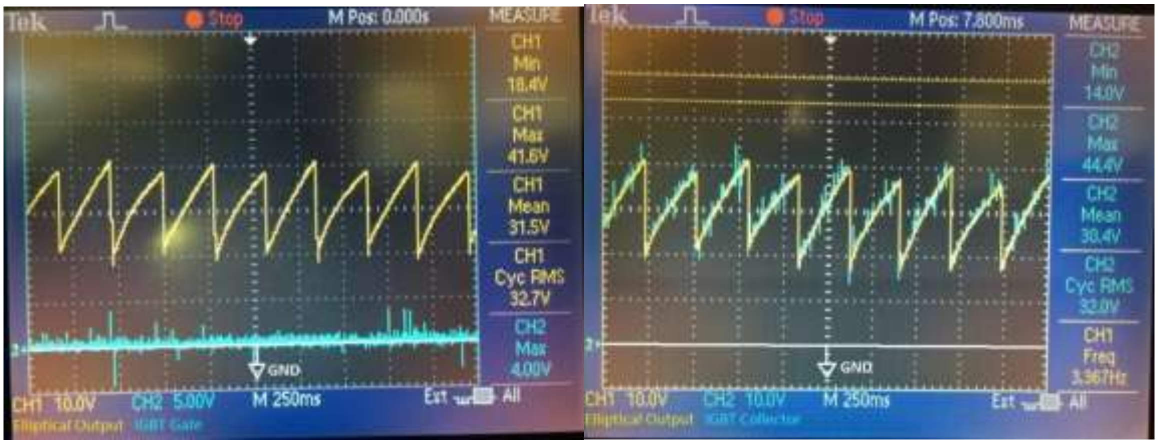

Figure 8-9: Oscilloscope capture of input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 4, 100 SPM

When increasing the ERS setting to 6, the elliptical output voltage waveform resembles that of an OVPC diverting power within the established input voltage range. This remains true even when increasing the ERS all the way to 18. Figure 8-10 shows the waveforms for the elliptical output voltage, as well as the IGBT's gate and collector for a resistance setting of 6. Appendix A.6 includes the oscilloscope captures of the waveforms for resistance settings of 8 to 18. All oscilloscope captures from resistance settings of 8 to 18 share the same time scale of 25 ms per division. As the ERS increases, we observe an increasing frequency of power diversion occurrences.

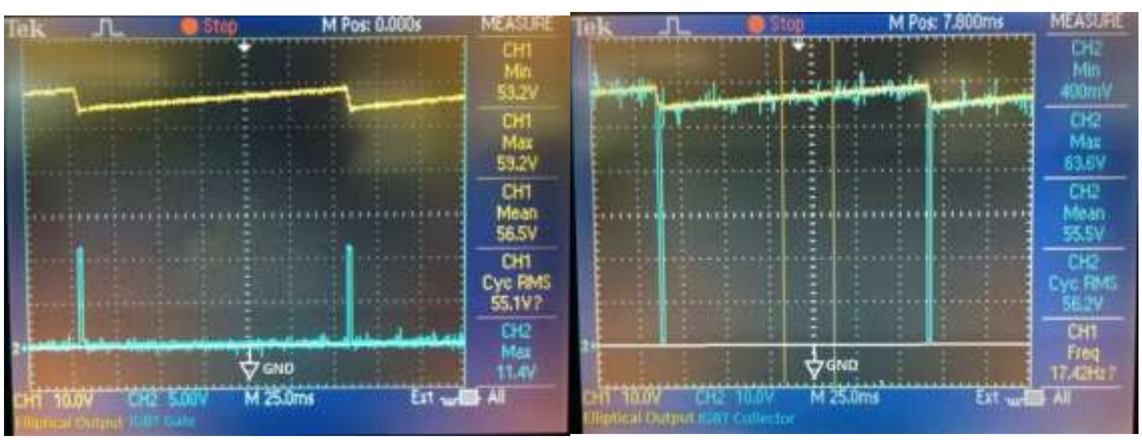

Figure 8-10: Oscilloscope capture of input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 6, 100 SPM.

We attempt to record AC output measurements for an ERS of 18, but fail to acquire a maximum power measurement. At this setting, the M215 inverter produces AC power and has a blinking green LED. Shortly into the data collection, the M215 inverter ceases to blink green. Meanwhile, the oscilloscopes display the sawtooth-like waveform indicating the OVPC still diverts power from the CUI converter. In addition, the Fluke multimeter measures 27.67 V at the output of the CUI. The fuses have not blown so the CUI still works. About a minute passes before the M215 blinks green again. Then, the power meter displays a measured output power, before displaying 0 W. This cycle repeats, and the inverter has to undergo its startup process again. Because of the constant cycle of the M215 resetting and starting back up, we do not collect data for an elliptical resistance of 20. The next subsection details full system testing at a few elliptical resistances for a set pace of 150 SPM.

8.2.3 150 SPM Pace

With the replacement CUI surviving testing at a 100 SPM pace, we move to increasing the pace to 150 SPM and set the ERS back down to 2. After 90 seconds of running, the inverter generates AC power to the grid and recording data begins. Figure 8-11 shows the elliptical output, gate, and collector voltages for a resistance setting of 2. The waveform of the elliptical output voltage resembles the waveform of Figure 8-9. The two waveforms have similar minimum and maximum points, while the voltage doesn’t surpass the threshold for power diversion. Figure 8-11 has a time scale five times smaller than that of Figure 8-9, which explains why more periods in the waveform appear in Figure 8-9. After recording data, we increase the resistance setting to 4.

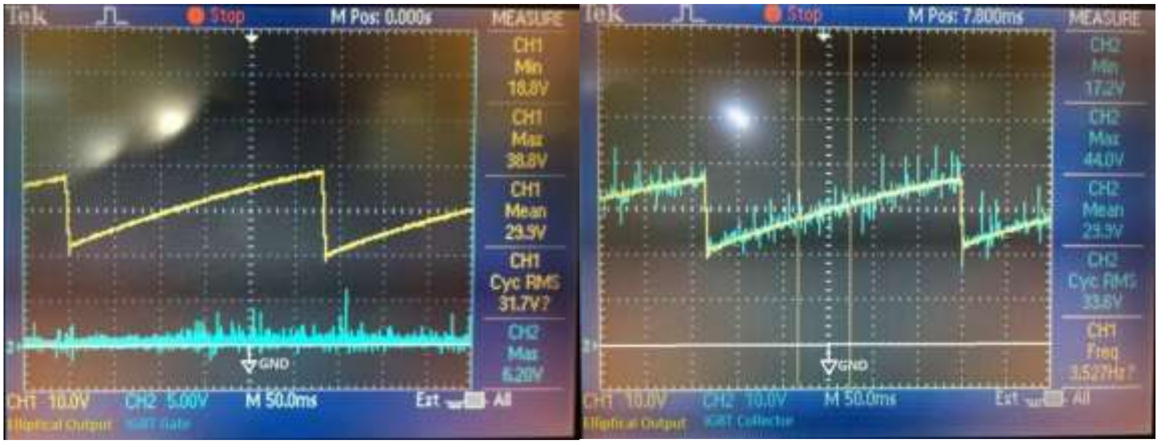

Figure 8-11: Oscilloscope capture of input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 2, 150 SPM

Figure 8-12 shows a change in the voltage signals when increasing the ERS to 4. These waveforms resemble those when running at a 100 SPM pace for resistance settings of 6 to 18. The elliptical output voltage ranges from 51.2 V to 58.8 V due to the parameters of the OVPC, and the OVPC regularly diverts excess power. Although we record data for this resistance setting, the M215 inverter's LED cease blinking green indicating it needs to start up again.

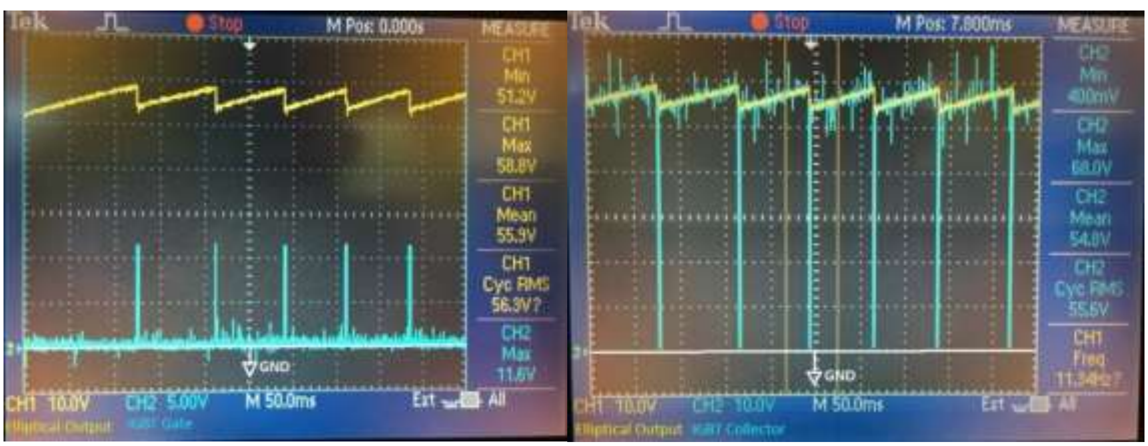

Figure 8-12: Oscilloscope capture of input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 4, 150 SPM

After increasing the ERS to 6 and having the M215 startup and blink green, we anticipate a reset. Shortly after the inverter starts up, the M215 inverter stops blinking green and has to undergo the 90-second startup period again. The elliptical user continues

to run while the inverter restarts, but their pace slows to about 125 SPM. When the inverter starts up again, the inverter still stops producing AC power after a few seconds and resets again. Unable to collect data, we investigate what causes the inverter to reset. We first theorize that the output voltage of the CUI converter drops below the minimum operating range of the M215 and fails to rise within the operating range before the M215 shuts down. To test this, we add an available Fluke scopemeter at the DC-DC converter's output while leaving the Fluke multimeter connected at the output as well.

It takes a few attempts to attain a proper oscilloscope capture of the CUI's output voltage. To view the full behavior, we increase the time scale of the Fluke scopemeter to one second per division. Figure 8-13 shows the waveforms of the system's input voltage, gate voltage, and the output voltage of the CUI. The left image shows a CUI DC-DC converter output 28 V before fluctuating for a second, then dip down to about 8 V and decrease further to 4 V. After reaching its lowest point, the output voltage of the DC-DC converter gradually steps up to achieving its ideal voltage output of about 28 V. Once the M215 starts up, the inverter has an operating range of 16-48 V [13]. Looking at the left image, the scopemeter shows the CUI's output voltage drops well below 16 V. It then takes a little over 4 seconds for the CUI's output voltage to increase above 16 V, but by this time the M215 inverter stops producing power and must undergo its 90-second startup cycle. The right oscilloscope image shows an input voltage rise and fall in the 50 V range before decreasing in a saw-tooth pattern to 25.6 V. Then the input voltage rises to a 58.4 V maximum, and the OVPC begins to divert power again. The input voltage rising from 25.6 V occurs as the CUI's output voltage increases from 4 V.

Figure 8-13: Oscilloscope captures of the CUI DC-DC converter's output voltage (red), input voltage from the elliptical to the CUI (yellow), and the IGBT gate voltage (blue). The left image has a time scale of 1 s/div while the right image has a time scale of 100 ms/div.

The maximum power point tracking (MPPT) of the M215 inverter causes the CUI's output voltage to drop and sustain a low voltage before charging back up. When producing AC power, the M215 inverter tries to maximize the amount of DC power it can convert into AC power. Prior efficiency testing with the M215 inverter and a high power DC source in Chapter 3.2.3 shows that the M215 inverter prefers to pull the maximum amount of current allowed by the DC source. This often leads to the DC source supplying a voltage below the set test level, which the data tables in Appendix A.2 show. A user running on the elliptical at a 150 SPM produces more input power to the DC-DC converter than running at a slower pace, which may cause the CUI to output more current. As the CUI tries to output more current, the M215's MPPT causes the voltage from the CUI to decrease in order to pull more current and potentially maximize the power the M215 receives from the CUI. Instead, the M215 pulls too much current causing the CUI's output voltage to drop below the microinverter's minimum operating voltage and shut off the inverter.

We end the test session without collecting data for an ERS of 6 or beyond. The inverter consistently resetting itself while testing makes it difficult to acquire

measurements when the M215 inverter produces AC power. Testing with a 150 SPM pace suggests that a system that uses a CUI DC-DC converter cannot consistently produce power to the grid without a means of stabilizing the CUI's output voltage.

8.2.4 Data Tables and Efficiency Plots

Table 8-1 tabulates measurements recorded during the first 100 SPM pace test session of a full system test with the CUI and M215 inverter. At the low ERSs of 2 and 4, the elliptical outputs a voltage that averages less than 30 V. The measured minimum and maximum currents flowing into the CUI DC-DC converter all measure positive and the average output power from the M215 inverter measures a few watts. Increasing the resistance setting to 6 and beyond allows the input voltage to reach a maximum in the 58.8-59.2 V range and a minimum in the range of 52.8-53.2 V. The maximum current across the sense resistor decreases from 0.363 A down to 0.221 A when increasing the ERS from 4 to 6. For an ERS of 8 and beyond, the maximum current measured across the sense resistor the increases with the ERS. Meanwhile the minimum current across the sense resistor measures negative at an ERS of 6. The minimum current across the sense resistor continues to measure negative but decreases in magnitude as the ERS increases. With an exception of and ERS of 4, the minimum AC power the M215 produces measured 0 W. The measured maximum and calculated average AC output powers do not follow a linear trend with an increasing ERS. At an ERS of 6, 16, and 18, the M215 outputs a maximum of 1.94-1.95 W of AC power. However, at other resistance settings, the M215 outputs a maximum power ranging from 13.37 W to 14.36 W.

Table 8-2 collects the data measured during the second 100 SPM trial. When comparing Table 8-2 to Table 8-1, the measured input voltages on oscilloscope 1

resemble those of trial 2, with one exception. The input voltage waveforms and measurements for an ERS of 2 differ greatly between the two trials. The second trial yields greater voltage measurements from the elliptical's output. In addition, the sense resistor in the second trial senses a much greater current flow into the DC-DC converter. Consequently, this implies a much greater input power to the CUI during the second trial than the first. Unlike the first trial, we cannot collect data when setting the elliptical resistance to 20 due to the M215 microinverter resetting after receiving too low of an input voltage from the CUI converter.

Comparing Table 8-1 with Table 8-2 also reveals differences between the recorded input currents and powers at a 100 SPM pace. For the first trial, the maximum voltage across the sense resistor tends to increase with the ERS. Consequently, the maximum current and power into the CUI increase linearly as well. However, this same trend with the sense resistor does not occur during the second trial of this test setup. In the second trial, the maximum voltage across the sense resistor equals 11.94 mV for a jogging pace of 100 SPM. In the second trial, the maximum voltage across the sense resistor increases to 12.66 mV with an ERS of 4, but then decreases down to 7.28 mW when setting the ERS to 10. The sense resistor sees a maximum voltage drop of 13.18 mV when setting the ERS to 16. Beyond this, the maximum sense resistor voltage drops down to 0.65 mV with an ERS of 18. Overall, the first trial saw an increasing trend with the maximum sense resistor voltage and input current, whereas the second trial saw more consistency with maximum sense resistor voltages measuring above 10 mV. In addition, the average current to the CUI measures a positive number for each resistance

during the first trial, but measures negative for the second trial starting at an ERS of 6. AC power output also differs between the two trials, but not as drastically.

Table 8-3 shows the small collection of data for full system testing with the CUI DC-DC converter and running at a pace of 150 SPM. For an ERS of 2, the elliptical produces a voltage below the threshold for input power diversion but produces 7.27 W of AC power. When increasing the ERS to 4, the input voltage increases and requires the OVPC to divert excess power. The input power and output power also increase. Compared to the first trial of data when running at a 100 SPM pace, running at a 150 SPM pace at low ERS produces an equivalent amount of input power when running at a 100 SPM paces at higher ERSs. Although a faster pace produces more power to the DC-DC converter's input, this doesn't mean an increase in efficiency. Table 8-3 shows the system produces AC power with 32.4% maximum efficiency for an ERS of 2 but this efficiency drops to 16.6% when increasing the ERS to 4. When increasing the resistance to 6, we encounter a problem of the M215 inverter resetting itself. The previous section of this report further discusses the issue in detail. No data collection occurs for resistance settings greater than 4 for a 150 SPM pace.

There exists a ringing that causes high frequency oscillations to occur on the IGBT's terminals. This ringing appears in the oscilloscope captures displaying either the gate or collector signals. The peaks in the oscillations have a frequency in the range of 36-37 kHz. This ringing occurs in all phases of elliptical testing, and may cause the fuses to break despite measuring currents below their maximum rating in this chapter. We further examine the ringing as we test in Chapter 8.3.1 and Chapter 8.3.2, where the ringing appears to increase in amplitude.

The OVPC refrains from diverting excess power from the CUI converter for a few resistance settings due to the input voltage not surpassing the voltage threshold for power diversion. Power diversion occurs at higher ERSs since these settings produce a sufficient input voltage from the elliptical to warrant overvoltage protection. Coincidentally, the minimum current across the sense resistor measures negative for the same resistance settings when the OVPC diverts excess power from the CUI. This suggests that power flows away from the DC-DC converter's input. The wiring diagram of Figure 8-2 shows the sense resistor in place between the output of the elliptical and node A. Rather than sensing the total current flowing into the CUI, the sense resistor helps with measuring the total current flowing into the CUI *and* OVPC. Since the OVPC has a voltage divider with resistors totaling to a nominal 170 kΩ, less than half of a milliamp of current flows into the OVPC and the rest into the DC-DC converter. For this reason, we assume the calculated current through the sense resistor equals the DC-DC converter input current. Due to the OVPC diverting power, a negative voltage across the sense resistor means current diverting from both the CUI and OVPC to the elliptical's resistor, and not just the minimum current into the CUI. Note that the minimum currents calculated through the sense resistor do not equal any of the calculated currents into the IGBT's collector. The calculated current into the IGBT's collector represents the total diverted current. Collector current includes the current diverted from the CUI converter, and current supplied by the elliptical while the OVPC diverts.

We initially intended to use the input voltage measurements from Oscilloscope 1, the minimum collector voltage, and the measured resistance of the diverting resistor when calculating the current through the diverting branch, and the dissipated power. The

difference between the maximum input voltage and minimum collector voltage over the measured diverting resistance yields the maximum current through the diverting resistor. Likewise, the difference between the minimum input voltage and minimum collector voltage over the diverting resistor yields the minimum current into the IGBT's collector. Lastly, the difference between the average input voltage and minimum collector voltage over the diverting resistor yields the minimum current into the IGBT's collector. Assuming the collector has an average minimum voltage of 1.0 V should yield more appropriate calculations than the actual measured minimum caused by a negative voltage transient spike. The minimum, maximum, and average powers the diverting resistor dissipates come from the product of squaring the value of the current through the resistor with its measured resistance. The next section details a similar full system testing, but including a Vicor DC-DC converter in place of the CUI.

Table 8-1: Data collected from first round of Full System testing with the CUI DC-DC converter, Enphase M215 microinverter, and an OVPC. Fields highlighted yellow represent recorded measurements while non-highlighted represent calculations. Target pace of runner = 100 SPM. Diverting resistor measures 9.85 Ω.

Full System Testing with CUI DC-DC Converter and Enphase M215 Inverter

Elliptical	Oscilloscope 1 Channel 1 (DC)				Oscilloscope 2 Channel 2 (DC)					OVPC Diverting - Calculate (DC)					
Restance Setting (ERS)	V_{IN} MIN (V)	V_{IN} PEAK (V)	V_{IN} AVG (V)	V_{IN} RMS (V)	V_c MIN (V)	V_c PEAK (V)	V_c AVG (V)	V_c RMS (V)	Does OVPC Divert?	I_{divert} MIN (A)	I_{divert} MAX (A)	I_{divert} AVG (A)	P_{divert} MIN (W)	P_{divert} MAX (W)	P_{divert} AVG (W)
2	18.0	31.6	25.6	24.8	18	35.6	25.2	21.8	NO	0	0	0	0	0	0
4	17.2	38.4	29.2	27.8	17.6	40.0	29.7	28.9	NO	0	0	0	0	0	0
6	53.2	59.2	56.7	55.2	0.8	64.0	55.1	55.8	YES	5.3	5.9	5.7	276.6	343.9	315.0
8	53.2	59.2	56.7	56.7	0.4	64.4	54.8	55.7	YES	5.3	5.9	5.7	276.6	343.9	315.0
10	52.8	59.2	56.7	56.6	0.4	66.0	52.8	55.1	YES	5.3	5.9	5.7	272.4	343.9	315.0
12	52.8	59.2	56.6	56.5	-1.2	64.8	52.8	54.5	YES	5.3	5.9	5.6	272.4	343.9	313.8
14	52.8	58.8	56.2	55.0	-0.8	68.8	44.2	50.6	YES	5.3	5.9	5.6	272.4	339.2	309.3
16	52.8	58.8	55.9	56.0	-1.0	63.6	41.3	48.5	YES	5.3	5.9	5.6	272.4	339.2	306.0
18	52.8	59.2	56.0	57.0	-2.8	65.2	41.0	47.0	YES	5.3	5.9	5.6	272.4	343.9	307.1
20	52.8	58.8	55.9	54.5	-4.4	63.2	37.0	45.6	YES	5.3	5.9	5.6	272.4	339.2	306.0

Elliptical	Agilent Multimeter (DC)			CUI Input Current & Power - Calculate (DC)						M215 Output - Power Meter (AC)						Efficiency	
Restance Setting (ERS)	V_{sense} MIN (mV)	V_{sense} MAX (mV)	V_{sense} AVG (mV)	I_{sense} MIN (A)	I_{sense} MAX (A)	I_{sense} AVG (A)	P_{in} MIN (A)	P_{in} MAX (A)	P_{in} AVG (A)	V_{out} MIN (V)	V_{out} MAX (V)	I_{out} MIN (mA)	I_{out} MAX (mA)	P_{out} MIN (W)	P_{out} MAX (W)	MIN (%)	MAX (%)
2	0.61	1.31	0.92	0.06	0.13	0.09	1.13	4.25	2.42	230.9	231.2	65.7	78.0	0.00	2.89	0.0	68.1
4	0.86	3.54	1.66	0.09	0.36	0.17	1.52	13.94	4.97	230.7	231.0	68.1	87.8	0.48	5.36	31.6	38.4
6	-3.59	2.15	0.33	-0.37	0.22	0.03	-19.59	13.05	1.92	230.3	231.0	0.0	74.5	0.00	1.94	0.0	14.9
8	-3.08	2.83	0.40	-0.32	0.29	0.04	-16.81	17.18	2.33	230.8	231.2	65.8	108.6	0.00	14.1	0.0	82.1
10	-2.28	5.34	0.35	-0.23	0.55	0.04	-12.35	32.42	2.04	230.7	231.1	65.8	103.0	0.00	13.63	0.0	42.0
12	-1.52	7.76	0.29	-0.16	0.80	0.03	-8.23	47.12	1.68	230.5	230.9	65.6	93.1	0.00	13.37	0.0	28.4
14	-0.59	11.08	0.26	-0.06	1.14	0.03	-3.20	66.82	1.50	229.8	230.7	65.6	102.6	0.00	14.36	0.0	21.5
16	-0.42	11.26	0.32	-0.04	1.15	0.03	-2.27	67.91	1.83	232.2	233.0	66.1	74.9	0.00	1.95	0.0	2.9
18	0.07	11.32	0.30	0.01	1.16	0.03	0.38	68.73	1.73	231.8	232.0	66.0	74.6	0.00	1.95	0.0	2.8
20	-0.11	16.72	0.30	-0.01	1.71	0.03	-0.60	100.83	1.72	231.7	232.3	65.9	160.8	0.00	13.41	0.0	13.3

Table 8-2: Data collected from second round of Full System testing with the CUI DC-DC converter, Enphase M215 microinverter, and an OVPC. Fields highlighted yellow represent recorded measurements while non-highlighted represent calculations. Target pace of runner = 100 SPM. Diverting resistor measures 9.85 Ω.

Full System Testing with CUI DC-DC Converter and Enphase M215 Inverter																	
Elliptical	Oscilloscope 1 Channel 1 (DC)				Oscilloscope 2 Channel 2 (DC)					OVPC Diverting - Calculate (DC)						Fluke MM (DC)	
Restance Setting (ERS)	V_{IN} MIN (V)	V_{IN} PEAK (V)	V_{IN} AVG (V)	V_{IN} RMS (V)	V_c MIN (V)	V_c PEAK (V)	V_c AVG (V)	V_c RMS (V)	Does OVPC Divert?	I_{divert} MIN (A)	I_{divert} MAX (A)	I_{divert} AVG (A)	P_{divert} MIN (W)	P_{divert} MAX (W)	P_{divert} AVG (W)	V_{DC-DC} MIN (V)	V_{DC-DC} MAX (V)
2	48.4	58.8	54.3	55.4	0.8	64.8	54.2	-	YES	4.8	5.9	5.4	228.1	339.2	288.4	27.62	27.79
4	18.4	41.6	31.5	32.7	14.0	44.4	30.4	32.0	NO	0	0	0	0	0	0	14.00	28.08
6	53.2	59.2	56.5	55.1	0.4	63.6	55.5	56.2	YES	5.3	5.9	5.6	276.6	343.9	312.7	8.05	27.70
8	52.8	59.2	56.4	56.5	0.4	61.6	54.6	55.4	YES	5.3	5.9	5.6	272.4	343.9	311.6	4.16	27.68
10	52.8	58.8	56.5	54.9	0.4	64.8	53.6	54.9	YES	5.3	5.9	5.6	272.4	339.2	312.7	4.70	27.67
12	52.8	58.8	56.2	56.3	-1.6	64.4	52.5	54.9	YES	5.3	5.9	5.6	272.4	339.2	309.3	5.31	27.69
14	52.4	58.4	55.8	55.8	-2.0	70.0	43.1	50.4	YES	5.2	5.8	5.6	268.2	334.5	304.9	10.70	27.67
16	52.4	58.4	55.8	56.0	-6.4	68.8	48.8	49.8	YES	5.2	5.8	5.6	268.2	334.5	304.9	3.74	27.70
18	52.4	58.4	55.7	56.6	-4.4	66.4	32.6	44.6	YES	5.2	5.8	5.6	268.2	334.5	303.8	3.76	27.68
20																	

Full System Testing with CUI DC-DC Converter and Enphase M215 Inverter																
Elliptical	Agilent Multimeter (DC)			CUI Input Current & Power - Calculate (DC)						Inverter Output - Power Meter (AC)						Efficiency	
Restance Setting (ERS)	V_{sense} MIN (mV)	V_{sense} MAX (mV)	V_{sense} AVG (mV)	I_{sense} MIN (A)	I_{sense} MAX (A)	I_{sense} AVG (A)	P_{in} MIN (A)	P_{in} MAX (A)	P_{in} AVG (A)	V_{out} MIN (V)	V_{out} MAX (V)	I_{out} MIN (mA)	I_{out} MAX (mA)	P_{out} MIN (W)	P_{out} MAX (W)	MIN (%)	MAX (%)
2	-15.73	11.94	0.15	-1.61	1.22	0.02	-78.09	72.01	0.84	231.6	231.8	65.6	73.1	0.00	1.28	0.0	1.8
4	-19.67	12.66	0.17	-2.02	1.30	0.02	-37.12	54.01	0.55	231.2	231.4	0.0	95.4	0.00	7.10	0.0	13.1
6	-18.65	12.48	-0.09	-1.91	1.28	-0.01	-101.76	75.79	-0.52	231.1	231.4	0.0	117.5	0.00	10.69	0.0	14.1
8	-18.87	11.54	-0.22	-1.94	1.18	-0.02	-102.19	70.07	-1.27	231.2	231.4	66.8	108.2	0.00	13.14	0.0	18.8
10	-9.85	7.28	-0.11	-1.01	0.75	-0.01	-53.34	43.90	-0.64	230.8	231.0	0.0	239.3	0.00	15.16	0.0	34.5
12	-4.34	11.22	-0.10	-0.45	1.15	-0.01	-23.50	67.67	-0.55	231.0	231.2	67.2	111.1	0.00	14.60	0.0	21.6
14	-0.62	10.79	-0.09	-0.06	1.11	-0.01	-3.33	64.63	-0.49	231.1	231.2	67.3	106.8	0.00	16.77	0.0	25.9
16	-1.65	13.18	-0.08	-0.17	1.35	-0.01	-8.87	78.94	-0.48	230.9	231.2	67.2	94.6	0.00	17.38	0.0	22.0
18	-2.05	0.65	-0.87	-0.21	0.07	-0.09	-11.02	3.89	-4.97	230.7	230.9	67.2	67.3	0.00	0.00	0.0	0.0
20																	

Table 8-3: Data collected from second round of Full System testing with the CUI DC-DC converter, Enphase M215 microinverter, and an OVPC. Fields highlighted yellow represent recorded measurements while non-highlighted represent calculations. Target pace of runner = 150 SPM. Diverting resistor measures 9.85 Ω.

Full System Testing with CUI DC-DC Converter and Enphase M215 Inverter

Elliptical	Oscilloscope 1 Channel 1 (DC)				Oscilloscope 2 Channel 2 (DC)					OVPC Diverting - Calculate (DC)						Fluke MM (DC)	
Restance Setting (ERS)	V_{IN} MIN (V)	V_{IN} PEAK (V)	V_{IN} AVG (V)	V_{IN} RMS (V)	V_c MIN (V)	V_c PEAK (V)	V_c AVG (V)	V_c RMS (V)	Does OVPC Divert?	I_{divert} MIN (A)	I_{divert} MAX (A)	I_{divert} AVG (A)	P_{divert} MIN (W)	P_{divert} MAX (W)	P_{divert} AVG (W)	V_{DC-DC} MIN (V)	V_{DC-DC} MAX (V)
2	18.8	38.8	29.9	31.7	17.2	44.0	29.9	33.6	NO	0	0	0	0	0	0	27.62	27.79
4	51.2	58.8	55.9	56.3	0.4	68.0	54.8	55.6	YES	5.1	5.9	5.6	255.8	339.2	306.0	14.00	28.08
6																	
8																	
10																	
12																	
14																	
16																	
18																	
20																	

Elliptical	Agilent Multimeter (DC)			CUI Input Current & Power - Calculate (DC)						Inverter Output - Power Meter (AC)						Efficiency	
Restance Setting (ERS)	V_{sense} MIN (mV)	V_{sense} MAX (mV)	V_{sense} AVG (mV)	I_{sense} MIN (A)	I_{sense} MAX (A)	I_{sense} AVG (A)	P_{in} MIN (A)	P_{in} MAX (A)	P_{in} AVG (A)	V_{out} MIN (V)	V_{out} MAX (V)	I_{out} MIN (mA)	I_{out} MAX (mA)	P_{out} MIN (W)	P_{out} MAX (W)	MIN (%)	MAX (%)
2	-13.40	5.63	-0.11	-1.37	0.58	-0.01	-25.84	22.42	-0.34	230.7	230.8	67.1	95.2	0.00	7.27	0.0	32.4
4	-10.59	10.54	-0.11	-1.09	1.08	-0.01	-55.61	63.56	-0.63	230.6	230.9	0.0	123.5	0.00	10.55	0.0	16.6
6																	
8																	
10																	
12																	
14																	
16																	
18																	
20																	

Maximum efficiency refers to the ratio of the maximum power output to the maximum input power. Comparing the maximum efficiency columns for both trials at a 100 SPM pace shows few similarities. Figure 8-14 below plots the maximum efficiency calculations of collected data for each set elliptical resistance. The two trials at a 100 SPM pace have similar efficiency calculations for set resistance levels of 6, 10, 12, 14, and 18. The first test trial starts with a maximum efficiency calculation of 68.1% for an ERS of 2, but then trends down to 14.9% when increasing the ERS to 4. When setting the ERS to 8, the calculated maximum efficiency jumps to 82.1%. When testing for higher resistance settings, the efficiency declines to calculations of 2.9% and 2.8% for resistance settings of 16 and 18. Unlike the first trial, the second test trial starts with a lower maximum efficiency calculation of 1.8% for an ERS of 2. The maximum efficiency calculation increases with an increasing ERS up to an ERS of 10 where the maximum efficiency calculates to 34.5%. Increasing the ERS further then lowers the maximum efficiency calculation within the range of 21.6% to 25.9%. The maximum efficiency calculations for the second trial drops to 0% at an ERS of 18 due to the lack of an AC output power measurement greater than 0 W. Figure 8-14 also includes the two data points from testing with a 150 SPM elliptical pace. Due to complications with the M215 inverter resetting, the figure lacks data points for efficiency calculations at other resistance settings for a 150 SPM pace.

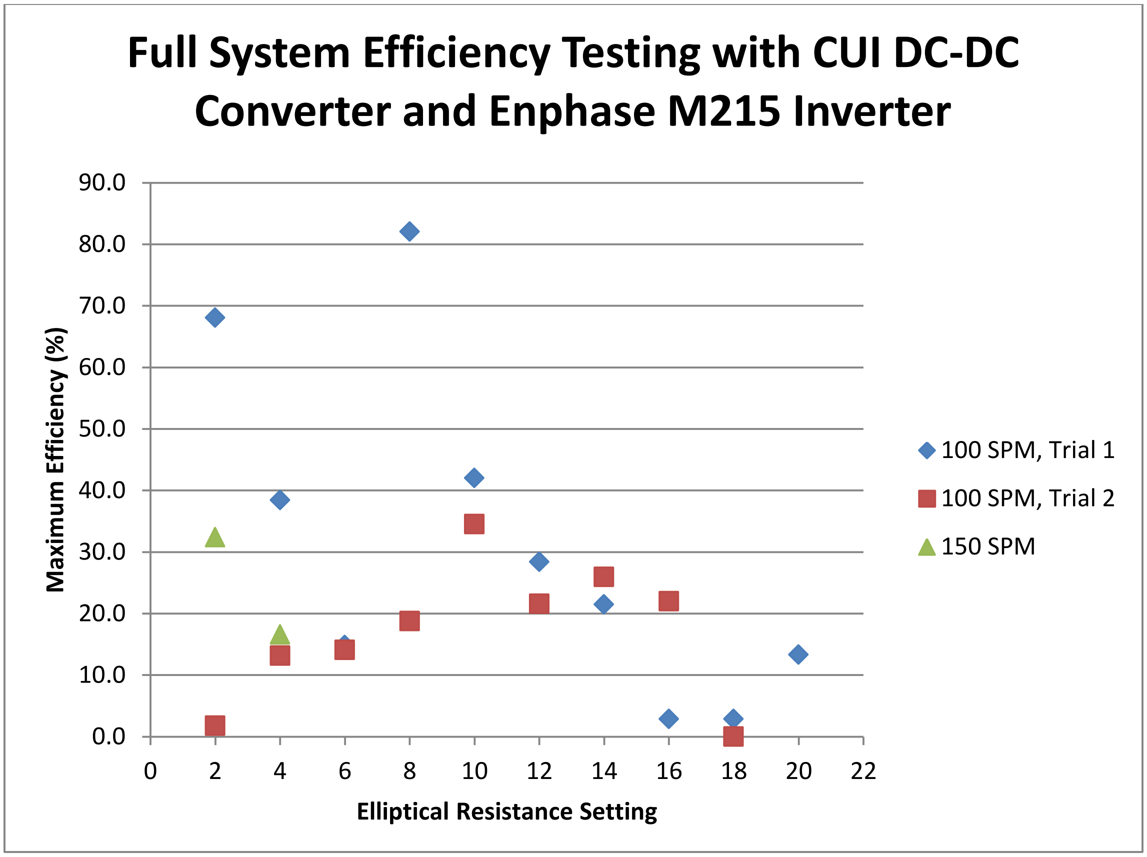

Figure 8-14: Scatter plot shows the efficiencies for full system testing with the CUI DC-DC converter and Enphase M215 inverter. Plot includes efficiencies calculated from the ratio of maximum output power to maximum input power. The three sets of data come from the two trials of testing with a 100 SPM pace, and a 150 SPM pace on the Precor elliptical.

8.3 Full System Testing with Vicor DC-DC Converter and M215 Inverter

After testing the CUI DC-DC converter and M215 inverter, we conduct similar testing with the M215 inverter with the Vicor DC-DC converter. Because prior testing with the CUI ended in the malfunction of the CUI, we acquire fuses to protect the Vicor. A fuse rated for 5 A protects the Vicor's input while a fuse rated for 8 A ensures overcurrent protection between the Vicor and M215 inverter.

The Vicor converter also has slightly different OVPC than the one used to protect the CUI. Comparing Figure 8-15 below with Figure 8-1 in section 8.2 shows the Vicor has a different voltage divider used to scale down the voltage for the LT1017 comparator. Prior testing in Chapter 5 shows the OVPC designed for the Vicor converter diverts

power when the input voltage surpasses 27.4 V and ceases diverting power when the voltage reduces to 22.5 V.

We intend to follow a similar procedure of collecting data as before by starting with a 100 SPM pace and a set elliptical resistance of 2. Unlike testing in Chapter 7, we have an additional multimeter measuring the output voltage of the Vicor DC-DC converter. We expect the inverter to convert DC power into AC while someone runs on elliptical. Power diversion may not occur if the DC-DC converter outputs an insufficient voltage. While the CUI can supply a sufficient output voltage to power the M215 in most cases, the Vicor may not. Therefore, testing includes a multimeter to measure the Vicor's voltage output. Regarding the data table, we add three columns to record the MIN, MAX, and AVG voltages measured from the Vicor.

Figure 8-16 depicts a wiring diagram that corresponds with the circuit diagram of Figure 8-15. Refer to Appendix B.8 for details about the necessary equipment and steps for setting up and conducting the test. The following sections detail the results from this phase of testing.

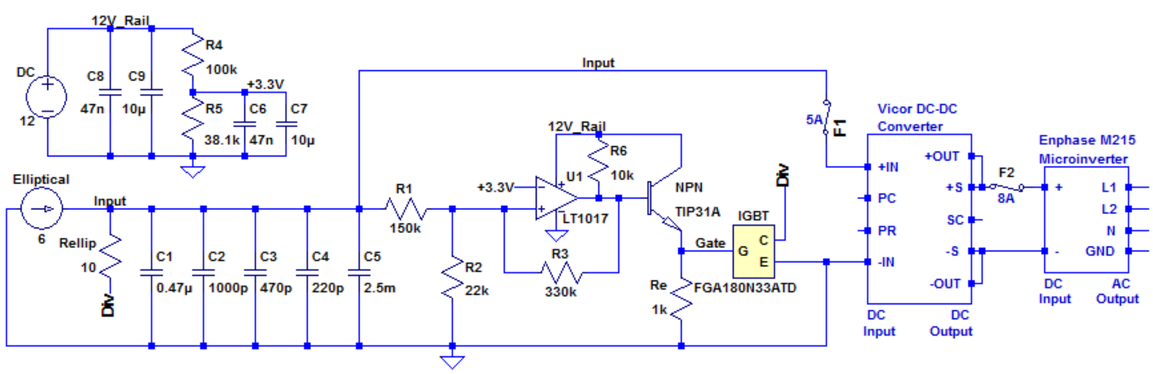

Figure 8-15: Circuit Diagram for an Elliptical test session involving Precor elliptical machine, Vicor DC-DC converter, and Enphase M215 microinverter.

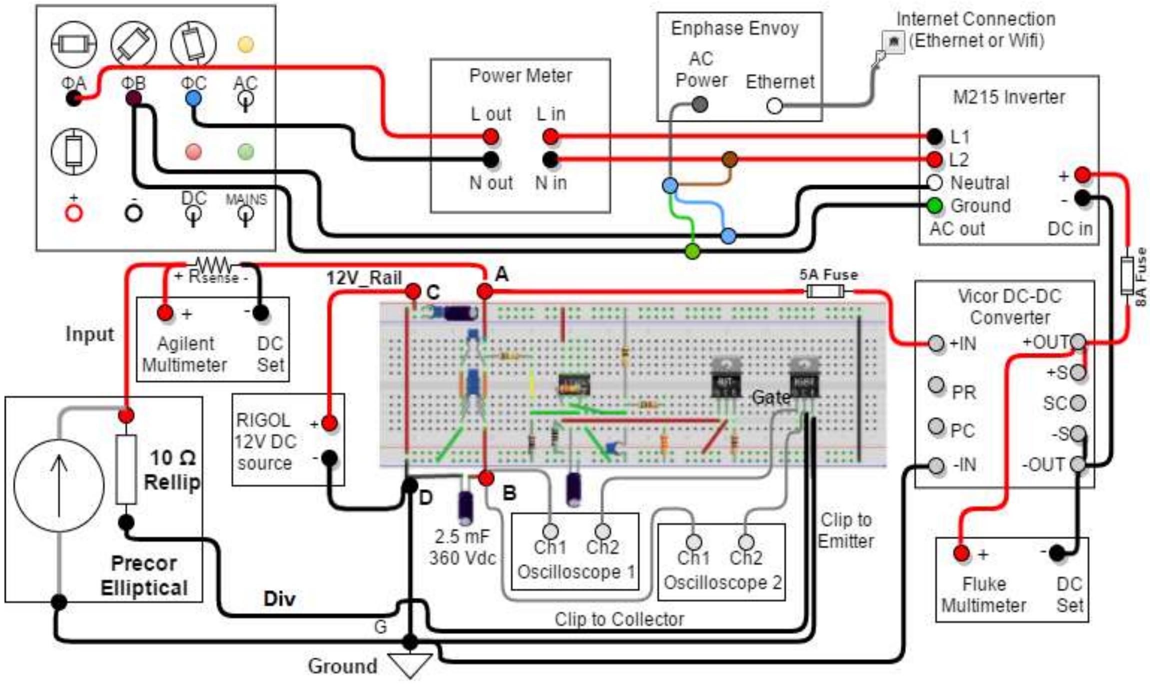

Figure 8-16: Wiring Diagram of a full system test including the Precor elliptical, Vicor DC-DC converter, and Enphase M215 inverter.

8.3.1 100 SPM Pace

The Vicor DC-DC converter behaves differently than the CUI at low resistances. Figure 8-17 shows the oscilloscope captures of the elliptical output voltage as well as the IGBT's gate and collector signals for an ERS of 2 and a pace of 100 SPM. Note the signal on the IGBT's gate experiences frequent oscillation of a few volts from ground. These spikes in the signal do not indicate a sufficient or sustained gate voltage to activate the IGBT. The collector signal waveform shows less oscillation in voltage magnitude, and does not indicate a significant deviation from the input signal towards 0 V. This denies an occurrence of the OVPC diverting excess power. In addition, Figure 8-17 measures a maximum input voltage of 12 V, well below the OVPC's input voltage threshold of 27.4 V.

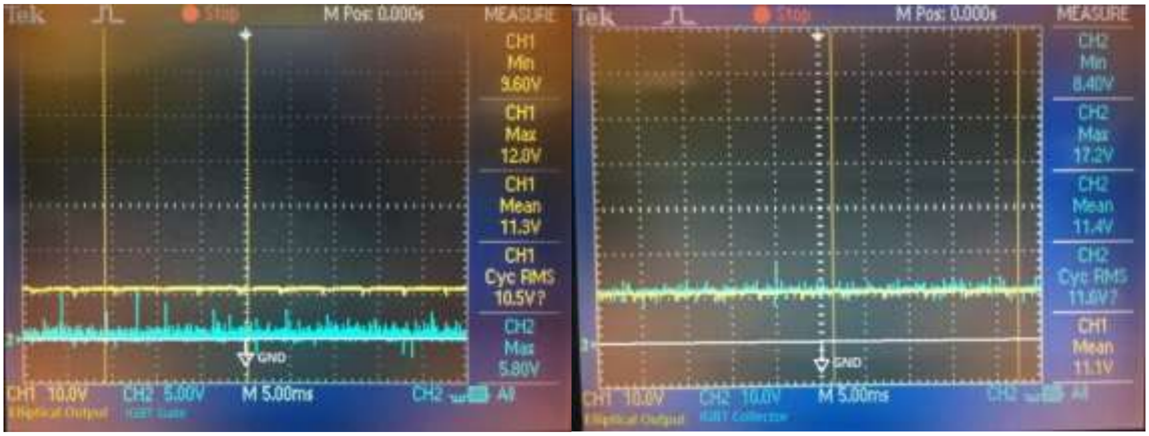

Figure 8-17: Oscilloscope capture of input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 2, 100 SPM

Figure 8-18 depicts the same oscilloscope capture of Figure 8-17, but with a smaller time scales. The right oscilloscope reveals a pattern of the input waveform quickly dip and rise to a level voltage. The frequency between dips in the input waveform measures 211.9 Hz. Since the input waveform does not experience an increasing and decreasing voltage due to the IGBT, the switching that occurs within the Vicor DC-DC converter must influence the source voltage we observe. The left oscilloscope capture in Figure 8-18 measures a frequency of 31.85 kHz at which transient voltage spikes appear on the IGBT’s gate. Testing in Chapter 5.3.4 measures the IGBT’s gate response time on the order of a couple hundred microseconds. The IGBT has a slower response time than the duration of the transient spike, so these spikes should not cause the IGBT to divert power. With a smaller time scale, the high frequency oscillation on the IGBT’s gate appears as a faint ringing. Although not measured in Figure 8-18, the IGBT’s collector terminal experiences the same ringing as the gate terminal.

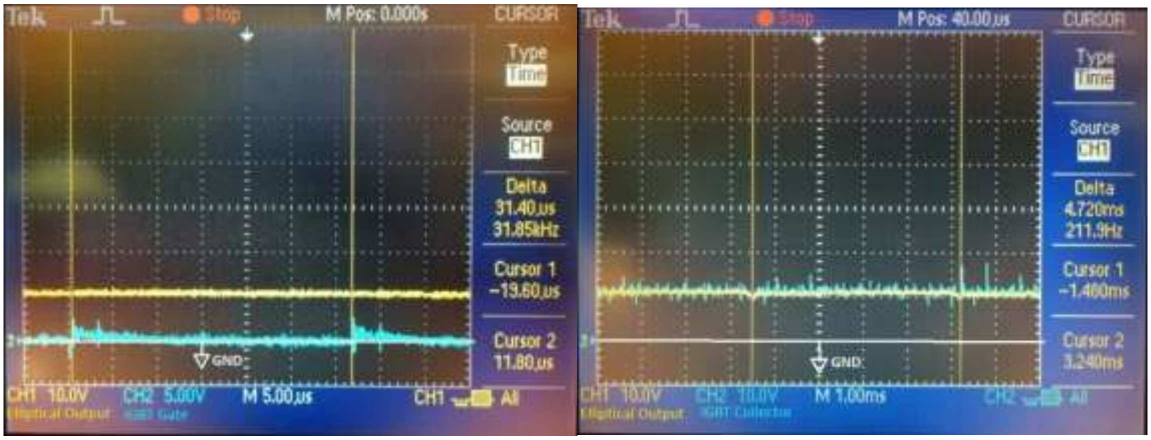

Figure 8-18: Oscilloscope capture of input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance Setting = 2, 100 SPM

In the couple of minutes that pass, the Vicor never outputs a sufficient voltage to power the M215 inverter. Thus, the power measures 0 W of AC power generated. After finishing collecting data, we increase the elliptical resistance to 4, and prepare to collect more data.

For a resistance setting of 4 and a 100 SPM pace, the M215 inverter's LED starts blinking green after about 90 seconds. The Fluke multimeter measures a voltage at the Vicor's output ranging from 19.56 V to 22.72 V. Despite the M215 flashing green, the inverter does not output AC power. A faint high frequency buzzing emanates from the Vicor, similar to when testing the efficiency of the Vicor converter in Chapter 4.2.

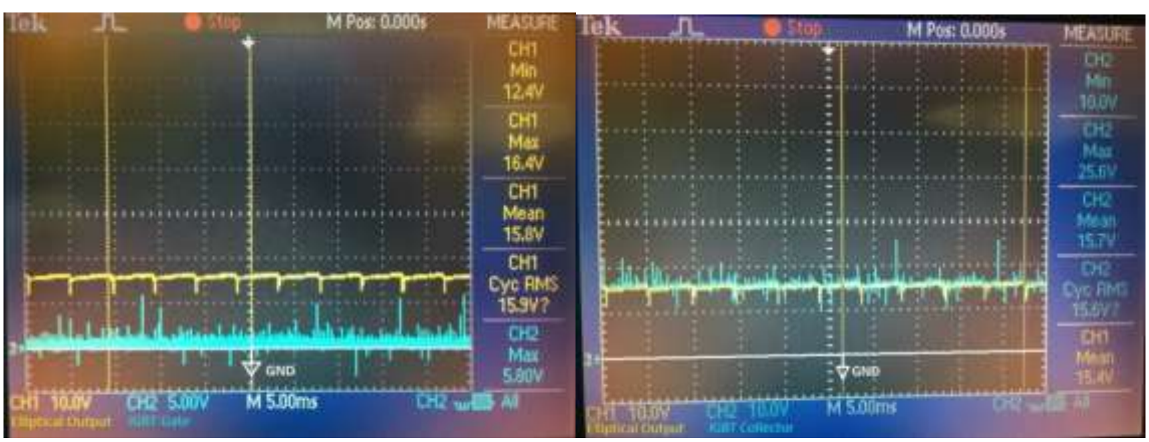

Figure 8-19: Oscilloscope capture of input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 4, 100 SPM

Figure 8-19 shows oscilloscope captures of the elliptical output signal as well as the IGBT's gate and collector signals for this test setting. Comparing the waveforms of Figure 8-19 to Figure 8-17 reveals more fluctuation in the voltage signals, especially with the elliptical output and IGBT collector voltage. Similar to Figure 8-17, the collector signal not dropping to 0 V in Figure 8-19 indicates no power diversion through the IGBT.

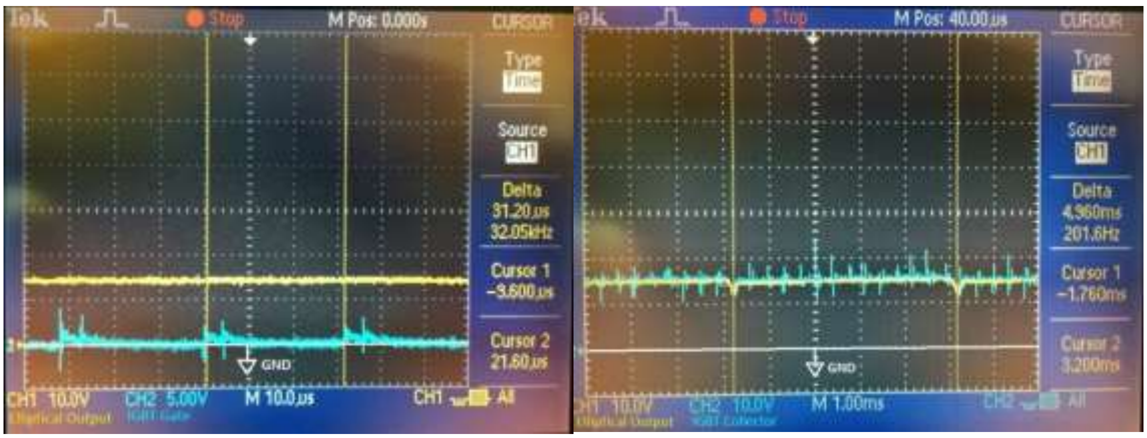

Figure 8-20: Oscilloscope capture of input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 4, 100 SPM

Decreasing the timescale of the oscilloscope captures in Figure 8-19 to 10 µs per division and 1 ms per division yields the waveforms in Figure 8-20. In the right image, we again observe the pattern of the input waveform quickly dipping and rising to a level voltage. The frequency in dips measures 201.6 Hz, close to the measured frequency with an ERS of 2. Again, the switching that occurs within the Vicor DC-DC converter must influence the source voltage. In the left image, the frequency between transient spikes on the IGBT gate signal also measures closely to the previous test at 32.05 kHz.

Moving on, the elliptical resistance level steps up to 6. The elliptical voltage still stays below the OVPC's threshold, but the M215 inverter generates AC power. The waveform of the elliptical voltage, seen in Figure 8-21, shows an input voltage waveform

with a more prominent rise and decline. This pattern correlates to the Vicor converter supplying a sufficient output voltage for the M215 inverter to convert into AC power.

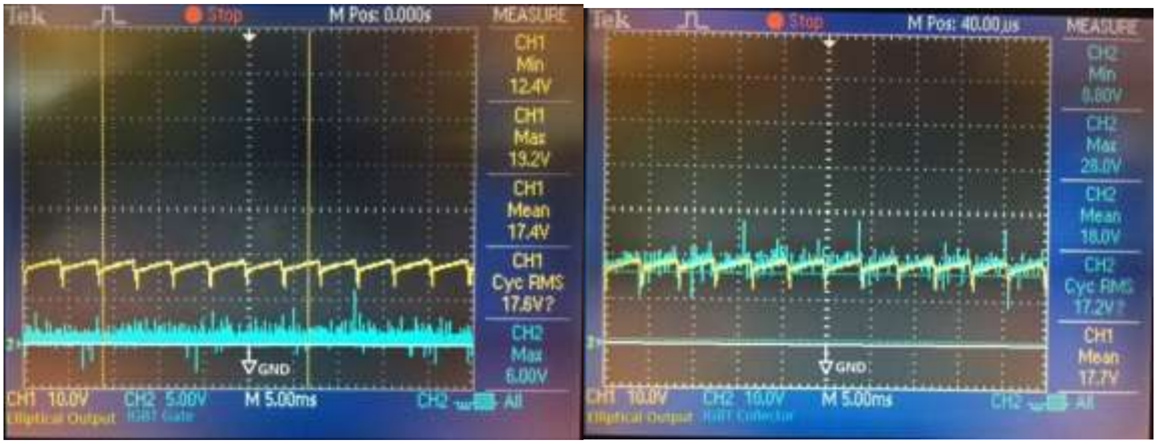

Figure 8-21: Oscilloscope capture of elliptical output voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 6, Pace = 100 SPM

Figure 8-22 shows the same waveforms of Figure 8-21 with smaller time scales. The left picture has a time scale of 5 μs per division and measures a 31.65 kHz frequency in peak voltage spikes of the IGBT's gate. Likewise, the right picture has a time scale of 1 ms per division to measure a 225.2 Hz frequency between the dips observed on the elliptical output voltage. These measurements show little change from the frequency measurements in Figure 8-18 and Figure 8-20. With the elliptical set to a higher resistance, the ringing on the IGBT's terminals appears to increase in magnitude.

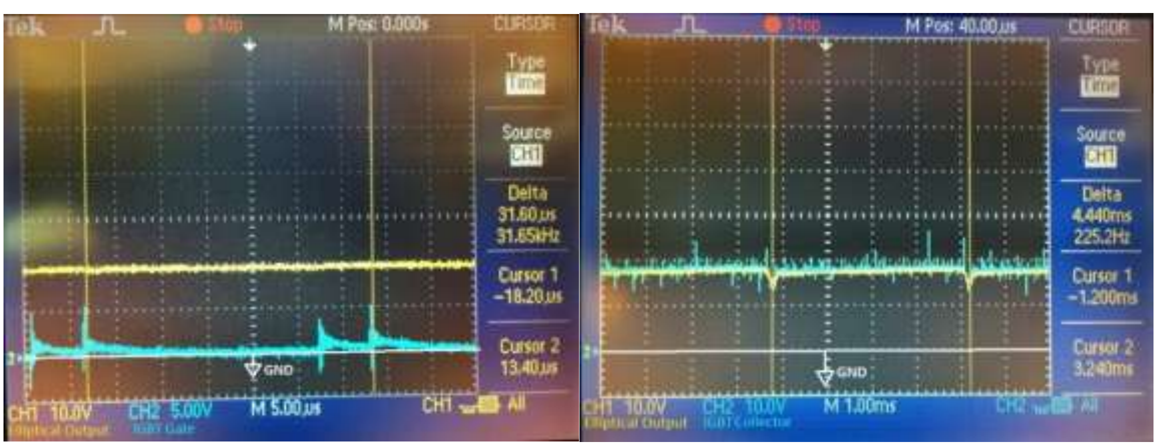

Figure 8-22: Oscilloscope capture of elliptical output voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 6, Pace = 100 SPM

After collecting data for resistance level 6, we increase the elliptical resistance to 8. At this setting, the OVPC diverts excess power from the Vicor DC-DC converter. The sound of the DC-DC converter's high pitched buzzing increases in volume at this resistance. Figure 8-23 illustrates power diverting through the IGBT. The gate signal in the left picture periodically pulls to 12 V when the input voltage reaches a measured maximum of 27.6 V as expected. During that time, the collector signal waveform on the right picture periodically deviates from the source voltage to having an average voltage just above ground. The collector and gate waveforms still experience oscillations in their signals despite the elliptical output having a smoother waveform at 10 ms per division and 25 ms per division. Notice the gate signal fails to sustain a 12 V average signal for the full duration that the elliptical output voltage decreases.

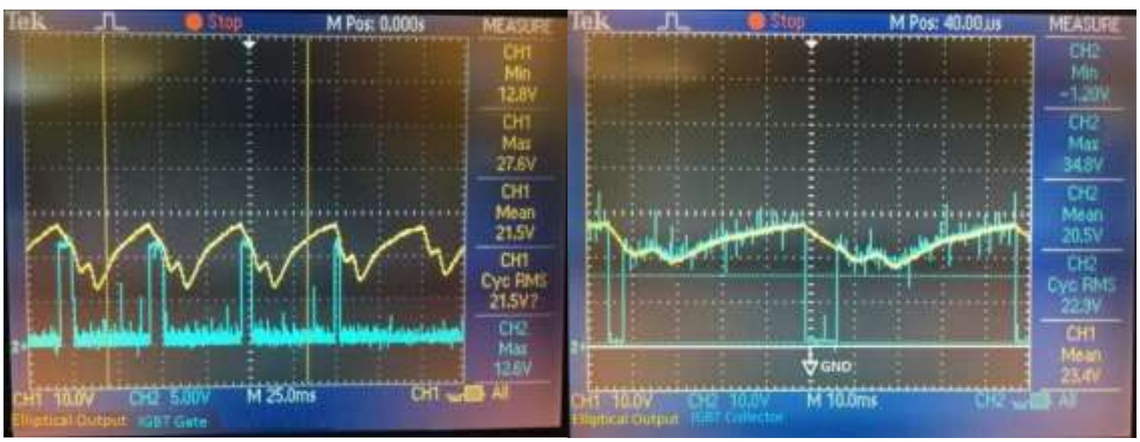

Figure 8-23: Oscilloscope capture of elliptical output voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 8, Pace = 100 SPM

Figure 8-24 shows the same waveforms of the right oscilloscope capture in Figure 8-23 but using cursors to measure a few points of interest. The left picture measures an average collector voltage of 0.8 V. While this does not equate to the minimum collector voltage observed in Figure 8-23, an average voltage of about 0.8 V measures about 0.3 V less than the typical collector-to-emitter saturation voltage [19].

The oscilloscope capture on the right includes cursor measurements showing the input voltage levels that start and end power diversion. The oscilloscope shows the OVPC diverts power around 27.6 V and ceases when the voltage drops below 22.4 V. This matches closely with the voltages obtained when testing the efficiency of the Vicor's OVPC in Chapter 5.2.2. Even after the OVPC ceases to divert excess power, the voltage into the DC-DC converter still decreases, then increases slightly and decreases again before rising towards 27.6 V again.

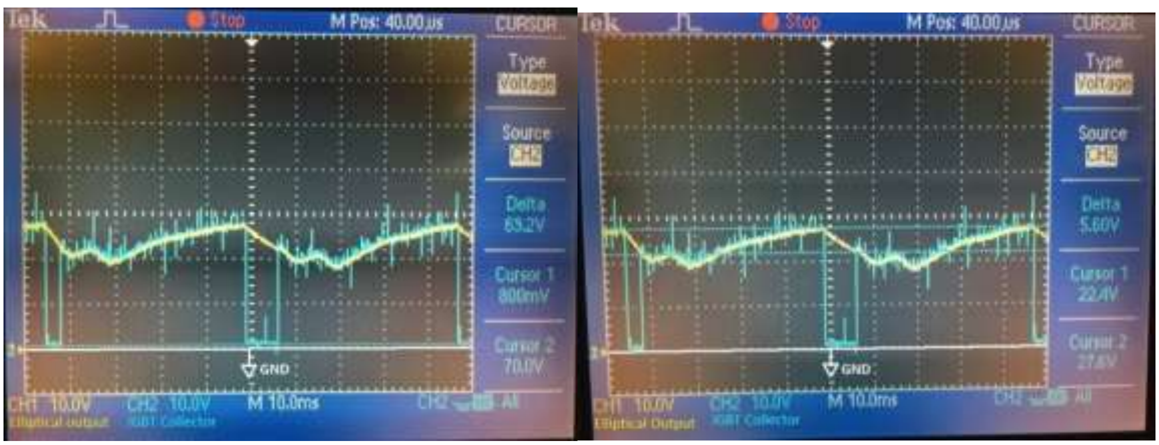

Figure 8-24: Oscilloscope capture of elliptical output voltage (yellow) and IGBT collector voltage (blue). The left picture shows average measurement of IGBT collector voltage when IGBT diverts power. The right picture measures the input voltage when IGBT starts and stops diverting power. Elliptical Resistance = 8, Pace = 100 SPM

As we increase the elliptical resistance to 10, the system continues to produce AC power. The noise coming from the DC-DC Converter soon turns into click-like beeping noises. About 30 seconds later the DC-DC converter stops making noise and the microinverter ceases AC power production. The Fluke measures about 3.3 V on the Vicor's output, which leads to checking the fuses and finding a blown 5 A fuse. The blown fuse leaves hinders data collection for this resistance level and beyond when running with a 100 SPM pace. However, the Agilent multimeter measures a maximum of 33.7 mV across the sense resistor, which calculates to 3.46 A of current flowing into the

Vicor. So despite the sense resistor sensing a maximum 3.46 A of current, testing still manages to break a protective 5 A rated fuse.

How the Vicor behaves when powered by the Precor elliptical may cause the fuse to break. In Table 8-4, the Vicor receives a maximum input power of about 95 W at an ERS of 10, and the oscilloscope measures a maximum input voltage of 27.6 V. If the Vicor attempts to maintain receiving that amount of power, then a decrease in supplied voltage to the DC-DC converter causes the Vicor to pull more current from its power source. A voltage drop down to the minimum supplied voltage of 18.0 V means the Vicor converter would receive about 5.3 A of supplied current, which exceeds the fuse's 5 A rating. Full system testing with the Vicor DC-DC converter shows the EHFEM project needs a DC-DC converter with a superior operating range than the Vicor offers. The EHFEM system needs a DC-DC converter than can operate at lower input voltages than the Vicor allows, and receive input currents exceeding 5 A or more.

For calculating values such as the current into the IGBT's collector and the power the diverting resistor dissipates, we intended to use the same method when testing with the CUI and M215. For calculations, this method assumes the collector voltage equals the measured elliptical output voltage when the IGBT switches. This method also assumes a minimum collector voltage of 1.0 V when calculating the currents and powers through the diverting resistor. This should yield more accurate calculations than oscilloscope measurements containing transient spikes. When testing with the Vicor DC-DC converter and M215, this method proves inaccurate. This method suffices for testing with the CUI DC-DC converter and M215 inverter, because the source voltage no longer decreases in magnitude after the OVPC ceases diverting power. However, the oscilloscope captures in

Figure 8-24 show the input voltage continues to decrease even after the IGBT turns off and power diversion ceases. Therefore, what the oscilloscope measures as the minimum elliptical output voltage does not equal the collector voltage observed when the IGBT turns off. For this reason, we decide that collector voltage measurements use a cursor to measure the collector voltage at the moment the OVPC stops diverting excess power.

8.3.2 150 SPM Pace

Increasing the pace of the runner on the elliptical to 150 SPM produces similar results as when running at a 100 SPM pace. At a resistance setting of 2, the waveforms in Figure 8-25 feature similar patterns as the oscilloscope captures in Figure 8-17. The Vicor DC-DC converter elicits a faint high frequency buzzing. Both gate and collector terminals of the IGBT experience high frequency transients on their terminals while no power diversion through the elliptical's 10 Ω resistor occurs. Meanwhile the elliptical output voltage appears mostly DC, but periodically has a short dip and rise in its signal. Comparing Figure 8-25 with Figure 8-17 also shows the average input voltage increases with the pace of the runner. The Vicor's maximum voltage output measures 19.36 V. Even while running at a 150 SPM pace, the inverter cannot produce AC power with the elliptical resistance set to 2.

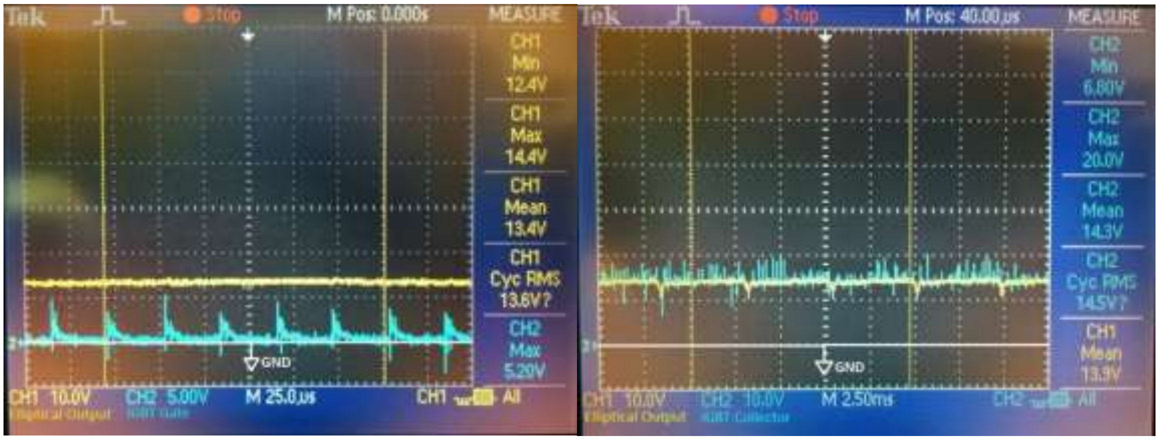

Figure 8-25: Oscilloscope capture of elliptical output voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 2, Pace = 150 SPM

Figure 8-26 captures the same voltage signals in Figure 8-25 using smaller time scales for more accurate frequency measurements. The frequency of the peak oscillations that appear on the IGBT's gate measure 31.85 kHz, and the frequency between dips on the input voltage measure 206.6 Hz. These frequencies measure closely to previous measurements when testing with a 100 SPM pace. The frequent ringing oscillations and dips do not vary with the runner's pace.

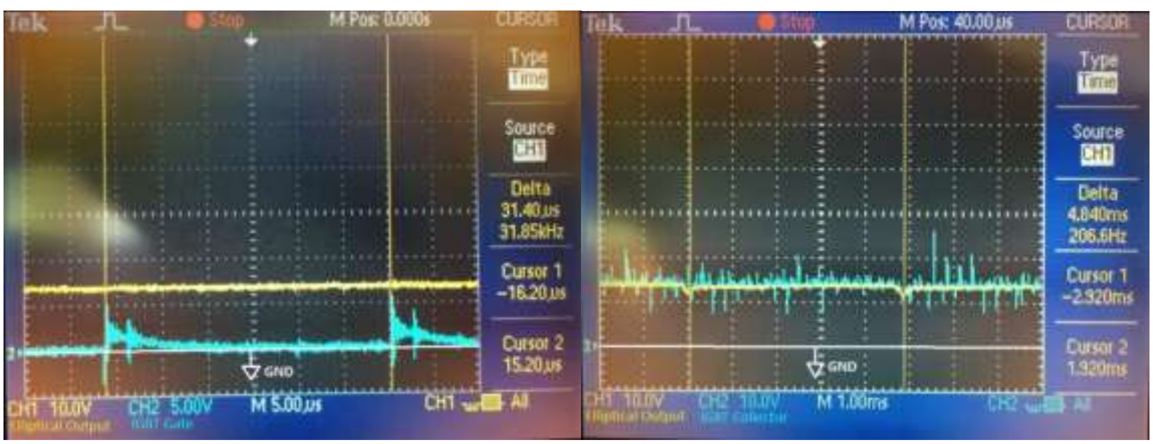

Figure 8-26: Oscilloscope capture of elliptical output voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 2, Pace = 150 SPM

When increasing the elliptical resistance to 4, the Vicor outputs a sufficient voltage for the microinverter to generate AC power. The elliptical produces an output voltage that, when sent to the Vicor, mimics the waveforms of Figure 8-19 and

Figure 8-21. As the system continues to produce AC power, the input voltage never surpassed the OVPC's voltage threshold for power diversion. Figure 8-27 shows a lack of a gate signal sustaining a 12 V signal and the collector signal failing to descend to a near-ground level voltage.

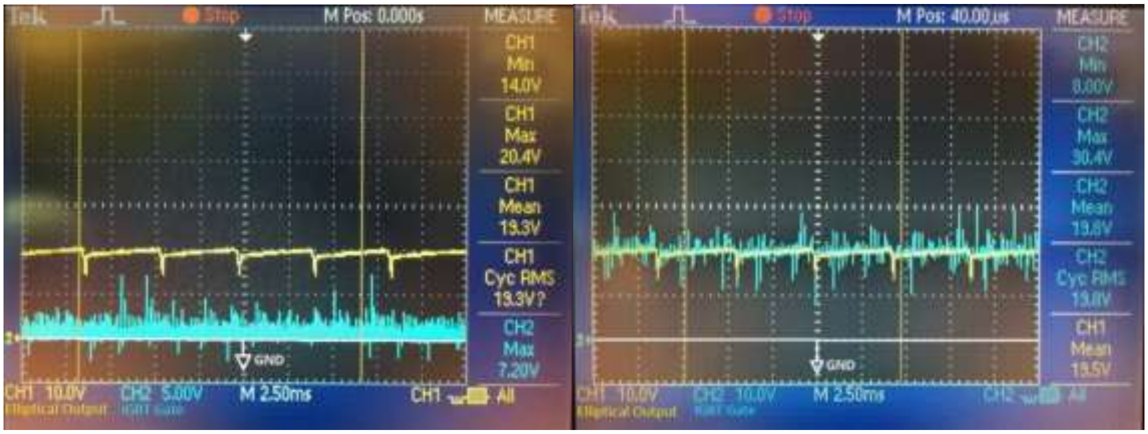

Figure 8-27: Oscilloscope capture of elliptical output voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 4, Pace = 150 SPM

Frequency measurements in Figure 8-28 show a familiar trend. The peak oscillating points on the IGBT's gate signal continue to have a frequency ranging between 31 kHz and 32 kHz. Likewise, the elliptical output voltage sees a switching frequency in the range of 200 Hz to 230 Hz.

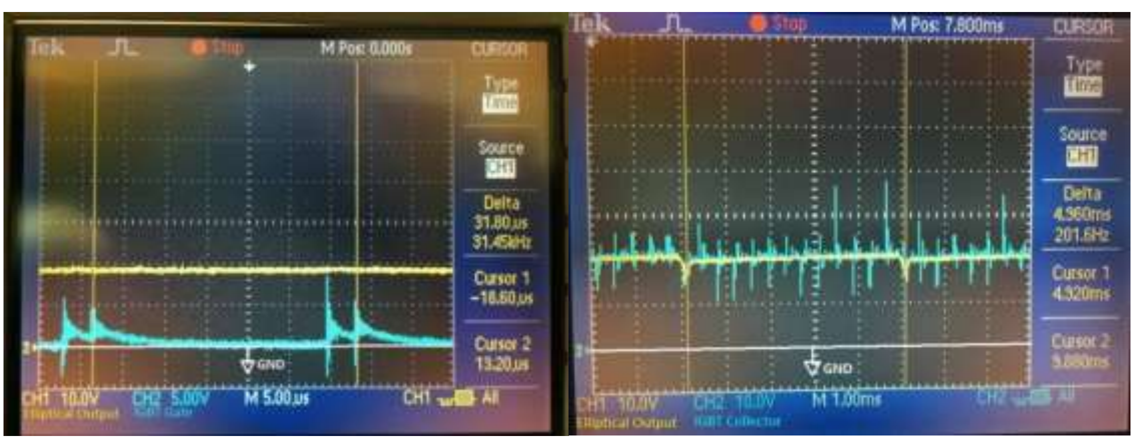

Figure 8-28: Oscilloscope capture of elliptical output voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Oscilloscope cursors measure the frequency between peaks of ringing oscillations on the IGBT as well as the frequency in dips on the Input Voltage. Elliptical Resistance = 4, Pace = 150 SPM

When increasing the elliptical resistance setting to 6, the M215 inverter outputs AC power and the OVPC diverts excess elliptical power. The sound coming from the Vicor slightly increases in volume. The waveforms in Figure 8-29 confirm power diversion. The gate signal's DC voltage level in the left picture increases to 12 V when in the input waveform decreases. At the same time, the collector voltage in the right picture decreases to a near-ground level DC voltage. The periodic dip and rise in input voltage no longer appears when the OVPC diverts power. Even with the OVPC diverting power, ringing still occurs on the IGBT gate and collector signals. The right oscilloscope capture shows a maximum collector voltage of 41.2 V due to a high frequency transient despite the elliptical output voltage still showing no such spike.

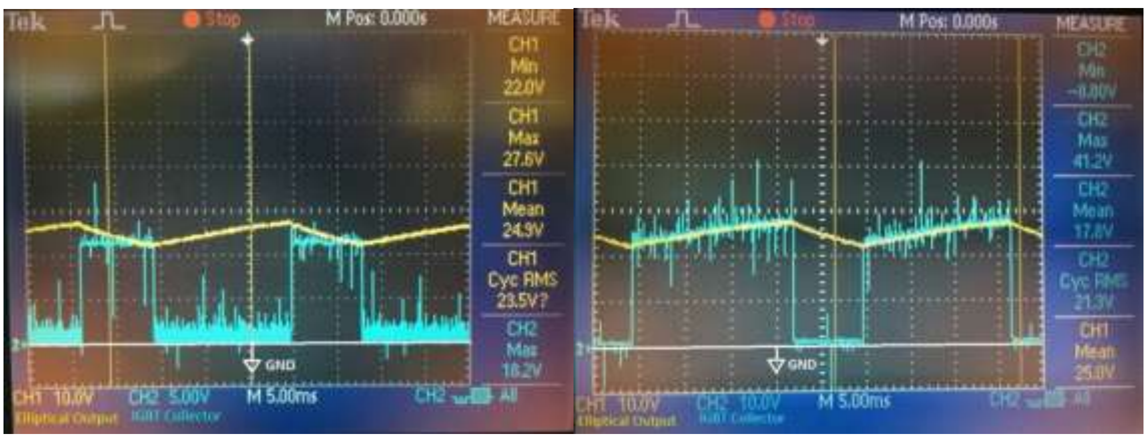

Figure 8-29: Oscilloscope capture of elliptical output voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 6, Pace = 150 SPM

Figure 8-30 features oscilloscope measurements that measure the minimum DC-level voltage of the IGBT, and the input voltage levels when the IGBT starts and stops diverting power. Unlike similar waveforms in Figure 8-24, the elliptical output voltage only decreases when the OVPC diverts excess power. Cursor 2 in the left oscilloscope capture measures an average minimum collector voltage of 1.2 V, about 0.4 V greater than the measurement in Figure 8-24. The cursors in the right picture of Figure 8-30

measure a maximum input voltage of 27.6 V and a minimum input voltage of 22.0 V. These equal the oscilloscope measurements in the left capture of Figure 8-29, and closely match the cursor measurements in Figure 8-24.

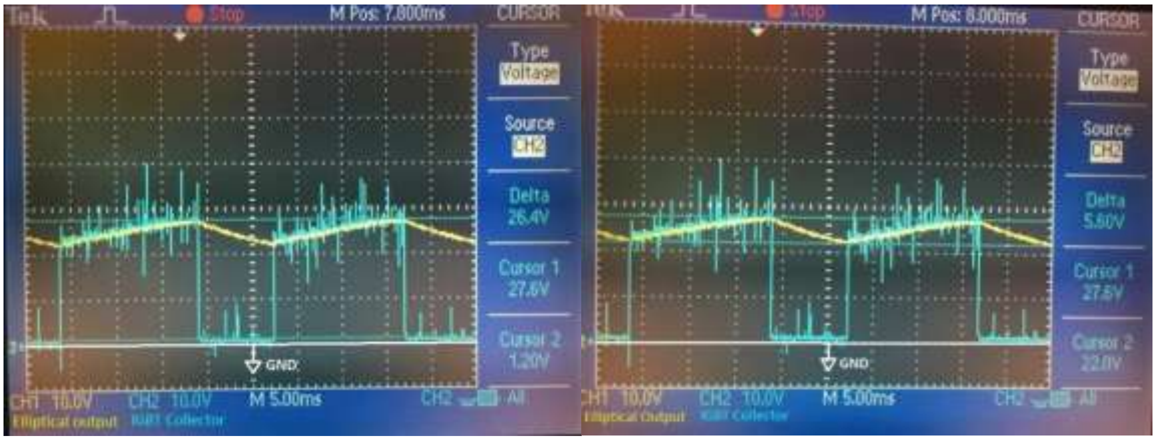

Figure 8-30: Oscilloscope capture of elliptical output voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 6, Pace = 150 SPM

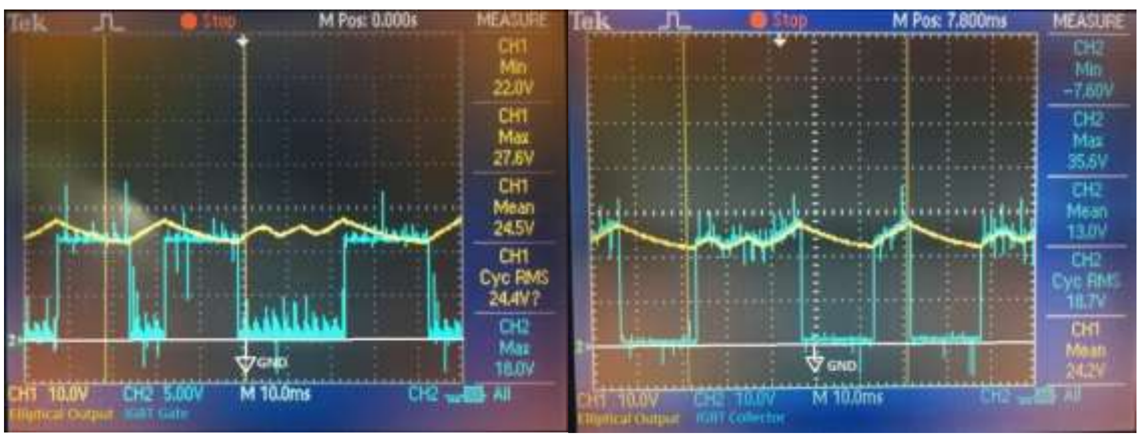

Figure 8-31: Oscilloscope capture of elliptical output voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 8, Pace = 150 SPM

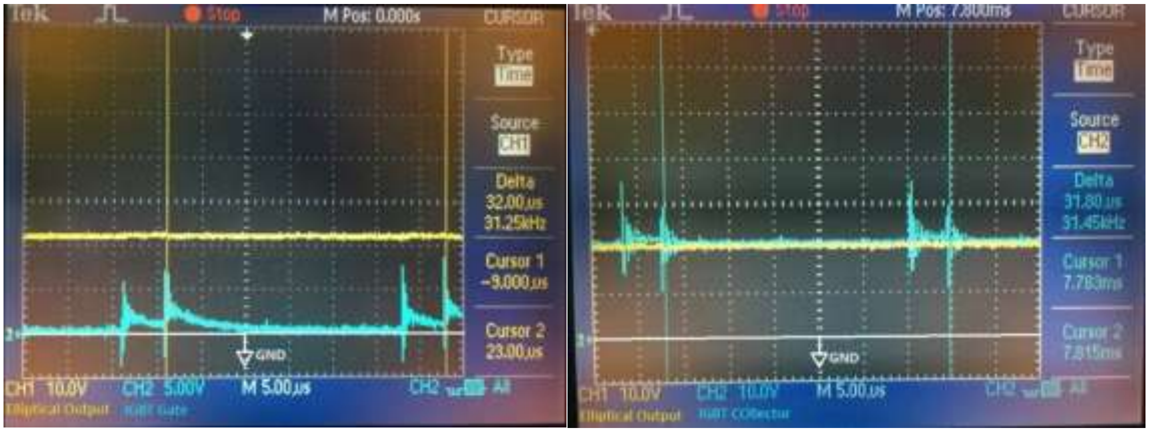

Figure 8-32: Oscilloscope capture of elliptical output voltage (yellow) and IGBT collector voltage (blue). Elliptical Resistance = 8, Pace = 150 SPM

After increasing the resistance setting to 8, the system continues to generate AC power, and the OVPC continues to divert excess power. Figure 8-31 shows the input voltage achieves a maximum of 27.6 V as the IGBT's gate signal pulls high, reducing the input voltage until the input voltage reduces to 22.0 V. Figure 8-32 compares the ringing signals occurring on the gate and collector. The oscilloscopes measure similar frequencies between transient spikes within the range of 31 kHz to 32 kHz. These appear similar to the gate and collector frequency measurements at lower elliptical resistances. Neither running pace, elliptical resistance, nor whether the OVPC diverts power directly causes the ringing.

Figure 8-33 measures the minimum and maximum elliptical output voltage and average minimum collector voltage when the OVPC diverts power. The scope captures show voltage measurements similar to Figure 8-29 with the elliptical resistance set to 6. Oscilloscope 1 further shows that even though the input voltage may decline sometime after the OVPC ceases power diversion, the elliptical output has its minimum voltage at the moment when the OVPC stops diverting power.

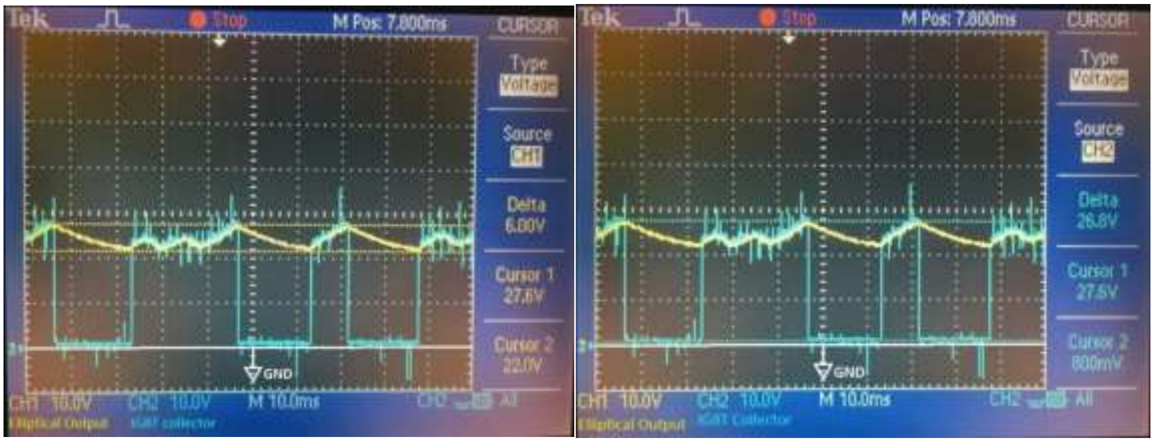

Figure 8-33: Oscilloscope capture of elliptical output voltage (yellow) and IGBT collector voltage (blue). Elliptical Resistance = 8, Pace = 150 SPM

After increasing the elliptical resistance to 10, the inverter continues to generate AC power to the grid, but only for a short time. Just as when running at a 100 SPM pace, increasing the resistance to 10 overloads the 5 A fuse at the Vicor's input. This occurs before we could record any data for this elliptical resistances setting. After the fuse breaks, the Vicor no longer emits a high frequency sound and the Fluke multimeter measures only a few volts at the output. When the fuse breaks, the elliptical output can no longer supply a voltage to the Vicor. Because of this, the voltage from the elliptical builds until the OVPC diverts excess power through the 10 Ω resistor. When running at an ERS of 8, the Agilent multimeter measures a maximum voltage across the sense resistor of 19.94 mV. This calculates to a maximum input current of 2.05 A to the DC-DC converter, less than half of the fuse's rating. Just like when running at 100 SPM, the input fuse breaks due to unforeseen transients. These high frequency transient currents pass through the sense resistor without the digital multimeter measuring them. Should these transients exists, neither oscilloscope manages to detect significant voltage spikes from the elliptical's output.

Unlike when running at a 100 SPM pace, calculating current into the IGBT's collector and the power dissipated by the diverting resistor follows the intended method. This means the using source voltage measurements from Oscilloscope 1, the minimum collector voltage, and the measured resistance of the diverting resistor. The difference between the maximum input voltage and minimum collector voltage over the measured diverting resistance yields the maximum current through the diverting resistor. The difference between the minimum input voltage and minimum collector voltage over the diverting resistor yields the minimum current into the IGBT's collector. Finally, the difference between the average input voltage and minimum collector voltage over the diverting resistor yields the minimum current into the IGBT's collector. Each calculation assumes an average voltage when dealing with the above calculations involving the minimum collector voltage. Squaring the value of the current through the resistor with the measured resistance yields the minimum, maximum, and average power the resistor dissipates.

So far, the above method works when testing the Vicor and M215 at a 150 SPM pace. Oscilloscope 1 in Figure 8-33 uses cursors to show the input voltage reaches its minimum voltage when the IGBT turns off. However, the oscilloscope measures an average input voltage, which may not equate to the average input voltage observed as the IGBT diverts power. If any higher elliptical resistance settings show the input voltage reaches a minimum while the IGBT does not divert power, then the test requires cursor measurements like Figure 8-24.

During testing, we observe frequent ringing on the IGBT's gate and collector terminals. The frequencies between peak transients measure between 31 kHz and 32 kHz

and do not vary with the ERS, or the runner's pace. The cause of the ringing remains a curiosity. Generally, ringing occurs when electrical pulses cause parasitic capacitances and inductances to resonate at their characteristic frequency [26]. External sources may induce noise given the multitude of cables crossing and connecting to test equipment. These oscillations occur at regular intervals regardless of elliptical performance or components connected. This suggests that the OVPC design may cause the ringing; meaning the resistors, capacitors, BJT, or IGBT used influence the ringing. While these unwanted oscillations do not seem to cause any false triggers for diverting power, their existence still causes concern. With ringing comes a change in voltage potential, and this causes extra current to flow. Every spike on the collector waveform means the diverting resistor sees a voltage difference even when the OVPC does not divert power. With the ringing still present, the system subjects the OVPC to extra heating of components, parasitic losses, and possible false triggers [26].

A fuse rated for 5 A may provide too much protection. Reflecting back to conducting an efficiency test on the Vicor DC-DC converter, the BK Precision had a 7.5 A current limit. The DC source supplied a maximum of 7.1 A to the Vicor while not causing the converter to fail short circuit protection. A fuse rated for 7.0 A or 7.5 A may prove more adequate and allow for elliptical testing at higher resistance settings. However, we only had access to 5 A and 8 A fuses at the time, and an 8 A fuse may not adequately protect the Vicor at its input.

8.3.3 Data Tables and Efficiency Plot

Table 8-4 tabulates data for full system testing using the Vicor DC-DC converter, the M215 microinverter, and running at a 100 SPM pace. Table 8-5 collects similar data

but for a 150 SPM pace. Both tables show the input voltage increases with an increasing ERS. Additionally, the voltage the elliptical generates increases when a user runs at the faster pace of 150 SPM. Both Table 8-4 and Table 8-5 list a maximum power dissipation of 71.8 W through the diverting resistor and IGBT. Meanwhile Table 8-1 and Table 8-2 in Section 8.2.4 list 343.9 W of the same dissipated power. The diverting resistor dissipates 79.1% less power when the system uses a Vicor DC-DC converter due to the lower input voltage the elliptical produces. A system with the Vicor also produces AC power consistently once able to produce AC power. Output AC current and power measurements increase as the ERS increases, but, unfortunately, the system fails to function properly for ERSs above 8. In contrast, tests with the CUI DC-DC converter frequently yield 0 W of minimum AC output power. Meanwhile the maximum AC power measurements range from a few watts to as much as 17.38 W for a given ERS.

Note about the power meter measurements: When multiplying the AC voltage with the AC current, the resulting power calculation does not equal the respective power measurement. For example, at an ERS of 8 for 150 SPM, the maximum output voltage equals 232.1 V and the maximum output current equals 186.7 mA. The product of the voltage and current equals 43.3 W instead of the listed 28.1 W. In addition, even when the system fails to produce AC power, the power meter still measures about 66 mA of current to the grid. The power meter does not indicate polarities with measurements for this test. This 66 mA constitutes only the AC current the M215 microinverter needs to power up and not the actual current the M215 inverter outputs to the grid. Subtracting 66 mA from the 186.7 mA measurement and multiplying the difference with 231.2 V

calculates to 28.0 W of power. Therefore, the power meter measures about 66 mA of extra current for each measurement than what the M215 inverter produces to the grid.

The CUI DC-DC converter proves more reliable over a wider range of elliptical resistance settings when the user runs at a 100 SPM pace. At this pace, a system with the CUI functions up to an ERS of 18 or 20, as the trials show. At a 150 SPM pace, however, the CUI proves less reliable and only able to produce power without the M215 inverter resetting at an ERS of 2. Meanwhile, a system with the Vicor DC-DC converter has a smaller elliptical resistance range in which it produces AC power. At a 100 SPM pace, a Vicor system produces AC power consistently and efficiency, but only for ERS of 6 and 8. At lower settings, the system manages to operate without disrupting the user in any way, but produces no power to the grid. Increasing the pace to 150 SPM increases the range in power production to include an ERS of 4. Still, the operating range remains limited for a full system that uses a Vicor. For the EHFEM system to produce AC power more consistently than demonstrated in this chapter, the project needs a DC-DC converter that can operate with lower input voltages and higher input current.

Both Table 8-4 and Table 8-5 have an unrealistic minimum efficiency calculation denoted by an orange highlight. Table 8-4 lists a minimum efficiency calculation of 201.5% and Table 8-4 lists a minimum efficiency calculation of 344.4%. Efficiency calculations exceed 100% when the minimum output power measurement exceeds the product of the minimum input voltage and minimum current through the sense resistor. Measuring and collecting data occurs over a short period with the Precor elliptical in use. We first record the voltage measurements from the oscilloscope, then collect the voltages across the sense resistor, which yield the input current calculations, and then record the

output AC power measurements. The calculated input power that results may not represent an accurate instantaneous power, which may yield and unrealistic efficiency.

Table 8-4: Data collected from first round of Full System testing with the Vicor DC-DC converter, Enphase M215 microinverter, and an OVPC. Fields highlighted yellow represent recorded measurements. Target pace of runner = 100 SPM. Dissipating resistor measures 9.85 Ω.

Full System Testing with Vicor DC-DC Converter and Enphase M215 Inverter																	
Elliptical	Oscilloscope 1 Channel 1 (DC)				Oscilloscope 2 Channel 2 (DC)				OVPC Diverting - Calculate (DC)							Fluke MM (DC)	
Restance Setting (ERS)	V_{IN} MIN (V)	V_{IN} PEAK (V)	V_{IN} AVG (V)	V_{IN} RMS (V)	V_c MIN (V)	V_c PEAK (V)	V_c AVG (V)	V_c RMS (V)	Does OVPC Divert?	I_{divert} MIN (A)	I_{divert} MAX (A)	I_{divert} AVG (A)	P_{divert} MIN (W)	P_{divert} MAX (W)	P_{divert} AVG (W)	V_{DC-DC} MIN (V)	V_{DC-DC} MAX (V)
2	9.6	12.0	11.3	10.5	8.4	17.2	11.4	11.6	NO	0	0	0	0	0	0	14.53	18.36
4	12.4	16.4	15.8	15.9	10.0	25.6	15.7	15.6	NO	0	0	0	0	0	0	19.56	22.72
6	12.4	19.2	17.4	17.6	8.8	28.0	18.0	17.2	NO	0	0	0	0	0	0	33.80	35.90
8	12.8	27.6	21.5	21.5	0.8	34.8	20.5	22.9	YES	1.2	2.7	2.1	14.1	71.8	42.7	35.70	35.90
10	18.0	27.6	23.2	23.8	0.8	36.4	10.2	14.3	YES	1.7	2.7	2.3	29.3	71.8	50.0		
12																	
14																	
16																	
18																	
20																	

Full System Testing with Vicor DC-DC Converter and Enphase M215 Inverter																			
Elliptical	Agilent Multimeter (DC)			Vicor Input Current & Power - Calculate (DC)						Inverter Output - Power Meter (AC)						Efficiency	
Restance Setting (ERS)	V_{sense} MIN (mV)	V_{sense} MAX (mV)	V_{sense} AVG (mV)	I_{sense} MIN (A)	I_{sense} MAX (A)	I_{sense} AVG (A)	P_{in} MIN (A)	P_{in} MAX (A)	P_{in} AVG (A)	V_{out} MIN (V)	V_{out} MAX (V)	I_{out} MIN (mA)	I_{out} MAX (mA)	P_{out} MIN (W)	P_{out} MAX (W)	MIN (%)	MAX (%)
2	1.51	2.90	2.05	0.15	0.30	0.21	1.49	3.57	2.38	232.0	232.2	65.8	65.9	0.00	0.00	0.0	0.0
4	3.52	6.51	5.01	0.36	0.67	0.51	4.48	10.95	8.12	231.9	232.1	65.7	65.9	0.00	0.00	0.0	0.0
6	6.41	14.78	10.90	0.66	1.52	1.12	8.15	29.11	19.45	232.0	232.2	76.6	112.3	2.05	10.44	25.1	35.9
8	3.44	24.56	11.44	0.35	2.52	1.17	4.52	69.52	25.23	231.8	232.1	105.0	156.7	9.10	21.1	201.5	30.3
10		33.7			3.46			95.40			232.2		242.5		26.34		
12																	
14																	
16																	
18																	
20																	

Table 8-5: Data collected from first round of Full System testing with the Vicor DC-DC converter, Enphase M215 microinverter, and an OVPC. Fields highlighted yellow represent recorded measurements. Target pace of runner = 150 SPM. Dissipating resistor measures 9.85 Ω.

Full System Testing with Vicor DC-DC Converter and Enphase M215 Inverter																		
Elliptical	Oscilloscope 1 Channel 1 (DC)				Oscilloscope 2 Channel 2 (DC)				OVPC Diverting - Calculate (DC)							Fluke MM (DC)	
Restance Setting (ERS)	V_{IN} MIN (V)	V_{IN} PEAK (V)	V_{IN} AVG (V)	V_{IN} RMS (V)	V_c MIN (V)	V_c PEAK (V)	V_c AVG (V)	V_c RMS (V)	Does OVPC Divert?	I_{divert} MIN (A)	I_{divert} MAX (A)	I_{divert} AVG (A)	P_{divert} MIN (W)	P_{divert} MAX (W)	P_{divert} AVG (W)	V_{DC-DC} MIN (V)	V_{DC-DC} MAX (V)
2	12.4	14.4	13.4	13.6	6.8	20.0	14.3	14.5	NO	0	0	0	0	0	0	18.74	19.36
4	14.0	20.4	19.3	19.3	8.8	30.4	19.8	19.8	NO	0	0	0	0	0	0	2.36	31.28
6	22.0	27.6	24.9	23.5	-8.8	41.2	17.8	21.3	YES	2.1	2.7	2.4	44.8	71.8	58.0	35.80	35.90
8	20.8	27.6	23.8	23.4	-6.0	34.4	8.88	12.5	YES	2.0	2.7	2.3	39.8	71.8	52.8	31.80	35.90
10																	
12																	
14																	
16																	
18																	
20																	

Full System Testing with Vicor DC-DC Converter and Enphase M215 Inverter																	
Elliptical	Agilent Multimeter (DC)			Vicor Input Current & Power - Calculate (DC)						Inverter Output - Power Meter (AC)						Efficiency	
Restance Setting (ERS)	V_{sense} MIN (mV)	V_{sense} MAX (mV)	V_{sense} AVG (mV)	I_{sense} MIN (A)	I_{sense} MAX (A)	I_{sense} AVG (A)	P_{in} MIN (A)	P_{in} MAX (A)	P_{in} AVG (A)	V_{out} MIN (V)	V_{out} MAX (V)	I_{out} MIN (mA)	I_{out} MAX (mA)	P_{out} MIN (W)	P_{out} MAX (W)	MIN (%)	MAX (%)
2	3.70	4.87	4.24	0.38	0.50	0.43	4.71	7.19	5.83	232.0	232.1	65.8	65.9	0.00	0.00	0.0	0.0
4	6.44	8.45	7.80	0.66	0.87	0.80	9.25	17.68	15.44	231.8	232.2	74.4	85.6	1.95	4.90	21.1	27.7
6	4.12	11.78	5.80	0.42	1.21	0.59	9.30	33.35	14.81	232.0	232.2	86.6	160.0	5.07	17.44	54.5	52.3
8	3.01	19.94	10.50	0.31	2.05	1.08	6.42	56.45	25.63	231.8	232.1	164.0	186.7	22.10	28.10	344.2	49.8
10																	
12																	
14																	
16																	
18																	
20																	

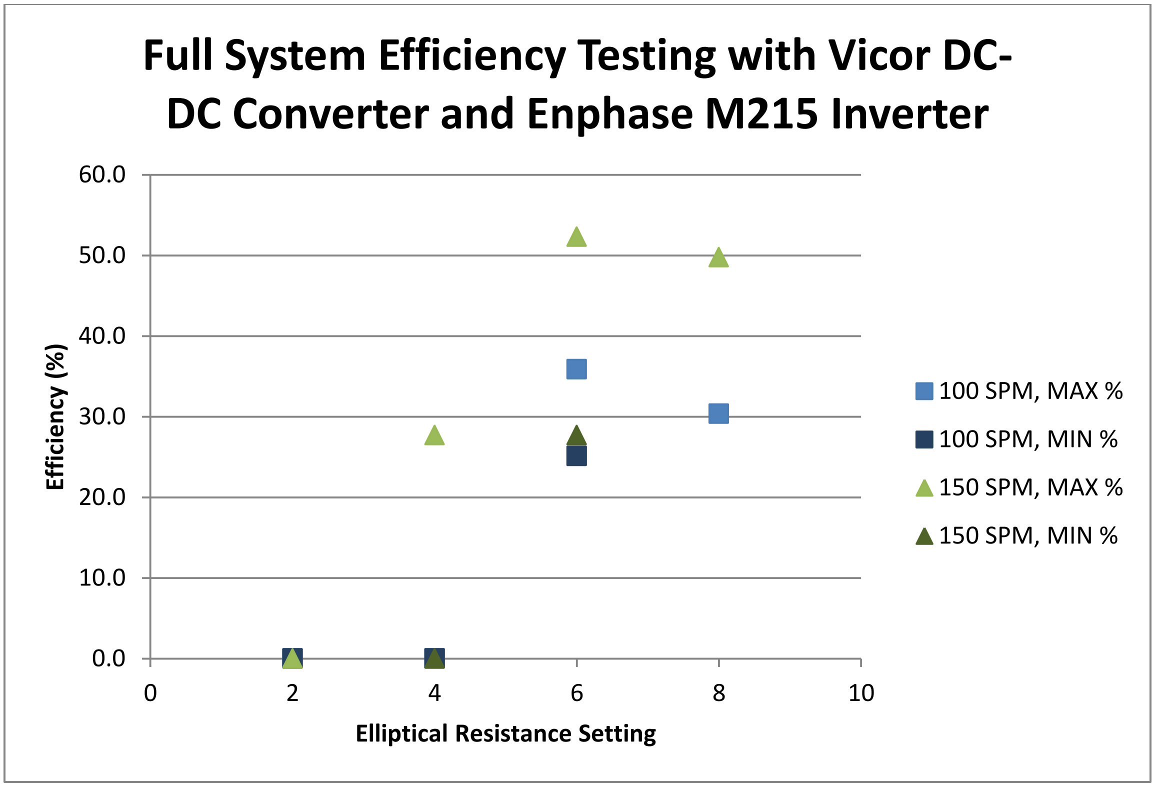

Figure 8-34: Scatter plot showing the minimum and maximum efficiency calculations for their given elliptical resistance setting. Plot includes efficiencies for both 100 SPM and 150 SPM pace.

A full system with a Vicor DC-DC converter produces AC power as efficiently, if not more, on average than a system with the CUI converter. For the first trial at a 100 SPM pace, the CUI DC-DC converter functions on average with an efficiency of 17.3%. For the second trial at 100 SPM, the efficiency average drops to 8.4%. This excludes the calculated maximum power efficiency calculations that exceed 100%, but includes the minimum power efficiencies of 0%. A full system with the Vicor DC-DC converter produces AC power with an average efficiency of 30.5% at a 100 SPM pace when the inverter produces AC power. At a 150 SPM pace, this average efficiency increases to 41.1% when producing AC power. These averages for the Vicor do not include the 0% efficiencies, since the system does not produce power, or efficiencies exceeding 100%. Including the 0% efficiencies for the ERS that fail to power the microinverter drops the efficiencies down to 13.1% for a 100 SPM pace and 29.3% for a

150 SPM pace. Figure 8-34 above plot the maximum-power and minimum-power efficiency calculations for the 100 SPM and 150 SPM test paces. The plot does not include efficiency calculations exceeding 100%.

CHAPTER 9: CONCLUSION AND FUTURE PROJECTS

Through different test system combinations involving the Precor EFX-546i Elliptical Trainer, this report explores whether the EHFEM project produces AC power to the grid more efficiently and consistently with a DC-DC converter. Tests use an overvoltage protection circuit (OVPC) commercially available DC-DC converters and DC-AC inverters. When testing without a DC-DC converter, the system converts DC generated power to AC power with an average efficiency of 85.0% when running at a pace of 100 SPM. This efficiency decreases slightly to 83.0% when increasing the runner's pace to 150 SPM. Full system testing includes a CUI DC-DC converter between the elliptical and M215 microinverter followed by exchanging the CUI with a Vicor DC-DC converter. With the CUI DC-DC converter, the EHFEM system produces AC power with average efficiencies of 17.3% and 8.4% over two test runs at a 100 SPM pace. With the CUI converter and running with a 150 SPM pace, the system has an average efficiency of 12.3%, but only produces AC power for an elliptical resistance setting (ERS) of 2 or 4. Using the Vicor DC-DC converter, the system produces AC power to the grid with average efficiencies of 30.5% for a 100 SPM pace and 41.1% for a 150 SPM pace. By including input protection in the form of the OVPC, this report demonstrated a functioning EHFEM system with the Vicor converter. Unfortunately, an EHFEM system with a Vicor converter encounters new problems. When setting the elliptical's resistance beyond 8, a fuse rated for 5 A breaks to prevent the Vicor from overcurrent damage. Additionally, an EHFEM system with the Vicor may fail to produce AC power to the grid for low elliptical resistance settings and paces.

Comparing the test setups shows the EHFEM system converts user generated power to AC power more efficiently without the inclusion of a DC-DC converter. However, the system only manages to produce AC power continuously across all elliptical resistance settings when testing with the CUI DC-DC converter, and running at a pace of 100 SPM. Initially, full system testing with the CUI DC-DC converter functions continuously across all elliptical resistance settings. However, in a subsequent test, the system fails to produce AC power when increasing the elliptical's set resistance to 18 or 20. While including a DC-DC converter may lower the overall efficiency, the EHFEM system must not fail to operate while in use. An EHFEM system comprised of the CUI DC-DC converter and Enphase M215 microinverter proves most favorable among all test combinations in this report, because it generates AC power more consistently to the grid without interruption.

This report reveals issues that hinder data collection when conducting elliptical testing. Testing in Chapter 7 fails to collect data at higher ERSs, because the Precor elliptical trainer interrupts testing when it resets while in use. When the elliptical resets, the ERS also resets back to a setting of 1, and this causes the elliptical to cease generating power to the microinverter. The Enphase M215 microinverter maximizes power conversion by pulling more current from the elliptical. This behavior causes the elliptical output voltage to drop below the microinverter's minimum operating voltage, thus causing the microinverter and elliptical to reset. Full system testing with the CUI in Chapter 8 saw issues similar to those in Chapter 7. The M215 microinverter would periodically reset after pulling too much current from the CUI DC-DC converter and cause the converter's output voltage to drop below the microinverter's minimum

operating voltage. Unlike the problems encountered in Chapter 7, testing in Chapter 8 does not experience the Precor elliptical resetting when the microinverter resets. When we conducted elliptical testing in Chapter 7 and Chapter 8, we lacked the current limiter from previous senior projects in the test setups. Including a current limiter at the input of a microinverter may alleviate the problem of the inverter pulling too much current and causing the system to reset. Testing with the Vicor DC-DC converter in Chapter 8 eventually overloads a fuse protecting the DC-DC converter's input. Although a multimeter and sense resistor measure a maximum current of 3.46 A into the Vicor, testing still manages to break a protective 5 A rated fuse. Either the Agilent multimeter measuring the voltage across the sense resistor yields inaccurate measurements, or the voltage spikes due to ringing seen on the IGBT's collector terminal cause the fuse to break. Future projects should consider the voltage ratings of the fuses, or use slow-blow fuses to mitigate the fuses from opening too early. If using slow-blow fuses, then one should exercise caution as this can increase the risk of overloading a DC-DC converter or microinverter.

While this thesis improved upon the OVPC by including a current buffer to drive the IGBT, one may choose to use a commercially available IGBT gate driver instead for further improved performance. One may also elect to use a MOSFET in place of the IGBT. Funsten et al. [5] originally chose to use an IGBT for its high current and power capabilities. If a new OVPC uses a MOSFET, it must have a high enough peak current rating and able to handle the power channeled through the diverting branch. The existing OVPC also effectively dumps half of the generated power when the IGBT turns on to divert excess power. A future project could design an OVPC that dumps less power when diverting, or figure out a means of using or storing the diverted power from the elliptical's load. Additionally, when the OVPC diverts excess power

through another branch, this changes the load seen by the generator. A new OVPC should consider a design that maintains a constant load seen by the power source.

Future projects can also improve upon testing methods used in this report. The way we calculated the efficiency of the DC-DC converters in this report used voltage values measured by the BK Precision power supply and a power meter. Any future project that characterizes the efficiency of a DC-DC converter should use a digital multimeter and measure the voltages at the contact points of a converter's input and output. Testing the efficiency of a DC-DC converter may also use an electronic load instead of a resistive load. We initially used an electronic load when characterizing the CUI DC-DC converter, but testing then yielded some efficiency calculations exceeding 100%. This error may have arose from not measuring the converter's input and output voltages from the contact points of the converter rather than just using an electronic load. Future projects that use the CUI converter should consider the peak current rating of the inductor at the input. Also, future project using the Vicor DC-DC converter should look into another means of attaching filtering capacitors to the converter without using a breadboard, because a breadboard can induce unwanted noise in the system. Lastly, while not available for this project, measuring with a 3 channel or 4 channel isolated oscilloscope would also help test protocol and collecting data.

This project uses commercially available DC-DC converters and microinverters to produce a final EHFEM design. Using these off-the-shelf components show a proof of concept, however, the EHFEM project needs custom components for optimal performance. The EHFEM project should produce AC power to the grid more efficiently and consistently if equipped with a customized DC-DC converter and DC-AC microinverter. Kou [2] designed a DC-DC converter that satisfies its design requirements, but failed under testing from an overvoltage condition. Future EHFEM projects can continue progress by repairing and improving on Kou's DC-DC converter design.

Meanwhile the EHFEM project still lacks a customized microinverter for use with the Precor elliptical trainer instead of using a microinverter designed for a solar panel. Other projects can design a custom DC-AC inverter that adheres to the parameters of the EHFEM project. Once a functioning custom DC-DC converter and inverter exist, a future EHFEM project should integrate the components with the improved overvoltage protection circuit used in this report. Doing so can prove definitively if the EHFEM project produces AC power to the grid efficiently across all elliptical operating conditions when including a DC-DC converter.

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APPENDIX A — RELEVANT DATA

A.1 Tables Collecting Data for M175 Efficiency Testing

Table A-1: Enphase M175 microinverter efficiency data with 1.5 A maximum input DC current.

DC input current set to 1.5 A													
Set	BK Precision DC Source (DC)						Power Meter (AC)				Efficiency		
Test Level (V)	Vin low (V)	Vin high (V)	Iin low (A)	Iin high (A)	Pin low (W)	Pin high (W)	Vout (V)	Iout (mA)	Pout low (W)	Pout high (W)	Low (%)	High (%)	AVG (%)
23	23.00	23.00	0.017	0.017	0.4	0.4	53.7	53.7	0.19	0.19	48.3	48.3	48.3
24	24.00	24.00	0.017	0.017	0.4	0.4	53.6	53.6	0.18	0.18	45.5	45.5	45.5
25	23.81	24.88	0.69	1.45	16.4	36.1	140.9	147.1	24.0	24.5	145.8	67.9	106.8
26	23.81	25.01	0.91	1.49	21.7	37.3	167.8	186.6	27.6	27.6	127.4	74.1	100.7
27	23.67	26.09	1.19	1.49	28.2	38.9	183.3	194.0	30.4	32.7	107.9	84.1	96.0
28	25.46	26.13	1.44	1.47	36.7	38.4	221.7	221.7	34.8	34.8	94.9	90.6	92.8
29	26.46	27.12	1.44	1.47	38.1	39.9	230.0	230.0	36.3	36.3	95.3	91.1	93.2
30	27.42	28.12	1.44	1.47	39.5	41.3	238.7	238.7	37.6	37.6	95.2	91.0	93.1
31	28.49	29.15	1.44	1.47	41.0	42.9	246.7	246.7	39.0	39.0	95.1	91.0	93.0
32	29.46	30.12	1.44	1.47	42.4	44.3	254.9	254.9	40.5	40.5	95.5	91.5	93.5
33	30.47	31.11	1.44	1.47	43.9	45.7	263.4	263.4	41.9	41.9	95.5	91.6	93.6
34	31.44	32.12	1.44	1.47	45.3	47.2	271.2	271.2	43.2	43.2	95.4	91.5	93.5
35	32.42	33.13	1.45	1.47	47.0	48.7	279.7	279.7	44.7	44.7	95.1	91.8	93.4
36	33.44	34.14	1.44	1.47	48.2	50.2	288.0	288.0	46.0	46.0	95.5	91.7	93.6
37	34.46	35.10	1.45	1.47	50.0	51.6	296.5	296.5	47.4	47.4	94.9	91.9	93.4
38	35.46	36.13	1.44	1.47	51.1	53.1	304.3	304.3	48.7	48.7	95.4	91.7	93.5
39	36.42	37.11	1.44	1.47	52.4	54.6	313.1	313.1	50.2	50.2	95.7	92.0	93.9
40	37.41	38.10	1.44	1.47	53.9	56.0	321.5	321.5	51.1	51.1	94.9	91.2	93.0
41	38.44	39.11	1.44	1.47	55.4	57.5	330.0	330.0	52.8	52.8	95.4	91.8	93.6
42	39.47	40.11	1.47	1.47	58.0	59.0	337.9	337.9	54.3	54.3	93.6	92.1	92.8

Table A-2: Enphase M175 microinverter efficiency data with 2.0 A maximum input DC current.

DC input current set to 2.0 A							
Set Test	BK Precision DC Source (DC)			Power Meter (AC)			
Level (V)	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (mA)	P_{out} (W)	Efficiency (%)
23	23.00	0.018	0.4	231.6	53.0	0.0	0.0
24	24.00	0.017	0.4	231.6	53.0	0.0	0.0
25	24.17	1.89	45.7	231.7	191	42.2	92.4
26	24.92	1.97	49.1	231.8	205	45.4	92.5
27	25.93	1.96	50.8	231.7	212	47.3	93.1
28	26.94	1.96	52.8	231.7	219	49.1	93.0
29	27.93	1.97	55.0	231.7	227	50.9	92.5
30	28.93	1.97	57.0	231.7	235	52.8	92.6
31	29.94	1.96	58.7	231.6	243	54.7	93.2
32	30.95	1.96	60.7	231.5	251	56.5	93.1
33	31.96	1.96	62.6	231.6	258	58.3	93.1
34	32.96	1.97	64.9	231.5	266	60.1	92.6
35	33.97	1.97	66.9	231.6	273	61.9	92.5
36	34.98	1.97	68.9	231.5	280	63.7	92.4
37	35.97	1.97	70.9	231.6	289	65.5	92.4
38	36.99	1.97	72.9	231.6	296	67.3	92.4
39	37.99	1.96	74.5	231.6	304	69.1	92.8
40	38.98	1.97	76.8	231.0	312	71.0	92.5
41	39.99	1.97	78.8	231.8	320	72.8	92.4
42	41.00	1.96	80.4	231.8	327	74.6	92.8
45	41.06	1.99	81.7	231.7	334	76.1	93.1
50	41.08	1.99	81.7	231.7	334	76.2	93.2

Table A-3: Enphase M175 microinverter efficiency data with 2.5 A maximum input DC current.

DC input current set to 2.5 A							
Set Test Level (V)	BK Precision DC Source (DC)			Power Meter (AC)			Efficiency (%)
	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (mA)	P_{out} (W)	
23	23.00	0.0177	0.4	231.4	53.0	0.0	0.0
24	24.00	0.0171	0.4	231.4	53.0	0.0	0.0
25	24.21	2.22	53.7	231.4	223	49.8	92.7
26	24.47	2.46	60.2	231.3	249	56.0	93.0
27	25.49	2.46	62.7	231.2	258	58.3	93.0
28	26.51	2.46	65.2	231.3	269	60.7	93.1
29	27.52	2.47	68.0	231.1	279	63.0	92.7
30	28.50	2.47	70.4	231.2	288	65.3	92.8
31	29.51	2.47	72.9	231.0	299	67.7	92.9
32	30.51	2.47	75.4	230.9	306	70.0	92.9
33	31.51	2.47	77.8	230.8	316	72.3	92.9
34	32.52	2.47	80.3	230.8	325	74.6	92.9
35	33.51	2.47	82.8	230.9	335	77.0	93.0
36	34.52	2.47	85.3	230.9	345	79.3	93.0
37	35.52	2.47	87.7	231.0	358	81.6	93.0
38	36.51	2.47	90.2	231.2	368	84.0	93.1
39	37.53	2.47	92.7	231.1	378	86.4	93.2
40	38.54	2.47	95.2	231.1	388	88.6	93.1
41	39.51	2.47	97.6	231.0	397	90.8	93.0
42	40.53	2.47	100.1	230.9	407	93.1	93.0
45	41.12	2.50	102.7	231.1	418	95.6	93.1
50	41.12	2.50	102.7	231.0	418	95.6	93.1

Table A-4: Enphase M175 microinverter efficiency data with 3.0 A maximum input DC current.

DC input current set to 3.0 A							
Set Test Level (V)	BK Precision DC Source (DC)			Power Meter (AC)			Efficiency (%)
	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (mA)	P_{out} (W)	
23	23.00	0.018	0.4	232.4	54.0	0.0	0.0
24	24.00	0.017	0.4	232.4	54.0	0.0	0.0
25	24.22	2.55	61.8	232.4	253	57.3	92.8
26	24.27	2.91	70.6	232.4	288	65.5	92.7
27	25.08	2.96	74.2	232.5	303	68.9	92.8
28	26.07	2.96	77.2	232.5	314	71.8	93.0
29	27.08	2.96	80.2	232.5	326	74.6	93.1
30	28.08	2.96	83.1	232.5	338	77.5	93.2
31	29.07	2.96	86.0	232.5	350	80.3	93.3
32	30.06	2.96	89.0	232.0	362	83.1	93.4
33	31.09	2.96	92.0	232.2	375	85.9	93.3
34	32.06	2.96	94.9	232.1	386	88.7	93.5
35	33.07	2.96	97.9	232.1	398	91.5	93.5
36	34.07	2.96	100.8	232.2	410	94.2	93.4
37	35.08	2.96	103.8	232.2	422	97.1	93.5
38	36.10	2.96	106.9	232.4	434	99.8	93.4
39	37.08	2.97	110.1	232.1	446	102.5	93.1
40	38.09	2.97	113.1	232.4	457	105.4	93.2
41	39.08	2.97	116.1	232.3	469	108.2	93.2
42	40.07	2.97	119.0	232.3	481	111.1	93.4
45	41.17	3.00	123.5	232.3	500	115.4	93.4
50	41.16	3.00	123.5	232.5	499	115.2	93.3

Table A-5: Enphase M175 microinverter efficiency data with 3.5 A maximum input DC current.

DC input current set to 3.5 A							
Set Test	BK Precision DC Source (DC)			Power Meter (AC)			
Level (V)	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (mA)	P_{out} (W)	Efficiency (%)
23	23.00	0.018	0.4	231.7	53.0	0.0	0.0
24	24.00	0.017	0.4	231.7	53.0	0.0	0.0
25	24.25	2.88	69.8	232.0	285	64.7	92.6
26	24.29	3.27	79.4	232.0	323	73.7	92.8
27	24.60	3.44	84.6	231.8	346	78.9	93.2
28	25.63	3.45	88.4	231.8	360	82.3	93.1
29	26.63	3.45	91.9	231.9	374	85.7	93.3
30	27.64	3.45	95.4	231.8	388	89.0	93.3
31	28.63	3.45	98.8	231.9	402	92.3	93.4
32	29.61	3.45	102.2	231.9	416	95.5	93.5
33	30.62	3.45	105.6	231.8	430	98.8	93.5
34	31.62	3.45	109.1	231.8	444	102.1	93.6
35	32.62	3.46	112.9	231.9	458	105.3	93.3
36	33.63	3.46	116.4	231.9	472	108.6	93.3
37	34.64	3.46	119.9	232.0	486	112.0	93.4
38	35.63	3.46	123.3	232.0	500	115.3	93.5
39	36.64	3.46	126.8	232.1	514	118.6	93.6
40	37.64	3.46	130.2	232.1	529	121.9	93.6
41	38.64	3.46	133.7	232.1	543	125.2	93.6
42	39.64	3.46	137.2	232.0	558	128.6	93.8
45	41.21	3.49	143.8	232.0	586	135.2	94.0
50	41.21	3.49	143.8	232.0	586	135.2	94.0

Table A-6: Enphase M175 microinverter efficiency data with 4.0 A maximum input DC current.

DC input current set to 4.0 A							
Set Test Level (V)	BK Precision DC Source (DC)			Power Meter (AC)			Efficiency (%)
	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (mA)	P_{out} (W)	
23	23.00	0.018	0.4	231.6	53.0	0.0	0.0
24	24.00	0.017	0.4	231.4	53.0	0.0	0.0
25	24.29	3.18	77.2	231.7	315	71.6	92.7
26	24.32	3.61	87.8	231.9	356	81.6	92.9
27	24.36	3.90	95.0	231.9	386	88.3	92.9
28	25.23	3.93	99.2	231.9	402	92.3	93.1
29	26.21	3.94	103.3	232.0	418	96.1	93.1
30	27.23	3.94	107.3	232.0	434	99.8	93.0
31	28.21	3.94	111.1	232.0	451	103.6	93.2
32	29.21	3.94	115.1	231.7	467	107.4	93.3
33	30.18	3.94	118.9	232.1	483	111.3	93.6
34	31.19	3.94	122.9	232.0	499	115.0	93.6
35	32.22	3.95	127.3	232.1	515	118.8	93.3
36	33.21	3.95	131.2	232.0	531	122.6	93.5
37	34.23	3.95	135.2	232.2	548	126.5	93.6
38	35.21	3.95	139.1	232.2	564	130.3	93.7
39	36.18	3.95	142.9	232.2	580	134.0	93.8
40	37.20	3.95	146.9	232.1	596	137.8	93.8
41	38.19	3.96	151.2	232.3	612	141.5	93.6
42	39.19	3.96	155.2	232.2	628	145.3	93.6
45	41.26	3.99	164.6	232.2	669	154.7	94.0
50	41.25	3.99	164.6	232.2	669	154.6	93.9

Table A-7: Enphase M175 microinverter efficiency data with 4.5 A maximum input DC current.

DC input current set to 4.5 A							
Set Test	BK Precision DC Source (DC)			Power Meter (AC)			
Level	V_{in}	I_{in}	P_{in}	V_{out}	I_{out}	P_{out}	Efficiency
(V)	(V)	(A)	(W)	(V)	(mA)	(W)	(%)
23	23.00	0.018	0.4	231.6	53.0	0.0	0.0
24	24.00	0.017	0.4	231.7	53.0	0.0	0.0
25	24.30	3.41	82.9	231.7	337	76.9	92.8
26	24.38	3.87	94.4	231.8	383	87.8	93.1
27	24.40	4.20	102.5	231.9	414	95.0	92.7
28	24.89	4.32	107.5	232.0	435	100.0	93.0
29	25.91	4.33	112.2	231.9	453	104.1	92.8
30	26.90	4.33	116.5	231.8	471	108.3	93.0
31	27.87	4.33	120.7	231.8	489	112.5	93.2
32	28.90	4.33	125.1	231.9	506	116.7	93.3
33	29.87	4.33	129.3	231.8	524	120.8	93.4
34	30.88	4.34	134.0	231.8	542	125.0	93.3
35	31.88	4.34	138.4	231.6	560	129.2	93.4
36	32.84	4.34	142.5	231.7	578	133.4	93.6
37	33.85	4.34	146.9	231.6	596	137.4	93.5
38	34.84	4.34	151.2	231.6	614	141.6	93.6
39	35.85	4.34	155.6	231.6	632	145.8	93.7
40	36.85	4.34	159.9	231.8	650	150.0	93.8
41	37.85	4.34	164.3	231.6	667	154.1	93.8
42	38.84	4.35	169.0	231.7	685	158.2	93.6
45	41.29	4.40	181.7	231.9	737	170.2	93.7
50	41.28	4.40	181.6	231.9	736	170.2	93.7

Table A-8: Enphase M175 microinverter efficiency data with 5.0 A maximum input DC current.

DC input current set to 5.0 A							
Set Test Level (V)	BK Precision DC Source (DC)			Power Meter (AC)			Efficiency (%)
	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (mA)	P_{out} (W)	
23	23.00	0.0177	0.4	231.6	53.0	0.0	0.0
24	24.00	0.0171	0.4	231.5	53.0	0.0	0.0
25	24.34	3.76	91.5	231.7	370	84.9	92.8
26	24.37	4.26	103.8	231.8	420	96.3	92.8
27	24.42	4.62	112.8	231.8	455	104.7	92.8
28	24.44	4.89	119.5	231.9	482	110.9	92.8
29	25.41	4.91	124.8	231.8	502	115.6	92.7
30	26.37	4.91	129.5	231.8	522	120.4	93.0
31	27.41	4.91	134.6	231.9	543	125.0	92.9
32	28.36	4.91	139.2	231.6	563	129.9	93.3
33	29.36	4.91	144.2	231.7	583	134.6	93.4
34	30.38	4.92	149.5	231.8	603	139.3	93.2
35	31.37	4.92	154.3	231.7	624	144.0	93.3
36	32.37	4.93	159.6	231.8	644	148.7	93.2
37	33.34	4.93	164.4	231.9	664	153.4	93.3
38	34.36	4.93	169.4	231.9	684	158.4	93.5
39	35.35	4.93	174.3	231.9	704	162.8	93.4
40	36.35	4.93	179.2	231.9	725	167.6	93.5
41	37.33	4.93	184.0	231.9	745	172.4	93.7
42	38.33	4.93	189.0	231.9	765	177.1	93.7
45	42.71	4.55	194.3	231.9	745	182.0	93.7
50	48.69	4.17	203.0	231.9	765	190.0	93.6

Table A-9: Enphase M175 microinverter efficiency data with 5.0 A maximum input DC current.

DC input current set to 5.5 A							
Set Test	BK Precision DC Source (DC)			Power Meter (AC)			
Level	V_{in}	I_{in}	P_{in}	V_{out}	I_{out}	P_{out}	Efficiency
(V)	(V)	(A)	(W)	(V)	(mA)	(W)	(%)
23	23.00	0.0117	0.3	231.4	53.0	0.0	0.0
24	24.00	0.0171	0.4	231.4	53.0	0.0	0.0
25	24.37	4.03	98.2	231.8	397	91.0	92.7
26	24.41	4.57	111.6	231.8	450	103.5	92.8
27	24.46	4.97	121.6	231.9	488	112.4	92.5
28	24.47	5.27	129.0	231.8	518	119.4	92.6
29	25.02	5.38	134.6	231.8	541	124.7	92.6
30	25.98	5.39	140.0	231.9	563	129.9	92.8
31	26.97	5.39	145.4	231.9	585	135.1	92.9
32	27.97	5.39	150.8	231.7	608	140.3	93.1
33	28.96	5.40	156.4	231.7	630	145.3	92.9
34	29.96	5.40	161.8	231.5	652	150.5	93.0
35	30.98	5.40	167.3	231.7	675	155.8	93.1
36	31.96	5.40	172.6	231.6	697	160.9	93.2
37	32.95	5.40	177.9	231.7	719	166.1	93.4
38	33.95	5.41	183.7	231.7	741	171.3	93.3
39	34.94	5.41	189.0	231.7	764	176.6	93.4
40	36.13	5.37	194.0	231.7	784	181.4	93.5
41	38.16	5.08	193.9	231.6	785	181.8	93.8
42	39.80	4.87	193.8	232.0	785	181.4	93.6
45	43.77	4.44	194.3	232.1	786	181.9	93.6
50	49.29	4.14	204.1	232.1	826	191.2	93.7

Table A-10: Enphase M175 microinverter efficiency data with 6.0 A maximum input DC current.

DC input current set to 6.0 A							
Set Test Level (V)	BK Precision DC Source (DC)			Power Meter (AC)			Efficiency (%)
	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (mA)	P_{out} (W)	
23	23.00	0.018	0.4	231.6	53.0	0.0	0.0
24	24.00	0.017	0.4	231.5	53.0	0.0	0.0
25	24.39	4.31	105.1	231.8	424.0	97.3	92.6
26	24.46	4.88	119.4	231.8	479.0	110.4	92.5
27	24.48	5.30	129.7	231.7	521.0	120.0	92.5
28	24.49	5.63	137.9	231.8	553	127.6	92.5
29	24.61	5.85	144.0	231.9	578	133.5	92.7
30	25.61	5.86	150.1	231.0	604	138.9	92.6
31	26.62	5.87	156.3	231.2	628	144.6	92.5
32	27.60	5.87	162.0	231.5	651	150.0	92.6
33	28.62	5.88	168.3	231.7	674	155.6	92.5
34	29.55	5.88	173.8	231.8	698	161.2	92.8
35	30.57	5.89	180.1	231.8	723	167.1	92.8
36	31.53	5.89	185.7	231.7	747	172.7	93.0
37	32.58	5.89	191.9	231.5	773	178.4	93.0
38	34.66	5.62	194.8	231.5	784	181.2	93.0
39	36.48	5.33	194.4	231.5	785	181.5	93.3
40	38.04	5.11	194.4	231.5	785	181.5	93.4
41	39.42	4.91	193.6	231.5	785	181.4	93.7
42	40.71	4.76	193.8	231.4	787	181.6	93.7
45	44.37	4.39	194.8	231.4	789	182.8	93.8
50	49.71	4.12	204.8	231.2	832	192.0	93.7

Table A-11: Enphase M175 microinverter efficiency data with 6.5 A maximum input DC current.

DC input current set to 6.5 A							
Set Test	BK Precision DC Source (DC)			Power Meter (AC)			
Level	V_{in}	I_{in}	P_{in}	V_{out}	I_{out}	P_{out}	Efficiency
(V)	(V)	(A)	(W)	(V)	(mA)	(W)	(%)
23	23.00	0.018	0.4	229.6	53.0	0.21	51.9
24	24.00	0.017	0.4	229.7	53.1	0.21	51.2
25	24.42	4.59	112.1	230.0	453.3	103.4	92.2
26	24.47	5.19	127.0	230.0	512.5	117.1	92.2
27	24.51	5.63	138.0	230.0	556.5	127.3	92.3
28	24.55	5.99	147.1	230.0	591	135.3	92.0
29	24.52	6.28	154.0	230.0	618	141.6	92.0
30	25.24	6.34	160.0	230.1	643	147.5	92.2
31	26.22	6.35	166.5	230.2	669	153.6	92.3
32	27.19	6.35	172.7	230.7	695	159.6	92.4
33	28.19	6.35	179.0	230.7	721	165.7	92.6
34	29.19	6.36	185.6	230.9	746	171.8	92.5
35	30.20	6.36	192.1	230.9	773	177.9	92.6
36	32.21	6.10	196.5	230.7	793	182.4	92.8
37	34.55	5.64	194.9	230.6	788	181.4	93.1
38	36.17	5.36	193.9	230.5	788	181.3	93.5
39	37.52	5.19	194.7	230.6	790	181.7	93.3
40	38.87	5.01	194.7	230.5	791	181.7	93.3
41	40.10	4.84	194.1	230.5	791	181.8	93.7
42	41.34	4.69	193.9	230.3	791	181.7	93.7
45	44.76	4.35	194.7	230.4	794	182.6	93.8
50	49.98	4.12	205.9	230.4	838	192.9	93.7

Table A-12: Enphase M175 microinverter efficiency data with 7.0 A maximum input DC current.

DC input current set to 7.0 A							
Set Test Level (V)	BK Precision DC Source (DC)			Power Meter (AC)			Efficiency (%)
	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (mA)	P_{out} (W)	
23	23.00	0.018	0.4	230.4	53.3	0.21	51.6
24	24.00	0.017	0.4	230.6	53.3	0.22	53.6
25	24.45	4.86	118.8	231.0	477.7	109.5	92.2
26	24.50	5.49	134.5	230.9	539.5	123.8	92.0
27	24.52	5.95	145.9	230.7	585.6	134.4	92.1
28	24.58	6.33	155.6	230.7	623	142.9	91.8
29	24.59	6.63	163.0	230.7	652	150.0	92.0
30	24.90	6.81	169.6	230.9	676	155.7	91.8
31	25.87	6.82	176.4	230.9	705	162.1	91.9
32	26.84	6.83	183.3	230.7	734	168.9	92.1
33	27.80	6.84	190.2	230.6	762	175.3	92.2
34	28.81	6.83	196.8	231.2	788	181.7	92.3
35	32.25	6.11	197.0	231.0	792	182.4	92.6
36	34.13	5.71	194.9	230.7	787	181.2	93.0
37	35.63	5.46	194.5	229.4	792	181.3	93.2
38	36.93	5.27	194.6	230.6	788	181.4	93.2
39	38.20	5.10	194.8	230.6	790	181.8	93.3
40	39.40	4.94	194.6	230.7	789	181.7	93.4
41	40.61	4.79	194.5	230.5	790	181.7	93.4
42	41.73	4.66	194.5	230.5	792	182.0	93.6
45	44.99	4.35	195.7	230.6	795	182.6	93.3
50	49.99	4.11	205.5	230.3	838	192.6	93.7

Table A-13: Enphase M175 microinverter efficiency data with 7.5 A maximum input DC current.

DC input current set to 7.5 A							
Set Test Level (V)	BK Precision DC Source (DC)			Power Meter (AC)			Efficiency (%)
	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (mA)	P_{out} (W)	
23	23.00	0.018	0.4	230.5	53.4	0.22	54.7
24	23.99	0.017	0.4	230.6	53.4	0.22	54.3
25	24.48	5.13	125.6	231.0	504.3	115.6	92.1
26	24.51	5.79	141.9	230.9	568.4	130.4	91.9
27	24.56	6.26	153.7	230.9	615.6	141.5	92.0
28	24.60	6.66	163.8	230.9	654	150.5	91.9
29	24.61	7.00	172.3	230.9	686	157.9	91.7
30	24.66	7.25	178.8	230.9	712	163.8	91.6
31	25.50	7.29	185.9	231.1	740	170.4	91.7
32	26.51	7.29	193.3	230.8	771	177.7	91.9
33	29.22	6.81	199.0	230.9	797	183.6	92.3
34	31.70	6.23	197.5	231.0	794	183.2	92.8
35	33.42	5.87	196.2	231.0	790	182.3	92.9
36	34.91	5.61	195.8	231.0	789	181.7	92.8
37	36.20	5.39	195.1	231.1	789	181.9	93.2
38	37.45	5.20	194.7	231.0	789	181.9	93.4
39	38.63	5.05	195.1	231.0	790	182.0	93.3
40	39.81	4.89	194.7	231.3	788	181.8	93.4
41	40.91	4.77	195.1	231.0	791	182.2	93.4
42	41.91	4.65	194.9	231.2	791	182.4	93.6
45	44.99	4.33	194.8	231.1	793	182.6	93.7
50	49.99	4.11	205.5	230.8	836	192.6	93.7

A.2 Tables Collecting Data for M215 Efficiency Testing

Table A-14: Enphase M215 microinverter efficiency data with 0.5 A maximum input DC current.

DC input current set to 0.5A														
Set	BK Precision DC Source (DC)						Power Meter (AC)					Efficiency		
Test Level (V)	V_{in} low (V)	V_{in} high (V)	I_{in} low (A)	I_{in} high (A)	P_{in} low (W)	P_{in} high (W)	V_{out} (V)	I_{out} low (mA)	I_{out} high (mA)	P_{out} low (W)	P_{out} high (W)	Low (%)	High (%)	AVG (%)
15	15.0	15.0	0.024	0.024	0.4	0.4	231.7	65.9	65.9	0.0	0.0	0.0	0.0	0.0
16	16.0	16.0	0.022	0.022	0.4	0.4	232.0	65.9	65.9	0.0	0.0	0.0	0.0	0.0
17	15.0	16.7	0.414	0.499	6.2	8.3	231.7	94.8	96.4	6.74	6.78	108.5	81.4	94.9
18	15.8	17.7	0.488	0.501	7.7	8.9	231.9	99.8	101.4	7.48	7.64	97.0	86.2	91.6
20	17.9	19.7	0.489	0.507	8.8	10.0	231.9	107.0	108.2	8.39	8.56	95.9	85.7	90.8
25	22.8	24.6	0.474	0.500	10.8	12.3	231.8	125.7	126.6	10.88	10.95	100.7	89.0	94.8
30	27.9	29.4	0.489	0.502	13.6	14.8	231.7	145.8	147.0	13.25	13.41	97.1	90.9	94.0
31	28.7	30.6	0.489	0.504	14.0	15.4	231.6	150.0	151.4	13.70	13.83	97.6	89.7	93.6
32	29.6	31.4	0.482	0.504	14.3	15.8	231.6	152.1	155.9	14.0	14.44	98.1	91.2	94.7
33	30.9	32.3	0.498	0.504	15.4	16.3	231.6	156.6	160.8	14.4	15.0	93.6	92.1	92.9
34	31.4	33.5	0.498	0.498	15.6	16.7	231.6	169.0	181.3	14.5	16.0	92.7	95.9	94.3
35	32.4	34.5	0.498	0.498	16.1	17.2	231.5	178.2	179.6	15.4	15.6	95.4	90.8	93.1
36	33.7	35.5	0.498	0.498	16.8	17.7	231.5	183.3	184.2	16.0	16.0	95.3	90.5	92.9
37	34.7	36.6	0.498	0.498	17.3	18.2	231.7	187.6	189.1	16.5	16.5	95.5	90.5	93.0
38	34.7	37.1	0.498	0.498	17.3	18.5	231.7	190.1	192.0	16.8	16.8	97.2	90.9	94.1
39	34.6	37.1	0.498	0.498	17.2	18.5	231.9	190.4	192.0	16.8	16.8	97.5	90.9	94.2
40	34.5	37.0	0.498	0.498	17.2	18.4	231.6	190.9	191.9	16.8	16.8	97.8	91.2	94.5
41	34.6	37.0	0.498	0.498	17.2	18.4	231.7	190.9	192.3	16.8	16.8	97.5	91.2	94.3
42	34.6	37.1	0.498	0.498	17.2	18.5	231.7	190.2	192.0	16.8	16.8	97.5	90.9	94.2

Table A-15: Enphase M215 microinverter efficiency data with 1.0 A maximum input DC current.

DC input current set to 1.0A												
Set	BK Precision DC Source (DC)						Power Meter (AC)			Efficiency		
Test Level (V)	V_{in} low (V)	V_{in} high (V)	I_{in} low (A)	I_{in} high (A)	P_{in} low (W)	P_{in} high (W)	V_{out} (V)	Iout (AC) (mA)	Pout (AC) (W)	Low (%)	High (%)	AVG (%)
15	15.0	15.0	0.024	0.024	0.4	0.4	231.7	65.6	0.0	0.0	0.0	0.0
16	16.0	16.0	0.022	0.022	0.4	0.4	231.7	65.6	0.0	0.0	0.0	0.0
17	16.0	16.7	0.753	0.969	12.0	16.2	231.7	119.2	12.82	106.4	79.2	92.8
18	16.8	17.7	0.932	0.999	15.7	17.7	231.7	133.3	15.0	95.8	84.8	90.3
20	17.9	19.7	0.950	0.999	17.0	19.7	231.7	144.8	16.9	99.4	85.9	92.6
25	22.8	24.6	0.954	1.000	21.8	24.6	231.5	177.4	21.7	99.8	88.2	94.0
30	27.9	29.4	0.955	1.002	26.6	29.5	231.7	210.6	26.4	99.1	89.6	94.3
31	28.7	30.6	0.966	1.000	27.7	30.6	231.8	217.5	27.3	98.5	89.2	93.8
32	29.6	31.4	0.944	1.000	27.9	31.4	231.9	224.3	28.3	101.3	90.1	95.7
33	30.9	32.3	0.964	1.003	29.8	32.4	231.8	230.7	29.3	98.4	90.4	94.4
34	31.4	33.5	0.968	1.001	30.4	33.5	232.0	237.7	30.2	99.4	90.1	94.7
35	32.4	34.5	0.963	1.002	31.2	34.6	231.8	244.7	31.2	100.0	90.3	95.1
36	33.7	35.5	0.967	1.000	32.6	35.5	231.7	251.4	32.2	98.8	90.7	94.8
37	34.7	36.6	0.962	1.001	33.4	36.6	231.5	258.9	33.0	98.9	90.1	94.5
38	34.7	37.1	0.998	0.998	34.6	37.0	231.6	265.7	34.1	98.5	92.1	95.3
39	34.6	37.1	0.998	0.998	34.5	37.0	231.7	265.7	34.1	98.8	92.1	95.4
40	34.5	37.0	0.998	0.998	34.4	36.9	231.7	265.2	34.1	99.0	92.3	95.7
41	34.6	37.0	0.998	0.998	34.5	36.9	231.7	265.6	34.1	98.8	92.3	95.5
42	34.6	37.1	0.998	0.998	34.5	37.0	231.7	265.8	34.1	98.8	92.1	95.4

Table A-16: Enphase M215 microinverter efficiency data with 1.5 A maximum input DC current.

DC input current set to 1.5A														
Set	BK Precision DC Source (DC)						Power Meter (AC)					Efficiency		
Test Level (V)	V_{in} low (V)	V_{in} high (V)	I_{in} low (A)	I_{in} high (A)	P_{in} low (W)	P_{in} high (W)	V_{out} (V)	I_{out} low (mA)	I_{out} high (mA)	P_{out} low (W)	P_{out} high (W)	Low (%)	High (%)	AVG (%)
15	15.0	15.0	0.024	0.024	0.4	0.4	231.9	65.6	65.6	0.0	0.0	0.0	0.0	0.0
16	16.0	16.0	0.022	0.022	0.4	0.4	231.9	65.7	65.7	0.0	0.0	0.0	0.0	0.0
17	15.9	16.2	1.246	1.323	19.8	21.4	232.1	137.9	137.9	19.1	19.1	96.4	89.1	92.8
18	16.2	16.8	1.444	1.481	23.4	24.9	231.9	156.9	156.9	22.6	22.6	96.6	90.8	93.7
20	18.3	18.8	1.452	1.481	26.6	27.8	231.7	171.8	171.8	25.4	25.4	95.6	91.2	93.4
25	23.2	23.7	1.447	1.485	33.6	35.2	231.8	212.6	212.6	32.6	32.6	97.1	92.6	94.9
30	28.2	28.7	1.454	1.486	41.0	42.6	231.5	254.7	254.7	39.8	39.8	97.1	93.3	95.2
31	29.2	29.6	1.468	1.485	42.9	44.0	231.5	263.1	263.1	41.2	41.2	96.1	93.7	94.9
32	30.2	30.7	1.463	1.484	44.2	45.6	231.7	271.1	271.1	42.6	42.6	96.4	93.5	95.0
33	31.2	31.7	1.458	1.484	45.5	47.0	231.7	279.9	279.9	44.1	44.1	96.9	93.7	95.3
34	32.2	32.7	1.459	1.486	47.0	48.6	231.5	288.5	288.5	45.5	45.5	96.9	93.6	95.2
35	33.2	33.7	1.462	1.489	48.5	50.2	231.5	297.1	297.1	46.8	46.8	96.4	93.3	94.8
36	34.2	34.7	1.469	1.485	50.2	51.5	231.5	305.4	305.4	48.2	48.2	95.9	93.5	94.7
37	33.9	36.1	1.498	1.498	50.8	54.1	231.3	310.0	322.0	47.7	49.9	93.9	92.3	93.1
38	34.6	37.0	1.498	1.498	51.8	55.4	231.3	316.4	334.9	46.5	53.1	89.7	95.8	92.8
39	35.3	37.3	1.497	1.501	52.8	56.0	231.4	381.6	401.6	49.9	54.4	94.4	97.2	95.8
40	35.3	37.5	1.498	1.498	52.9	56.2	231.4	373.3	401.0	50.2	53.3	94.9	94.9	94.9
41	35.4	37.5	1.498	1.498	53.0	56.2	231.7	374.3	402.4	49.9	53.5	94.1	95.2	94.7
42	35.4	37.7	1.498	1.498	53.0	56.5	231.8	374.8	401.3	50.1	53.3	94.5	94.4	94.4

Table A-17: Enphase M215 microinverter efficiency data with 2.0 A maximum input DC current.

DC input current set to 2.0A												
Set	BK Precision DC Source (DC)						Power Meter (AC)			Efficiency		
Test Level (V)	V_{in} low (V)	V_{in} high (V)	I_{in} low (A)	I_{in} high (A)	P_{in} low (W)	P_{in} high (W)	V_{out} (V)	Iout (AC) (mA)	Pout (AC) (W)	Low (%)	High (%)	AVG (%)
15	15.0	15.0	0.024	0.024	0.4	0.4	231.1	65.5	0.0	0.0	0.0	0.0
16	16.0	16.0	0.022	0.022	0.4	0.4	230.9	65.5	0.0	0.0	0.0	0.0
17	15.9	16.3	1.422	1.618	22.6	26.4	231.2	157.9	22.7	100.4	86.1	93.2
18	15.8	16.4	1.889	1.943	29.8	31.9	231.2	191.1	28.8	96.5	90.4	93.4
20	17.7	18.4	1.890	1.957	33.5	36.0	231.4	213.8	32.8	98.0	91.1	94.6
25	22.6	23.3	1.919	1.960	43.4	45.7	231.4	269.2	42.2	97.3	92.4	94.9
30	27.6	28.3	1.937	1.964	53.5	55.6	231.8	324.5	51.6	96.5	92.8	94.7
31	28.7	29.3	1.923	1.964	55.2	57.5	231.8	335.9	53.5	96.9	93.0	95.0
32	29.7	30.2	1.938	1.964	57.6	59.3	231.7	347.4	55.4	96.2	93.4	94.8
33	30.7	31.3	1.93	1.962	59.3	61.4	231.7	358.3	57.2	96.5	93.1	94.8
34	31.7	32.3	1.938	1.961	61.4	63.3	231.2	369.7	59.2	96.4	93.5	94.9
35	32.7	33.2	1.938	1.965	63.4	65.2	231.4	381.5	61.0	96.3	93.5	94.9
36	33.8	34.2	1.942	1.967	65.6	67.3	231.4	392.5	62.9	95.8	93.5	94.7
37	36.1	36.1	1.999	1.999	72.2	72.2	231.4	307.7	68.7	95.2	95.2	95.2
38	36.1	36.1	1.999	1.999	72.2	72.2	231.1	307.7	68.6	95.1	95.1	95.1
39	36.1	36.1	1.999	1.999	72.2	72.2	231.3	307.7	68.6	95.1	95.1	95.1
40	36.1	36.1	1.999	1.999	72.2	72.2	231.1	307.8	68.7	95.2	95.2	95.2
41	36.1	36.1	1.999	1.999	72.2	72.2	231.3	307.8	68.6	95.1	95.1	95.1
42	36.1	36.1	1.999	1.999	72.2	72.2	231.4	307.5	68.6	95.1	95.1	95.1

Table A-18: Enphase M215 microinverter efficiency data with 2.5 A maximum input DC current.

DC input current set to 2.5A														
Set	BK Precision DC Source (DC)						Power Meter (AC)					Efficiency		
Test Level (V)	V_{in} low (V)	V_{in} high (V)	I_{in} low (A)	I_{in} high (A)	P_{in} low (W)	P_{in} high (W)	V_{out} (V)	I_{out} low (mA)	I_{out} high (mA)	P_{out} low (W)	P_{out} high (W)	Low (%)	High (%)	AVG (%)
15	15.0	15.0	0.024	0.024	0.4	0.4	229.6	64.9	64.9	0.0	0.0	0.0	0.0	0.0
16	16.0	16.0	0.022	0.022	0.4	0.4	229.9	65.0	65.0	0.0	0.0	0.0	0.0	0.0
17	16.29	16.73	1.290	2.011	21.0	33.6	230.0	153.5	157.7	23.07	23.86	109.8	70.9	90.4
18	16.49	17.63	1.530	2.430	25.2	42.8	230.5	180.4	182.3	30.9	30.9	122.5	72.1	97.3
20	18.98	18.98	2.480	2.480	47.1	47.1	230.4	209.4	209.4	44.4	44.4	94.3	94.3	94.3
25	24.00	24.00	2.490	2.490	59.8	59.8	230.6	257.3	257.3	56.5	56.5	94.5	94.5	94.5
30	28.99	28.99	2.480	2.480	71.9	71.9	231.0	307.5	307.5	68.5	68.5	95.3	95.3	95.3
31	29.99	29.99	2.490	2.490	74.7	74.7	230.9	317.9	317.9	70.9	70.9	94.9	94.9	94.9
32	31.00	31.00	2.490	2.490	77.2	77.2	230.7	328.7	328.7	73.3	73.3	95.0	95.0	95.0
33	32.01	32.01	2.480	2.480	79.4	79.4	230.7	338.5	338.5	75.7	75.7	95.4	95.4	95.4
34	33.00	33.00	2.480	2.480	81.8	81.8	230.4	349.0	349.0	78.1	78.1	95.4	95.4	95.4
35	34.01	34.01	2.490	2.490	84.7	84.7	230.5	358.5	358.5	80.5	80.5	95.1	95.1	95.1
36	35.01	35.01	2.480	2.480	86.8	86.8	230.4	368.9	368.9	82.8	82.8	95.4	95.4	95.4
37	36.01	36.01	2.480	2.480	89.3	89.3	230.8	378.7	378.7	85.3	85.3	95.5	95.5	95.5
38	36.14	36.14	2.498	2.498	90.3	90.3	231.0	381.3	381.3	85.9	85.9	95.1	95.1	95.1
39	36.14	36.14	2.498	2.498	90.3	90.3	231.0	381.5	381.5	85.9	85.9	95.1	95.1	95.1
40	36.13	36.13	2.498	2.498	90.3	90.3	230.9	381.5	381.5	85.9	85.9	95.2	95.2	95.2
41	36.15	36.15	2.498	2.498	90.3	90.3	230.8	381.5	381.5	85.9	85.9	95.1	95.1	95.1
42	36.14	36.14	2.498	2.498	90.3	90.3	230.7	381.8	381.8	85.9	85.9	95.1	95.1	95.1

Table A-19: Enphase M215 microinverter efficiency data with 3.0 A maximum input DC current.

DC input current set to 3.0A							
Set Test Level (V)	BK Precision (DC)			Power Meter (AC)			Efficiency (%)
	Vin (DC) (V)	Iin (DC) (A)	Pin (DC) (W)	Vout (AC) (V)	Iout (AC) (mA)	Pout (AC) (W)	
15	15.00	0.0236	0.4	231.4	65.3	0.0	0.0
16	16.00	1.15	18.4	231.4	114.7	14.6	79.3
17	16.22	2.75	44.6	231.4	198.0	41.9	93.9
18	16.71	2.97	49.6	231.5	216.8	46.6	93.9
20	18.72	2.97	55.6	231.5	239.8	52.4	94.2
25	23.72	2.98	70.7	231.5	300.4	66.9	94.6
30	28.70	2.98	85.5	231.4	360.6	81.3	95.1
31	29.70	2.98	88.5	231.6	373.0	84.2	95.1
32	30.71	2.98	91.5	231.6	384.9	87.0	95.1
33	31.71	2.98	94.5	231.5	397.4	89.9	95.1
34	32.71	2.98	97.5	231.5	409.8	92.8	95.2
35	33.70	2.99	100.8	231.5	422.2	95.7	95.0
36	34.71	2.99	103.8	231.5	434.6	98.6	95.0
37	35.72	2.98	106.4	231.5	446.5	101.4	95.3
38	36.19	2.998	108.5	231.5	454.0	103.2	95.1
39	36.18	2.998	108.5	231.6	454.0	103.2	95.1
40	36.19	2.998	108.5	231.7	453.9	103.2	95.1
41	36.18	2.998	108.5	231.7	453.9	103.2	95.1
42	36.19	2.998	108.5	231.7	453.7	103.1	95.0

Table A-20: Enphase M215 microinverter efficiency data with 3.5 A maximum input DC current.

DC input current set to 3.5A							
Set	BK Precision (DC)			Power Meter (AC)			
Test Level (V)	Vin (DC) (V)	Iin (DC) (A)	Pin (DC) (W)	Vout (AC) (V)	Iout (AC) (mA)	Pout (AC) (W)	Efficiency (%)
15	15.00	0.0235	0.4	231.2	65.4	0.0	0.0
16	16.00	1.14	18.2	231.0	114.6	14.6	80.0
17	16.26	3.10	50.4	231.0	218.6	47.2	93.6
18	16.42	3.46	56.8	231.0	244.0	53.3	93.8
20	18.45	3.46	63.8	231.0	271.8	60.0	94.0
25	23.43	3.47	81.3	231.0	342.8	76.9	94.6
30	28.42	3.47	98.6	231.3	413.9	93.8	95.1
31	29.42	3.48	102.4	231.5	428.2	97.1	94.8
32	30.43	3.48	105.9	231.5	422.9	100.4	94.8
33	31.42	3.48	109.3	231.3	457.1	103.9	95.0
34	32.41	3.48	112.8	231.2	471.4	107.1	95.0
35	33.42	3.48	116.3	231.4	485.8	110.6	95.1
36	34.43	3.48	119.8	231.2	500.0	113.9	95.1
37	35.42	3.48	123.3	231.2	514.6	117.2	95.1
38	36.22	3.498	126.7	231.0	528.6	120.5	95.1
39	36.24	3.498	126.8	231.3	528.4	120.5	95.1
40	36.22	3.498	126.7	231.3	528.1	120.4	95.0
41	36.22	3.498	126.7	231.3	528.1	120.4	95.0
42	36.25	3.498	126.8	231.2	528.1	120.5	95.0

Table A-21: Enphase M215 microinverter efficiency data with 4.0 A maximum input DC current.

DC input current set to 4.0A							
Set	BK Precision (DC)			Power Meter (AC)			
Test Level (V)	Vin (DC) (V)	Iin (DC) (A)	Pin (DC) (W)	Vout (AC) (V)	Iout (AC) (mA)	Pout (AC) (W)	Efficiency (%)
15	15.00	0.0235	0.4	231.5	65.4	0.0	0.0
16	16.00	1.14	18.2	231.4	114.4	14.6	80.0
17	16.29	3.43	55.9	231.3	239.2	52.3	93.6
18	16.32	3.89	63.5	231.3	268.8	59.5	93.7
20	18.15	3.95	71.7	231.3	302.0	67.4	94.0
25	23.12	3.96	91.6	231.3	383.6	86.6	94.6
30	28.12	3.97	111.6	231.5	465.5	105.8	94.8
31	29.13	3.97	115.6	231.3	481.9	109.6	94.8
32	30.13	3.97	119.6	229.9	497.8	113.4	94.8
33	31.12	3.97	123.5	231.6	514.1	117.3	94.9
34	32.13	3.98	127.9	231.7	530.1	121.2	94.8
35	33.12	3.98	131.8	231.6	546.5	125.0	94.8
36	34.12	3.98	135.8	231.6	563.0	128.8	94.8
37	35.12	3.975	139.6	231.6	579.3	132.7	95.1
38	36.11	3.98	143.7	231.5	595.8	136.4	94.9
39	36.29	3.998	145.1	231.6	601.3	137.8	95.0
40	36.28	3.998	145.0	231.5	601.4	137.7	94.9
41	36.28	3.998	145.0	231.5	601.8	137.7	94.9
42	36.28	3.998	145.0	231.5	601.4	137.7	94.9

Table A-22: Enphase M215 microinverter efficiency data with 4.5 A maximum input DC current.

DC input current set to 4.5A							
Set Test Level (V)	BK Precision (DC)			Power Meter (AC)			Efficiency (%)
	Vin (DC) (V)	Iin (DC) (A)	Pin (DC) (W)	Vout (AC) (V)	Iout (AC) (mA)	Pout (AC) (W)	
15	15.00	0.0235	0.4	231.6	65.4	0.0	0.0
16	16.00	1.14	18.2	231.7	114.4	14.6	80.0
17	16.31	3.75	61.2	231.8	259.3	57.3	93.7
18	16.38	4.27	69.9	231.6	292.4	65.2	93.2
20	17.85	4.44	79.3	231.6	330.5	74.2	93.6
25	22.85	4.45	101.7	231.8	422.4	95.9	94.3
30	27.83	4.46	124.1	231.8	514.1	117.5	94.7
31	28.85	4.47	129.0	231.6	532.7	121.8	94.4
32	29.83	4.47	133.3	231.6	551.3	126.0	94.5
33	30.84	4.47	137.9	231.6	569.7	130.4	94.6
34	31.84	4.47	142.3	231.4	588.6	134.8	94.7
35	32.82	4.47	146.7	231.7	606.4	139.0	94.7
36	33.83	4.47	151.2	231.7	625.5	143.4	94.8
37	34.84	4.47	155.7	231.5	644.0	147.7	94.8
38	35.83	4.47	160.2	231.6	662.2	152.0	94.9
39	36.32	4.498	163.4	231.8	675.7	155.0	94.9
40	36.31	4.498	163.3	231.6	674.5	155.0	94.9
41	36.31	4.498	163.3	231.8	674.8	155.0	94.9
42	36.32	4.498	163.4	232.0	674.8	155.0	94.9

Table A-23: Enphase M215 microinverter efficiency data with 5.0 A maximum input DC current.

DC input current set to 5.0A							
Set	BK Precision (DC)			Power Meter (AC)			
Test Level (V)	Vin (DC) (V)	Iin (DC) (A)	Pin (DC) (W)	Vout (AC) (V)	Iout (AC) (mA)	Pout (AC) (W)	Efficiency (%)
15	15.00	0.0235	0.4	232.1	65.5	0.0	0.0
16	16.00	1.16	18.6	232.2	114.3	14.9	80.3
17	16.36	4.09	66.9	232.0	228.8	62.1	92.8
18	16.41	4.62	75.8	232.1	314.3	70.6	93.1
20	17.61	4.94	87.0	232.0	358.3	80.9	93.0
25	22.56	4.94	111.4	232.2	460.0	105.0	94.2
30	27.54	4.96	136.6	231.9	562.5	128.8	94.3
31	28.53	4.96	141.5	232.0	582.2	133.7	94.5
32	29.54	4.96	146.5	232.1	602.8	138.4	94.5
33	30.55	4.96	151.5	232.0	623.5	143.2	94.5
34	31.54	4.96	156.4	232.0	644.0	148.0	94.6
35	32.53	4.96	161.3	232.0	664.5	152.8	94.7
36	33.54	4.96	166.4	231.8	684.9	157.8	94.9
37	34.53	4.96	171.3	232.0	706.0	162.6	94.9
38	35.52	4.96	176.2	232.1	726.0	167.4	95.0
39	36.38	4.998	181.8	232.3	748.0	172.5	94.9
40	36.39	4.998	181.9	232.2	748.0	172.5	94.8
41	36.39	4.998	181.9	232.0	749.0	172.5	94.8
42	36.39	4.998	181.9	232.0	749.0	172.5	94.8

Table A-24: Enphase M215 microinverter efficiency data with 5.5 A maximum input DC current.

DC input current set to 5.5A							
Set Test Level (V)	BK Precision DC Source (DC)			Power Meter (AC)			Efficiency (%)
	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (mA)	P_{out} (W)	
15	14.99	0.0236	0.4	231.9	65.6	0	0
16	15.99	1.15	18.4	231.9	114.0	14.6	79.4
17	16.38	4.39	71.9	231.9	299.0	66.8	92.9
18	16.40	4.98	81.7	232.0	337.4	75.9	92.9
20	17.38	5.40	93.9	231.9	385	87.2	92.9
25	22.31	5.43	121.1	232.0	497	113.4	93.6
30	27.29	5.44	148.5	231.7	610	139.8	94.2
31	28.30	5.44	154.0	231.7	633	145.0	94.2
32	29.30	5.44	159.4	231.8	655	150.3	94.3
33	30.29	5.45	165.1	231.7	678	155.5	94.2
34	31.27	5.44	170.1	231.8	701	160.9	94.6
35	32.28	5.45	175.9	231.8	724	166.3	94.5
36	33.27	5.45	181.3	232.0	745	171.6	94.6
37	34.26	5.45	186.7	232.1	768	176.9	94.7
38	35.28	5.45	192.3	232.1	790	182.2	94.8
39	36.27	5.45	197.7	232.1	813	187.4	94.8
40	36.45	5.497	200.4	232.1	823	189.7	94.7
41	36.29	5.497	199.5	231.8	823	189.6	95.0
42	36.43	5.497	200.3	232.0	823	189.6	94.7

Table A-25: Enphase M215 microinverter efficiency data with 6.0 A maximum input DC current.

DC input current set to 6.0A							
Set Test	BK Precision DC Source (DC)			Power Meter (AC)			
Level	V_{in}	I_{in}	P_{in}	V_{out}	I_{out}	P_{out}	Efficiency
(V)	(V)	(A)	(W)	(V)	(mA)	(W)	(%)
15	14.99	0.023	0.3	231.1	65.7	0	0
16	15.99	1.14	18.2	231.0	114.5	14.5	79.5
17	16.40	4.69	76.9	231.0	319.8	71.5	93.0
18	16.50	5.32	87.8	231.0	361.1	81.2	92.5
20	17.10	5.87	100.4	231.0	412.2	93.2	92.8
25	22.10	5.93	131.1	231.0	534.0	121.7	92.9
30	27.00	5.93	160.1	231.0	657.4	150.3	93.9
31	28.04	5.94	166.6	231.0	681.6	156.1	93.7
32	29.00	5.93	172.0	231.0	707	162.0	94.2
33	30.40	5.93	180.3	231.0	732	167.8	93.1
34	31.00	5.93	183.8	231.0	756	173.6	94.4
35	32.00	5.94	190.1	231.0	781	179.3	94.3
36	33.00	5.94	196.0	231.0	805	184.9	94.3
37	34.00	5.94	202.0	231.0	830	190.7	94.4
38	35.00	5.94	207.9	231.0	855	196.5	94.5
39	36.00	5.94	213.8	231.0	879	202.2	94.6
40	36.50	5.99	218.6	231.0	900	206.8	94.6
41	36.50	5.99	218.6	231.0	900	206.9	94.6
42	36.50	6.00	219.0	231.0	900	206.8	94.4

Table A-26: Enphase M215 microinverter efficiency data with 6.3 A maximum input DC current.

DC input current set to 6.3A							
Set Test Level (V)	BK Precision DC Source (DC)			Power Meter (AC)			Efficiency (%)
	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (mA)	P_{out} (W)	
15	14.99	0.0235	0.4	231.5	65.6	0.0	0
16	15.99	1.14	18.2	231.4	114.0	14.6	80.1
17	16.45	4.86	79.9	231.8	330	73.9	92.4
18	16.50	5.52	91.1	231.5	373	84.2	92.4
20	16.90	6.19	104.6	231.5	426	96.7	92.4
25	21.90	6.20	135.8	231.6	554	126.6	93.2
30	26.82	6.22	166.8	231.6	682	156.7	93.9
31	27.84	6.22	173.2	231.6	709	162.8	94.0
32	28.83	6.23	179.6	231.5	735	168.8	94.0
33	29.83	6.23	185.8	231.8	760	174.9	94.1
34	30.80	6.23	191.9	231.6	787	180.9	94.3
35	31.82	6.24	198.6	231.7	812	186.9	94.1
36	32.82	6.24	204.8	231.5	838	193.0	94.2
37	33.80	6.24	210.9	231.8	864	199.9	94.8
38	34.52	6.24	215.4	231.7	890	205.0	95.2
39	35.81	6.24	223.5	231.6	916	210.9	94.4
40	36.52	6.30	230.1	231.8	941	217.2	94.4
41	36.51	6.30	230.0	231.7	942	217.1	94.4
42	36.52	6.29	229.7	231.5	942	217.0	94.5

Table A-27: Enphase M215 microinverter efficiency data with 6.4 A maximum input DC current.

DC input current set to 6.4A							
Set Test	BK Precision DC Source (DC)			Power Meter (AC)			
Level (V)	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (mA)	P_{out} (W)	Efficiency (%)
15	14.99	0.0235	0.4	229.9	65.0	0.0	0
16	16.00	1.14	18.2	229.9	114.0	14.4	78.9
17	16.40	4.94	81.0	229.9	335.5	74.9	92.5
18	16.50	5.57	91.9	229.7	380.2	85.1	92.6
20	16.90	6.27	106.0	229.7	434.4	97.8	92.3
25	21.80	6.30	137.3	229.7	564.7	128.1	93.3
30	26.79	6.31	169.0	230.8	639.5	158.5	93.8
31	27.76	6.32	175.4	230.7	720	164.7	93.9
32	28.77	6.32	181.8	230.5	746	171.0	94.0
33	29.75	6.32	188.0	230.4	775	177.1	94.2
34	30.77	6.33	194.8	230.2	802	183.2	94.1
35	31.77	6.33	201.1	230.3	827	189.3	94.1
36	32.77	6.33	207.4	230.3	854	195.5	94.2
37	33.75	6.33	213.6	230.2	881	201.4	94.3
38	34.76	6.34	220.4	230.3	906	207.5	94.2
39	35.75	6.34	226.7	229.9	935	213.7	94.3
40	36.53	6.39	233.4	229.8	963	220.3	94.4
41	36.55	6.40	233.9	230.0	963	220.4	94.2
42	36.55	6.40	233.9	229.7	964	220.3	94.2

Table A-28: Enphase M215 microinverter efficiency data with 6.5 A maximum input DC current.

DC input current set to 6.5A							
Set Test Level (V)	BK Precision DC Source (DC)			Power Meter (AC)			Efficiency (%)
	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (mA)	P_{out} (W)	
15	14.99	0.0235	0.4	231.7	65.5	0.0	0
16	16.00	1.14	18.2	231.3	114.5	14.57	79.9
17	16.40	4.99	81.8	231.5	337.3	75.7	92.5
18	16.50	5.67	93.6	231.6	381.5	86.2	92.1
20	16.85	6.37	107.3	231.7	435.5	99.0	92.2
25	21.79	6.39	139.2	231.8	567.3	129.7	93.1
30	26.72	6.42	171.5	230.2	704	160.8	93.7
31	27.73	6.42	178.0	230.0	732	167.0	93.8
32	28.73	6.42	184.4	230.0	759	173.2	93.9
33	29.71	6.42	190.7	231.2	785	179.4	94.1
34	30.71	6.42	197.2	229.8	813	185.6	94.1
35	31.72	6.43	204.0	230.0	839	191.8	94.0
36	32.71	6.43	210.3	229.9	866	198.1	94.2
37	33.71	6.43	216.8	229.9	893	204.3	94.3
38	34.72	6.43	223.2	230.0	920	210.5	94.3
39	35.71	6.43	229.6	229.9	947	216.8	94.4
40	36.49	6.47	236.1	229.9	976	223.2	94.5
41	36.50	6.50	237.3	229.8	980	223.8	94.3
42	36.50	6.49	236.9	231.4	972	223.8	94.5

Table A-29: Enphase M215 microinverter efficiency data with 7.0 A maximum input DC current.

DC input current set to 7.0A							
Set Test	BK Precision DC Source (DC)			Power Meter (AC)			
Level (V)	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (mA)	P_{out} (W)	Efficiency (%)
15	14.99	0.0235	0.4	232.4	65.6	0.0	0
16	16.00	1.15	18.4	232.2	114.0	14.6	79.3
17	16.48	5.26	86.7	232.3	355	80.2	92.5
18	16.51	5.99	98.9	232.4	402	91.2	92.2
20	16.61	6.85	113.8	232.8	458	104.4	91.8
25	21.50	6.87	147.7	232.7	598	137.4	93.0
30	26.45	6.89	182.2	232.0	742	170.8	93.7
31	27.45	6.90	189.4	232.0	771	177.6	93.8
32	28.46	6.90	196.4	232.1	799	184.2	93.8
33	29.44	6.91	203.4	232.1	827	190.8	93.8
34	30.45	6.91	210.4	232.0	856	197.5	93.9
35	31.43	6.91	217.2	232.2	884	204.1	94.0
36	32.42	6.91	224.0	232.2	913	210.8	94.1
37	33.43	6.92	231.3	232.2	941	217.1	93.8
38	34.43	6.92	238.3	232.4	969	224.2	94.1
39	36.28	6.64	240.9	232.3	983	227.3	94.4
40	37.93	6.37	241.6	232.3	986	228.0	94.4
41	39.41	6.12	241.2	232.4	985	228.0	94.5
42	40.73	5.93	241.5	232.6	985	228.3	94.5

Table A-30: Enphase M215 microinverter efficiency data with 7.5 A maximum input DC current.

DC input current set to 7.5A							
Set Test Level (V)	BK Precision DC Source (DC)			Power Meter (AC)			Efficiency (%)
	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (mA)	P_{out} (W)	
15	15.00	0.0235	0.4	230.6	65.1	0.0	0
16	15.99	1.14	18.2	230.6	114.0	14.5	79.5
17	16.51	5.56	91.8	230.6	376.0	84.6	92.2
18	16.55	6.30	104.3	230.4	426.0	96.1	92.2
20	16.69	7.25	121.0	230.6	486.0	110.2	91.1
25	21.27	7.36	156.5	230.6	634.0	144.8	92.5
30	26.19	7.39	193.5	230.6	782.0	180.6	93.3
31	27.20	7.39	201.0	232.8	812	187.7	93.4
32	28.18	7.40	208.5	232.7	842	194.7	93.4
33	29.17	7.40	215.9	232.7	872	201.8	93.5
34	30.16	7.40	223.2	232.8	903	209.0	93.6
35	31.17	7.40	230.7	232.7	934	216.1	93.7
36	32.15	7.40	237.9	232.8	964	223.2	93.8
37	34.11	7.12	242.9	231.2	988	227.5	93.7
38	35.96	6.75	242.7	231.2	990	227.6	93.8
39	37.42	6.48	242.5	231.2	993	228.1	94.1
40	38.76	6.25	242.3	231.4	991	228.3	94.2
41	40.05	6.06	242.7	230.8	996	228.9	94.3
42	41.27	5.89	243.1	230.9	996	228.9	94.2

A.3 Extra CUI DC-DC Converter Data

Table A-31: CUI DC-DC Converter efficiency data with efficiency calculations exceeding 100% for test level voltages of 28 V and below.

DC input current set to 7.5A							
Test Level (V)	BK Precision DC Source (DC)			Power Meter (DC)			Efficiency (%)
	V_{in} (V)	I_{in} (A)	P_{in} (W)	V_{out} (V)	I_{out} (A)	P_{out} (W)	
26	26.00	2.81	73.06	27.44	2.75	75.3	103.1
27	27.00	2.72	73.55	27.44	2.74	75.2	102.2
28	28.00	2.68	75.04	27.44	2.74	75.2	100.2
29	29.00	2.62	76.10	27.45	2.75	75.3	99.0
30	30.00	2.58	77.31	27.45	2.75	75.3	97.4
31	31.00	2.53	78.40	27.44	2.74	75.3	96.0
32	32.00	2.49	79.71	27.44	2.74	75.2	94.3
33	33.00	2.46	81.18	27.44	2.74	75.2	92.6
34	34.00	2.41	81.97	27.44	2.74	75.2	91.7
35	35.00	2.36	82.53	27.44	2.74	75.1	91.0
36	35.99	2.30	82.85	27.44	2.74	75.1	90.6
37	37.00	2.26	83.47	27.43	2.74	75.1	90.0
38	38.00	2.21	83.98	27.43	2.74	75.0	89.3
39	38.99	2.18	84.92	27.43	2.74	75.0	88.3
40	40.00	2.13	85.04	27.43	2.74	75.0	88.2
41	40.99	2.07	84.77	27.43	2.74	75.0	88.5
42	41.99	2.02	84.69	27.43	2.74	75.0	88.6
43	42.99	1.97	84.69	27.43	2.73	75.0	88.6
44	43.99	1.93	84.72	27.43	2.73	75.0	88.5
45	45.00	1.88	84.78	27.43	2.73	75.0	88.5
46	46.00	1.84	84.82	27.43	2.73	75.0	88.4
47	47.00	1.81	84.88	27.42	2.73	74.9	88.2
48	48.00	1.77	84.96	27.42	2.73	74.9	88.2
49	48.99	1.74	85.00	27.43	2.73	74.9	88.1
50	50.00	1.70	85.05	27.42	2.73	74.9	88.1
51	50.99	1.67	85.15	27.42	2.73	74.9	88.0
52	52.00	1.64	85.23	27.42	2.73	74.9	87.9
53	53.00	1.61	85.33	27.42	2.73	74.9	87.8
54	54.00	1.58	85.43	27.42	2.73	74.9	87.7
55	54.99	1.56	85.51	27.42	2.73	74.9	87.6
56	55.99	1.52	85.27	27.42	2.73	74.9	87.8
57	56.99	1.50	85.71	27.42	2.73	74.9	87.4
58	57.99	1.48	85.83	27.42	2.73	74.9	87.3
59	58.99	1.46	85.95	27.42	2.73	74.9	87.1
60	59.99	1.43	86.03	27.42	2.73	74.9	87.1
61	60.99	1.41	86.12	27.42	2.73	74.9	87.0

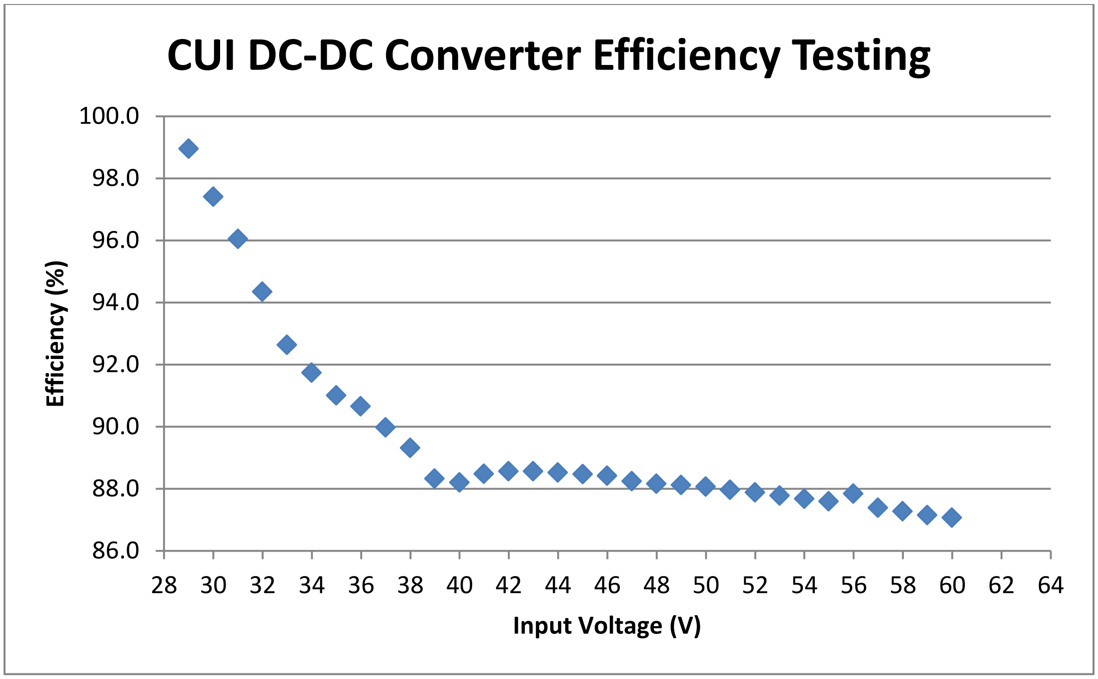

Figure A-1: Scatter plot of CUI DC-DC converter efficiency data from Table A-31 for a supplied input voltage range.

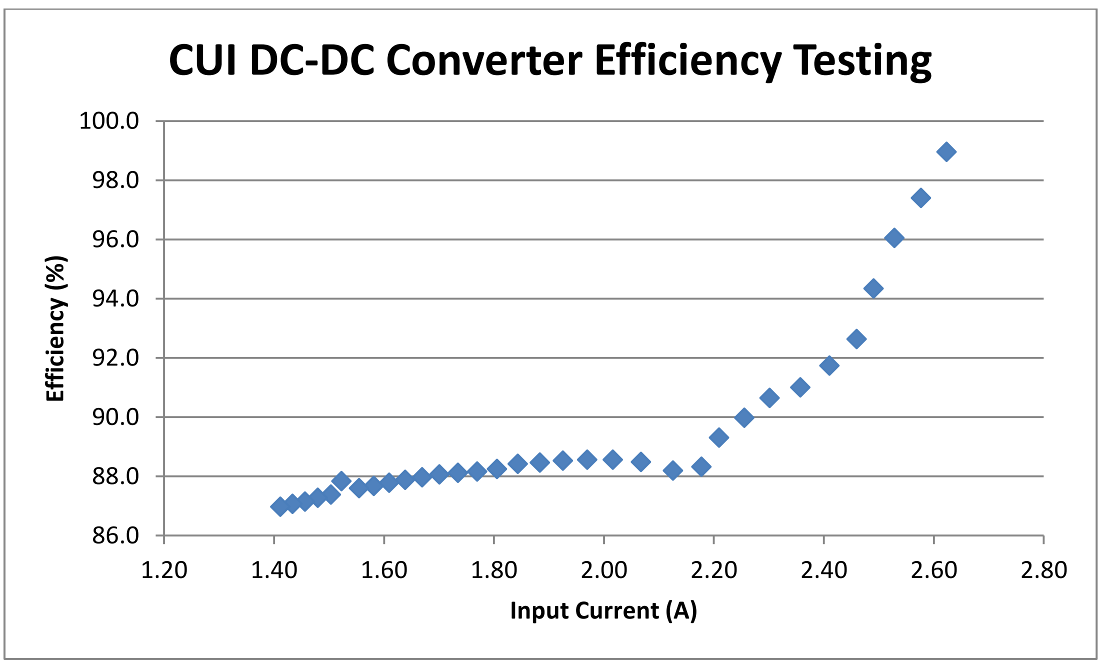

Figure A-2: Scatter plot of CUI DC-DC converter efficiency data from Table A-31 for a supplied input current range.

A.4 Extra Data for DC-DC Converter and Microinverter Combination Testing

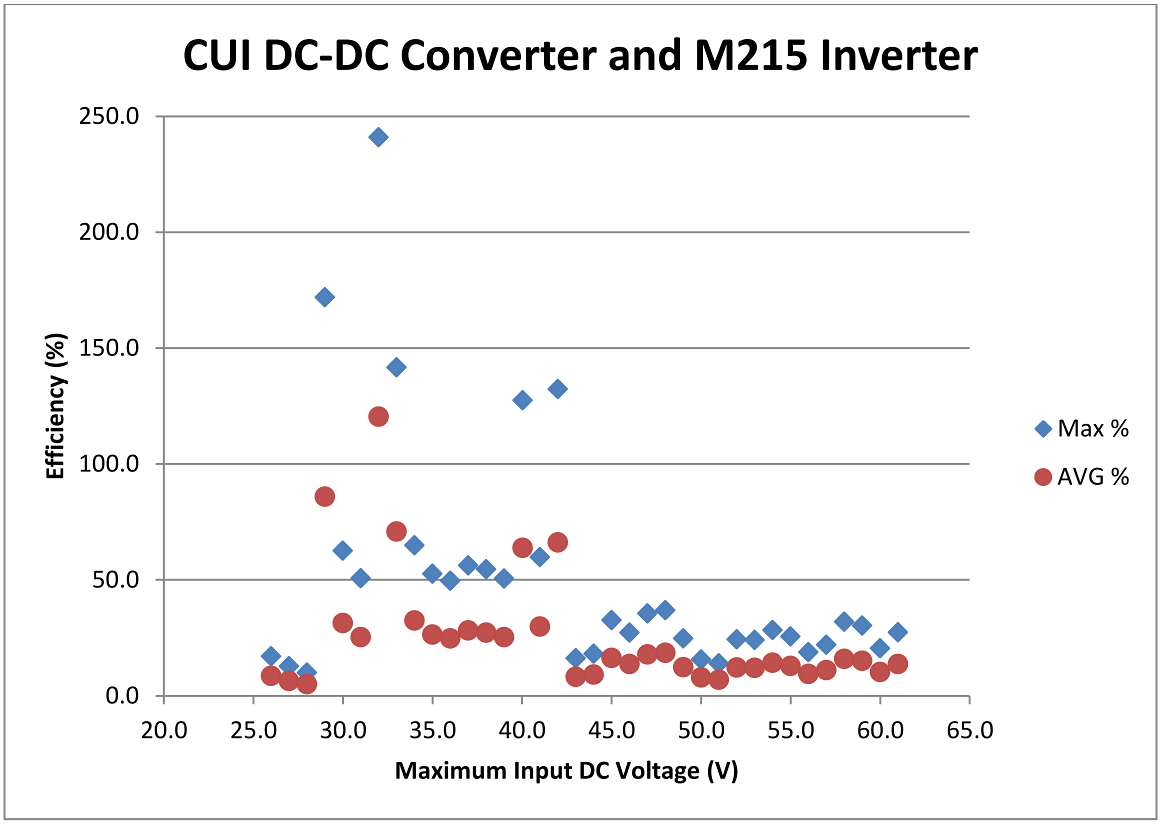

Figure A-3: CUI DC-DC Converter and Enphase M215 Inverter efficiency plot. Scatter plot includes calculated maximum and average efficiency calculations from power measurements including those greater than 100%.

A.5 Extra Data for Elliptical Testing without a DC-DC Converter

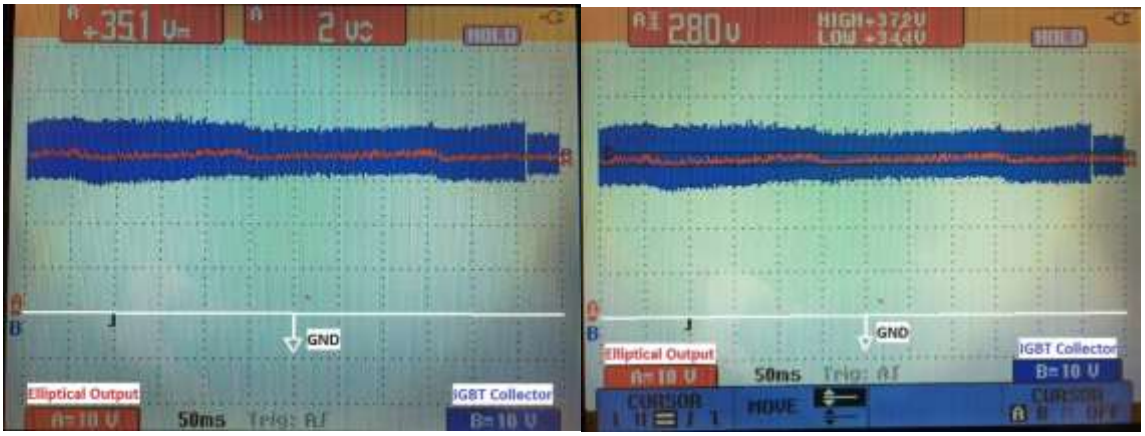

Figure A-4: Waveform captures of the Elliptical Output (red) and IGBT Collector (blue) voltages using an Isolated Scopemeter. The left image displays the average electrical output voltage measurement. The right image displays the maximum and minimum voltage measurements via cursors. Elliptical Resistance Setting = 4, Pace = 100 SPM.

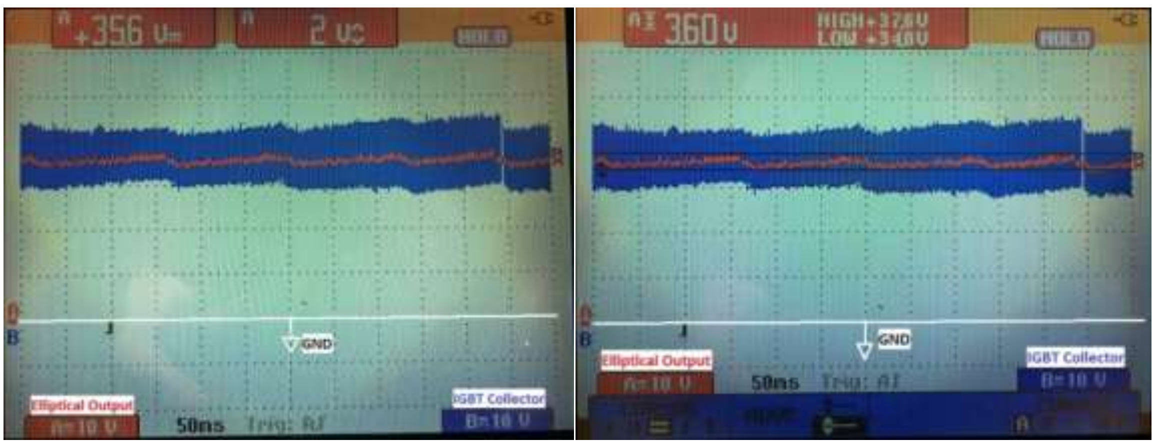

Figure A-5: Waveform captures of the Elliptical Output (red) and IGBT Collector (blue) voltages using an Isolated Scopemeter. The left image displays the average electrical output voltage measurement. The right image displays the maximum and minimum voltage measurements via cursors. Elliptical Resistance Setting = 6, Pace = 100 SPM.

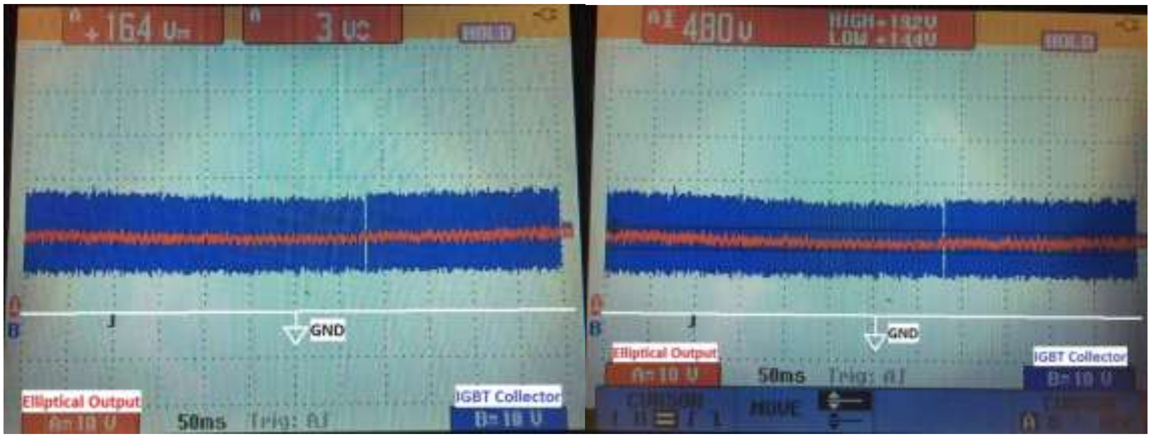

Figure A-6: Waveform captures of the Elliptical Output (red) and IGBT Collector (blue) voltages using an Isolated Scopemeter. The left image displays the average electrical output voltage measurement. The right image displays the maximum and minimum voltage measurements via cursors. Elliptical Resistance Setting = 12, Pace = 100 SPM.

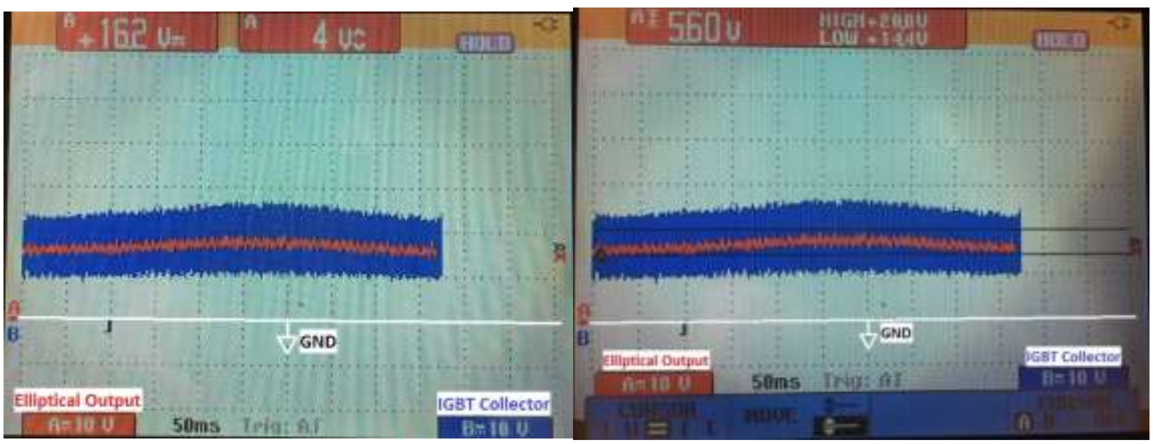

Figure A-7: Waveform captures of the Elliptical Output (red) and IGBT Collector (blue) voltages using an Isolated Scopemeter. The left image displays the average electrical output voltage measurement. The right image displays the maximum and minimum voltage measurements via cursors. Elliptical Resistance Setting = 14, Pace = 100 SPM.

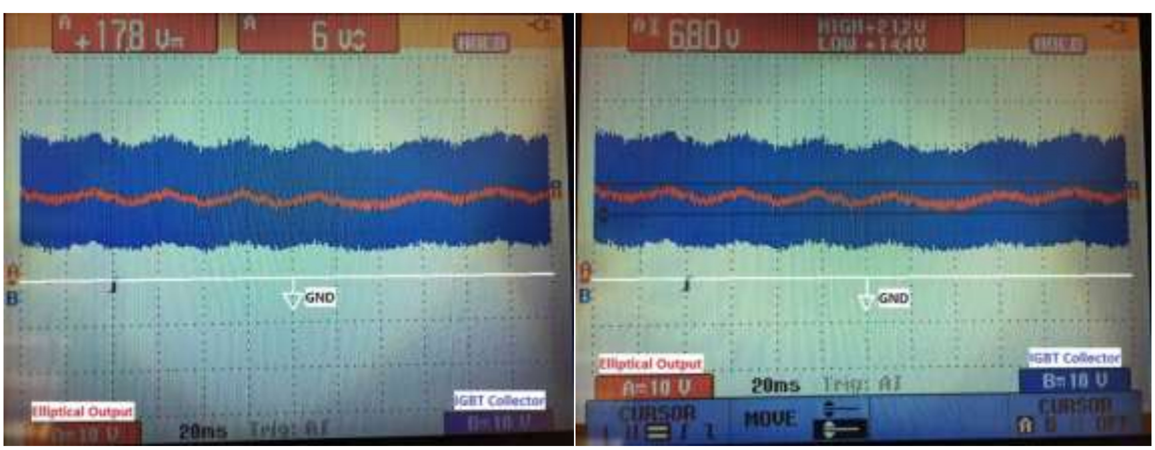

Figure A-8: Waveform captures of the Elliptical Output (red) and IGBT Collector (blue) voltages using an Isolated Scopemeter. The left image displays the average electrical output voltage measurement. The right image displays the maximum and minimum voltage measurements via cursors. Elliptical Resistance Setting = 6, Pace = 150 SPM.

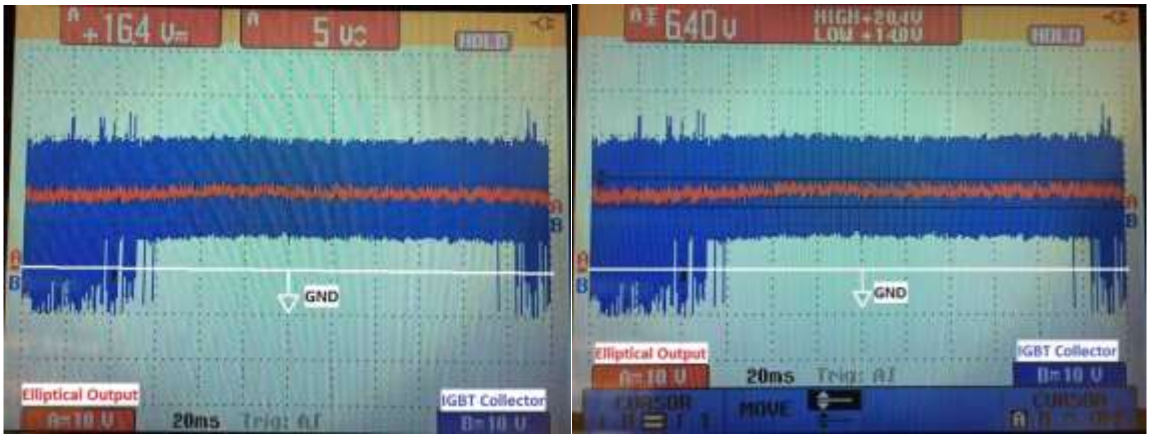

Figure A-9: Waveform captures of the Elliptical Output (red) and IGBT Collector (blue) voltages using an Isolated Scopemeter. The left image displays the average electrical output voltage measurement. The right image displays the maximum and minimum voltage measurements via cursors. Elliptical Resistance Setting = 12, Pace = 150 SPM.

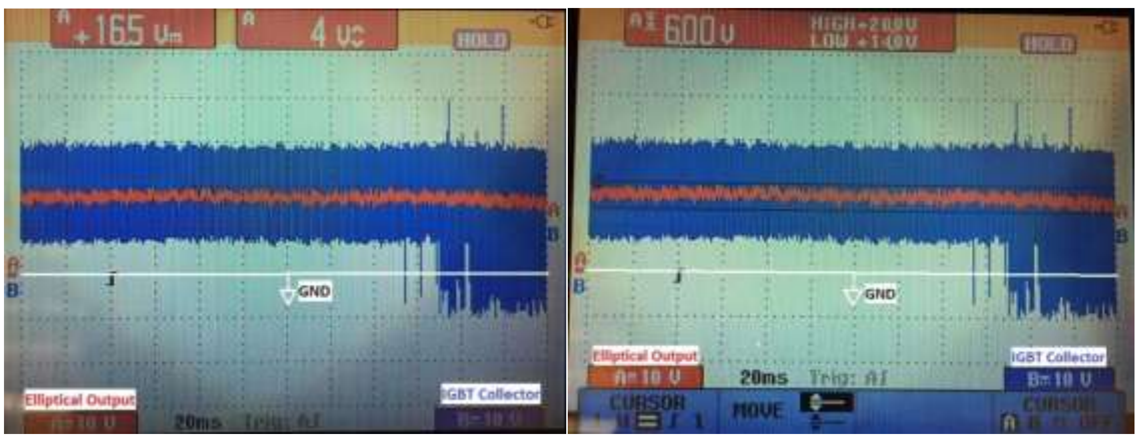

Figure A-10: Waveform captures of the Elliptical Output (red) and IGBT Collector (blue) voltages using an Isolated Scopemeter. The left image displays the average electrical output voltage measurement. The right image displays the maximum and minimum voltage measurements via cursors. Elliptical Resistance Setting = 14, Pace = 150 SPM.

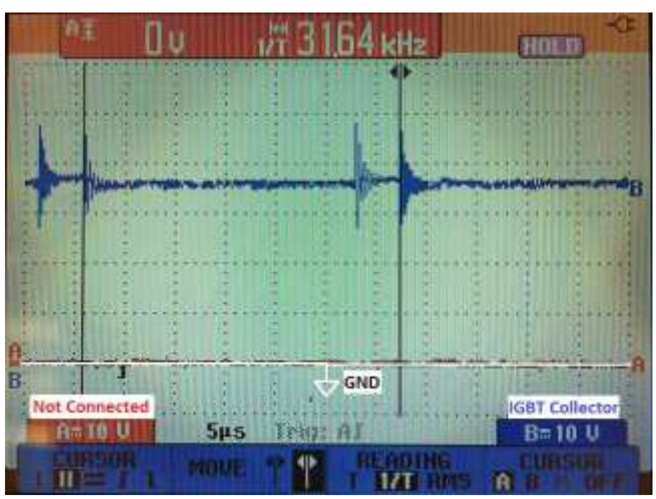

Figure A-11: Oscilloscope cursors measure the frequency between ringing oscillation peaks on the IGBT. Elliptical Resistance Setting = 4, Pace = 150 SPM.

A.6 Extra Data for Full System Testing

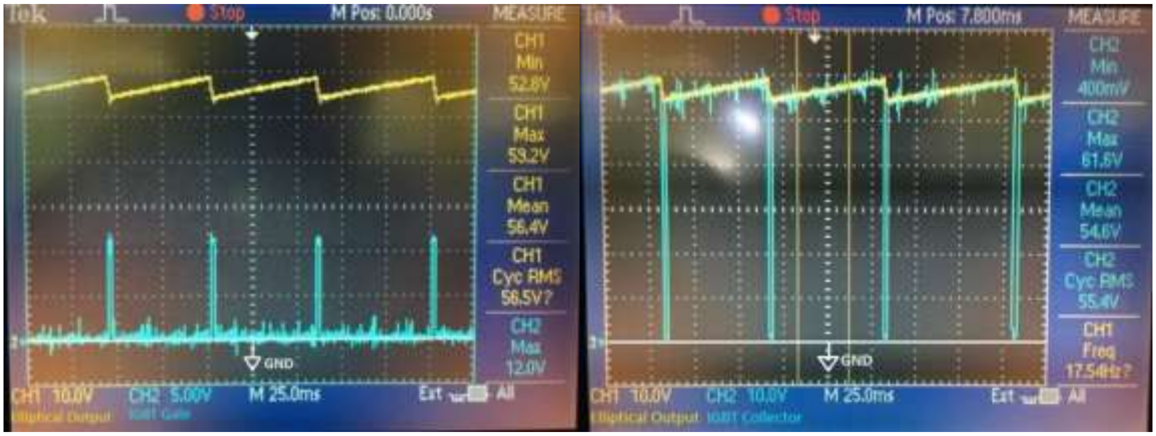

Figure A-12: Oscilloscope capture of input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 8, 100 SPM

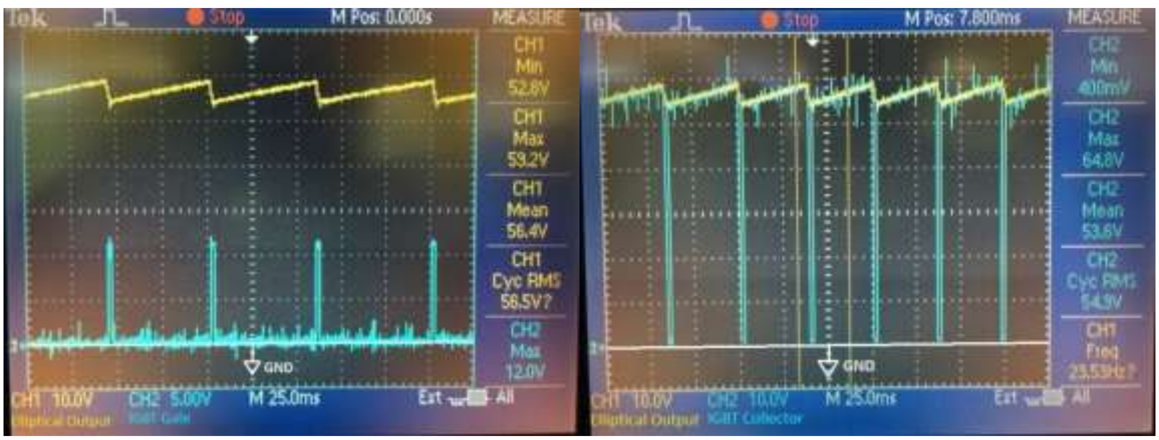

Figure A-13: Oscilloscope capture of input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 10, 100 SPM

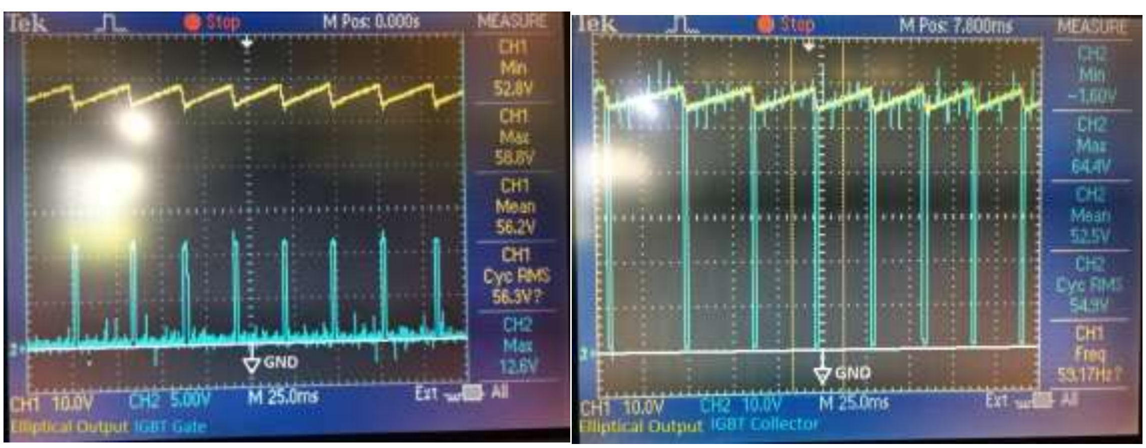

Figure A-14: Oscilloscope capture of input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 12, 100 SPM

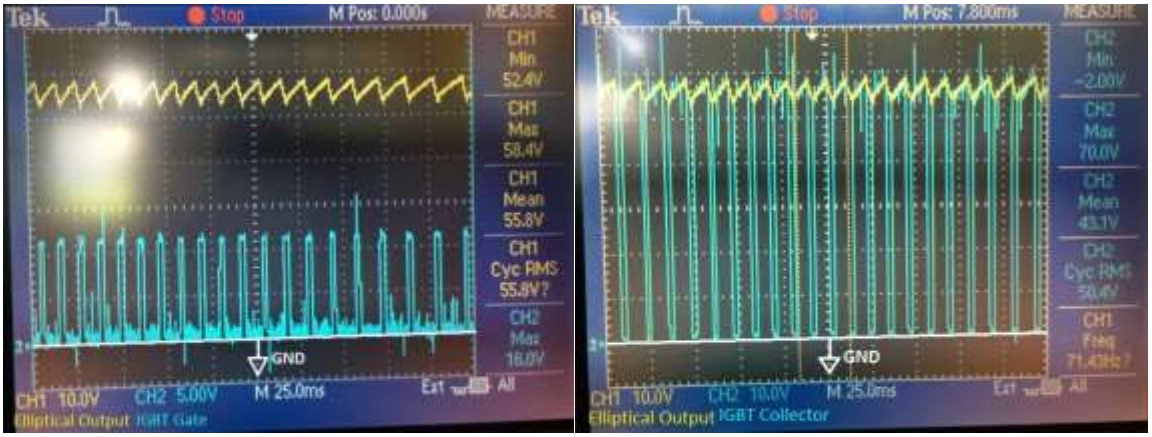

Figure A-15: Oscilloscope capture of input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 14, 100 SPM

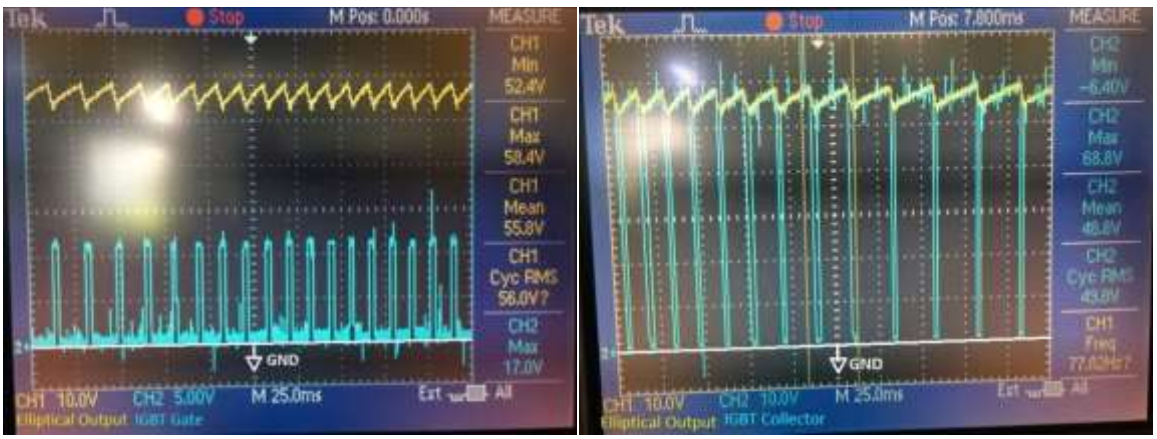

Figure A-16: Oscilloscope capture of input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 14, 100 SPM

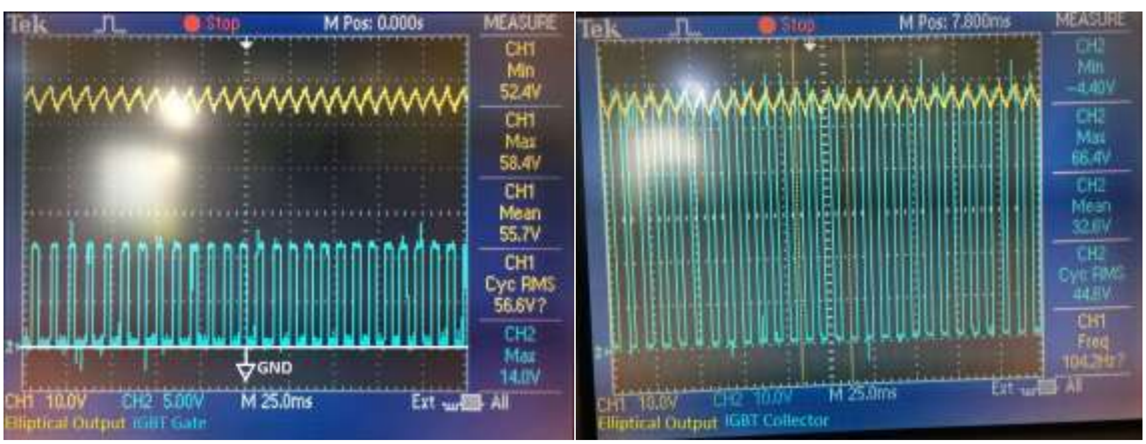

Figure A-17: Oscilloscope capture of input voltage (yellow), IGBT gate voltage (blue, left), and IGBT collector voltage (blue, right). Elliptical Resistance = 18, 100 SPM

APPENDIX B — TEST PROTOCOLS AND NECESSARY EQUIPMENT

B.1 Preparing the Precor Elliptical Trainer for Testing

Begin by removing the protective housing on the back of the Precor elliptical. Remove the sides of the housing first. A hex key screw secures the side panels as shown in Figure B-1. Using an Allen wrench or hex key sized for 4 mm or 5/32 inches, remove the two screws.

Figure B-1: Photo of the back of the protective housing. Remove hex key screws with 4 mm or 5/32 in. to remove side panels.

Next, remove the left side panel by twisting on the panel clockwise to unlock the protective panel from the elliptical. Remove the right side panel by twisting in a counterclockwise direction as shown in Figure B-2 below. Place the panels a safe distance away from the testing area.

Figure B-2: Turn counterclockwise to remove right side panel seen here. Turn clockwise to remove the left side panel.

Next, remove the top panel with a 1/4 in flathead screwdriver to unscrew the two remaining screws that secure the top panel to the rest of the elliptical. Figure B-3 below shows one of the two screws. The other screw exists on the opposite side. After removing both screws, the top panel slides out easily from the bottom of the housing by lifting up the panel.

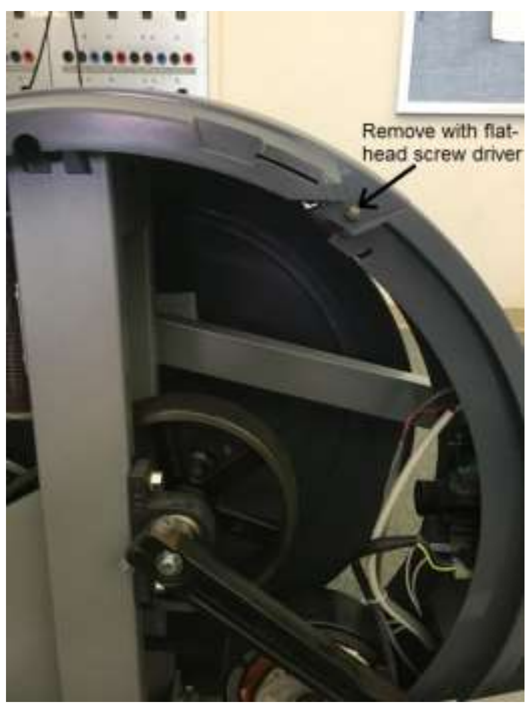

Figure B-3: Remove screw to remove back housing panel. This picture shows only one of the screws to remove. The other one resides on the other side of the elliptical.

There exists a small area where wires can connect to the elliptical's load resistor and extend from the elliptical without obstructing elliptical movement. Figure B-4 attempts to show the space where test wires can connect elliptical circuitry. Any wires entangling in moving parts can cause major damage to the elliptical, any of the EHFEM components, the testing equipment, or a user. Moving parts include the black and silver metal bars seen in Figure B-4 that move alongside the elliptical as a user pedals.

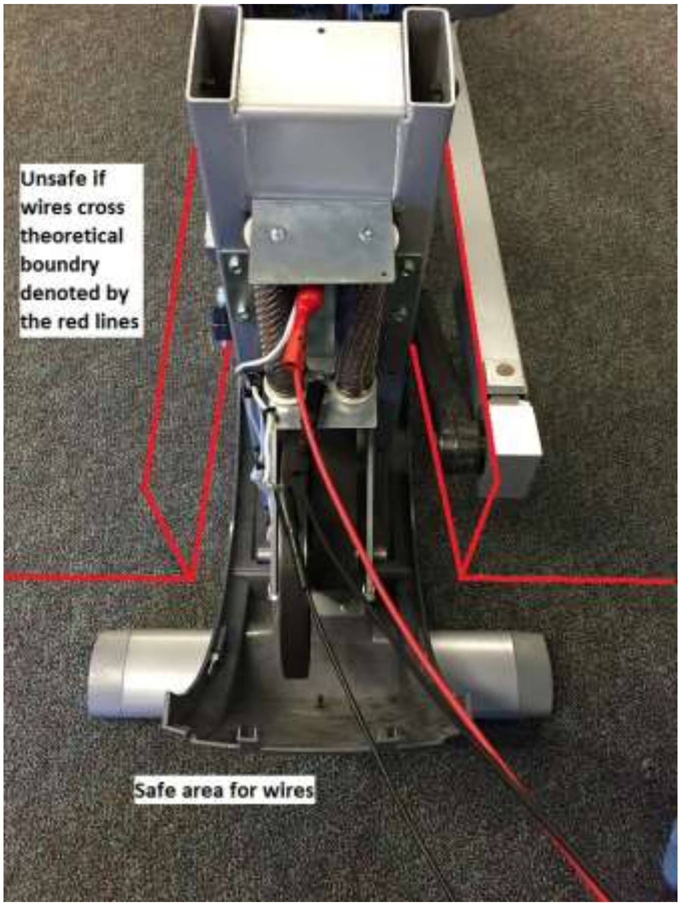

Figure B-4: Wires connecting to the elliptical must not cross the boundary separating non-moving parts and wires from the elliptical's rotating pedal beams or risk entangling with the elliptical when in use.

Verify the resistance of the load resistor. The elliptical's load resistor consists of two 20 Ω, 240 W resistors connected in parallel to form a 10 Ω load. This load resides within the back panel portion of the elliptical and a mounting bracket secures the load in place. Use an Agilent multimeter to measure the actual resistance of the load.

The elliptical resistor measures: **9.85 Ω** .

Using a 3/8 inch nut driver, disconnect the lower white wire that connects the load resistor to the elliptical's energy generating circuit. When testing, a red banana-to-banana cable clips to the top of the load resistor with an alligator clip. Another red banana-to-banana cable clips to the bottom of the load resistor and connects to the IGBT's collector pin in the OVPC. The white wire disconnected from the load resistor now connects to the ground node. Figure B-5 below shows a picture of this connection.

Figure B-5: Picture showing the bottom white wire disconnected from the elliptical's internal resistor and connecting to a test system's ground wire. The red wire in this photo connects to the input of an OVPC and the black wire at the other end of the resistor connects to an IGBT's collector terminal.

Lastly, verify the elliptical battery's voltage using an Agilent multimeter. The Precor elliptical houses the battery in the smaller housing towards the bottom-front of the elliptical. Figure B-6 shows a picture of the battery within the housing. The battery's voltage should measure 12 V.

The Battery Voltage Measures: **13.02 V** .

Figure B-6: Picture showing the 12-Volt battery within its protective housing located towards the bottom-front of the Precor elliptical.

We measure the battery voltage in anticipation of using the battery when testing with the elliptical. This 12-Volt battery would supply the 12 V potential as part of the OVPC. However, as shown in Figure 2-2 in Chapter 2, the wires from the battery connect to the energy generating circuit with special connectors. We cannot safely connect to the battery without interfering with the energy harvesting circuit and instead use a RIGOL DP832 9313-PS DC source to supply the 12-Volt rail. A final EHFEM design seeks to incorporate the elliptical's internal battery.

B.2 Delivering Power to Room 150 in Engineering East

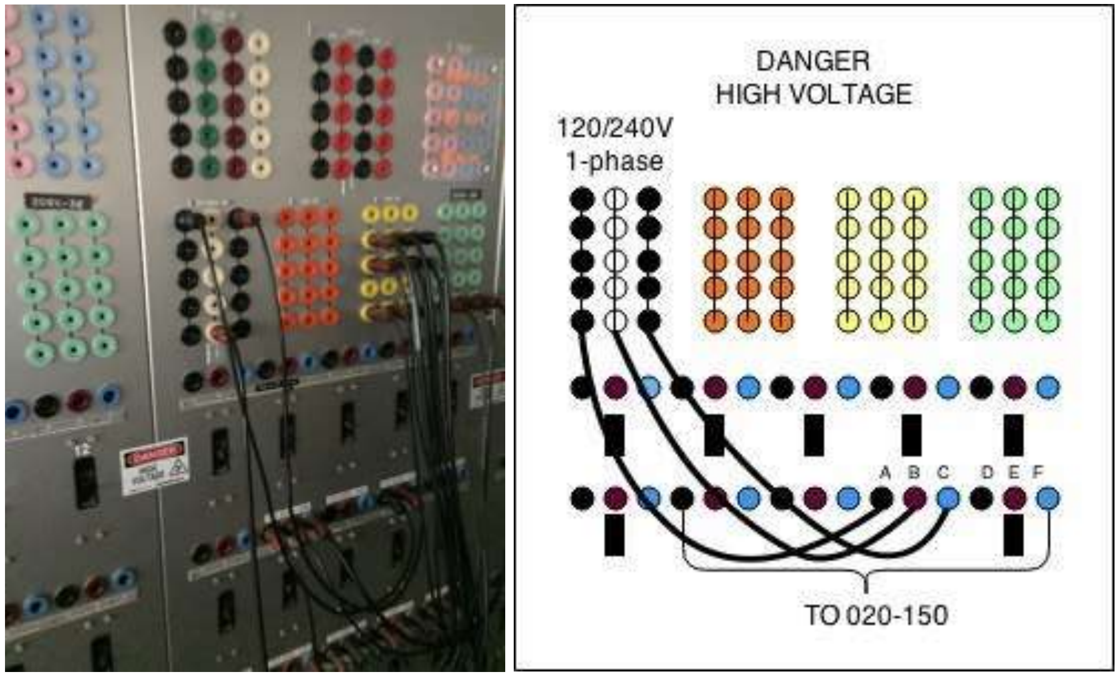

Figure B-7: The main power grid in room 102 supplies various voltage levels and phases of AC power to other rooms of Engineering East. The left picture shows the power wall in room 102 while the right diagram shows the connections necessary to deliver 240 V of line-to-line AC power to room 102.

In room 102 of Engineering East, connect the 120/240V single-phase AC power source to the A, B, and C terminals as shown in Figure B-7. Doing so supplies a +120V line, -120V line, and a neutral line to room 150. The specific grouping of the A, B, and C terminals have the label **T1**. The left image in Figure B-7 shows a picture of the power wall with power connectors delivering power to the panel in room 150. The right image depicts a simplified diagram of the power wall with label otherwise not easily seen in the picture.

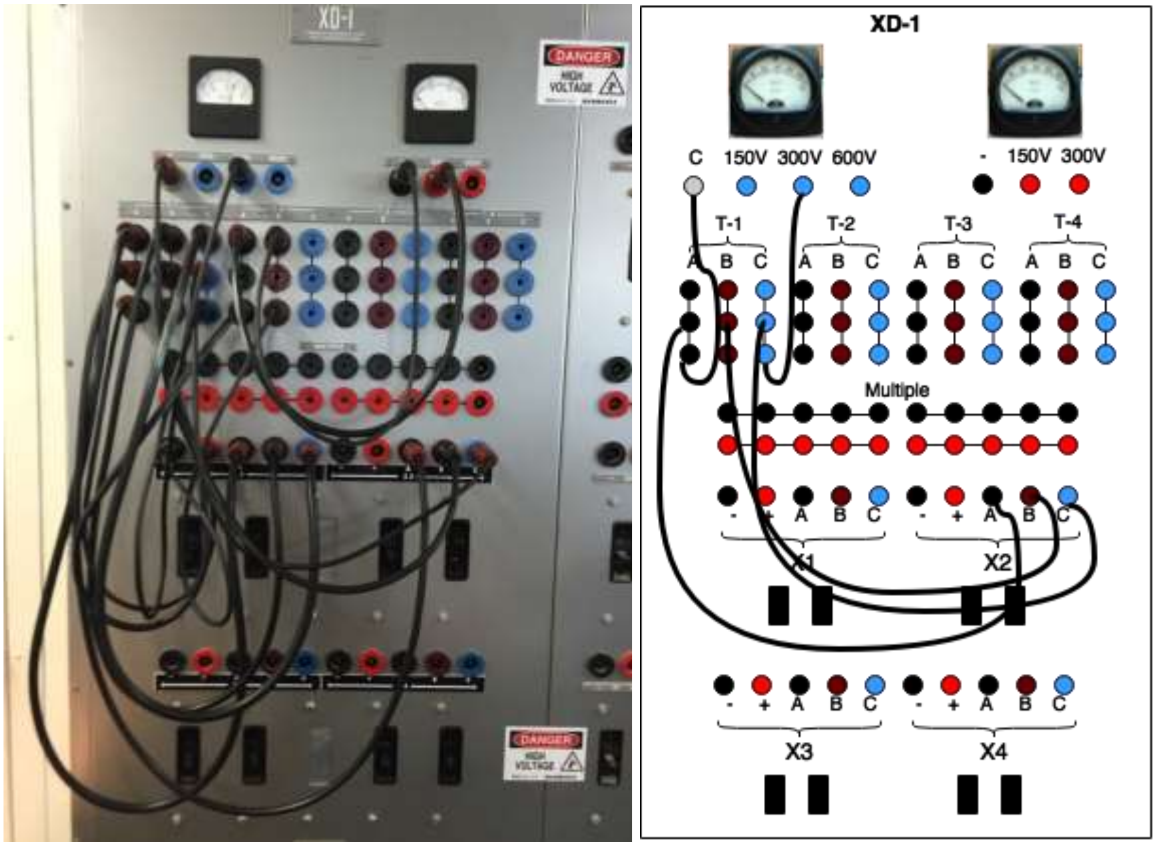

Figure B-8: Room 150 power grid. The left picture shows the power panel with the voltage meter displaying between 230 V AC and 240 V AC at the top-left. The right diagram highlights the connections necessary to connect the lab bench in room 150 to the AC power grid.

Next, supply power to lab bench **X2** in room 150. On the XD-1 power panel in room 150, verify that the panel receives power from room 102. The meter at the top of the panel should read 120V line-neutral AC voltage, or 240V line-line AC voltage. Use high power cables to transfer the power delivered from room 102 to connecting nodes labeled T-1 in Figure B-8. Connect the C power terminal to terminal A and connect the 300V power terminal to terminal C. To deliver AC power to the lab bench, connect the A, B, and C terminals of T-1 to the A, B, and C terminals of X2. The left image in Figure B-8 shows a picture of the power wall with power connectors delivering power to the panel in room 150. The right image depicts a simplified diagram of the power wall with labels otherwise not easily seen in the picture.

Figure B-9: An Agilent multimeter measures 231.4 V of AC voltage on the X2 lab bench in room 150, confirming the bench receives power and testing can begin.

Verify that lab bench X2 receives AC power by connecting an Agilent multimeter to the lab bench as shown in Figure B-9. Set the multimeter to measure AC voltage and measure the line-line and line-neutral voltages. Measure the line-line voltage by connecting banana-to-banana cables to the ϕA and ϕC terminals. Figure B-9 above shows a photo of an Agilent Multimeter measuring the line-line AC voltage. Measure the line-neutral voltage by connecting banana-to-banana cables to the ϕA and ϕB terminals.

Line-Line Voltage: **232.1 V_{ac}**.

Line-Neutral Voltage: **116.1 V_{ac}**.

After verifying the lab bench receives power, conducting any sort of testing at the lab bench can commence.

B.3 Testing Both Enphase M175 and Enphase M215 Microinverters

Necessary Equipment

Enphase M175-24-240 Microinverter		Multimeter: Agilent U3401A	
Enphase M215-60-2LL-S25-IG Microinverter		Oscilloscope: Tektronix TDS 2002	
DC Source: BK Precision Model 9153		Banana-to-Banana cables	(8)
Power meter: GWINSTEK GPM-8212		Spade lug-to-Banana cables	(2)
High power cables for Power Wall	(8)	Oscilloscope Scope Probe	(1)

Test Setup and Procedure

I. Connect the M175 microinverter to the electrical grid using a lab bench. Figure B-10 depicts the wiring diagrams for connecting the M175 and M215 inverters to the lab bench

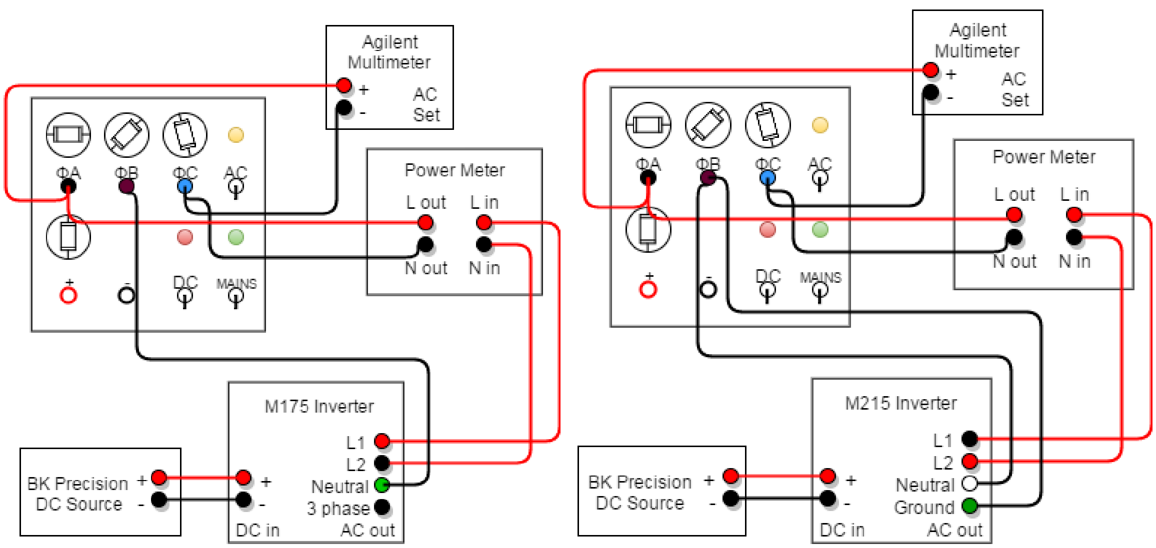

Figure B-10: Wiring diagrams for testing the Enphase M175 microinverter (left) and M215 microinverter (right).

1. Test the microinverters using a high-power lab bench in room 150, a DC source capable of supplying up to 50 V and 7.5 A, a power meter, and a multimeter.

a. Connect the DC Source to the Input of the microinverter via spade lug-to-banana cable. The banana ends of the cables should connect directly to the DC input of each microinverter.

b. **For the Enphase M175 microinverter:** Connect the AC output of the M175 microinverter to the high-power lab bench in room 150 through a power meter as shown in Figure B-10.

   i. Connect the red output port of M175 microinverter, “L1”, to the red input port of the power meter, “L in”. Use a banana-to-banana cable.

      1. Both “L1” and “L2” have red banana-to-banana cables connecting to the M175’s black output cables via an adapter. A piece of red electrical tape distinguishes one of the inverter’s output power lines from the other. The M175 inverter should function regardless of which line connects to ϕA or ϕC, so arbitrarily select one as “L1” and the other as “L2”.

   ii. Connect “L out” of the power meter to the “ϕA” terminal of the power bench. Use a banana-to-banana cable.

   iii. Connect the red output port of the M175 microinverter, “L2”, to the black input port of the power meter, “N in”. Use a banana-to-banana cable.

   iv. Connect “N out” of the power meter to the “ϕC” terminal of the power bench. Use a black banana-to-banana cable.

   v. Connect the black output port of the M175 microinverter, neutral, to the “ϕB” terminal of the power bench. Use a banana-to-banana cable.

vi. Leave the black, “3-phase” wire connection disconnected. This setup operates in single phase.

c. **For the Enphase M215 microinverter:** Connect the output of the microinverter to the electrical grid in the lab. “L1” and “L2” of the microinverter must feed the input and output of the power meter.

i. Connect the black output port of M215 microinverter, “L1”, to the red input port of the power meter, “L in”. Use a banana-to-banana cable.

ii. Connect “L out” of the power meter to the “ϕA” terminal of the power bench. Use a banana-to-spade lug cable.

iii. Connect the red output port of the M215 microinverter, “L2”, to the black input port of the power meter, “N in”. Use a banana-to-banana cable.

iv. Connect “N out” of the power meter to the “ϕC” terminal of the power bench. Use a banana-to-spade lug cable.

v. Connect the white output port of the M215 microinverter, neutral, to the “ϕB” terminal of the power bench. Use a banana-to-spade lug cable.

vi. Connect the green output port of the M215 microinverter, ground, to the “ϕB” terminal of the power bench. Use a banana-to-spade lug cable.

2. After establishing all connections, verify each microinverter functions before collecting data.

a. Turn ON the AC circuit breaker for the AC branch. Always de-energize the AC branch circuit before servicing or swapping the microinverters.

b. Set the DC source to 35 V, the current limit to 3.5 A, and supply a DC input to the microinverter.

c. **The M175** has a minimum startup voltage of 32 V and turnoff voltage of 24 V.

   i. After supplying power to the Inverter, the inverter elicits 16 short beeps. This acknowledges the inverter receives AC or DC power.

   ii. After about 40 seconds, the Inverter beeps 6 times. These beeps produce a more audible tone than the previous 16 beeps. Although this indicates proper inverter startup, the beeping occurs after either supplying DC power, the Inverter connects to an AC grid, or both.

   iii. After another five minutes, the M175 Microinverter should output AC power if connected to a DC source and an AC output.

      1. If at any time a user ceases to supply a DC input to the inverter after this five minute startup, and the M175 inverter remains connected to the AC grid, the Inverter may produce AC power to the grid about 3-5 seconds after supplying a new DC input.

d. **The M215** has a minimum startup voltage of 22 V and a turn-off voltage of 16 V.

   i. A green status LED should come on and blink six times after a 90 second wait time while the inverter powers up. If the inverter continues to flash green, then the microinverter operates normally. If

the LED flashes red, then the microinverter does not operating normally.

ii. The M215 microinverter only blinks green when connecting an Envoy to the system. Since this efficiency test does not include an Enphase Envoy, then under normal operation the M215 blinks orange. Future tests detailed in this report do include an Envoy.

iii. Unlike the Enphase M175 microinverter, if the M215 inverter stops receiving a DC input within the operating range after generating AC power, the inverter must repeat the startup process

3. Collect data. Record the supplied voltage and current from the BK Precision, and the output voltage, current, and power readings from the power meter.

   a. Tabulate data for varying current limits and input voltages supplying the **M175 inverter**.

      i. Set the current limit to 0.5 A, and set the input voltage to 32 V. Increase the input voltage setting on the DC source by 1 V steps until the limit reaches 42 V.

      ii. Set the input voltage back to 32 V and decrease the input voltage by 1 V steps down to 23 V. The inverter should cease to output AC power when input voltage falls below 24 V.

         1. Increase the current limit by 0.5 A and repeat the previous two steps until current limit equals 7.5 A.

   b. Tabulate Data for varying current limits and input voltages supplying the **M215 inverter**.

i. Set the current limit to 0.5 A, and slowly increase the input voltage to 30 V. Increase the input voltage setting on the DC source by 1 V steps until the limit reaches 42 V. Record the DC inputs and AC outputs.

ii. Set the input voltage back to 25 V and decrease the set input voltage by 1 V steps down to 15 V. The Inverter should cease generating AC power when the test level equals 16 V.

    1. Increase the current limit by 0.5 A and repeat the previous two steps until current limit equals 7.5 A.

B.4 Preparing the DC-DC Converters for Testing

Necessary Equipment

Vicor V28A36T200BL2 DC-DC Converter	Banana-to-Banana cables	(4)
CUI VHK200W-Q48-S28 DC-DC Converter	Spade lug-to-Banana cables	(2)
DC Source: BK Precision Model 9153	Alligator clips	(6)
Power meter: GWINSTEK GPM-8212	Capacitors: 4.7 nF (4); 0.2 µF (1)	
Multimeter: Agilent U3401A	Capacitors: 47 µF, 100 µF	
C300KR10E 10Ω, 300W Resistive Load	Inductor: 12 µH	

BK Precision 8514 1200W Programmable DC Electronic Load

Vicor V28A36T200BL2 DC-DC Converter

I. Connect the Vicor DC-DC converter to test equipment at a test bench as shown in Figure B-11.

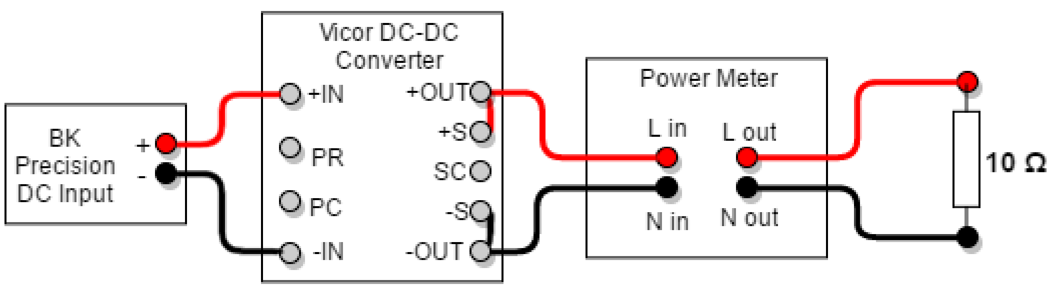

Figure B-11: Wiring Diagram for testing Vicor V28A36T200BL2 DC-DC converter with resistive load.

1. Connect the DC source to the input of the DC-DC converter. The DC source should supply up to 28 V and 7.5 A. Use spade lug-to-banana cables and attach alligator clips to the banana leads so they may clip onto the DC-DC converter. Connect the alligator end of the red cable to the Vicor's "+IN" input and clip the alligator end of the black cable to the "-IN" input.

2. Connect the output of the DC-DC Converter to the input of the Power Meter. Use banana-to-banana cables with alligator clips on one end of the leads to attach to the DC-DC converter's output. Let "+OUT" connect to "L in" and let "–OUT" connect to "N in".
3. Connect "L out" and "N out" of the power meter to the terminals of the 10 Ω resistive load using banana-to-banana cables. Attach alligator clips to the ends of the banana-to-banana to ensure a secure connection to the resistor. The resistor must dissipate as much as 200 W of power and not burn out. The provided C300KR10E 10 Ω resistor can handle up to 300 W.
   a. Use the Agilent multimeter to measure the resistance of the resistor.
   b. The multimeter measures a resistance of **9.92 Ω**.
4. (Optional Method) Instead of using the power meter the Agilent multimeter can measure the output voltage across the resistive load. Knowing the measured resistance allows for calculating the current and power dissipation through the resistor. For this case, connect the load to the output of the DC-DC converter with banana-to-banana cables with alligator clips at all cable ends. Then connect the multimeter in parallel with the load with banana-to-banana cables.

II. Once establishing all connections, verify that the DC-DC converter can take an input voltage up to 28 V and output 36 V.

1. Set the current limit to 7.5 A to protect from overloading the DC-DC converter, and set the input voltage to 2.0 V. Do not turn on the DC source yet.

2. Test with no load conditions first. Disconnect the resistive load from the power meter. Increase the voltage in 2.0 V steps up to 20 V. Verify that the output of the DC-DC converter reads 36 V. Turn off the DC source.
3. Reconnect the 10 Ω, 300 W resistive load. Set the DC source back to 2.0 V and supply power to the Vicor DC-DC converter once more. Increase the input voltage in 2.0 V steps up to 20 V while filling out the table below. Increase the input voltage setting on the DC source in step of one volt while continuing to fill out the table until the input voltage equals 28 V.

CUI VHK200W-Q48-S28 DC-DC Converter

I. Connect the CUI DC-DC converter to test equipment at a test bench as shown in Figure B-11.

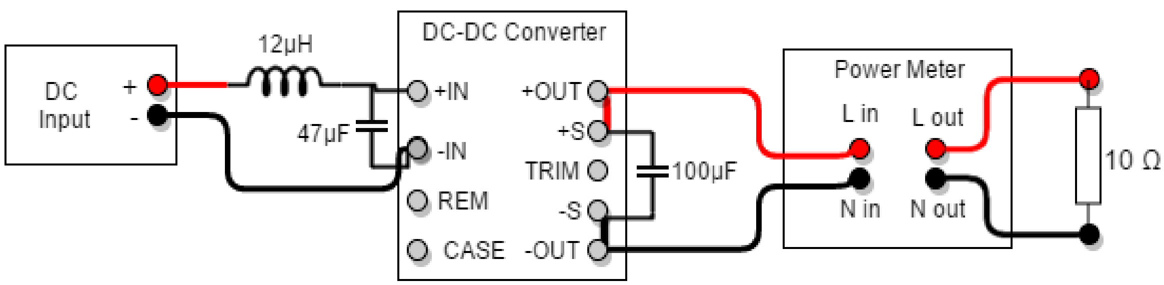

Figure B-12: Wiring Diagram for CUI VHK200W-Q48-S28 DC-DC Converter. Note the shorts connecting +OUT to +S and –OUT to –S on the DC-DC Converter.

1. The BK Precision can supply up to 61 V and 7.5 A. Use spade lug-to-banana cables, and attach alligator clips to the banana leads so that they may connect to the DC-DC converter and inductor. Let the red cable connect the positive output of the DC source to the 12 µF inductor, and let the black cable connect the negative output of the DC source to the "–Vin" terminal of the DC-DC converter.

2. Instead of using the electronic, one can use a power meter and a high-power resistive load. Connect the 10 Ω load to the output of the DC-DC converter with banana-to-banana cables with alligator clips at all cable ends.
3. (Optional.) One may use a programmable electronic load instead of a resistive load. For this, connect the CUI DC-DC converter's output to an electronic load, and set the electronic load to function with a constant 10 Ω load. Use banana-to-banana cables with alligator clips on one end of each cable. Clip the alligator end of the red cable to the CUI's "+OUT" output and plug the banana end into a positive input on the electronic load. With a black cable, connect the CUI's "-OUT" output to one of the electronic load's negative terminals.

II. Once establishing all connections, verify that the DC-DC converter can take an input voltage up to 75 V and output 28 V.

1. Set the current limit to 7.5 A to protect from overloading the DC-DC converter. Do not turn on the DC source yet.
2. Test with no load conditions first. Disconnect the resistive load from the power meter. Increase the voltage in steps of 5.0 V to 45 V. Verify that the output of the DC-DC converter reads 28 V. Turn off the DC source.
3. Reconnect the 10 Ω, 300 W resistive load. Set the DC source back to 26 V and supply power to the CUI DC-DC converter once more. Increase the input voltage in steps of 1.0 V until 61 V while filling out the associated table in Excel. Use Excel to plot the Efficiency of the DC-DC Converter.

B.5 Revisiting the Overvoltage Protection Circuit

Necessary Equipment

Overvoltage Protection Circuit		10 Ω, 300 W Resistive Load	(2)
DC Source:	RIGOL DP832 9313-PS	Banana-to-Banana cables	(6)
DC Source:	Agilent E3630A	Spade lug-to-Banana cables	(2)
Power meter:	GWINSTEK GPM-8212	Banana-to-Grabber cables	(4)
Multimeter:	Agilent U3401A	Alligator clips	(8)
Fluke portable Multimeter		Heat Sink for IGBT	
+3.3 V source or voltage dividing circuit			

Overvoltage protection Circuit Test Setup and Procedure

I. Prepare the overvoltage protection circuit for testing.

1. If testing lacks the microcontroller to supply the 3.3 V reference voltage for the negative terminal of the comparator (PIN 2), use a voltage divider to supply a reference voltage from the +12V rail. The following voltage divider equation yields 3.3 V from a 12 V source.

$$3.3\text{V} = 12\text{V}\left(\frac{\text{Ra}}{\text{Ra} + \text{Rb}}\right)$$

   a. Manipulating the voltage divider equation with a target voltage of 3.3 V from a 12 V supply yields the following ratio for resistor values:

$$\text{Ra} = 2.636(\text{Rb})$$

   b. Select appropriate resistor values. These resistors should have a resistance of tens of kiloohms or higher so that the voltage divider draws less than a milliamp of current from the +12V rail.

      i. Selected resistor values:

Ra) Nominal: **100 kΩ** **Measured:** **98.25 kΩ**

Rb) Nominal: **38.1 kΩ** **Measured:** **37.15 kΩ**

Note: Two resistors make up Rb's 38.1 kΩ resistance—a 33 kΩ resistor and 5.1 kΩ resistor.

c. Using the multimeter, measure the voltage that the voltage divider supplies to the negative terminal of the comparator. The comparator turns on and activates the IGBT to divert excess power when the positive terminal of the comparator (PIN 3) exceeds the reference voltage.

i. **Measured reference voltage:** **3.282 V**

II. Measure the 10 Ω resistive loads. Let one act in place of the DC-DC converter, and let the other take the role of diverting excess power from the converter.

1. The multimeter measured actual resistances of the resistors:

$\mathbf{R_{Load} = 10.5\ \Omega}$ $\mathbf{R_{diverting} = 9.82\ \Omega}$

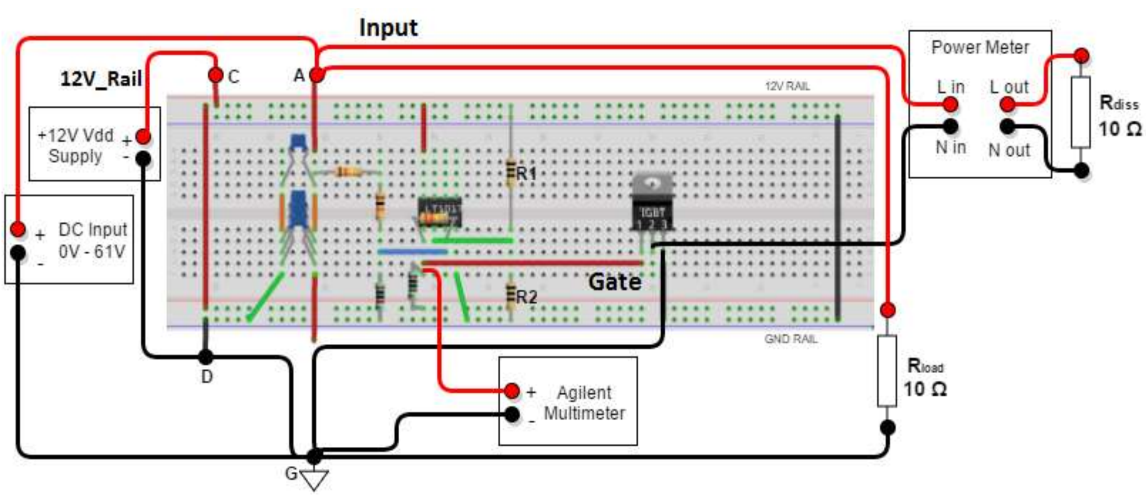

Figure B-13: Wiring diagram of overvoltage protection circuit constructed on a breadboard and test equipment.

III. Connect the over-voltage protection circuit to test equipment as shown in Figure B-13.

1. Connect the BK Precision DC source to the over-voltage protection circuit.

    a. Using spade lug-to-banana cables with alligator clips, connect the positive output of the DC source to the capacitor bank at node A. Connect the negative output of the DC source to ground at node G.
    b. Note that the BK Precision has a maximum output voltage rating of 61 V and a maximum output current of 9.1 A.
2. Connect the 10 Ω resistive load to the overvoltage protection circuit.
    a. Use a banana-to-banana cable to connect one end of the 10 Ω load resistor to node A.
    b. Connect the ground end of the resistor to the GND rail of the breadboard. Using a banana-to-grabber cable, connect the banana end to ground node G and grab the wire at node D.
3. Supply a 12 V DC source to the positive rail of the breadboard.
    a. Using banana-to-grabber cables connect the positive output of the DC source to node C and the negative output of the source to node D.
4. Connect the multimeter to the circuit so that the device measures the voltage at the positive and negative inputs of the comparator.
    a. Use a banana-to-banana cable to connect the negative end of the multimeter to ground at connecting node G.
    b. Use a banana-to-grabber to connect the positive end of the multimeter to one of the input terminals of the comparator. Figure 5-3 shows the multimeter probing the positive input terminal with a banana-to-grabber. When testing, we use the same multimeter to measure both positive and negative input terminals of the comparator separately.

5. Connect the power meter to the circuit so that it measures the output voltage, current and power to the diverting 10 Ω resistor.
    a. Use a banana-to-banana cable to connect the input at node A to "L in" on the power meter.
    b. Use a banana-to-banana cable to connect "N in" of the power meter to the IGBT's collector pin. Use an alligator clip to connect the banana lead to the collector pin.
    c. Plug a banana-to-banana lead into "L out" of the power meter and connect the other end to the diverting resistor with an alligator clip.
    d. Repeat the previous step by connecting "N out" of the power meter to the other end of the resistor.
    e. Use a banana-to-banana with an alligator attachment on one end to connect the IGBT's emitter pin to ground node G.
6. Attach a heat sink to the IGBT. Otherwise, the IGBT overheats when diverting excess power from the load. This report uses the same MA-302-55E heat sink used in previous senior projects [22].
    a. Clip silver backside of the IGBT against the inside wall of the heat sink.

IV. Test the overvoltage protection circuit and record measurements in accordance with Table 1 for varying levels of input voltage.

1. Set the DC Input voltage to 40 V. Increase the voltage by 1 V steps up to 50 V and record measurements. Then, increase the input voltage by 0.1 V steps up to 51 V and continue to record data. Note the voltage when the IGBT turns on and diverts excess power. Next, increase the voltage in steps of 1 V up to 53

V, and record data for those two steps. Record the input voltage when the IGBT turns on.

2. Decrease the DC source voltage by 1 V steps down to 46 V and record measurements. Then, decrease the source voltage in 0.1 V steps down to 46 V. Record the input voltage when the IGBT turns off and ceases its power diversion.

3. **IGBT switches ON when:** $\boldsymbol{V_{in}} =$ **50.5 V**

   IGBT switches OFF when: $\boldsymbol{V_{in}} =$ **46.4 V**

B.6 DC-DC Converter and Microinverter Combination Testing

Necessary Equipment

Vicor V28A36T200BL2 DC-DC Converter		Banana-to-Banana cables	(6)
CUI VHK200W-Q48-S28 DC-DC Converter		Spade lug-to-Banana cables	(2)
Enphase M175-24-240 Microinverter		Banana-to-Grabbers	(4)
Enphase M215-60-2LL-S25-IG Microinverter		Short Banana-to-Banana	(1)
DC Source:	BK precision Model 9153	Alligator clips	(6)
Power meter:	GWINSTEK GPM-8212	0.010 Ω Sense Resistor	
Multimeter:	Fluke 8840A	Multimeter: Agilent U3401A	

Vicor DC-DC Converter and M175 Microinverter Efficiency Testing Protocol

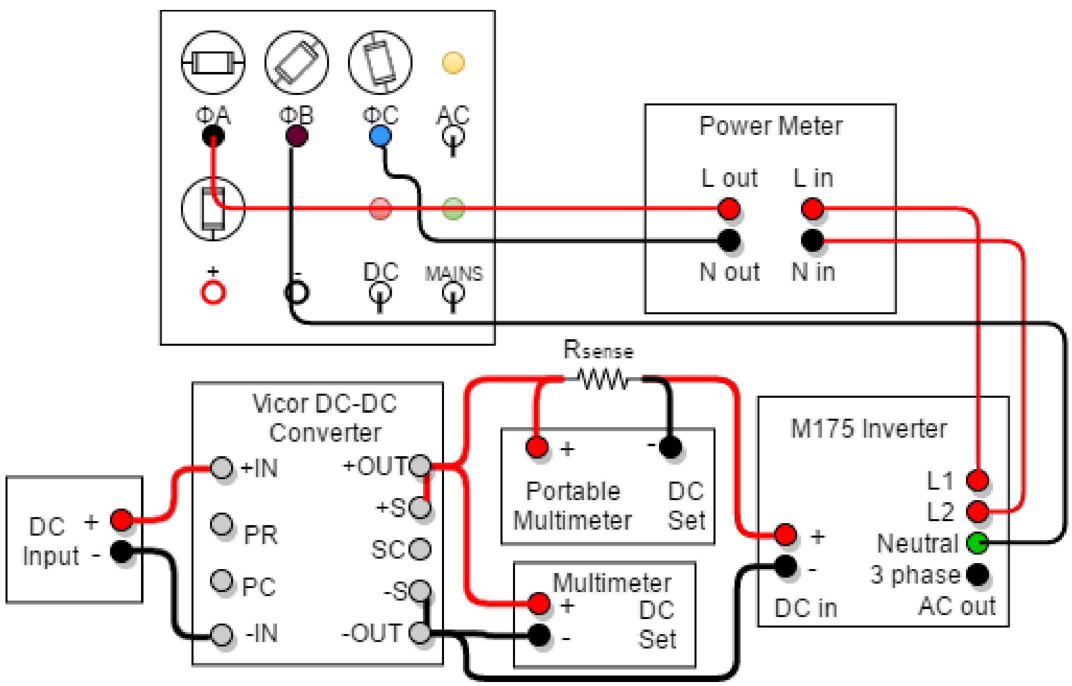

Figure B-14: Wiring Diagram for testing Vicor V28A36T200BL2 DC-DC converter with Enphase M175 microinverter.

I. Connect the Vicor DC-DC converter to the M175 microinverter and set up multimeters to take measurements as shown in Figure B-14.

1. Connect the BK Precision DC source to the input of the DC-DC converter. The DC source supplies up to 28 V and 7.5 A. Use spade lug-to-banana cables, and attach alligator clips to the banana leads so that they may connect to the DC-DC converter
2. Connect the output of the DC-DC Converter to the DC input of the inverter. Also connect a current sense resistor between the “+OUT” output of the Vicor DC-DC converter and the positive DC input of the M175 inverter.
    a. Let “–OUT” connect to the –DC input with a black banana-to-banana cable.
    b. Use a short banana-to-banana cable with two alligator clips to connect the sense resistor to “+OUT” of the DC-DC converter. Use a red banana-to-banana cable but with one alligator clip to connect the other end of the sense resistor to the +DC input.
3. Connect the Fluke multimeter to the output of the Vicor DC-DC converter using banana-to-banana cables. Have the multimeter measure the voltage difference between “+OUT” and “–OUT”.
4. Setup the Agilent multimeter to measure the voltage drop across the sense resistor. Use banana-to-grabber cables.

II. Connect the AC output of the M175 microinverter to the high-power lab bench in room 150 through a power meter as shown in Figure B-14.

1. Connect the black output port of M175 microinverter, “L1”, to the red input port of the power meter, “L in”. Use a banana-to-banana cable. Arbitrarily select one of the red wires as “L1” and the other “L2”.

2. Connect “L out” of the power meter to the ϕA terminal of the power bench. Use a banana-to-banana cable.
3. Connect the red output port of the M175 microinverter, “L2”, to the black input port of the power meter, “N in”. Use a banana-to-banana cable.
4. Connect “N out” of the power meter to the “ϕC” terminal of the power bench. Use a banana-to-banana cable.
5. Connect the white output port of the M175 microinverter, ground, to the “ϕB” terminal of the power bench. Use a banana-to-banana cable.
6. Leave the black, “3-phase” wire connection disconnected. This setup operates in single phase.

III. Once establishing all connections, verify each component functions before collecting data.

1. Turn ON the AC circuit breaker for the AC branch. Always de-energize the AC branch circuit before servicing.
2. Set the BK Precision to supply 22 V with a current limit of 7.5 A to the Vicor DC-DC converter. The power meter should read an output voltage of 36 V from the Vicor DC-DC converter, enough to power the inverter. The M175 Microinverter has a startup voltage of 32 V and turnoff voltage of 24 V.
3. After supplying power to the Inverter, the inverter elicits 16 short beeps. This acknowledges inverter connection to an AC or DC source.
4. After about 40 seconds, the Inverter beeps 6 times. These beeps elicit more audibly than the 16 beeps. This indicates proper inverter startup.
5. After another five minutes, the M175 Microinverter should output AC power.

IV. Collect data.

1. Set the DC source back to 10 V and supply power to the Vicor DC-DC converter once more. Increase the input voltage by 1 V steps until 28 V while tabulating data.

CUI DC-DC Converter and M175 Microinverter Efficiency Testing Protocol

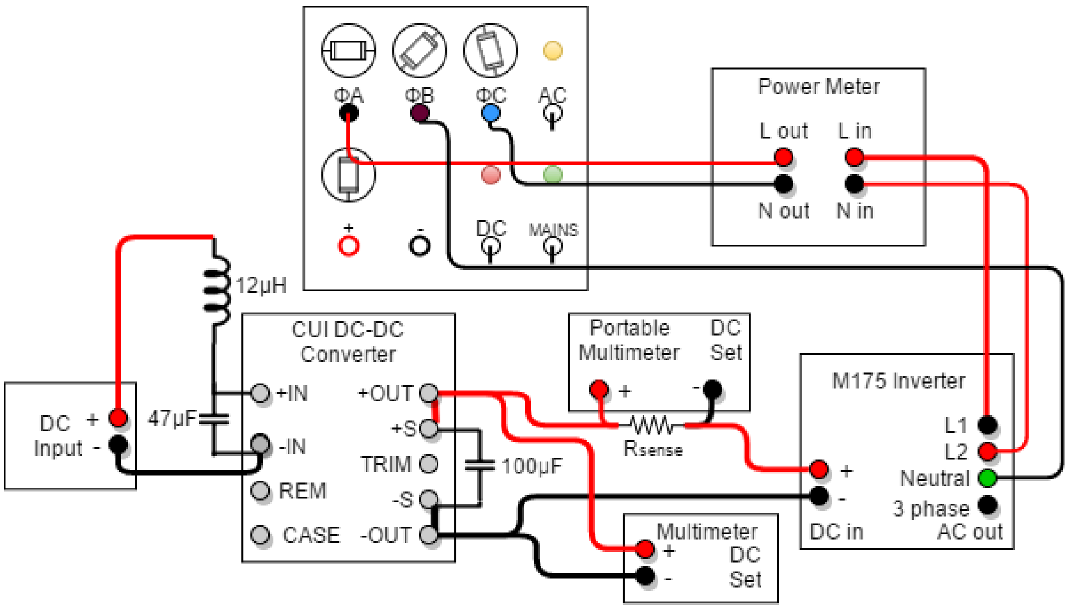

Figure B-15: Wiring Diagram for testing CUI V28A36T200BL2 DC-DC converter with Enphase M175 microinverter.

I. Connect the CUI DC-DC converter to a DC source and the M175 microinverter through a power meter as shown in Figure B-15.

1. The BK Precision supplies up to 61 V and 7.5 A. Use spade lug-to-banana cables, and attach alligator clips to the banana leads so that they may connect to the DC-DC converter and inductor.

   a. Let the red cable connect the positive output of the DC source to the 12 μF inductor, and let the black cable connect the negative output of the DC source to the "–IN" terminal of the DC-DC converter.

2. Connect the output of the CUI DC-DC Converter to the DC input of the M175 inverter. Also connect a current sense resistor between the "+OUT" output of the CUI DC-DC converter and the positive DC input of the M175 inverter.
    a. Let "–OUT" connect to the –DC input with a black banana-to-banana cable.
    b. Use a short banana-to-banana cable with two alligator clips to connect the sense resistor to "+OUT" of the DC-DC converter. Use a red banana-to-banana cable but with one alligator clip to connect the other end of the sense resistor to the +DC input.
3. Connect a Fluke multimeter to the output of the CUI DC-DC converter using banana-to-banana cables. Measure the voltage difference between "+OUT" and "–OUT".
4. Setup an Agilent multimeter to measure the voltage drop across the sense resistor. Use banana-to-grabbers.

II. Connect the AC output of the M175 microinverter to the high-power lab bench in room 150 through a power meter as shown in Figure B-15.

1. Connect the black output port of M175 microinverter, "L1", to the red input port of the power meter, "L in". Use a banana-to-banana cable. Arbitrarily select one of the red wires as "L1" and the other "L2".
2. Connect "L out" of the power meter to the "ϕA" terminal of the power bench. Use a banana-to-banana cable.
3. Connect the red output port of the M175 microinverter, "L2", to the black input port of the power meter, "N in". Use a banana-to-banana cable.

4. Connect “N out” of the power meter to the “ϕC” terminal of the power bench. Use a banana-to-banana cable.
5. Connect the white output port of the M175 microinverter, ground, to the “ϕB” terminal of the power bench. Use a banana-to-banana cable.
6. Leave the black, “3-phase” wire connection disconnected. This setup operates in single phase.

III. Once establishing all connections, verify each component functions before collecting data.

1. Turn ON the AC circuit breaker for the AC branch. Always de-energize the AC branch circuit before servicing.
2. Set the DC source to 22 V, the current limit to 7.5 A, and supply an output to the CUI DC-DC converter. The power meter should read an output voltage of 28 V from the CUI DC-DC converter and hopefully power up the inverter. The M175 microinverter has a startup voltage of 32 V and turnoff voltage of 24 V.
3. After supplying power to the Inverter, the inverter elicits 16 short beeps. This acknowledges inverter connection to an AC or DC source.
4. After about 40 seconds, the Inverter beeps 6 times. These beeps elicit more audibly than the 16 beeps. This indicates proper inverter startup.
5. After another five minutes, the M175 microinverter should output AC power.

IV. Collect data.

1. Set the DC source back to 26 V and supply power to the CUI DC-DC converter once more. Increase the input voltage by 1 V steps until 61 V while tabulating data.

Vicor DC-DC Converter and M215 Microinverter Efficiency Testing Protocol

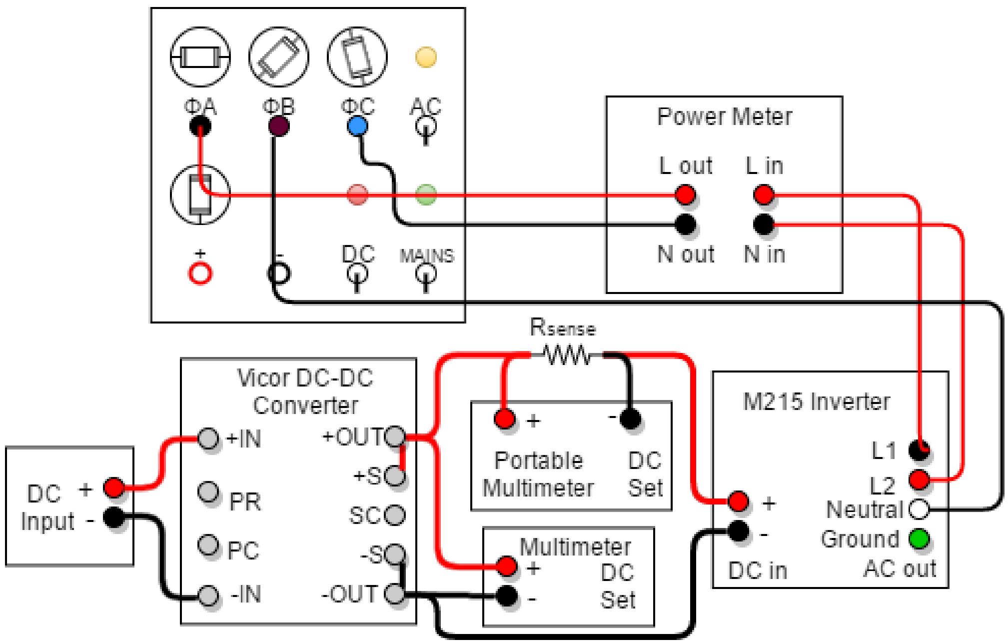

Figure B-16: Wiring Diagram for testing Vicor V28A36T200BL2 DC-DC converter with Enphase M215 microinverter.

I. Connect the Vicor DC-DC converter to the M215 microinverter through a power meter as shown in Figure B-16.

1. Connect the DC source to the input of the DC-DC converter. The DC source supplies up to 28 V and 7.5 A. Use spade lug-to-banana cables, and attach alligator clips to the banana leads so that they may connect to the DC-DC converter

2. Connect the output of the DC-DC Converter to the DC input of the inverter. Also connect a current sense resistor between the “+OUT” output of the Vicor DC-DC converter and the positive DC input of the M215 inverter.

a. Let "–OUT" connect to the –DC input with a black banana-to-banana cable.

b. Use a short banana-to-banana cable with two alligator clips to connect the sense resistor to "+OUT" of the DC-DC converter. Use a red banana-to-banana cable but with one alligator clip to connect the other end of the sense resistor to the +DC input.

3. Connect a Fluke multimeter to the output of the Vicor DC-DC converter using banana-to-banana cables. Measure the voltage difference between "+OUT" and "–OUT".

4. Setup an Agilent multimeter to measure the voltage drop across the sense resistor. Use banana-to-grabbers.

II. Connect the AC output of the M215 microinverter to the high-power lab bench in room 150 through a power meter as shown in Figure B-16.

1. Connect the black output port of M215 microinverter, "L1", to the input port of the power meter, "L in". Use a banana-to-banana cable.

2. Connect "L out" of the power meter to the "ϕA" terminal of the power bench. Use a banana-to-banana cable.

3. Connect the red output port of the M215 microinverter, "L2", to the other input port of the power meter, "N in". Use a banana-to-banana cable.

4. Connect "N out" of the power meter to the "ϕC" terminal of the power bench. Use a banana-to-banana cable.

5. Connect the white output port of the M215 microinverter, neutral, to the "ϕB" terminal of the power bench. Use a banana-to-banana cable.

6. Connect the green output port of the M215 microinverter, ground, to the "ϕB" terminal of the power bench. Use a banana-to-banana cable.

III. Once establishing all connections, verify each component functions before collecting data.

1. Turn ON the AC circuit breaker for the AC branch. Always de-energize the AC branch circuit before servicing.
2. The M215 has a startup voltage threshold of 22 V. Once the input voltage reaches 22 V, it takes about 90 seconds for the inverter to complete its startup process. A green LED means the inverter operates normally.
3. Set the DC source to 22 V, the current limit to 7.5 A, and supply a DC input to the Vicor DC-DC converter.
4. The Fluke multimeter should read an output voltage of about 28 V from the DC-DC converter. Verify.
5. After about 60 seconds, the LED on the M215 inverter blinks six times in one second intervals indicating the end of the inverter's start up. The inverter's LED pauses briefly from emitting before indicating whether or not the inverter started up successfully. If the inverter continues to flash green, then the microinverter operates normally. If the LED flashes red, then the microinverter does not operate normally.
   a. Troubleshooting: See Chapter 3.2.4 for troubleshooting options if the M215 inverter LED emits a solid or flashing red light.

b. The M215 microinverter only blinks green with an envoy connected to the system. This test setup does not include an Enphase envoy, so under normal operation the M215 blinks orange.

IV. Collect data.

1. With the BK Precision set to supplying 22 V, increase the input voltage by 1 V steps until 28 V while filling out the table in Excel.
2. Set the voltage back to 22 V and then decrease the input voltage by 1 V steps until 10 V and continue to collect data.

CUI DC-DC Converter and M215 Microinverter Efficiency Testing Protocol

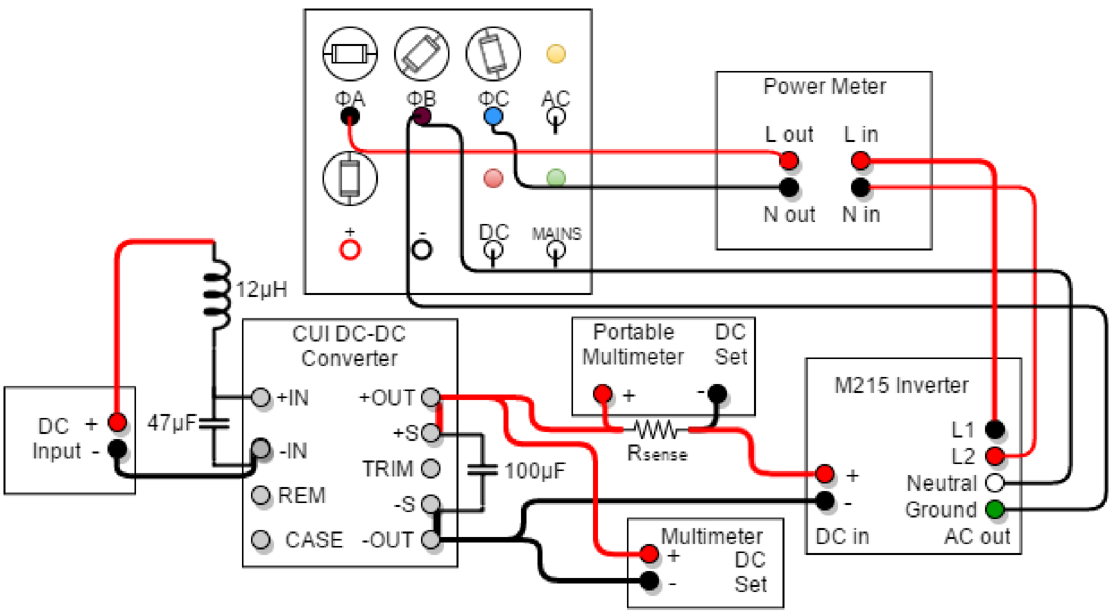

Figure B-17: Wiring Diagram for testing CUI V28A36T200BL2 DC-DC converter with Enphase M215 microinverter.

I. Connect the CUI DC-DC converter to a DC source and the M175 microinverter through a power meter as shown in Figure B-17.

1. The BK Precision supplies up to 61 V and 7.5 A. Use spade lug-to-banana cables, and attach alligator clips to the banana leads so that they may connect to the DC-DC converter and inductor.

a. Let the red cable connect the positive output of the DC source to the 12 µF inductor, and let the black cable connect the negative output of the DC source to the "–IN" terminal of the DC-DC converter.

2. Connect the output of the CUI DC-DC Converter to the DC input of the M175 inverter. Also connect a current sense resistor between the "+OUT" output of the CUI DC-DC converter and the positive DC input of the M175 inverter.

   a. Let "–OUT" connect to the –DC input with a black banana-to-banana cable.

   b. Use a short banana-to-banana cable with two alligator clips to connect the sense resistor to "+OUT" of the DC-DC converter. Use a red banana-to-banana cable but with one alligator clip to connect the other end of the sense resistor to the +DC input.

3. Connect a Fluke multimeter to the output of the CUI DC-DC converter using banana-to-banana cables. Measure the voltage difference between "+OUT" and "–OUT".

4. Setup an Agilent multimeter to measure the voltage drop across the sense resistor. Use banana-to-grabbers.

II. Connect the AC output of the M215 microinverter to the high-power lab bench in room 150 through a power meter as shown in Figure B-17.

1. Connect the black output port of M215 microinverter, "L1", to the input port of the power meter, "L in". Use a banana-to-banana cable.

2. Connect "L out" of the power meter to the "ϕA" terminal of the power bench. Use a banana-to-banana cable.

3. Connect the red output port of the M215 microinverter, “L2”, to the other input port of the power meter, “N in”. Use a banana-to-banana cable.
4. Connect “N out” of the power meter to the “ϕC” terminal of the power bench. Use a banana-to-banana cable.
5. Connect the white output port of the M215 microinverter, neutral, to the “ϕB” terminal of the power bench. Use a banana-to-banana cable.
6. Connect the green output port of the M215 microinverter, ground, to the “ϕB” terminal of the power bench. Use a banana-to-banana cable.

III. Once establishing all connections, verify each component functions before collecting data.

1. Turn ON the AC circuit breaker for the AC branch. Always de-energize the AC branch circuit before servicing.
2. The M215 has a startup voltage threshold of 22 V. Once the input voltage surpasses 22 V, it takes about 60 seconds for the inverter to emit six green blinks. A green LED means the inverter operates normally.
3. Set the DC source to 36 V, the current limit to 7.5 A, and supply an output to the CUI DC-DC converter.
4. The Multimeter should read an output voltage of about 28 V from the DC-DC converter. Verify.
5. After about 60 seconds, the LED on the M215 inverter blinks six times in one second intervals indicating the end of the inverter’s start up. The inverter’s LED pauses briefly from emitting before indicating whether or not the inverter started up successfully. If the inverter continues to flash green, then

the microinverter operates normally. If the LED flashes red, then the microinverter does not operate normally.

a. Troubleshooting: See Chapter 3.2.4 for troubleshooting option if the M215 inverter LED emits a solid or flashing red light.
b. The M215 microinverter only blinks green with an envoy connected to the system. This test setup does not include an Enphase envoy, so under normal operation the M215 blinks orange.

IV. Collect data.

1. Set the DC source back to 26 V and supply power to the CUI DC-DC converter once more. Increase the input voltage by 1 V steps until 61 V while tabulating data.

B.7 Precor EFX 546i Elliptical Testing without a DC-DC Converter

Necessary Equipment

Precor Elliptical	EFX 546i	Overvoltage protection Circuit	(2)
Vicor V28A36T200BL2 DC-DC Converter		Banana-to-Banana cables	(15)
CUI VHK200W-Q48-S28 DC-DC Converter		Spade lug-to-Banana cables	(2)
Enphase M175-24-240 Microinverter		Banana-to-Grabbers	(5)
Enphase M215-60-2LL-S25-IG Microinverter		Short Banana-to-Banana	(1)
DC Source:	RIGOL DP832 9313-PS	Alligator clips	(13)
Power meter:	GWINSTEK GPM-8212	Short leads	(4)
Multimeter:	Fluke 8840A	Capacitors:	47 μF, 100 μF
Multimeter:	Agilent U3401A	Capacitors:	4.7 nF (4); 0.2 μF (1)
DC Source:	BK Precision (for troubleshooting)	Capacitor:	2.5 mF
Fuses:	8 A max rating, 5 A max rating	Inductor:	12 μH

Overvoltage Protection Circuit and M175 Microinverter Test Protocol

I. Connect the M175 microinverter and its OVPC to the Precor Elliptical as depicted in Figure B-17. Test with one person operating the elliptical while another person collects data.

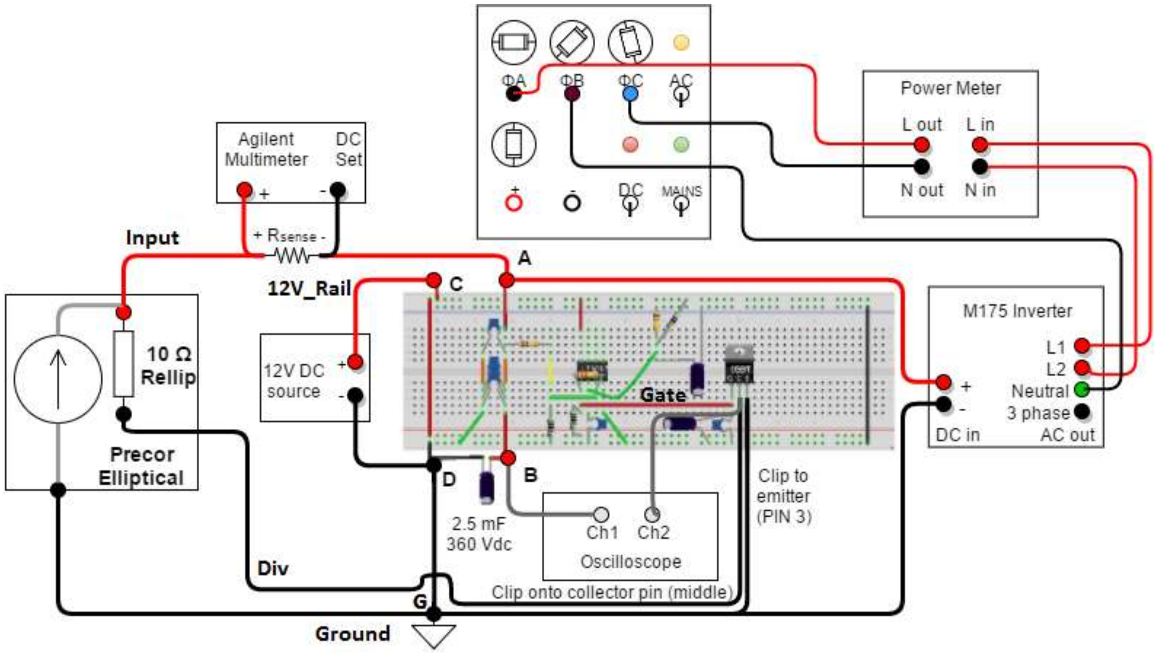

Figure B-18: Test setup for elliptical, M175 inverter, and the Overvoltage Protection Circuit designed for the M175 inverter. Breadboard in wiring diagram has capacitors between the 3.3 V reference source and ground as well as between the IGBT's gate and ground.

1. Connect the elliptical's internal resistor to the OVPC. For this phase of testing, the 10 Ω resistor built into the elliptical acts as the diverting resistor, and the Enphase M175 inverter takes the place of the "load". Make sure to disconnect the lower white wire of the energy harvesting circuit from the internal resistor. Connecting a small 0.010 Ω nominal sense resistor allows the tester to measure the total current produced from the elliptical.
   a. Using a banana-to-banana cable with alligator clips attachments on both ends, let a red wire connect the top of the elliptical's 10 Ω resistive load the "+" end of the sense resistor, R_{sense}. Connect the "–" end of the sense resistor to node A using another red banana-to-banana cable with alligator clips on both ends.
   b. Let a black banana-to-banana cable with alligator clips connect the bottom of the resistive load to the IGBT's collector pin (PIN 2).

c. Finish connecting the elliptical output using two black banana-to-banana cables with an alligator clip attached to one end of each cable. Attach one alligator end of a cable to the lower white wire previously disconnected from the internal resistor. The alligator end of the other cable to the IGBT's emitter (PIN 3). Join the two banana ends of the two cables together to form ground node G.

d. Setup an Agilent multimeter to measure the voltage drop across the sense resistor using red and black banana-to-grabber cables.

e. Measured sense resistor's resistance: **9.75 mΩ**.

2. Use a RIGOL DP832 9313-PS DC source on the lab bench to supply a 12 V DC source to the OVPC.

   a. Using banana-to-grabber cables, connect the positive output of the DC source to the +12V rail at node C, and connect the negative output of the DC source to the ground rail at node D.

   b. Using another banana-to-grabber cable, establish a common ground between the Precor elliptical machine and OVPC by connecting node D to node G.

3. Connect the 2.5 mF to the OVPC. Like the others used in the capacitive filtering bank, the 2.5 mF capacitor must have a high voltage rating. The one used for testing has a DC voltage rating of 360 V.

   a. Use short banana-to-banana leads with alligator clips attached to each banana end.

b. Use a red short lead to connect the positive end of the capacitor to the input at node B. Use a black short lead to connect the negative end of the capacitor to ground at node D.

4. Connect the Enphase M175 microinverter's input to the OVPC. Connect the M175 microinverter's output to an AC grid, and have a power meter measure the AC power output by the inverter.
   a. Connect a red banana-to-banana cable from node A to the positive input of the M175 microinverter. Connect a black banana-to-banana cable from node G to the negative input of the M175 microinverter.
   b. Connect the AC output of the M175 microinverter to the high-power lab bench in room 150 through a power meter as shown in Figure B-17.
      i. Connect the red output port of M175 microinverter, "L1", to the red input port of the power meter, "L in". Use a banana-to-banana cable.
         1. Note: "L1" and "L2" appear the same from the M175 Inverter, so arbitrarily select one as "L1" and the other as "L2".
      ii. Connect "L out" of the power meter to the "ϕA" terminal of the power bench. Use a banana-to-banana cable.
      iii. Connect the red output port of the M175 microinverter, "L2", to the "N in" port of the power meter. Use a banana-to-banana cable.
      iv. Connect "N out" of the power meter to the "ϕC" terminal of the power bench. Use a black banana- to-banana cable.

v. Connect the black output port of the M175 microinverter, neutral, to the "ϕB" terminal of the power bench. Use a black banana-to-banana cable.

vi. Leave the black, "3-phase" wire connection disconnected. This setup operates in single phase.

5. Connect the oscilloscopes to the OVPC. The oscilloscopes help measure the elliptical's output voltage and the voltage on the IGBT's collector terminal.
   a. Connect a scope probe from Channel 1 on the oscilloscope to node B on the OVPC. This allows the oscilloscope to measure the voltage level produced from the elliptical machine at the capacitive filtering bank, which filters out high frequency transient responses.
   b. Connect another scope probe from Channel 2 on the oscilloscope to the IGBT's collector pin. Doing so allows for measuring the voltage drop across the diverting 10 Ω resistor and ensures proper switching for the IGBT.
   c. Using the "measure" button on the oscilloscope, set the oscilloscope to measure the peak voltage, average voltage, and rms voltage at Channel 1. For Channel 2, have the oscilloscope measure the peak and average voltage differences between Channel 1 and Channel 2.
6. After establishing all connections, verify that the M175 microinverter functions before collecting data.
   a. Turn ON the AC circuit breaker for the AC branch. Always de-energize the AC branch circuit before servicing.

b. Set the DC source to 35 V, the current limit to 3.5 A, and supply a DC input to the microinverter.
c. After supplying power to the Inverter, the inverter elicits 16 short beeps. This acknowledges that the inverter sees a connection to an AC or DC source.
d. After about 40 seconds, the Inverter elicits six slightly more audible beeps than the previous 16 beeps. This indicates proper inverter startup. This beeping occurs only after supplying DC power, connecting the Inverter to an AC grid, or both.
e. The M175 Microinverter should output AC power after another five minutes with both a DC source and AC source connected.
    i. Note: If at any time a user ceases to supply a DC input to the inverter after this five minute startup with the M175 inverter still connected to the AC grid, the Inverter should produce AC power to the grid about 3-5 seconds after supplying a new DC input.

7. Observe the performance of the overvoltage protection circuit when tested with the Precor Elliptical. The nature of this testing consists of a variable input source in the form of a user running on the elliptical. The user’s variable input source causes the elliptical to output a varying voltage level to the overvoltage protection circuits. The runner on the Precor elliptical and the person recording the data must fully cooperate to ensure efficient and accurate data collection. The elliptical user focuses on maintaining a consistent pace while another person records measurements.

a. Turn ON the AC circuit breaker for the AC branch. Always de-energize the AC branch circuit before servicing.

b. Begin testing by having a user run on the elliptical at a pace of 100 strides per minute (SPM), the equivalent of a brisk walk. Set the resistance setting of the elliptical set to 2. The Precor elliptical starts with a resistance setting of 1 and cannot output power at this setting.

c. While in use, record the peak, average, and rms voltages outputting from the elliptical when a user runs at 100 SPM. Use the oscilloscope to read this data.

d. Channel 2 of the oscilloscope indicates if and when the overvoltage protection circuit diverts excess power from the elliptical's load. Channel 2 probes the IGBT's collector (PIN 2). When the collector signal deviates from the elliptical output voltage dropping to a low voltage level above ground, this indicates the OVPC diverts power. Make a note in the data table if this occurs and record the elliptical output voltage at which this IGBT switching occurs.

e. The Agilent multimeter measures the voltage across the sense resistor. Record the maximum, minimum, and average observed voltage potentials across the resistor. Use the MIN/MAX/AVG button to obtain theses values.

f. Should the OVPC operate as expected, the output voltage from the elliptical should decrease after the IGBT turns on. This voltage should decrease enough to deactivate the power diversion circuit, thus turning off

the IGBT, and the output voltage should rise again. If this occurs, record the measured peak, average, and rms voltages when the IGBT switches off. If the IGBT does not switch off, then record the lowest observed voltages for these measurements.

g. Should the IGBT divert excess power, the oscilloscope measures a voltage across the elliptical's diverting resistor. Record the observed range of voltages across the resistor.

h. Use Microsoft Excel to calculate the current flowing through the sense and diverting resistors. Also calculate the amount of power supplied by the elliptical and power dissipated by the diverting resistor.

i. Increase the resistance of the elliptical by 2 and repeat data collection in parts b-f. Do this until the resistance level maxes out at 20.

j. Repeat parts b-g and have the runner increase their pace to 150 SPM, the equivalent of a run.

Overvoltage Protection Circuit and M215 Microinverter Test Protocol

I. Connect the M215 microinverter and its OVPC to the Precor Elliptical. Test with one person operating the elliptical while another person collects data.

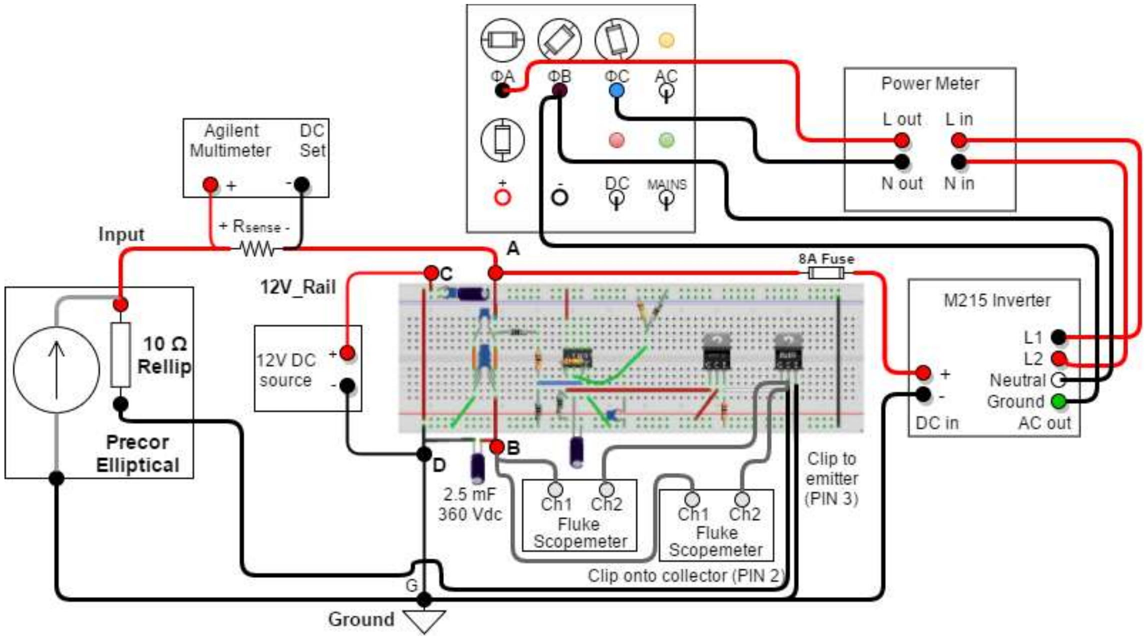

Figure B-19: Wiring diagram for Precor elliptical, M215 inverter, and the Overvoltage Protection Circuit designed for the M215 inverter.

1. Connect the elliptical's internal resistor to the OVPC as shown in Figure B-18. For this phase of testing, the 10 Ω resistor built into the elliptical acts as the diverting resistor, and the Enphase M215 inverter takes the place of the "load". Make sure to disconnect the lower white wire of the energy harvesting circuit from the internal resistor. Connecting a small 0.010 Ω nominal sense resistor allows the tester to measure the total current produced from the elliptical.
   a. Using a banana-to-banana cable with alligator clips attachments on both ends, let a red wire connect the top of the elliptical's 10 Ω resistive load the "+" end of the sense resistor, R_{sense}. Connect the "–" end of the sense resistor to node A using another red banana-to-banana cable with alligator clips on both ends.
   b. Let a black banana-to-banana cable with alligator clips connect the bottom of the resistive load to the IGBT's collector pin (PIN 2).

c. Finish connecting the elliptical output using two black banana-to-banana cables with an alligator clip attached to one end of each cable. Attach one alligator end of a cable to the lower white wire previously disconnected from the internal resistor. The alligator end of the other cable to the IGBT's emitter (PIN 3). Join the two banana ends of the two cables together to form ground node G.

d. Setup an Agilent multimeter to measure the voltage drop across the sense resistor using red and black banana-to-grabber cables.

e. Measured sense resistor's resistance: **9.75 mΩ**.

2. Use a RIGOL DP832 9313-PS DC source on the lab bench to supply a 12V DC source to the OVPC.

   a. Using banana-to-grabber cables, connect the positive output of the DC source to the +12V rail at node C, and connect the negative output of the DC source to the ground rail at node D.

   b. Using another banana-to-grabber cable, establish a common ground between the Precor elliptical machine and OVPC by connecting node D to node G.

3. Connect the 2.5 mF to the OVPC. Like the others used in the capacitive filtering bank, the 2.5 mF capacitor must have a high voltage rating. The one used for testing has a DC voltage rating of 360 V.

   a. Use short banana-to-banana leads with alligator clips attached to each banana end.

b. Use a red short lead to connect the positive end of the capacitor to the input at node B. Use a black short lead to connect the negative end of the capacitor to ground at node D.

4. Connect the Enphase M215 microinverter to the OVPC. Connect the M215 microinverter to an AC grid, and have a power meter measure the AC power output by the inverter.
   a. Connect a red banana-to-banana cable from node A to the positive input of the M215 microinverter. Connect a black banana-to-banana cable from node G to the negative input of the M215 microinverter.
   b. Connect the AC output of the M215 microinverter to the high-power lab bench in room 150 through a power meter as shown in Figure B-18.
      i. Connect the black output port of M215 microinverter, “L1”, to the red input port of the power meter, “L in”. Use a banana-to-banana cable.
      ii. Connect “L out” of the power meter to the “ϕA” terminal of the power bench. Use a banana-to-banana cable.
      iii. Connect the red output port of the M215 microinverter, “L2”, to the “N in” port of the power meter. Use a banana-to-banana cable.
      iv. Connect “N out” of the power meter to the “ϕC” terminal of the power bench. Use a black banana-to-banana cable.
      v. Connect the white output port of the M215 microinverter, neutral, to the “ϕB” terminal of the power bench. Use a black banana-to-banana cable.

vi. Also connect the green output port of the M215 microinverter, earth ground, to the "ϕB" terminal of the power bench. Use a black banana-to-banana cable.

5. Connect the Fluke 196C isolated scopemeters to the OVPC. The oscilloscope measure the elliptical's output voltage, and the voltage on the IGBT's collector terminal.
   a. Connect scope probes from Channel 1 on both scopemeters to node B on the OVPC. This allows the scopemeters to measure the voltage level produced from the elliptical machine at the capacitive filtering bank, which filters out high frequency transient responses.
   b. Connect another scope probe from Channel 2 on one of the oscilloscope to the IGBT's collector (PIN 2). Set one scopemeter to measure the peak voltages, and the other to measure the average voltage.
6. After establishing all connections, verify that the M175 microinverter functions before collecting data.
   a. Turn ON the AC circuit breaker for the AC branch. Always de-energize the AC branch circuit before servicing.
   b. Have an assistant begin running at a pace of at least 100 SPM and set the elliptical's resistance to 2. The Precor elliptical starts with a default resistance setting of 1 and cannot output power at this setting. As the user runs, the oscilloscopes should show an elliptical output voltage that varies between 36 V and 42 V.

c. After 90 seconds of receiving AC and DC power, the LED on the M215 inverter should blink green, indicating proper inverter startup.

d. The M215 microinverter should then output AC power to the grid.

   i. Note: If at any time a user ceases to supply a DC input to the inverter after completing startup with the M215 inverter still connected to the AC grid, the Inverter must undergo another startup period that last about 90 seconds before producing AC power again.

7. Observe the performance of the overvoltage protection circuit when tested with the Precor Elliptical. The nature of this testing consists of a variable input source in the form of a user running on the elliptical. The user's variable input source causes the elliptical to output a varying voltage level to the overvoltage protection circuits. The runner on the Precor elliptical and the person recording the data must fully cooperate to ensure efficient and accurate data collection. The elliptical user focuses on maintaining a consistent pace while another person records measurements.

   a. Turn ON the AC circuit breaker for the AC branch. Always de-energize the AC branch circuit before servicing.

   b. Begin testing by having a user run on the elliptical at a pace of 100 strides per minute (SPM), the equivalent of brisk walk. Set the resistance setting of the elliptical set to 2.

   c. While in use, record the peak and average voltages outputting from the elliptical when a user runs at 100 SPM. Use the scopemeters to read this data.

d. Channel 2 of the scopemeter indicates if and when the overvoltage protection circuit diverts excess power from the elliptical's load. Channel 2 probes the IGBT's collector (PIN 2).

e. The Agilent multimeter measures the voltage across the sense resistor. Record the maximum and minimum observed voltage potentials across the resistor and have Microsoft Excel calculate the average. If values fluctuate too much, use the MIN/MAX/AVG button to obtain theses values.

f. Should the OVPC operate as expected, the output voltage from the elliptical should decrease after the IGBT turns on. This voltage should decrease enough to deactivate the power diversion circuit, thus turning off the IGBT, and the output voltage should rise again. If this occurs, record the measured peak and average voltages when the IGBT switches off. If the IGBT does not switch off, then record the lowest observed voltages for these measurements.

g. Use Microsoft Excel to calculate the current flowing through the sense and diverting resistors. Also calculate the amount of power supplied by the elliptical and power dissipated by the diverting resistor.

h. Increase the resistance of the elliptical by 2 and repeat data collection in parts b-f. Do this until the resistance level maxes out at 20.

i. Repeat parts b-g and have the runner increase their pace to 150 SPM, the equivalent of a normal run.

B.8 Full System Testing

Necessary Equipment

Precor Elliptical	EFX 546i	Overvoltage protection Circuit	(2)
Vicor V28A36T200BL2 DC-DC Converter		Banana-to-Banana cables	(15)
CUI VHK200W-Q48-S28 DC-DC Converter		Spade lug-to-Banana cables	(2)
Enphase M175-24-240 Microinverter		Banana-to-Grabbers	(5)
Enphase M215-60-2LL-S25-IG Microinverter		Short Banana-to-Banana	(1)
DC Source:	RIGOL DP832 9313-PS	Alligator clips	(13)
Power meter:	GWINSTEK GPM-8212	Short leads	(4)
Multimeter:	Fluke 8840A	Capacitors: 47 μF, 100 μF	
Multimeter:	Agilent U3401A	Capacitors: 4.7 nF (4); 0.2 μF (1)	
DC Source:	BK Precision (for troubleshooting)	Capacitor: 2.5 mF	
Fuses:	8 A max rating, 5 A max rating	Inductor: 12 μH	

Test Protocol for Full System Testing with CUI DC-DC Converter and M215 Inverter

I. Connect the M215 microinverter, the CUI DC-DC converter, their OVPC, and current limiter to the Precor elliptical.

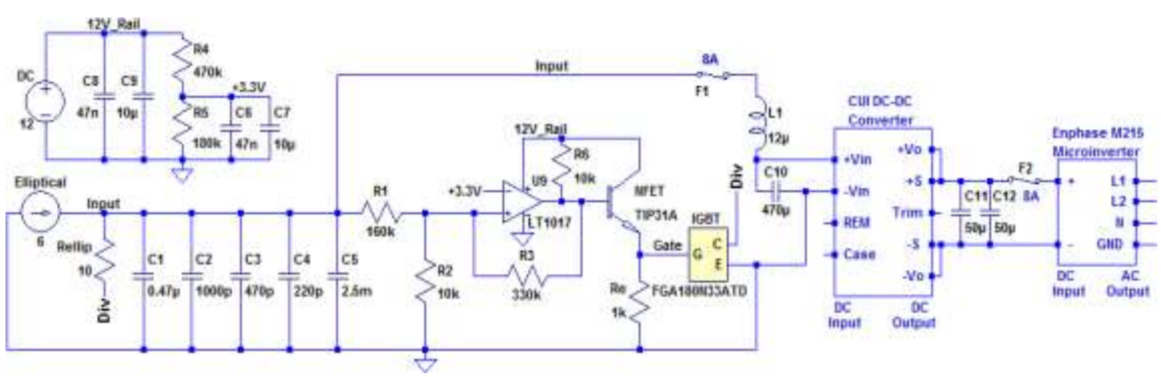

Figure B-20: Circuit Diagram for elliptical test session involving Precor elliptical trainer, CUI DC-DC converter, and Enphase M215 microinverter.

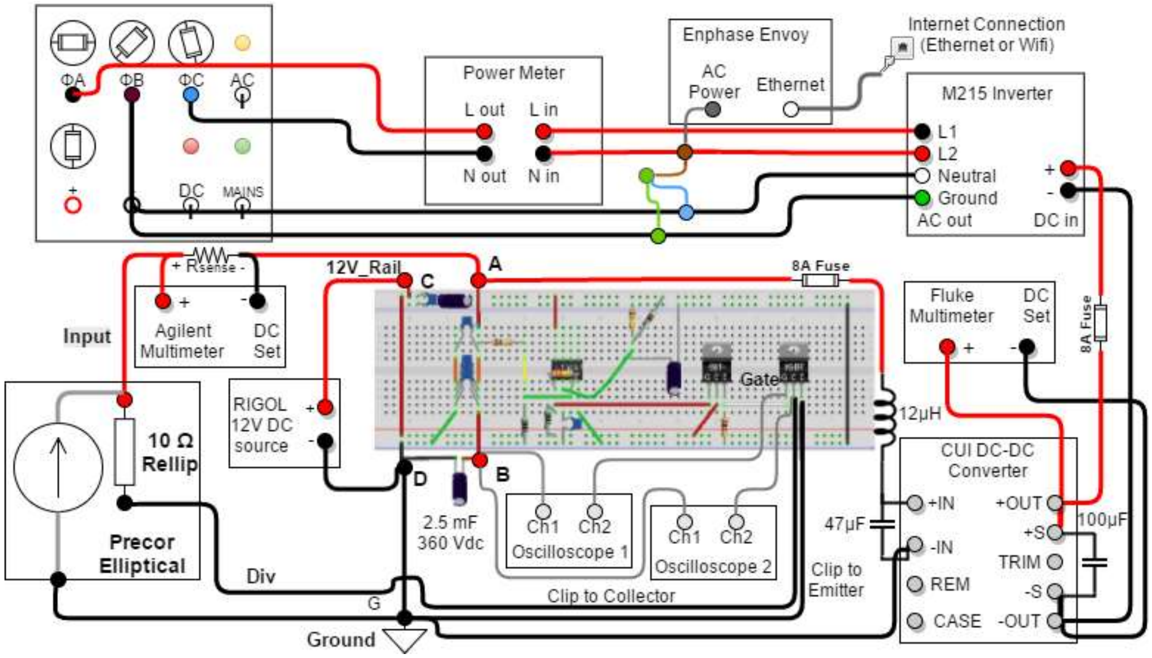

Figure B-21: Wiring Diagram of a full system test including the Precor trainer, CUI DC-DC converter, and Enphase M215 inverter.

1. Connect the elliptical's internal resistor to the OVPC as shown in the wiring diagram of Figure B-20. For this phase of testing, the elliptical's internal 10 Ω resistor acts as the diverting resistor, and the CUI DC-DC converter and Enphase M215 microinverter take the place of the "load". Make sure to disconnect the lower white wire of the energy harvesting circuit from the internal resistor. Connecting a small 0.010 Ω nominal sense resistor allows the tester to measure the total input current to the DC-DC converter.
   a. Using a banana-to-banana cable with alligator clip attachments on both ends, let a red wire connect the top of the elliptical's 10 Ω resistive load the "+" end of the sense resistor, R_{sense}. Connect the "–" end of the sense resistor to node A using another red banana-to-banana cable with alligator clips on both ends.

b. Let a black banana-to-banana cable with alligator clips connect the bottom of the resistive load to the IGBT's collector pin.

c. Finish connecting the elliptical output using two black banana-to-banana cables with an alligator clip attached to one end of each cable. Attach one alligator end of a cable to the lower white wire previously disconnected from the internal resistor. The alligator end of the other cable attaches to the IGBT's emitter. Join the two banana ends of the two cables together to form ground node G.

d. Set up an Agilent multimeter to measure the voltage drop across the sense resistor using red and black banana-to-grabber cables.

e. Measured sense resistor's resistance: **9.75 mΩ.**

2. Connect the elliptical's battery to the OVPC or connect a 12V DC source from a lab bench. The Precor elliptical houses a 12-Volt DC battery towards the lower front of the elliptical. Positive and negative wires run from the 12-Volt battery underneath the elliptical to the mechanical-to-electrical energy converting circuit housed in the back end of the elliptical. Ideally, testing would have the OVPC connect directly to the 12-Volt battery via the same connecters that connect the battery to the energy converting circuit. However, the present connecters from the 12-Volt battery to the energy converting circuit do not allow for other cables to safely connect to the battery without disconnecting the battery from the energy converting circuit. With connecting to the 12-Volt battery unable to take place, let an external DC source supply the necessary 12 V for the OVPC.

a. Using banana-to-grabber cables, connect the positive output of the DC source to the +12V rail at node C, and connect the negative output of the DC source to the ground rail at node D.

b. Using another banana-to-grabber cable, establish a common ground between the Precor elliptical machine and OVPC by connecting node D to node G.

3. Connect the 2.5 mF capacitor to the OVPC. Like the others used in the capacitive filtering bank, the 2.5 mF capacitor must have a high voltage rating. The one used for testing has a DC voltage rating of 360 V.

   a. Use short banana-to-banana leads with alligator clips attached to each banana end.

   b. Use a red short lead to connect the positive end of the capacitor to the input at node B. Use a black short lead to connect the negative end of the capacitor to ground at node D.

4. Connect the CUI DC-DC converter's input to Elliptical's output and OVPC, and connect the converter's output to the Enphase M215 inverter. Prior efficiency tests should already have the converter prepped for testing.

   a. Attach an alligator clip to one end of a red banana-to-banana cable. Connect the banana end to node A on the OVPC, and clip the alligator end to a fuse rate for 8 A. Using a short lead with an alligator clip on both ends attach one clip to the open end of the fuse and clip the other to the 12 µF inductor that connects to the "+Vin" input of the DC-DC Converter.

b. Attach an alligator clip to one end of a black banana-to-banana cable. Connect the banana end to ground at node G, and clip the alligator end to the "–Vin" terminal of the DC-DC converter.

c. With alligator clips attached, connect a red banana-to-banana cable from "+OUT" of the Vicor to one end of a fuse rated for 8 A. Using a short lead with one alligator clip, connect the other end of the fuse to the positive input of the M215 microinverter.

d. Connect a black banana-to-banana cable from "-OUT" of the CUI DC-DC Converter to the negative input of the M215 microinverter. Let one end of the banana cable have an alligator attachment and clip the alligator end to the CUI.

e. Connect the Fluke multimeter using banana-to-banana cables to measure the output voltage of the Vicor.

f. Note: The initial test with a 100 SPM running pace lacks both protective fuses and a Fluke multimeter at the DC-DC converter's output.

5. Connect the M215 microinverter to an AC grid, and have a power meter measure the AC power the inverter generates.

   a. Connect the AC output of the M215 microinverter to the high-power lab bench in room 150 through a power meter as shown in Figure B-20.

      i. Connect the black output port of M215 microinverter, "L1", to the red input port of the power meter, "L in". Use a red banana-to-banana cable.

ii. Connect “L out” of the power meter to the “ϕA” terminal of the power bench. Use a red banana-to-banana cable.

iii. Connect the red output port of the M215 microinverter, “L2”, to the “N in” port of the power meter. Use a red banana-to-banana cable.

iv. Connect “N out” of the power meter to the “ϕC” terminal of the power bench. Use a black banana-to-banana cable.

v. Connect the white output port of the M215 microinverter, neutral, to the “ϕB” terminal of the power bench. Use a black banana-to-banana cable.

vi. Also connect the green output port of the M215 microinverter, earth ground, to the “ϕB” terminal of the power bench. Use a black banana-to-banana cable.

6. Connect the Enphase Envoy to the M215 inverter and the Internet. The Envoy allows for monitoring the inverter’s energy output to the grid through Enphase’s Enlighten online software. In addition to reporting energy production, the Envoy also reports error messages from the inverter.

   a. The Envoy has an AC power cord adapted to connect to the M215 Inverter’s AC output. These three connectors (for line, neutral, and ground), connect at the same terminals where the banana-to-banana cables connect, but do not interfere with their connections.

      i. Connect the brown wire from the Envoy’s AC power adapter to the M215 inverter’s “L2” AC output connection, denoted by a red wire. A tester must connect to “L2” instead of “L1” because the “L1” wire

from the M215 inverter does not have the proper attachment to connect with the adapters on the Envoy's AC power cable.

ii. Connect the Envoy's blue AC wire to the M215's neutral white wire.

iii. Connect the Envoy's green wire to the M215's green earth ground wire.

b. Connect the envoy to the internet by establishing an Ethernet connection to the envoy from an internet router. If a wired connection cannot occur, then use a USB powered Wi-Fi adapter.

7. Connect the oscilloscopes to the OVPC. The oscilloscopes measure the elliptical's output voltage, the voltage on the IGBT's collector terminal, and monitor the voltage on the IGBT's gate terminal.

   a. Connect scope probes from Channel 1 on both oscilloscopes to node B on the OVPC. This allows the oscilloscopes to measure the voltage level produced from the elliptical machine at the capacitive filtering bank, which filters out high frequency transients.

   b. Connect a scope probe to Channel 2 of Oscilloscope 1 to the IGBT's gate. This allows a tester to monitor the signal on the IGBT's gate and ensure proper switching occurs.

   c. Connect a fourth scope probe from Channel 2 of Oscilloscope 2 to the IGBT's collector. Doing so allows for measuring the voltage drop across the diverting 10 Ω resistor and ensures proper switching for the IGBT.

   d. Using the "measure" button on the oscilloscopes, have Oscilloscope 1 measure the minimum voltage, peak voltage, average voltage, and rms

voltage of Channel 1. This displays voltage measurements on input voltage generated from the elliptical's output. Set Oscilloscope 2 to measure the minimum voltage, peak voltage, average voltage, and rms voltage on Channel 2. This displays voltage measurements on the IGBT's collector terminal.

8. After making all connections, verify that each component functions before collecting data. Before testers can record data, the M215 inverter must undergo its startup process.
    a. Have an assistant run on the Precor elliptical while a partner observes and collects data from the multimeter, power meter, and oscilloscopes.
        i. The Precor elliptical machine starts with a default resistance setting of 1. At this setting, the elliptical's energy harvesting generates no power to its load.
        ii. Set the resistance setting of the elliptical to 2 to begin energy generation.
        iii. Always have the person running stop and step down from the elliptical before servicing. Also make sure to completely discharge the 2.5 mF capacitor.
    b. Verify the OVPC works first. Disconnect the DC-DC converter from the OVPC by severing the DC-DC converter's connections at node A and node G.
        i. Oscilloscope 1 probes both the input voltage and IGBT's gate. With the DC-DC converter disconnected, an observer can see from

Channel 1 on the oscilloscope the input voltage rise to the threshold voltage that activates the IGBT for power diversion. Then the input voltage decreases until the input voltage falls below the lower threshold voltage where the IGBT ceases to divert power from the main line. With a 50 ms time scale on the oscilloscope, the input voltage signal appears as a sawtooth-like wave, similar to simulating the OVPC in LTspice with a current source. During the intervals where the oscilloscope shows then input voltage signal decrease, Channel 2 should show a signal that jumps to 12 V. Observation of these two signals confirms that the OVPC properly diverts power for its particular parameters.

ii. Reconnect the DC-DC converter to the OVPC.

c. Check the output voltage of the CUI DC-DC Converter. If testing lacks a spare multimeter, temporarily remove the banana-to-grabber cables probing the voltage across the sense resistor to check. Verify that the CUI outputs at least 22 V to the M215 inverter. The CUI typically outputs 27.9 V, but can output less voltage and still power the M215 inverter.

d. Turn ON the AC circuit breaker for the AC branch. Always de-energize the AC branch circuit before servicing.

e. The M215 has a startup voltage threshold of 22 V. Once the input voltage surpasses 22 V, it takes about 90 seconds for the inverter to emit six green blinks. A green LED means the inverter operates normally.

f. Have a user run on the Precor elliptical while a partner observes and collects data from the multimeter, power meter, and oscilloscopes.

   i. The Precor elliptical machine starts with a default resistance setting of 1. At this setting, the elliptical's energy harvesting generates no power to its load.

   ii. Set the resistance setting of the elliptical to 2 to begin energy generation.

g. After about 70 seconds, the LED on the M215 inverter blinks six times in one second intervals indicating the end of the inverter's start up. The inverter's LED pauses briefly from emitting before indicating whether or not the inverter started up successfully. If the inverter continues to flash green, then the microinverter operates normally. If the LED flashes red, then the microinverter does not operate normally.

   i. Troubleshooting: If a few seconds after the six green blinks the inverter blinks red every two seconds, the means the inverter fails to connect to an AC grid.

   ii. This problem occurred during initial testing of the M215 Microinverter. A severed connection in one of the AC lines, specifically, the connecting lead end of the "Line 1", prevented the microinverter from outputting AC power. Establishing a proper connection in the wire at the connecting node fixes this issue. See Chapter 3.2.5 for troubleshooting options.

iii. The inverter's LED may blink red at the end of the startup process a couple times before changing to green.

9. Testing may begin after confirming all components function.

   a. While a user runs on the Precor Elliptical, set the oscilloscope so it views 3-7 switching cycles of the input voltage. One cycle refers to the input voltage increasing, and then decreasing due to the IGBT diverting excess power. On low elliptical resistance settings (ERSs), once the M215 inverter generates AC power, the input voltage from the elliptical may not exceed the minimum threshold hold to require power diversion from the IGBT. In this case, the OVPC does not experience any switching cycles.

      i. The first oscilloscope probes the source voltage and IGBT's gate voltage, while the other oscilloscope probes the source voltage and IGBT's collector voltage.

      ii. Each Tektronix Oscilloscope used for testing can display five measurements. Having two oscilloscopes means not having to change mode of measurement or scope probe channel while in the middle of testing. The observer of this test session must record four kinds of voltage measurements for both the source voltage from the elliptical and the IGBT collector voltage.

      iii. When the oscilloscopes show 3-7 switching cycles of the input voltage, simultaneously press the STOP button on both oscilloscopes. This allows the observer to record data more easily.

iv. With Oscilloscope 1 displaying measurements for the source voltage and Oscilloscope 2 displaying measurements for the IGBT collector voltage, record their MIN, MAX, MEAN, and RMS voltages.

v. Use Excel to calculate values for the diverted current and power through the diverting resistor. For calculations, assume a collector voltage of 1.0 V when OVPC diverts.

b. The multimeter measures the voltage across the sense resistor. After pressing the STOP button on the oscilloscopes, press the “MinMax” on the Agilent multimeter. This sets the multimeter to remember the maximum, minimum, and average voltages seen across the sense resistor. Pressing the “MinMax” button cycles the multimeter to displaying the maximum value, then minimum value, then average value.

i. Record the minimum, maximum, and average voltages displayed by the multimeter.

ii. Use Microsoft Excel to calculate the minimum, maximum, and average currents flowing to the DC-DC converter’s input.

c. The power meter measures the voltage, current, and power output from the M215 inverter to the AC grid. Record the minimum and maximum values by taking advantage of the “Min” and “Max” button on the power meter.

d. Use Excel to calculate the average values and calculate the efficiency of the system.

Test Protocol for Full System Testing with Vicor DC-DC Converter and M215 Inverter

I. Connect the M215 microinverter, the Vicor DC-DC converter, the Vicor's OVPC, and current limiter to the Precor Elliptical.

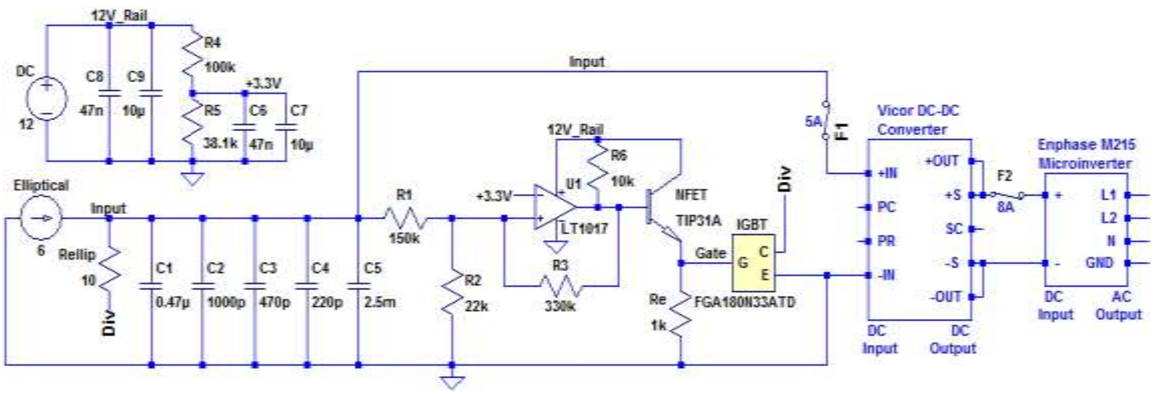

Figure B-22: Circuit Diagram for an Elliptical test session involving Precor elliptical trainer, Vicor DC-DC converter, and Enphase M215 microinverter.

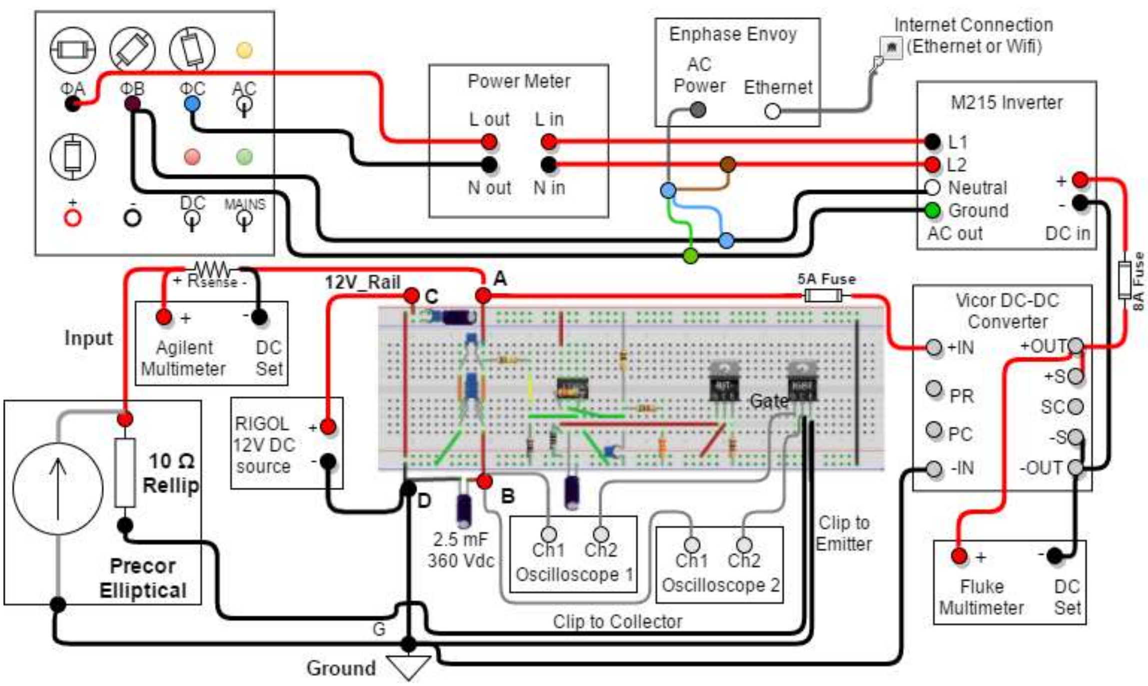

Figure B-23: Wiring Diagram of a full system test including the Precor elliptical trainer, Vicor DC-DC converter, and Enphase M215 inverter.

1. Connect the elliptical's internal resistor to the OVPC as shown in the wiring diagram of Figure B-22. For this phase of testing, the 10 Ω resistor built into the elliptical acts as the diverting resistor, and the Vicor DC-DC Converter

and Enphase M215 microinverter take the place of the “load”. Make sure to disconnect the lower white wire of the energy harvesting circuit from the internal resistor. Connecting a small 0.010 Ω nominal sense resistor allows the tester to measure the total input current to the DC-DC converter.

a. Using a banana-to-banana cable with alligator clips attachments on both ends, let a red wire connect the top of the elliptical’s 10 Ω resistive load the “+” end of the sense resistor, R_{sense}. Connect the “–” end of the sense resistor to node A using another red banana-to-banana cable with alligator clips on both ends.
b. Let a black banana-to-banana cable with alligator clips connect the bottom of the resistive load to the IGBT’s collector pin.
c. Finish connecting the elliptical output using two black banana-to-banana cables with an alligator clip attached to one end of each cable. Attach one alligator end of a cable to the lower white wire previously disconnected from the internal resistor. The alligator end of the other cable to the IGBT’s emitter. Join the two banana ends of the two cables together to form ground node G.
d. Set up an Agilent multimeter to measure the voltage drop across the sense resistor using red and black banana-to-grabber cables.
e. Measured sense resistor’s resistance: **9.75 mΩ**.

2. Connect the elliptical’s battery to the OVPC or connect a 12 V DC source from a lab bench. The Precor Elliptical houses a 12-Volt DC battery towards the lower front of the elliptical. Positive and negative wires run from the 12-

Volt battery underneath the elliptical to the mechanical-to-electrical energy converting circuit house in the back end of the elliptical. Ideally, testing would have the OVPC connect directly to the 12-Volt battery via the same connecters that connect the battery to the energy converting circuit. However, the present connecters from the 12-Volt battery to the energy converting circuit do not allow for other cables to safely connect to the battery without disconnecting the battery from the energy converting circuit. With connecting to the 12-Volt battery unable to take place, let an external DC source supply the necessary 12 V for the OVPC.

   a. Using banana-to-grabber cables, connect the positive output of the DC source to the +12V rail at node C, and connect the negative output of the DC source to the ground rail at node D.
   b. Using another banana-to-grabber cable, establish a common ground between the Precor elliptical machine and OVPC by connecting node D to node G.

3. Connect the 2.5 mF to the OVPC. Like the others used in the capacitive filtering bank, the 2.5 mF capacitor must have a high voltage rating. The one used for testing has a DC voltage rating of 360 V.
   a. Use short banana-to-banana leads with alligator clips attached to each banana end.
   b. Use a red short lead to connect the positive end of the capacitor to the input at node B. Use a black short lead to connect the negative end of the capacitor to ground at node D.

4. Connect the Vicor DC-DC converter's input to elliptical's output and OVPC, and connect the converter's output to the Enphase M215 inverter. Prior efficiency test sessions should already have the converter prepped with capacitors for testing. For this test, adequately protect the Vicor by placing protective fuses at the Vicor's input and output.
    a. Attach an alligator clip to one end of a red banana-to-banana cable. Connect the banana end to node A on the OVPC, and clip the alligator end to a fuse rated for 5 A. Using a short lead with alligator clips on both ends, attach one clip to the open end of the fuse and clip the other to the "+IN" input of the DC-DC converter.
    b. Attach an alligator clip to one end of a black banana-to-banana cable. Connect the banana end to ground at node G, and clip the alligator end to the "–IN" terminal of the DC-DC converter.
    c. With alligator clips attached, connect a red banana-to-banana cable from "+OUT" of the Vicor to one end of a fuse rated for 8 A. Using a short lead with one alligator clip, connect the other end of the fuse to the positive input of the M215 microinverter.
    d. Connect a black banana-to-banana cable from "–OUT" of the Vicor to the negative input of the M215 microinverter. Let one end of the banana cable have an alligator attachment and clip the alligator end to the Vicor.
    e. Connect the Fluke multimeter using banana-to-banana cables to measure the output voltage of the Vicor.

5. Connect the M215 microinverter to an AC grid, and have a power meter measure the AC power output the inverter generates.
    a. Connect the AC output of the M215 microinverter to the high-power lab bench in room 150 through a power meter as shown in Figure B-22.
        i. Connect the black output port of M215 microinverter, "L1", to the red input port of the power meter, "L in". Use a red banana-to-banana cable.
        ii. Connect "L out" of the power meter to the "ϕA" terminal of the power bench. Use a red banana-to-banana cable.
        iii. Connect the red output port of the M215 microinverter, "L2", to the "N in" port of the power meter. Use a red banana-to-banana cable.
        iv. Connect "N out" of the power meter to the "ϕC" terminal of the power bench. Use a black banana-to-banana cable.
        v. Connect the white output port of the M215 microinverter, neutral, to the "ϕB" terminal of the power bench. Use a black banana-to-banana cable.
        vi. Also connect the green output port of the M215 microinverter, earth ground, to the "ϕB" terminal of the power bench. Use a black banana-to-banana cable.
6. Connect the Enphase Envoy to the M215 inverter and the Internet. The Envoy allows for monitoring the microinverter's energy output to the grid through Enphase's Enlighten online software. In addition to reporting energy production, the Envoy also reports error messages from the inverter.

a. The Envoy has an AC power cord adapted to connect to the M215 Inverter's AC output. These three connectors (for line, neutral, and ground), connect at the same terminals where the banana-to-banana cables connect, but do not interfere with their connections.

    i. Connect the brown wire from the Envoy's AC power adapter to the M215 inverter's "L2" AC output connection, denoted by a red wire. A tester must connect to "L2" instead of "L1" because the "L1" wire from the M215 inverter does not have the proper attachment to connect with the adapters on the Envoy's AC power cable.

    ii. Connect the Envoy's blue AC wire to the M215's neutral white wire.

    iii. Connect the Envoy's green wire to the M215's green earth ground wire.

b. Connect the envoy to the internet by establishing an Ethernet connection to the envoy from an internet router. If a wired connection cannot occur, then use a USB powered Wi-Fi adapter.

7. Connect the oscilloscopes to the OVPC. The oscilloscope measure the elliptical's output voltage, the voltage on the IGBT's collector terminal, and monitor the voltage on the IGBT's gate terminal.

    a. Connect scope probes from Channel 1 on both oscilloscopes to node B on the OVPC. This allows the oscilloscopes to measure the voltage level produced from the elliptical machine at the capacitive filtering bank, which filters out high frequency transients.

b. Connect a scope probe to Channel 2 of Oscilloscope 1 to the IGBT's gate. This allows a tester to monitor the signal on the IGBT's gate and ensure proper switching occurs.

c. Connect a fourth scope probe from Channel 2 of Oscilloscope 2 to the IGBT's collector. Doing so allows for measuring the voltage drop across the diverting 10 Ω resistor and ensures proper switching for the IGBT.

d. Using the "measure" button on the oscilloscopes, have Oscilloscope 1 measure the minimum voltage, peak voltage, average voltage, and rms voltage of Channel 1. This displays voltage measurements on input voltage generated from the elliptical's output. Set Oscilloscope 2 to measure the minimum voltage, peak voltage, average voltage, and rms voltage on Channel 2. This displays voltage measurements on the IGBT's collector terminal.

8. After making all connections, verify that each component functions before collecting data. Before testers can begin recording data, the M215 inverter must undergo its startup process.

   a. Have an assistant run on the Precor elliptical while a partner observes and collects data from the multimeter, power meter, and oscilloscopes.

      i. The Precor elliptical machine starts with a default resistance setting of 1. At this setting, the elliptical's energy harvesting generates no power to its load.

      ii. Set the resistance setting of the elliptical to 2 to begin energy generation.

iii. Always have the person running stop and step down from the elliptical before servicing. Also make sure to completely discharge the 2.5 mF capacitor.

b. Verify the OVPC works first. Disconnect the DC-DC converter from the OVPC by severing the DC-DC converter's connections at node A and node G.

   i. Oscilloscope 1 probes both the input voltage and IGBT's gate. With the DC-DC converter disconnected, an observer can see from Channel 1 on the oscilloscope the input voltage rise to the threshold voltage that activates the IGBT for power diversion. Then the input voltage decreases until the input voltage falls below the lower threshold voltage where the IGBT ceases to divert power from the main line. With a 50 ms time scale on the oscilloscope, the input voltage signal appears as a sawtooth-like wave, similar to simulating the OVPC in LTspice with a current source. During the intervals where the oscilloscope shows then input voltage signal decrease, Channel 2 should show a signal that jumps to 12 V. Observation of these two signals confirms that the OVPC properly diverts power for its particular parameters.

   ii. Reconnect the DC-DC converter to the OVPC.

c. Check the output voltage of the CUI DC-DC Converter. If testing lacks a spare multimeter, temporarily remove the banana-to-grabber cables probing the voltage across the sense resistor to check. Verify that the

Vicor outputs at least 22 V to the M215 inverter. The Vicor typically outputs 35.9 V, but can output less voltage and still power the M215 inverter.

d. Turn ON the AC circuit breaker for the AC branch. Always de-energize the AC branch circuit before servicing.

e. The M215 has a startup voltage threshold of 22 V. Once the input voltage surpasses 22 V, it takes about 90 seconds for the inverter to emit six green blinks. A green LED means the inverter operates normally.

f. Have a user run on the Precor elliptical while a partner observes and collects data from the multimeter, power meter, and oscilloscopes.

    i. The Precor elliptical machine starts with a default resistance setting of 1. At this setting, the elliptical's energy harvesting circuitry fails to generate power to its load.

    ii. Raising the resistance setting of the elliptical to 4 while running at a 100 SPM pace produces sufficient voltage at the Vicor's output to startup the M215 inverter and begins energy conversion.

g. After about 70 seconds, the LED on the M215 inverter blinks six times in one second intervals indicating the end of the inverter's start up. The inverter's LED pauses briefly from emitting before indicating whether or not the inverter started up successfully. If the inverter continues to flash green, then the microinverter operates normally. If the LED flashes red, then the microinverter does not operate normally.

i. Troubleshooting: If a few seconds after the six green blinks the inverter blinks red every two seconds, the means the inverter fails to connect to an AC grid.

ii. This problem occurred during initial testing of the M215 Microinverter. A severed connection in one of the AC lines, specifically, the connecting lead end of the “Line 1”, prevented the microinverter from outputting AC power. Establishing a proper connection in the wire at the connecting node fixed this issue and allowed me to continue testing.

iii. The inverter’s LED may blink red at the end of the startup process a few times before changing to green.

9. Testing may begin once the M215 inverter starts up and converters DC power into AC power.

   a. While a user runs on the Precor Elliptical, set the oscilloscope so it views 3-7 switching cycles of the input voltage. One cycle refers to the input voltage increasing, and then decreasing due to the IGBT diverting excess power. On low elliptical resistance settings, once the M215 inverter generates AC power, the input voltage from the elliptical may not exceed the minimum threshold hold to require power diversion from the IGBT. In this case, the OVPC does not experience any switching cycles.

      i. The first oscilloscope probes the source voltage and IGBT’s gate voltage, while the other oscilloscope probes the source voltage and IGBT’s collector voltage.

ii. Each Tektronix oscilloscope used for testing can display five measurements. Having two oscilloscopes means not having to change mode of measurement or scope probe channel while in the middle of testing. The observer of this test session must record four kinds of voltage measurements for both the source voltage from the elliptical and the IGBT collector voltage.

iii. When the oscilloscopes show 3-7 switching cycles of the input voltage, simultaneously press the STOP button on both oscilloscopes. This allows the observer to record data more easily.

iv. With Oscilloscope 1 displaying measurements for the source voltage and Oscilloscope 2 displaying measurements for the IGBT collector voltage, record their MIN, MAX, MEAN, and RMS voltages.

v. Use Excel to calculate values for the diverted current and power through the diverting resistor. For calculations, assume a collector voltage of 1.0 V when OVPC diverts.

vi. If required for calculations, measure the input voltage when the OVPC starts and ceases diverting power. Also measure the average minimum collector voltage.

b. The multimeter measures the voltage across the sense resistor. After pressing the STOP button on the oscilloscopes, press the “MinMax” on the Agilent multimeter. This sets the multimeter to remember the maximum, minimum, and average voltages seen across the sense resistor. Pressing the

“MinMax” button cycles the multimeter to displaying the maximum value, then minimum value, then average value.

   i. Record the minimum, maximum, and average voltages displayed by the multimeter.
   ii. Use Microsoft Excel to calculate the minimum, maximum, and average currents flowing to the DC-DC converter’s input.

c. The power meter measures the voltage, current, and power output from the M215 inverter to the AC grid. Record the minimum and maximum values by taking advantage of the “Min” and “Max” button on the power meter.
d. Use Excel to calculate the average values and calculate the efficiency of the system.

APPENDIX C — PICTURES FOR CLEARING A TRIPPED GFI CONDITION

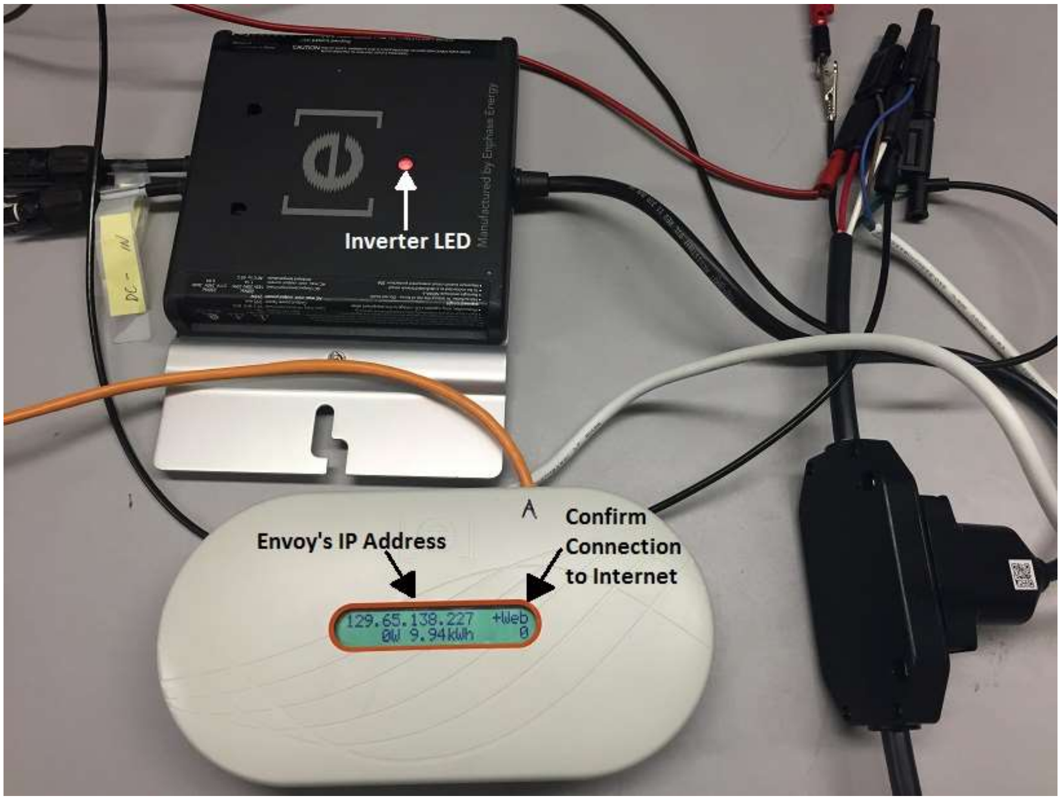

Figure C-1: Picture showing the M215 microinverter connected to the Envoy with other cables connecting to test equipment. Envoy displays an IP address and an internet connection while the M215 inverter LED emits a red light.

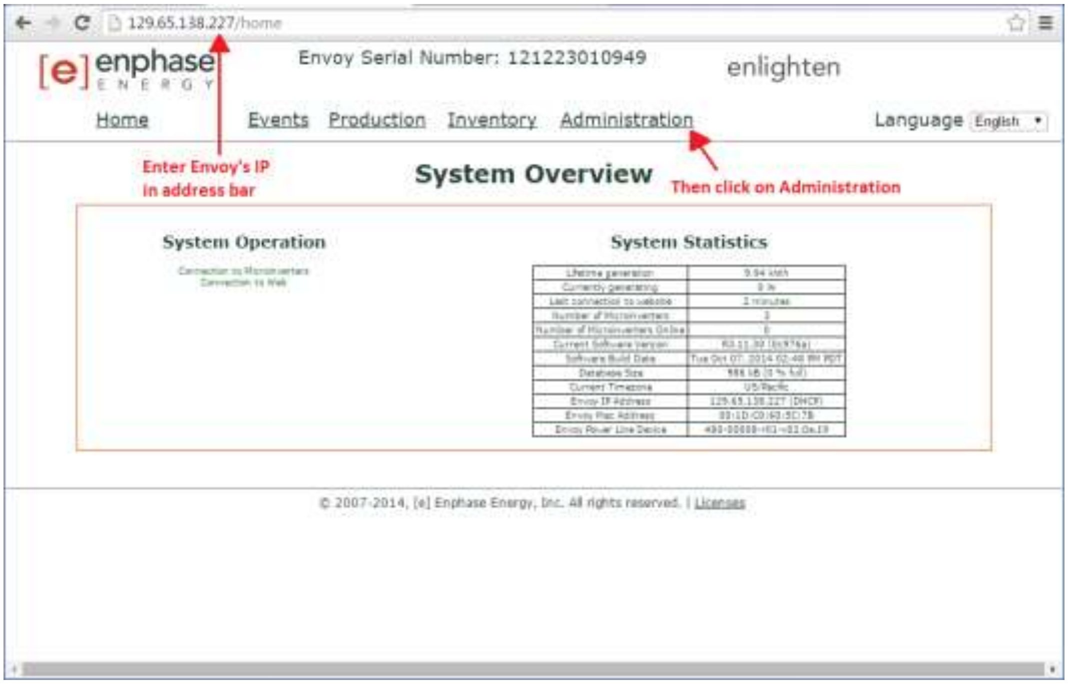

Figure C-2: Enter the Envoys displayed IP address (129.65.138.227) in the address bar of a web browser. This leads to the Envoy's home page. Then click on the Administration page.

Figure C-3: In the menu on the left side of the screen, click on "Device Conditions and Controls".

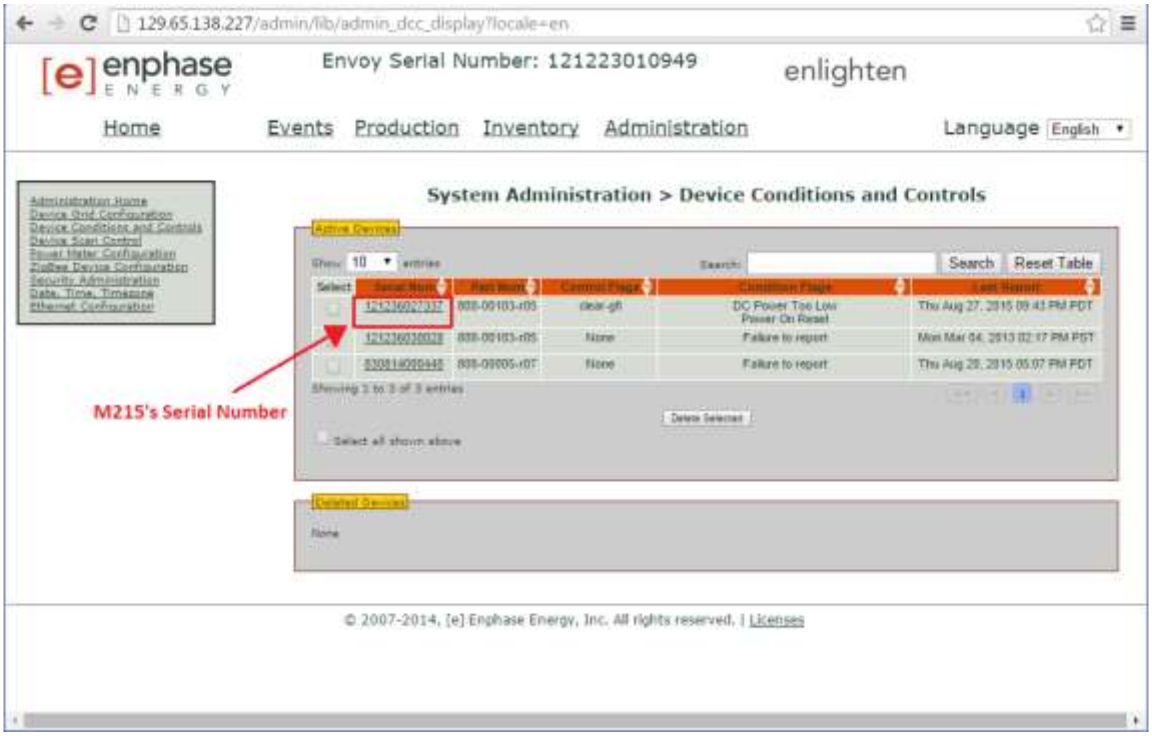

Figure C-4: Click on the serial number for the M215 inverter showing a "clear-gfi" control flag. Do not click on any of the boxes under "select" [14].

Figure C-5: Check the box that says "clear" under "clear-gfi" and click the "send command" button [14]. Do not select any other flags unless recommended by Enphase [14].

APPENDIX D — PICTURES OF EQUIPMENT

D.1 EHFEM Components

Figure D-1: Enphase M215-60-2LL-S25-IG Microinverter

Figure D-2: Enphase M175-24-240 Microinverter

Figure D-3: Enphase Envoy for monitoring and troubleshooting the M215 and M175 microinverters.

Figure D-4: Enphase Energy Management Unit (EMU) used for monitoring and troubleshooting the M175 microinverter.

Figure D-5: CUI VHK200W-Q48-S28 DC-DC Converter with filter capacitors and inductor.

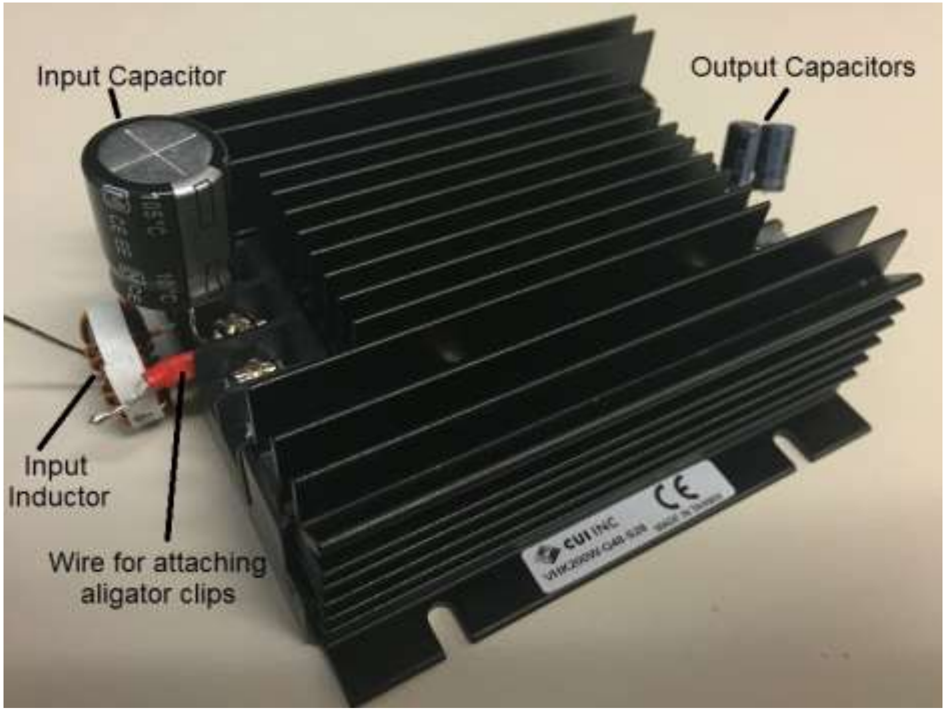

Figure D-6: Vicor V28A36T200BL2 DC-DC Converter with filter capacitors.

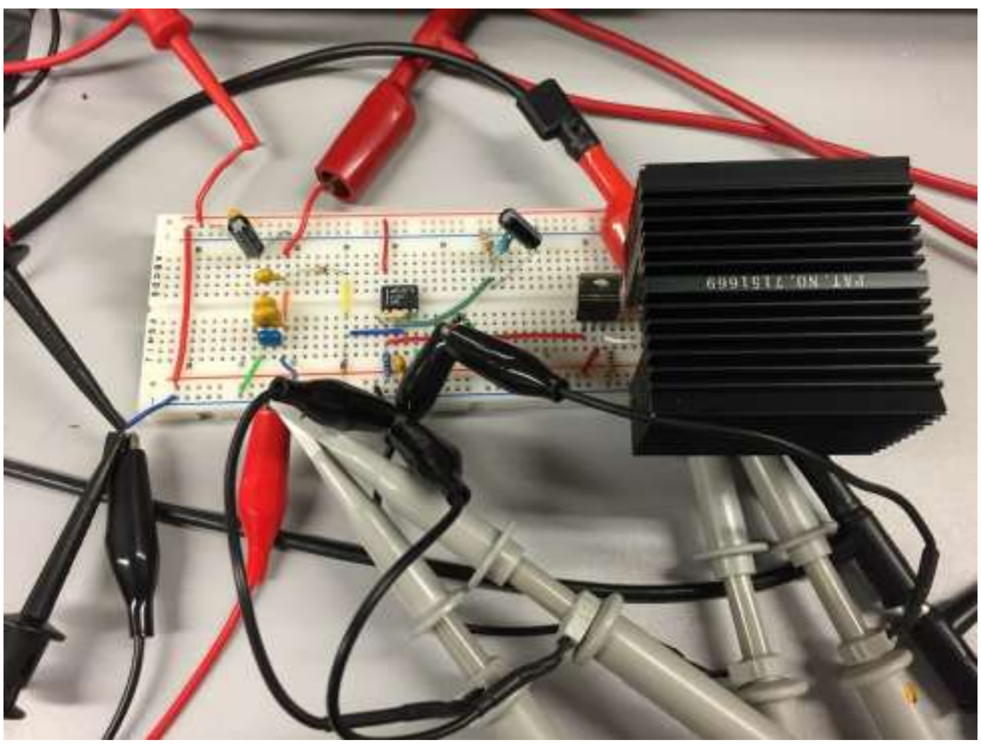

Figure D-7: Overvoltage Protection Circuit (OVPC) with cables and scope probes connecting to the nodes on the breadboard. Picture includes a heat sink protecting the IGBT with scope probes still able to reach the IGBT's terminals.

D.2 Test Equipment

Figure D-8: BK Precision Model 9153 High Power DC Source

Figure D-9: Agilent E3630A DC power Supply

Figure D-10: GW Instek GPM-8212 Power Meter

Figure D-11: Agilent U3401A Multimeter

Figure D-12: Fluke 8840A Multimeter

Figure D-13: Tektronix TDS 2002 Two Channel Digital Oscilloscope

Figure D-14: Fluke 196C Isolated Scopemeter

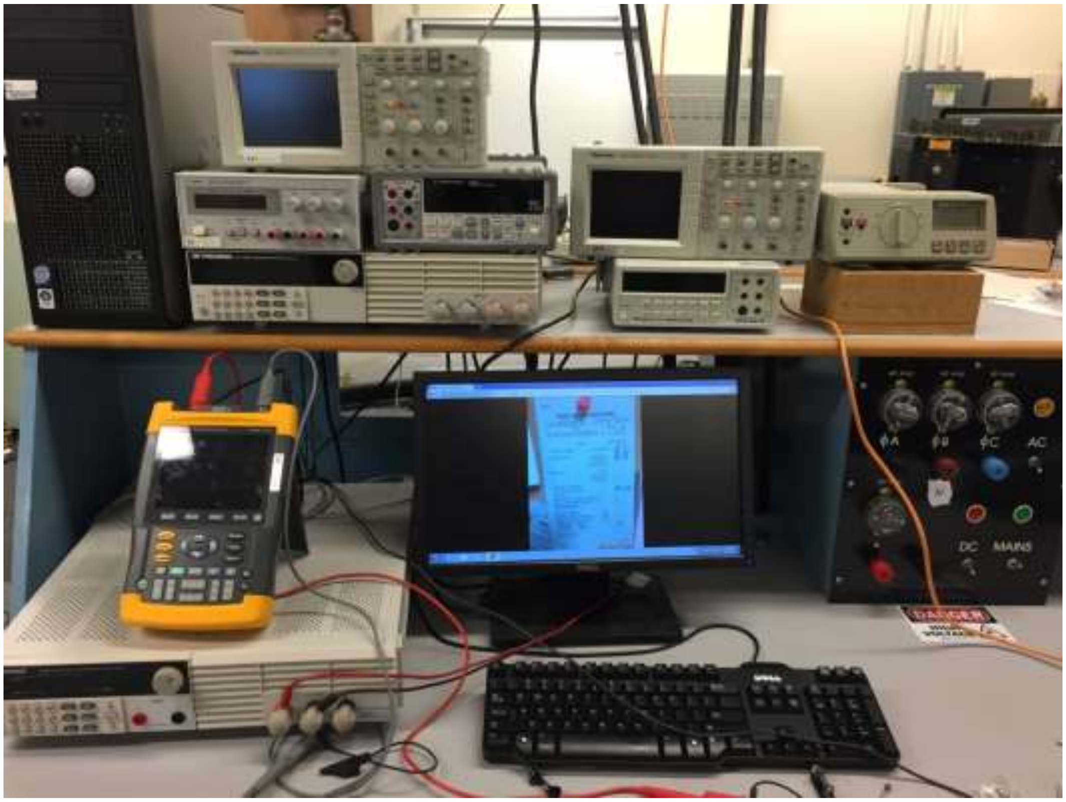

Figure D-15: Lab bench in room 150 of Engineering East with measurement test equipment

Figure D-16: High-power variable resistor used in earlier tests as the "load resistor" since this resistor can continuously dissipate power without heating to temperatures capable of burning on contact. Connecting cables via alligator clips to the top and bottom metal braces on the left side lets this physically large resistor equal 10 Ω.

APPENDIX E — COMPONENT PURCHASE INVOICE

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Fax 218-681-3380

Invoice # 50636250
U.S. $

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492 FELTON WAY
SN LUIS OBISP CA 93405-0000
CUSTOMER 7679397

Bill To: CAMERON R KIDDOO
492 FELTON WAY
SAN LUIS OBISPO CA 93405-0000

Terms	Invoice Date	Page
Visa	27-AUG-2015	1

Customer Purchase Order	Sales Order
	44005978

Back Orders	Account
Accepts to 26-SEP-2015	2327424

Entered By / Date	Shipped Via	Ship Date
A0FX/27-AUG-2015	UGT	27-AUG-2015

Easy to Remember: 1-800-DIGI-KEY

For Office Use Only	Received	VAT/Tax ID	Billing	Pack List No.	Printing Date	Currency Type	MSC #
	INTERNET		BILL SHIP	1	27-AUG-2015	U.S. $	0

Idx	Box	Ordered	Cancelled	Shipped	Item Number/Description	Back Order	Unit Price US $	Amount US $
1	1	1	0	1	102-2025-ND		219.40000	219.40 T
					CONVERTER DC-DC 28V 7.14A 200W			
					HTSUS: 8504.40.9580 ECCN: EAR99			
					LEAD: LEAD FREE ROHS: ROHS COMP	REACH: REACH	UNAFFECTED	OCT-2010
					COUNTRY/ORIGIN: TAIWAN			
					CAGE: OP9A7			
					BOX 1 SHIPPED UGT WEIGHT 1 LBS 13 OZS (0.82 KG)			
					BOX ID 1Z89E1R60303183889			
					TOTAL INVOICED			219.40
					SHIPPING CHARGES APPLIED			13.80
					** CHARGES SUBTOTAL **			233.20
					SALES TAX			17.55
					(T INDICATES TAXABLE AMOUNTS)			
					TOTAL CHARGED TO CREDIT CARD			250.75 U.S. $$
					YOUR CREDIT CARD HAS BEEN CHARGED THE ABOVE INDICATED AMOUNT			
					THE ORDER IS COMPLETE			
				Ship To:	CAMERON KIDDOO 492 FELTON WAY SN LUIS OBISP CA 93405-0000			
				Ship From:	DIGI-KEY 4206 33RD STREET NORTH FARGO ND 58102-0000			
				General -	WEB ORDER ID: 149388097			

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Contact Customer Service at 1-800-858-3616

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Figure E-1: Product invoice for the CUI VHK200W-Q48-S28 DC-DC converter (Part 1).

www.digikey.com
Orders 1-800-344-4539
Fax 218-681-3380

Invoice # 50636250
U.S. $

701 Brooks Ave. South, Thief River Falls, MN 56701-0677 USA

Sold To:
CAMERON KIDDOO
492 FELTON WAY
SN LUIS OBISP CA 93405-0000

CUSTOMER 7679397

Terms	Invoice Date	Page
Visa	27-AUG-2015	2
Customer Purchase Order	Shipped Via	
	UGT	

Easy to Remember:
1-800-DIGI-KEY

Idx	Box	Ordered	Cancelled	Shipped	Item Number/Description	Back Order	Unit Price US $	Amount US $
					These commodities, technology or software were exported from the United States in accordance with the Export Administration regulations. Diversion contrary to U.S. law prohibited.			
			CERTIFICATE OF COMPLIANCE:		The Digi-Key components included in the above shipment are genuine components and were provided by the applicable manufacturer to Digi-Key. Test reports (chemical, physical, electrical, etc., together with results of any tests performed by the manufacturer) are on file (either here or in the plant of the manufacturer) and will be made available upon request. These components have been handled in accordance with the requirements of applicable quality standards. This certification is valid only to the original customer and is not transferable. Contact Customer Service at 800-858-3616 if you have any questions. Kim Gilbert, Director, Customer Service			

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Figure E-2: Product invoice for the CUI VHK200W-Q48-S28 DC-DC converter (Part 2).