Lab-Scale Thyristor Rectifier and Static VAR Compensator Circuits

Custom/Typical Applications

By

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Table of Contents

Acknowledgements ................................................................................................................................. x
Abstract ...................................................................................................................................................... xi
1. Introduction ............................................................................................................................................ 1
2. Background ........................................................................................................................................... 4
   A. 4-Thyristor Bridge Rectifier .............................................................................................................. 4
   B. Static VAR Compensator ................................................................................................................... 6
3. Requirements ......................................................................................................................................... 9
   A. 4-Thyristor Bridge Rectifier Circuits ............................................................................................... 9
   B. Static VAR Compensator .................................................................................................................. 10
4. Design .................................................................................................................................................. 11
   A. 4-Thyristor Bridge Rectifier Circuits ............................................................................................... 11
   B. Static VAR Compensator .................................................................................................................. 12
5. Testing Procedures .............................................................................................................................. 14
   A. Firing Angle Test .............................................................................................................................. 14
   B. 4-Thyristor Bridge Rectifier Test ..................................................................................................... 15
   C. Static VAR Compensator Test ...................................................................................................... 16
6. Testing Results ...................................................................................................................................... 18
   A. AC Line regulator ............................................................................................................................ 23
   B. 4-SCR Bridge Rectifier .................................................................................................................... 36
   C. Static VAR Compensator ................................................................................................................ 46
7. Conclusion ............................................................................................................................................ 49
Bibliography .............................................................................................................................................. 51
Appendix A: Parts list ............................................................................................................................... 52
Appendix B: Hardware Configurations ..................................................................................................... 53
Appendix C: Lab manuals ........................................................................................................................... 55
List of Tables

Table 4.1: Measured parameters for SVC circuits at rated voltage. .......................... 12
Table 6.1 Measured Parameters for AC Line Regulator............................................ 23
Table 6.2: Measured parameters for Full wave rectifier circuit.................................. 36
Table 6.3: Measured Parameters for SVC circuit with 3uF Capacitor ....................... 46
Table 6.4: Measured Parameters for SVC circuit with 4uF Capacitor ....................... 46
Table 6.5: Measured Parameters for SVC circuit with 5uF Capacitor ....................... 47
Table 6.6: Measured Parameters for SVC circuit with 6uF Capacitor ....................... 47
Table 6.7: Measured Parameters for SVC circuit with 7uF Capacitor ....................... 47
Table B-1: Parts List for Thyristor Controlled Full Wave Rectifier Circuit.............. 53
List of Figures

Figure 1-1: Power Diode........................................................................................................ 1
Figure 1-2: Thyristor.......................................................................................................... 2
Figure 2-1: Uncontrolled Half Wave Rectifier with Resistive Load ......................... 4
Figure 2-2: Full Wave Thyristor controlled Rectifier Bridge................................. 5
Figure 2-3: FCRO 4100 Firing Board............................................................................. 5
Figure 2-4: SVC Circuit with Inductive Load............................................................... 7
Figure 3-1: Thyristor Module ....................................................................................... 9
Figure 4-1: Full Wave Thyristor controlled Rectifier Bridge.................................. 11
Figure 5-1: Full Bridge Rectifier with R load.............................................................. 14
Figure 5-2: Firing Angle vs. Gate Voltage ................................................................. 15
Figure 5-3: Orcad Capture schematic of Full Bridge Rectifier with Resistive Load. 16
Figure 5-4: AC Controller Circuit............................................................................... 16
Figure 6-1: Measured Firing angle vs. gate Voltage for FCRO 4100 firing board... 18
Figure 6-2: Firing Angle of 8.57° ............................................................................. 19
Figure 6-3: Firing Angle of 15° ................................................................................ 19
Figure 6-4: Firing Angle of 30° ................................................................................. 19
Figure 6-5: Firing Angle of 45° ............................................................................... 20
Figure 6-6: Firing Angle of 60° ................................................................................. 20
Figure 6-7: Firing Angle of 75° ............................................................................... 20
Figure 6-8: Firing Angle of 90° ............................................................................... 21
Figure 6-9: Firing Angle of 105° .............................................................................. 21
Figure 6-10: Firing Angle of 120° ................................................................. 21
Figure 6-11: Firing Angle of 135° ................................................................. 22
Figure 6-12: Firing Angle of 150° ................................................................. 22
Figure 6-13: Output Voltage of an AC Controller as a function of delay angle........ 24
Figure 6.14: Orcad Capture of Output voltage of an AC regulator at 0°.............. 24
Figure 6.15: Orcad Capture of Output voltage of an AC regulator at 5°.............. 25
Figure 6.16: Orcad Capture of Output voltage of an AC regulator at 15°.......... 25
Figure 6.17: Orcad Capture of Output voltage of an AC regulator at 30°......... 26
Figure 6.18: Orcad Capture of Output voltage of an AC regulator at 45°......... 26
Figure 6.19: Orcad Capture of Output voltage of an AC regulator at 60°....... 27
Figure 6.20: Orcad Capture of Output voltage of an AC regulator at 90°....... 27
Figure 6.21: Orcad Capture of Output voltage of an AC regulator at 120°..... 28
Figure 6.22: Orcad Capture of Output voltage of an AC regulator at 135°..... 28
Figure 6.23: Orcad Capture of Output voltage of an AC regulator at 150°..... 29
Figure 6.24: Orcad Capture of Output voltage of an AC regulator at 165°..... 29
Figure 6.25: Orcad Capture of Output voltage of an AC regulator at 180°..... 30
Figure 6-26: Vout of AC controller at 0.5V ..................................................... 31
Figure 6-27: Vout of AC controller at 1.0V ..................................................... 31
Figure 6-28: Vout of AC controller at 1.5V ..................................................... 32
Figure 6-29: Vout of AC controller at 2.0V ..................................................... 32
Figure 6-30: Vout of AC controller at 2.5V ..................................................... 33
Figure 6-31: Vout of AC controller at 3.0V ..................................................... 33
Figure 6-32: Vout of AC controller at 3.5V ............................................................... 34
Figure 6-33: Vout of AC controller at 4.0V ............................................................... 34
Figure 6-34: Vout of AC controller at 4.5V ............................................................... 35
Figure 6-35: Vout of AC controller at 5.0V ............................................................... 35
Figure 6.36: Orcad Capture of Output voltage of a full-wave rectifier at 0°.......... 37
Figure 6.37: Orcad Capture of Output voltage of a full-wave rectifier at 15°......... 37
Figure 6.38: Orcad Capture of Output voltage of a full-wave rectifier at 30°....... 38
Figure 6.39: Orcad Capture of Output voltage of a full-wave rectifier at 45°....... 38
Figure 6.40: Orcad Capture of Output voltage of a full-wave rectifier at 60°....... 39
Figure 6.41: Orcad Capture of Output voltage of a full-wave rectifier at 90°....... 39
Figure 6.42: Orcad Capture of Output voltage of a full-wave rectifier at 120°.... 40
Figure 6.43: Orcad Capture of Output voltage of a full-wave rectifier at 135°.... 40
Figure 6.44: Orcad Capture of Output voltage of a full-wave rectifier at 150°.... 41
Figure 6.45: Orcad Capture of Output voltage of a full-wave rectifier at 165°.... 41
Figure 6.46: Orcad Capture of Output voltage of a full-wave rectifier at 180°.... 42
Figure 6-47: Vout of Rectifier at 0.5V........................................................................ 42
Figure 6-48: Vout of Rectifier at 1.0V........................................................................ 43
Figure 6-49: Vout of Rectifier at 1.5V........................................................................ 43
Figure 6-50: Vout of Rectifier at 2.0V........................................................................ 43
Figure 6-51: Vout of Rectifier at 2.5 V........................................................................ 44
Figure 6-52: Vout of Rectifier at 3.0 V........................................................................ 44
Figure 6-53: Vout of Rectifier at 3.5V........................................................................ 44
Figure 6-54: Vout of Rectifier at 4.0V................................................................. 45
Figure 6-55: Vout of Rectifier at 4.5V................................................................. 45
Figure 6-56: Vout of Rectifier at 5.0V................................................................. 45
Figure 6.57: Power factor as a function of delay angle for SVC circuit.............. 48
Figure 6.58: Efficiency as a function of delay angle for SVC circuit................. 48
Figure B-1: Hardware Configuration for Thyristor Controlled Full Wave Rectifier 53
Figure B-2: Hardware Configuration for Static VAR Compensator ................. 54
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Abstract

The purpose of this project is to design thyrsitor circuits by using single-phase FCRO 4100 firing board donated by ENERPRO. These circuits in conjunction thyristor module will be used for future lab experiments power electronics courses.

The first part of this project is to study the effect of firing angle on a controlled single phase full bridge thyristor rectifier circuit. Furthermore, the resulting circuit setup will be implemented as a part of future lab experiment in EE 410 Power Electronics I course.

Then next purpose of this project is to build a small scale Static VAR Compensator (SVC) lab experiment for use in Power Electronics II course. The lab experiment will show how to correct power factor using thyristors in a phase controlled circuit. A resistor and inductor will be used to mimic a customer inductive load. A thyristor controlled reactor (TCR) in parallel with a capacitor will be the SVC. By adjusting the firing angle $\alpha$ of the TCR, we can either inject or absorb reactive power into the system to achieve a higher power factor and ultimately a more efficient power system.
1. Introduction

Power electronics is one of the most important aspects of Electrical Engineering. Power electronics involves the use of semiconductor devices to control the transfer of electrical power from the source to the load and vice versa [1]. It can control the electrical power in many different ways such as changing the amount of power transferred from source to load, converting the type of signals (e.g. AC signals to AC signals with different frequency or AC signals to DC signals), and many others [2]. As we use power electronics to perform power transfer and conversion, it is always important to maintain high system’s efficiency [1]. To achieve this crucial objective, power electronics uses switching techniques, by means of semiconductor devices as switches to prevent large losses [2]. Some of the common semiconductor switches implemented in power electronics circuits are power diodes and thyristors. Power diodes are uncontrollable switches because their on and off state cannot be controlled by their users [1]. That is, the power circuit solely determines their on and off conducting states. Figure 1-1 below shows a symbol of a diode on schematics.

![Power Diode Symbol](image)

On the input side of a diode, the node ‘a’ is called anode, and the output node ‘b’ is cathode. A diode turns on when it is forward biased, which means that the voltage on anode side is higher than cathode side. On the other hand, if the voltage on cathode side was higher than anode side or reverse biased, the diode turns off.
Though it looks similar to a diode, thyristor has an extra node called gate. This gate terminal offers the semi-controllability of a thyristor. To turn on a thyristor, a pulse of positive gate current needs to be applied at the gate, while keeping the voltage on the anode side higher than cathode side. When it is reverse biased, a thyristor will turn off just like a diode.

![SCR Diagram](image)

**Figure 1-2: Thyristor**

Diodes and Thyristors are particularly useful in applications which require the current to flow in one direction. This type of application in power conversion is called rectifier. Rectifier circuits in general convert AC signals to DC signals by using power diodes or by controlling the firing angle of thyristors or other controllable switches. The input of this circuit can be single-phase or multi-phase. The type of the output signals of rectifiers depends on the type of switches implemented. When power diodes are used in rectifiers, the rectifier circuit will produce a fixed output voltage, whereas if thyristors were used in the circuit, the DC output voltage will be controllable. The diode rectifier is useful when a fixed DC output voltage is needed such as that of PC power supply. The adjustable DC output voltage of Thyristor rectifier is handy in applications such as DC motor drive where adjustable DC is needed.

Power efficiency is a topic that has become more and more prominent as demand for electrical power grows. When inductive loads are added to the power system by customers, the sending voltage reduces which affects the amount of apparent power the utility has to supply because of the added volt-ampere reactive power or VAR. This in turn increases current drawn for the same amount of real power (Watts), which further increases the systems loss. The customer, on the other hand will have to pay more. This problem can be corrected normally
using corrective capacitors to supply the VAR. While using a set capacitance to correct the power factor is beneficial, loads can vary and a set capacitance can possibly lead to overcompensation which is an unnecessary boost in voltage which could damage loads. Hence, a better method to improve power factor is needed. The utility companies do their part to provide quality power; consumers must do their part using the efficiency of power electronics.

Recently, another technique to improve power factor or to compensate for VARs has been implemented using power electronics. With this method, continuous adjustment of VARs may be achieved [3]. Power electronics deals with the flow control of electricity through switching or power semiconductors. By using various solid-state switches and switching techniques, power can be efficiently delivered for usage.
2. Background

The main objective of this project is to design experiments for future power electronics labs. The following sections describe the developed circuits for this experiment.

A. 4-Thyristor Bridge Rectifier

The main objective of this part of the project is to design and build a single-phase thyristor bridge rectifier circuit. There are two basic types of rectifications: half-wave rectification and full-wave rectification.

The basic configuration of a half-wave rectifier is quite simple, consisting of an AC voltage source, a diode (or a thyristor), and a desired load in series. Though it satisfies the purpose of rectification circuits, half-wave rectifier is not practical because it produces high ripple factor (ratio between AC component to its root-mean-square [RMS] value), which result in a poor DC output voltage that requires high filtering. To solve this issue, we would instead focus on full-wave rectifier circuits.

![Uncontrolled Half Wave Rectifier with Resistive Load](image)

A basic configuration of full-wave rectifier circuit is shown in Figure 2-1. Though it shares the same purpose as that of half-wave rectifiers, full-wave rectifier performs better. Voltage source swings from positive to negative. During the positive cycle, thyristor Q1 and Q2 conduct and create a path for energy to flow. During the negative cycle, thyristor Q3 and Q4 conduct and again, creating another path for the energy to flow [4]. Therefore, unlike half-wave
rectifier whose output current is discontinuous, full-wave rectifier circuits have continuous current, which result in higher average output current. This also means a significant increase in average output voltage of full-wave rectifier compare to half-wave. Lastly, though peak to peak ripple of output voltage is the same for both circuits, the DC output voltage of full-wave rectifier circuits would be easier to be filtered because its ripple frequency is doubled.

![Figure 2-2: Full Wave Thyristor controlled Rectifier Bridge](image1.png)

The power electronics lab at Cal Poly San Luis Obispo recently received donation from Enerpro, Inc. in the form of 10 units of single-phase thyristor firing board shown on Figure 2-3.

![Figure 2-3: FCRO 4100 Firing Board](image2.png)
The firing board is essential in controlling thyristor switches such as those in thyristor bridge rectifier circuit. Hence, this donation presents an opportunity to expand its capability and to provide thyristor-rectifier lab experiment to help students to further understand the operation of controlled rectifier circuits. The proposed project is aimed to construct the single-phase rectifier circuit that employs the Enerpro Inc.'s firing boards. The circuit will be used as a lab experiment for future EE 410 course where students may learn the operation of a single-phase thyristor rectifier circuit.

B. Static VAR Compensator

Utility companies normally deal with varying inductive loads which can cause problems supplying power efficiently and economically. These inductive loads ultimately lag the power factor which results in low voltage being supplied to the customer. Alternatively, this causes a higher current to flow through the power system which in turn causes significant losses in the system. Although it is possible to put a capacitor in the system to account for the power factor, the load is always changing and a fixed capacitance would not be enough to compensate for the varying power factor. Moreover, a fixed capacitor may run into the risk of overcompensation which causes the system’s voltage to go up and may be damaging to loads.

A Static VAR Compensator (SVC) consists of a Thyristor-controlled Reactor (TCR) which is an inductance in series with a bidirectional thyristor switch as shown in Figure 2-4. The reactor performs in parallel with a corrective capacitor to adjust for a leading or lagging power factor [5]. The main function of a SVC is to absorb or supply reactive power based on the changing VAR requirement of the load. Hence, the use of an SVC allows for the application of power factor correction to maintain the unity power factor for a variable load.
The ability of the Thyristor-controlled Reactor (TCR) to limit current is a vital part of controlling power flow. The current is controlled by the firing angle ($\alpha$), which at 0° the switch is permanently closed, then slowly limits current as $\alpha$ increases to 180° where current is then zero. Limiting the current ultimately limits the reactive current which results in how much reactive power can be added to or subtracted from the system. With the SVC, when $\alpha = 0$ the current passes fully through the inductor bypassing the capacitor. Yet as $\alpha$ increases to 180°, current will be forced to slowly pass through the capacitor, and thus raise the lagging power factor of the system. Therefore the delay angle $\alpha$ may be directly related to how much power factor correction we need for the system.

Another objective in this project entails how power electronics is implemented in power systems and how they can affect one another. The SVC is a thyristor-based power electronic device used on power systems by utilities to maintain a unity power factor on a varying load. Observing how a SVC operates is therefore a great way to see how thyristors work in real world applications. Using the FCRO4100 firing board, recently donated by Enerpro, in combination with the thyristor board in the power electronics lab at Cal Poly allows the students to actually see how semi-controllable switches work, and how power electronics helps performance in a
power system. One objective of this project is to build a circuit such that students will see how thyristors affect the sinusoidal input voltage in an ac controller configuration. Hence, the goal of this project is to build a small scale SVC to show how thyristors can be used effectively to correct power factor using a reactor and a capacitor.
3. Requirements

In this section, the requirements to build thyristor based circuits will be listed.

A. 4-Thyristor Bridge Rectifier Circuits

A controlled full-wave rectifier circuit will be constructed to demonstrate how the process of rectification works. To be able to control the thyristors, Enerpro Inc.’s FCRO4100 firing board will be connected to each gate of the thyristors. Two types of load will be used for this project: Resistive load and R-L load (load resistance and load inductance). The thyristor circuit must be designed to make use of the currently available testing devices in the power electronics lab at Cal Poly. This includes the resistor load, inductor, capacitor, DC power supply, and the thyristor module as shown in Figure 3-1.

Figure 3-1: Thyristor Module
The thyristor circuit setup should also be designed with safety in mind and hence protection devices such as fuses will be placed whenever necessary. The thyristor rectifier circuit must not exceed the output current of 1A through the load with AC voltage input of 120V. Furthermore, two load setups will also be designed. First is the normal resistive load to show the operation and power quality of the rectifier circuit. The second is resistive load in series with inductive load to show how inductive load would affect the output voltage of full bridge rectifier. A lab manual containing step-by-step procedure on how to conduct the lab experiment will be provided as part of the deliverables of this project.

**B. Static VAR Compensator**

To demonstrate how thyristors work and how we use them to control power flow in an AC system, a small-scale SVC experiment will be developed. More specifically, the experiment is for the development of 8 small-scale SVC modules for the Cal Poly Power Electronics Lab. The recently donated FCRO4100 firing boards by Enerpro with thyristors provided by the Power Electronics Lab will be used for the experiment. The firing board is connected to the thyristor control terminals via banana to banana cables. To model an inductive load, a 0.5 H inductor and a 150 Ω resistor available in each lab bench will be used. A decade capacitor from 1-10 uF as well as a 0.5H inductor will be needed for the SVC Circuit. Because each 150 Ω resistor has a 0.82 A rating, the SVC circuit must be adjusted to stay within the current limit of the resistor. We will use 120Vrms ac input accessible from each lab bench for both the firing board as well as the SVC circuit. To compute the capacitor value, the voltage, current, power, and power factor of inductive load are measured using the power meter in the circuit shown in Figure 2-4.
4. Design

As mentioned in part III, it is required to design this project using components available in the power electronics lab. The parameters for both circuits are calculated using rated values.

A. 4-Thyristor Bridge Rectifier Circuits

\[ I_0 = 1A \]
\[ V_{dc} = 120V \]
\[ R_{Load} = 150\Omega \]
\[ \alpha_{min} = 5^\circ \]
\[ \alpha_{min} = 175^\circ \]
\[ V_{in} = \sqrt{2}V_{ac} = 169.7V \]
\[ V_{oMax} = \frac{V_{in}}{\pi} (1 + \cos \alpha_{min}) = 107.8V \]
\[ I_{oMax} = \frac{V_{oMax}}{R} = \frac{107.8}{150} = 0.72A \]

![Figure 4-1: Full Wave Thyristor controlled Rectifier Bridge](image-url)
Figure 4-1 illustrates the schematics for the thyristor controlled full bridge rectifiers, along with their values. We will construct a full-wave rectifier with an R load and observe how the change in thyristors firing angle affects the DC output voltage. This circuit can be more than just a rectification circuit when the setting of firing angle (how the thyristor is controlled) is set up in inverting mode, which is a firing angle between $90^0$ to $180^0$. The last requirement of this senior project design is to investigate how full-wave rectifier operates in inverting mode. Inverting mode means that the power flows from a DC side (load side) to the AC side. This can happen when a DC power supply is added in the load side of the circuit during inverting mode.

It is necessary to check the functionality of the firing board [6]. The firing angle of FCRO 4100 firing board can be controlled by applying certain amount of voltage to its output. Based on the manual, it claims to be able to vary the firing angle between $5^0$ to $175^0$ [6]. We will first have to check whether or not this statement is valid before starting to investigate the behavior of each circuit.

**B. Static VAR Compensator**

The next part is to determine the required parameters for the SVC circuit. The calculation is shown below which uses the values from Table 4-1 which are measured parameters at rated values.

| Table 4.1: Measured parameters for SVC circuits at rated voltage. |
|---------------------|------------------|---------------|-----------------|
| Voltage ($V_{rms}$) | Current ($mA_{rms}$) | Power (W) | Power Factor |
| 120                 | 206.5            | 6.6         | 0.266          |
The initial power factor is quite low and hence provides a good starting value for the SVC experiment. The following calculations illustrate what size corrective capacitor to use. A typical load output is 120Vac with a frequency of 60 Hz in the United States. Taking the inverse cosine of the power factor gives the system angle normally lagging. The apparent power can be found by multiplying the voltage and the current with the power factor angle. The load impedance can be found by squaring the voltage and dividing by the apparent power. This is because the unit for voltage is Volt and the apparent power unit is VA. Therefore $V^2 / \text{VA} = \text{V/A} = \Omega$. After finding the impedance we can find the corrective capacitance by multiplying the Reactance Load $X_L$ by $2\pi f$ and taking the inverse of the result. The final capacitance comes out to be 4.74 µF.

While a typical $\alpha$ firing angle will range from 0-180° the board limits the range to 5-175°. We were able to measure the board’s firing range and conclude that it can fire from 5-154°.

**Sample calculation**

\[
f = 60Hz \\
\cos^{-1}(pf) = \cos^{-1}(0.266) = 74.6^\circ \\
S = VI^* = (120 < 0)(0.2065 < 74.6^\circ) = 24.78 < 74.6^\circ \text{VA} \\
Z_{Load} = \frac{V^2}{S} = \frac{120^2}{24.78 < 74.6^\circ} = 581 < -74.6^\circ \Omega = 154.3 - j560 \\
C = \frac{1}{2\pi f X_c} = \frac{1}{377 < 560} = 4.74 \mu F
\]

The capacitance corresponding to the resonant frequency is 4.74µF.
5. Testing Procedures

A. Firing Angle Test

To verify the range of firing angle of FCRO-4100 board, a full bridge rectifier circuit need to be set up using any kind of load (since it does not affect the firing angle measurement). Then, the outputs of FCRO-4100 are to be connected to the gates and cathodes of the corresponding thyristors. Lastly, this circuit is to be supplied with 120 V AC, as shown in Figure 5-1.

![Figure 5-1: Full Bridge Rectifier with R load](image)

In addition to the circuit above, a 10k ohms resistor is implemented in the firing board. To make the firing angle work, at least a voltage of 0.5V needs to be sent across the gate of the firing board. This 10k ohms resistor allows a varying voltage of 0V to 5V to flow across the gate, thus allowing us to vary the firing angle. The relationship between the gate voltage and firing angle can be seen on Figure 5-2.
To measure the firing angle, two channels of scope probes are needed. The first channel is connected to tp4 pin in FCRO-4100 board, and the second one to tp6 pin. Tp4 pin sends a reference waveform to the scope output while tp6 is sending the firing angle waveform in respect to the amount of gate voltage sent across the FCRO-4100 board [6].

**B. 4-Thyristor Bridge Rectifier Test**

Next, we will move on to investigate the output voltage across the full bridge rectifier using a resistive load. First of all, we are to construct the circuit in Orcad Capture as shown in Figure 5-3 [7] and collect the simulations of the output voltage along with their values using a varying firing angle. Notice that this simulation is using diodes instead of thyristors. To model thyristors, the diodes are connected to a switch. The parameter of the switch has to work similarly as the gate of thyristors.

The FCRO4100 firing board needs to be connected to the thyristors via banana to banana cables. The firing board has a 1 KΩ potentiometer connected which will be used to vary the firing angle $\alpha$. 
Using the same circuit configuration on Figure 5-1, replace the load with 150 ohms resistor. Then, we will use Power Scope to measure the DC output voltage.

**C. Static VAR Compensator Test**

In order to verify that the thyristors and firing board work correctly, we will configure an AC controller circuit with a resistive load shown in Figure 5-4. We will then record and graph the output RMS voltage at the various firing angle.
Then, we will build the SVC circuit as shown in Figure 2-4. An AC power meter will be connected to the source and the SVC circuit to monitor the change in voltage, current, power, and power factor. We will connect a multimeter across the terminals of the potentiometer to measure the control voltage for changing the firing angle. Based on the datasheet the control voltage has a maximum range of 0 to 5V with a delay angle range of 5 to 175°. During the actual measurements, a maximum control voltage range of 0 to 5.12V and a delay angle range of 5 to 154° were observed. At max control voltage of 5.12V, $\alpha$ should be about 5°; and as we decrease the voltage, the firing angle increases all the way to 154° at 0.5V. While the curves of the theoretical delay angle vs. control voltage graph were similar to the test results, we were only able reach a maximum firing angle of 154° instead of the theoretical 175° that was stated in the Enerpro FCRO4100 manual. The overall circuit used to perform this procedure is shown in Figure 2-4.

Based on the calculated value of the capacitance in the testing procedures, a decade capacitor is used with a range of capacitance from 3µF to 7µF to show how a varying power factor can occur in the SVC. The multimeter will be used to gauge the delay angle outputted by the firing board, while the AC power meter is used to records voltage, current, power, and power factor. Power factor and efficiency plots as a function of delay angle were obtained for each capacitor values.
6. Testing Results

After conducting the experiment to test the range of firing angle, the firing angle of FCRO-4100 was observed to range from $5^\circ$ to $154^\circ$. The relationship between delay angle and gate voltage obtained experimentally as shown in Figure 7-1, is almost similar to the theoretical one as shown in Figure 5-2.

![Gate Delay Angle Transfer Function](image)

**Figure 6-1**: Measured Firing angle vs. gate Voltage for FCRO 4100 firing board.

Figures 6-2 through 6-12 below show the waveforms for the firing angle (top waveform) and reference signal (bottom waveform). The firing angle waveform is captured from tp4 of the FCRO 4100 firing board while the reference signal is captured from tp6 of the FCRO 4100 firing board. The reference signal stays the same throughout the plots while the plots of the firing angle change. The duty cycle of the firing angle increases with increasing firing angle value, $\alpha$. 
Figure 6-2: Firing Angle of 8.57°

Figure 6-3: Firing Angle of 15°

Figure 6-4: Firing Angle of 30°
Figure 6-5: Firing Angle of 45°

Figure 6-6: Firing Angle of 60°

Figure 6-7: Firing Angle of 75°
Figure 6-8: Firing Angle of 90°

Figure 6-9: Firing Angle of 105°

Figure 6-10: Firing Angle of 120°
As explained earlier, the duty cycle of the firing angle increases with increasing firing angle value, $\alpha$. 
A. AC Line regulator

Table 6.1 shows that the relationship between the measured and calculated values of the AC line regulator circuit. It can be seen that there’s a linearly inverse relationship between the control voltage and the firing angle as shown in figure 5.2 and 6.1. As firing angle decreases, the rms value of the output voltage increases as shown in figure 6.13. This in turn increases the efficiency of the AC Line regulator.

<table>
<thead>
<tr>
<th>$V_{\text{cont}}$ (V)</th>
<th>$T_{\text{off}}$ (ms)</th>
<th>$A$ (deg)</th>
<th>$V_{\text{in}}$ (V)</th>
<th>$I$ (mA)</th>
<th>$P_{\text{in}}$ (W)</th>
<th>$V_{\text{out}}$ (V)</th>
<th>$P_{\text{out}}$ (W)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
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Figures 6.14 to 6.25 show the simulation of output voltage of an AC line regulator as a function of firing angle. When the firing angle value, $\alpha=0$, we get a full 120 V$_\text{rms}$ waveform while the output is zero when $\alpha=180$. As $\alpha$ increases from 0 to 180, the output rms voltage decreases which is already shown in Figure 6.13.
Figure 6.15: Orcad capture of Output voltage of an AC line regulator at a delay angle of 5 °

Figure 6.16: Orcad capture of Output voltage of an AC line regulator at a delay angle of 15 °
Figure 6.17: Orcad capture of Output voltage of an AC line regulator at a delay angle of 30 °

Figure 6.18: Orcad capture of Output voltage of an AC line regulator at a delay angle of 45 °
Figure 6.19: Orcad capture of Output voltage of an AC line regulator at a delay angle of 60 °

Figure 6.20: Orcad capture of Output voltage of an AC line regulator at a delay angle of 90 °
Figure 6.21: Orcad capture of Output voltage of an AC line regulator at a delay angle of 120°

Figure 6.22: Orcad capture of Output voltage of an AC line regulator at a delay angle of 135°
Figure 6.23: Orcad capture of Output voltage of an AC line regulator at a delay angle of 150 °

Figure 6.24: Orcad capture of Output voltage of an AC line regulator at a delay angle of 165 °
Figures 6.26 to 6.35 show the experimental waveforms of the output voltage as a function of control voltage which in turn is inversely related to firing angle, $\alpha$. As the control voltage increases from 0.5V to 5V, the output rms voltage increases which is shown in each plot.
Figure 6-26: Vout of AC controller at 0.5V

Figure 6-27: Vout of AC controller at 0.5V
Figure 6-28: Vout of AC controller at 1.5V

Figure 6-29: Vout of AC controller at 2.0V
Figure 6-30: Vout of AC controller at 2.5V

Figure 6-31: Vout of AC controller at 3.0V
Figure 6-32: Vout of AC controller at 3.5V

Figure 6-33: Vout of AC controller at 4.0V
As can be seen from figure 6.30 to figure 6.34, the rms output voltage gets very close to the input (120 V_{rms}) once the control voltage exceeds 3.0V.
B. 4-SCR Bridge Rectifier

As can be seen from table 6.2, the firing angle is inversely proportional to the control voltage as expected. As the firing angle decreases, the rms output voltage gets very close to the input (120 V<sub>rms</sub>). At the same time, the efficiency also increases.

Table 6.2: Measured parameters for Full wave rectifier circuit

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<th>T&lt;sub&gt;off&lt;/sub&gt; (ms)</th>
<th>Angle (°)</th>
<th>V&lt;sub&gt;Inrms&lt;/sub&gt; (V)</th>
<th>P&lt;sub&gt;in&lt;/sub&gt; (W)</th>
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Figures 6.36 to 6.46 show the simulation of output voltage of a thyristor controlled full-wave bridge rectifier as a function of firing angle. When the firing angle value, \( \alpha = 0 \), we get a full 120 V<sub>rms</sub> waveform while the output is zero when \( \alpha = 180 \). As \( \alpha \) increases from 0 to 180, the output rms voltage decreases.
Figure 6.36: Orcad capture of Output voltage of a full wave rectifier at a delay angle of 0°

Figure 6.37: Orcad capture of Output voltage of a full wave rectifier at a delay angle of 15°
Figure 6.38: Orcad capture of Output voltage of a full wave rectifier at a delay angle of 30°

Figure 6.39: Orcad capture of Output voltage of a full wave rectifier at a delay angle of 45°
Figure 6.40: Orcad capture of output voltage of a full wave rectifier at a delay angle of 60°.

Figure 6.41: Orcad capture of output voltage of a full wave rectifier at a delay angle of 90°.
Figure 6.42: Orcad capture of Output voltage of a full wave rectifier at a delay angle of 120 °

Figure 6.43: Orcad capture of Output voltage of a full wave rectifier at a delay angle of 135 °
Figure 6.44: Orcad capture of Output voltage of a full wave rectifier at a delay angle of 150 °

Figure 6.45: Orcad capture of Output voltage of a full wave rectifier at a delay angle of 165 °
Figures 6.47 to 6.56 show the experimental waveforms of the output voltage as a function of control voltage which in turn is inversely related to firing angle, $\alpha$. As the control voltage increases from 0.5V to 5V, the output rms voltage increases which is shown in each plot.
Figure 6-48: Vout of Rectifier at 1.0V

Figure 6-49: Vout of Rectifier at 1.5V

Figure 6-50: Vout of Rectifier at 2.0V
Figure 6-51: Vout of Rectifier at 2.5 V

Figure 6-52: Vout of Rectifier at 3.0 V

Figure 6-53: Vout of Rectifier at 3.5V
As can be seen from figure 6.52 to figure 6.56, the rms output voltage gets very close to the input (120 V\textsubscript{rms}) once the control voltage exceeds 3.5V.
C. Static VAR Compensator

For the SVC circuits, the measured and calculated parameters were tabulated in tables 6.3 to 6.7. As the firing angle decreases so do the power factor and the efficiency. The efficiencies for each table stayed within the close range of 55%-70%.

Table 6.3: Measured Parameters for SVC circuit with 3uF Capacitor

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Table 6.4: Measured Parameters for SVC circuit with 4uF Capacitor

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Table 6.5: Measured Parameters for SVC circuit with 5uF Capacitor

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<th>I (mA)</th>
<th>P_{\text{in}} (W)</th>
<th>V_{\text{out}} (V)</th>
<th>I_{\text{out}} (mA)</th>
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Table 6.6 : Measured Parameters for SVC circuit with 6uF Capacitor

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<th>T_{\text{off}} (\text{ms})</th>
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<th>V_{\text{in}} (V)</th>
<th>I (mA)</th>
<th>P_{\text{in}} (W)</th>
<th>V_{\text{out}} (V)</th>
<th>I_{\text{out}} (mA)</th>
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</tr>
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</table>

Table 6.7: Measured Parameters for SVC circuit with 7uF Capacitor

47
Figure 6-57 shows a family of power factor plots as a function of firing angle. It can be seen that varying the capacitor of the SVC circuit has no impact on the efficiency of the SVC circuit. This is because, the efficiency does not depend on reactive power and the ESR (Equivalent Series Resistance) of the capacitor is negligible.
7. Conclusion

Thyristors are one of the essential components when dealing with controllable circuits. By implementing thyristors in full bridge rectifier, we were able to control its output voltage. As the firing angle at the gate of thyristors in controlled full bridge rectifier change, we can clearly observe how the firing angle can limit the output voltage and current of the rectifier circuit.

This senior project is a very useful tool for investigating the behavior of a thyristor controlled single-phase full wave rectifier. This project has been made so that it would be convenient to be put together using the power benches provided in the power electronics lab. A lab experiment has been structured in this project to hopefully further the future students’ understanding on a single-phase full bridge rectifier circuit.

Using the AC controller circuit effectively showed the phase control of the thyristors. This control allows the user to limit the overall voltage and current supplied by the source. By seeing the result of the phase control on the oscilloscope, it is easier to understand exactly how the bidirectional thyristor configuration limits the voltage and current. When this controller was connected in series with an inductor, and in parallel with capacitor, we were able to vary the amount of capacitance or inductance added to the system in order to achieve a unity power factor. This configuration is in fact the basis for the SVC circuit.

The Static VAR Compensator showed that it is capable of improving the power factor of an inductive load. As only a non-varying inductive load was tested, the SVC is still able to accommodate for a varying load with the phase control in the thyristors. Being able to vary the capacitance or inductance of a circuit is very beneficial because it makes the correction more flexible and cost efficient. Yet, adding an overly large capacitor could result in an over-
compensation which would require less delay angle for the system to be close to unity power factor.

Overall, the two lab-scale circuits successfully exhibit the usefulness of thyristors. For students, it is an effective way to see how power electronics helps deliver efficient power and assist in an easy and faster adjustment of the normally lagging power systems.
Bibliography


Appendix A: Parts list

Thyristor Module
A semi-controllable switch that turns on with a positive pulse and off as the voltage goes to zero.

FCRO 41000 Firing Board
Is connected to the gates of thyristor modules and is used to vary the firing angle of thyristors

Power Bench Resistor
Provide 15 resistors with a value of 150 ohms with 0.82A limit

Power Bench Inductor
Provide three inductors with a value of 0.5 H each with 10A limit

Power Bench Vac source
Provide 120 Vac to both thyristor module and FCRO 4100 firing board

Power Scope
Measure current and voltages as well as monitoring scope plots

Oscilloscope
Another waveform monitoring and capturing device

AC Power Meter
Measures the voltage, current, power and power factor of the input.

Sorted Cables (banana-banana, BNC-banana, BNC-grabber)
Used to connect all parts together

Decade Capacitor
Variable Capacitor, ranged from 1 µF – 10 µF. Must have at least 120Vac rating.

Power Bench Resistor
150 Ω with 0.82 Amperes rating.

Power Bench Inductor
0.5 H with 10 Ampere rating.
Appendix B: Hardware Configurations

Figure B-1: Hardware Configuration for Thyristor Controlled Full Wave Rectifier Circuit [8]

Table B-1: Parts List for Thyristor Controlled Full Wave Rectifier Circuit

<table>
<thead>
<tr>
<th>Part No.</th>
<th>Part Names</th>
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<tr>
<td>1</td>
<td>FCRO 4100 Firing Board</td>
</tr>
<tr>
<td>2</td>
<td>Thyristor Module</td>
</tr>
<tr>
<td>3</td>
<td>Power Scope</td>
</tr>
<tr>
<td>4</td>
<td>Power Bench Resistors</td>
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<td>Power Bench Inductors</td>
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<td>6</td>
<td>Voltage Source</td>
</tr>
<tr>
<td>7</td>
<td>Oscilloscope</td>
</tr>
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<td>8</td>
<td>AC Power Meter</td>
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</table>
Figure B-2: Hardware Configuration for Static VAR Compensator Circuit [9]
Appendix C: Lab manuals

EE 410 Lab Thyristor Controlled Single Phase Full-Wave Rectifier Experiment #X

OBJECTIVES:

To simulate and construct a thyristor controlled single phase full wave rectifier and to understand its use and operation.

EQUIPMENT (to be checked out):

- Banana to banana leads (4)
- Scope Probes (2)
- BNC to grabber (1)
- BNC to banana (1)
- Bag of short leads (1)

INTRODUCTION:

A thyristor controlled full wave rectifier circuit takes AC signal as its input and convert it to a controllable DC output signal. Figure 1-1 shows a thyristor controlled single phase full wave rectifier with a resistive load. This circuit is able to produce a controllable DC output voltage by controlling the thyristors firing angle, which allowing it to delay thyristors turn on time.

![Figure 1-1: Thyristor Controlled Single Phase Full Wave Rectifier with Resistive Load](image)

PROCEDURES:
1. **Pspice Simulation:**
   a. Build and simulate the circuit on Figure 1-3 below. Use $R = 150$ ohms for the load and $V_{\text{sin}} = 120\text{Vrms}$ at 60 Hz as input signal. Combination of $D_{\text{break}}$ and $S_{\text{break}}$ are used to model the thyristors.

   ![Figure 1-2: Simulation of Controlled Full Wave Rectifier with Resistive Load](image)

   - **Figure 1-2: Simulation of Controlled Full Wave Rectifier with Resistive Load**
   
   b. Use the PARAM part found in “Special” library to introduce a parameter for the firing angle $\text{ALPHA}$. Double click on the part and the property window appears. Click on the NEW button, type in ALPHA in the box, and then hit OK. Enter an initial value of 5 for ALPHA.

   c. For $V_{\text{pulse}}$, assign TR and TF to be 10ns. Also, enter ‘0’ for V1 and ‘1’ for V2.

   d. Derive mathematical expressions for the rest of $V_{\text{pulse}}$’s parameters (PER, TD, and PW in terms of $\text{ALPHA}$). Enter these values inside a bracket {} for each parameter.

   e. Place a voltage probe at the output voltage.

   f. Run the simulation, observe and capture the output voltage waveform.

   g. Use AVG() function in the probe window to obtain the average output voltage. Record this value.

   h. Change parameter $\text{ALPHA}$ to 15, 30, 45, 60, (increment of 15), 170 and repeat step f and g for each $\text{ALPHA}$. 
2. **Hardware:**
   In this lab, you will simulate and construct the thyristor controlled single phase full wave rectifier with a resistive load using the Thyristor module and FCRO-4100 firing board available in lab (Figure 1--3 and Figure 1-4).

![Figure 1-3: Thyristor Module](image)

![Figure 1-4: FCRO-4100 Firing Board](image)

FCRO-4100 firing board above will require having at least 0.5 V across it in order for it to turn on. Figure 1-5 below is the relationship between the gate voltage and firing angle.
Figure 1-5: Firing Angle VS Gate Voltage

Note: due to the use of relatively high power circuit, it is important to check your circuit with your instructor before turning it on. Additionally, turn off all power sources before disconnecting the circuit.

a) Connect the voltage source on the power bench to AC power meter. Set the Variac to 120V.

b) Turn the power bench off.

c) Set the potentiometer on FCRO-4100 firing board to 0 ohm.

d) Build the circuit as shown in Figure 1-6 below. Connect the load to a 150 ohm resistor at the power bench. Connect the input voltage of the firing board to the voltage source.
Figure 1-6: Schematic of Full Bridge Rectifier
Note: + X1 corresponds to the top left thyristor in the module.
-X1 corresponds to the bottom left thyristor in the module.
+ X2 corresponds to the bottom right thyristor in the module.
-X1 corresponds to the top right thyristor in the module.

e) Connect the voltmeter across the signal and common pin of the potentiometer. Measure the control voltage across pin 10 and 8 in J4.
f) Connect one channel of scope probe to tp4 (reference signal) and another on tp6 (firing angle waveform) on the FCRO-4100 board. Tp4 will show a reference waveform and tp6 will show the firing angle signal (square wave).
g) Fill in the reference angle and firing angle part of table 1.
h) This time, connect the power scope across the load of the rectifier.
i) Go to ‘SCOPE’ mode of power scope and observe the waveform. Does it match your simulation waveforms? Sketch the waveforms @ Gate Voltage = 5V, 2.5V, and 1V.
j) Fill in the rest of Table 1. Use scope meter to measure the average output voltage.

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<tr>
<th>Gate Voltage (V)</th>
<th>Reference signal (ms)</th>
<th>Firing Angle (ms)</th>
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**QUESTIONS**

1. What application(s) that can find controlled rectifier circuit to be useful?
2. How would it affect the output voltage if the rectifier is supplied with a three-phase source instead of a single-phase?

**OBJECTIVES:**

To learn the use of thyristor-based Static VAR Compensator for power factor correction.
EQUIPMENT (to be checked out):

- Banana to banana leads (14)
- Scope Probe (1)
- Digital Multimeter
- Oscilloscope
- AC Power Meter
- Lab Bench 150 Ω resistors
- Lab Bench 0.5 H inductors

INTRODUCTION:

A Static VAR Compensator (SCR) consists of a Thyristor-controlled Reactor (TCR) which is an inductance in series with a bidirectional thyristor switch and a capacitor in parallel. The SVC is able to adjust to a varying leading or lagging load and maintain power factor close to unity. The Static VAR Compensator is able to correct power factor using the thyristors to control the phase of the input power. Phase control utilizes a firing angle ($\alpha$) to delay the turn on of a thyristor and ultimately the input voltage. Figure 1 shows an AC Controller output Waveform when $\alpha = 45$.

![Figure 1 - AC Controller Output Voltage Waveform ($\alpha = 45^\circ$, $V_{\text{Control}} = 3.93$ V)](image)

PROCEDURES:

The Enerpro FCRO4100 board will be used as the firing board for the thyristor circuit. The control voltage will need to be monitored by the multimeter in order to calculate the firing angle. Figure 2, shows the relationship between the phase angle and control voltage provided by Enerpro Inc.
1. **AC Controller**

   a. Verify that the variac knob (located beneath the bench) is turned all the way counterclockwise
   b. Obtain a single-phase ac voltage of $120 \text{ V}_{\text{rms}}$ from the bench by slowly turning the variac knob from the bench by slowly turning the variac knob clockwise and measuring the voltage using the ac power meter.
   c. Turn the AC power OFF
d. Connect the circuit as shown in Figure 3.
   Note: + X1 corresponds to the top thyristor in the module.
   -X1 corresponds to the bottom thyristor in the module.

e. Connect the voltmeter across the signal and common pin of the
   potentiometer. Measure the control voltage across pin 10 and 8 in J4
   header.

f. Attach a scope probe across the resistor to see the output waveform.
   Make sure output waveform is somewhat similar to Figure 1.
g. Fill in Table 1, using your multimeter to measure control voltage across
   the potentiometer and a power meter to measure input voltage, current,
   and power. Use a separate multimeter to measure $V_{\text{out}}^{\text{rms}}$.
h. Graph $V_{\text{out}}^{\text{rms}}$ vs. Delay Angle.

<table>
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<th>Table 1: Measured and calculated parameters for AC controller</th>
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2. SVC Compensator

a. Build the circuit shown in Figure 4.
   Note: + X1 corresponds to the top thyristor in the module.
   -X1 corresponds to the bottom thyristor in the module.
b. Connect the voltmeter across the signal and common pin of the potentiometer. Measure the control voltage across pin 10 and 8 in J4 header.

c. Fill in Table 2, using your multimeter to measure control voltage across the potentiometer and a power meter to measure $V_{in}$, $I$, $P$, and power factor.

d. Also measure output voltage. Calculate output power and efficiency.

e. Repeat the above steps for capacitor values of 3, 5, 6 and 7µF.

f. Plot PF vs. delay angle and efficiency vs. delay angle for each procedure (combine the plots).

![SVC compensator setup diagram]

Figure 4: SVC compensator setup.

Table 2: Measured and calculated parameters for SVC circuit

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<thead>
<tr>
<th>Gate Voltage (V)</th>
<th>$V_{in}$ (Vrms)</th>
<th>$I_{in}$ (mA)</th>
<th>$P_{in}$ (W)</th>
<th>$V_{out}$ (Vrms)</th>
<th>Delay angle (°)</th>
<th>Power factor</th>
<th>$P_{out}$ (W)</th>
<th>Efficiency (%)</th>
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QUESTIONS

1) What trends are noticeable after graphing the AC Controller output voltage vs. delay angle?
2) What is the use of the inductor in a TCR?
3) Why is an SVC circuit useful?