EFFICIENCY PERFORMANCE IMPROVEMENT USING PARALLEL DC-DC
CONVERTERS WITH A DIGITAL CONTROLLER

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ABSTRACT

Efficiency Performance Improvement Using Parallel DC-DC Converters with a Digital Controller

Daniel Paul Forbes

A system to improve efficiency performance of a DC-DC converter is simulated and built. The proposed system combines multiple DC-DC converters in parallel and implements a digital control scheme and load-share controller. A model of the system is developed in MATLAB Simulink and the model demonstrates the improved converter's efficiency particularly at low load conditions. This simulation is then designed into a hardware system running three DC-DC converters in parallel, controlled by a microcontroller and a load-share controller. The hardware also confirms the simulation results, although some hardware refinements are evident as simulation results are superior. The system is designed to be scalable in the number of converters and the total output power, as well as being DC-DC converter topology-independent. Simulation results show the system maintaining better than 88 % efficiency over almost 90 % of the load range of the system. This system could be implemented where dynamic loads typically occur, such as in electric vehicle charging.

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Chapter 1. Introduction

In the developed world today there exist many technologies which rely on DC-DC converters. These technologies range from the simple cell phone charger and desktop computer power supply to large electric vehicle chargers and DC power distribution stations. Within all of these DC-DC converters there exist known inefficiencies which waste power during the use of the converter. Each converter is designed with a specific load current range in mind, and the efficiency is optimized over this load range. While the efficiency of DC-DC converters has improved recently, most still exhibit a drop-off in efficiency as the load current decreases.

With larger and larger DC-DC converters being designed and used in industry, the main components (inductors, capacitors, switches, diodes, etc.) become increasingly expensive and cumbersome large. As these converters are becoming more wide-spread, they are required to perform continuously without failures or faults, sometimes in harsh environmental conditions. These shortcomings of the DC-DC converter are what led to the development of systems employing parallel-connected DC-DC converters. These systems offer several advantages over single DC-DC converters, including increased reliability, decreased stress on critical components, improved efficiency, and increased flexibility [1, 2].

While paralleling converters has its advantages, care must be taken in designing a system due to the fact that DC-DC converters of the same model will not necessarily be identical [3]. Because of these differences between converters, a load-share scheme must be implemented to ensure equal currents through all converters. The literature shows that there are many different methods for load-share control, including passive and active control, and master-slave and master-less configurations, all of which have advantages and disadvantages [3, 2].

In distributed power systems, parallel-connected converters have been in use for many years [2]. In the emerging market of electric vehicles, there arises the need for high-power chargers which are reliable, cost effective, and very efficient [4]. These chargers most often use a constant-current constant-voltage charging scheme, in which the current starts out very high and decreases over the course of the charge cycle [5]. Because of this, a charger with high efficiency across a wide load range meets the need of today's advanced systems.

The goal of this thesis was to improve efficiency performance especially at low load while maintaining the full-load efficiency. The idea presented in this paper is a digitally-controlled system utilizing parallel-connected DC-DC converters. The use of parallel DC-DC converters will allow for the system to enable fewer converters during low-load operation and more converters during full-load, thus keeping the system operating closer to peak efficiency over a wider load range as compared to a single DC-DC converter.

In this paper, first a MATLAB Simulink model is developed to simulate the proposed system and verify general operation. In this model, a digital controller is coded into MATLAB and run during the simulation. Using the Simulink model as a starting point, a hardware implementation of the system is designed, built, and tested. This hardware is based around off-the-shelf DC-DC converters, a microcontroller, and a load-share controller. Firmware is developed to run on the microcontroller and control the system, and software is developed to run on a personal computer to capture data for the user. The results will show that indeed low-load efficiency can be improved with the proposed system, and that with further development could be implemented on any scale desired.

Chapter 2. Simulation

2.1 Simulink Model Development

Before implementing this thesis in hardware, a Simulink model was developed and studied. In this paper, the approach taken to model the DC-DC simply involves a load versus efficiency lookup table. Instead of modeling the converter directly, a model is developed which uses only the efficiency characteristics of a given DC-DC converter. In this way, the model can be applied to any converter topology and to any number of different converters within a single topology. The converter is modeled as an efficiency lookup table, with inputs of load current and a control signal to enable or disable each converter. The outputs of the converter are input and output power as well as efficiency. Figure 2-1 shows this model with inputs and outputs labeled. An accompanying MATLAB file can be modified to update the lookup table values, as well as the output voltage (V_o) value.

Figure 2-1. DC-DC Converter Efficiency Model

The efficiency model was then integrated into a parallel-connected DC-DC converter setup, as shown in Figure 2-2. In this complete model, total combined output current is divided by the number of active converters (discussed in more detail in the controller section below). This divided output current then feeds into the individual efficiency blocks to determine the efficiency

of the system. At the output of the efficiency model blocks, the input and output powers are summed and then divided to give a total efficiency for the complete system. Any converter not enabled does not contribute to the total power. A control case efficiency model is also fed by the total output current, and provides a comparison between the paralleled system and an equivalent stand-alone converter. The main controller block shown in Figure 2-2 runs a MATLAB function during runtime which acts as the digital controller of the system. This controller has the ability to enable or disable individual converters.

Figure 2-2. Complete Parallel-Connected DC-DC Converter Simulink Model

2.2 Controller

The controller in this model is implemented via a MATLAB function and included in the model shown in Figure 2-2. The present controller is fairly rudimentary, and was written to show the general functionality of the system as a whole. In future work, a much more sophisticated controller can be developed.

To test the validity of the model, example efficiency and load limit values were loaded into the controller. The controller functions by first looking at a table of efficiencies at various loads, and finding the peak efficiency and the corresponding load current. This load current ($I_{\max}$) becomes the current limit at which DC-DC converters are enable or disabled, depending on the total load. As an example, if there are a total of three parallel converters, then the total allowable load current is $3I_{\max}$. With three converters, there are three switch points. If the total load current is below $I_{\max}$, then only one converter is enabled. If the current is between $I_{\max}$ and $2I_{\max}$, then two converters are brought online, and so on.

This control scheme does not employ a master-slave type configuration as discussed in [6] and [7], but rather allows any converter to be enabled individually while the others are disabled. This will allow future development advantages such as thermal stress management. This means that future digital control schemes will look at converter temperature, and depending on the number of parallel converters enabled, will dynamically swap out converters that are running hot (due to long run times or environmental conditions). This adds an added level of control and robustness to the parallel-connected system.

2.3 Simulation Results and Discussion

For the simulation, efficiency curves for the paralleled DC-DC converters were taken from the datasheet of the TI PTEA415050N2AD converter (the same converter used in the hardware design). Figure 2-3 shows the curve used. In order to provide a meaningful comparison between

the paralleled converters and a single stand-alone converter, an off-the-shelf converter was found with a load capacity equal to the total of the paralleled converters. The converter chosen was Murata Power Solutions' UCH-5/30-D48N. As a way to normalize the paralleled converters and the single converter, the peak efficiency of the converters was matched, and the accompanying curve was shifted. This means that since the peak efficiency of the UCH-5/30-D48N was approximately 1 % above that of the PTEA415050N2AD, the curve of the UCH-5/30-D48N was lowered by 1 %. Figure 2-4 shows the original and shifted efficiency curves of the UCH-5/30-D48N DC-DC converter.

Figure 2-3. Load Current vs. Efficiency of the PTEA415050N2AD DC-DC

Figure 2-4. Load Current vs. Efficiency of the UCH-5/30-D48N DC-DC

Using the efficiency curves shown above, the simulation was run using an input current ramping from 0 A to 27 A. Compiling the simulation results produced the efficiency versus percent of total load current graph shown in Figure 2-5. This figure shows the simulation working as expected; from 10 % load to above 70 % load the parallel converter system is operating at a higher efficiency and past that the efficiencies are very close. At 10 % load, the parallel system has approximately an 8 % increase in efficiency. The switch points where consecutive converters are enabled are also evident from Figure 2-5. At 33 % load ($0.33 \times 27 \text{ A} = 9 \text{ A}$) the second converter is switched on, indicated by the small step reduction in efficiency. Similarly at 66 % load ($0.66 \times 27 \text{ A} = 18 \text{ A}$) the third converter is switched on. To reduce these efficiency steps, the switch current of 9 A was increased to 12 A, and the resulting improved parallel efficiency curve is shown in Figure 2-5.

Figure 2-5. Simulation Output Showing Efficiency Curves

These results shown in Figure 2-5 suggest that the proposed parallel-connected DC-DC converters outperform a single converter, especially under low-load conditions. The parallel converter demonstrated better than 88 % efficiency for almost 90 % of its load range, as compared to the single converter which only demonstrates 88 % efficiency or above for 73 % of its load range. From these simulation results it is clear that the improved paralleled system provides demonstrable gains over the single converter, and the remainder of this document will show one way of implementing it in hardware.

Chapter 3. Design Requirements

3.1 Design Goals

In order to limit the scope of this project to focus on efficiency improvement, certain design requirements were chosen. The hardware for this thesis will be based around three off-the-shelf DC-DC converters, each with a nominal input voltage of 48 VDC and an output voltage of 5 VDC. The allowable maximum current for each DC-DC will be 9 A, allowing for a total of 27 A for the system. This keeps the total output power of the system ($27\text{ A} \times 5\text{ V} = 135\text{ W}$) below the 150 W maximum of the available electronic load used for testing. These three DC-DC converters will be integrated into a system controlled by a microcontroller running custom firmware. The firmware will need to know input and output voltage and current for each DC-DC converter in order to calculate efficiency. This information will be provided to the microcontroller via sensors integrated into the system, discussed in more detail below. The main function of the embedded firmware will control the number of active DC-DC converters based on total system load. A load-share controller will be integrated into the output stage of the system in order to ensure equal currents through the enabled DC-DC converters. This load-share controller will be an integrated-circuit solution with supporting circuitry designed around the system's parameters. The microcontroller and supporting circuitry will be isolated from the power systems, including sensor outputs and control lines.

To accompany the hardware system, a computer-based software application will be developed to allow the user to view system parameters and record data. This software will receive information from the hardware system via serial communications with the microcontroller. This software application will also allow users who are unfamiliar with the hardware a simple means to view and gather data. For this thesis, the software will update at one second intervals.

3.2 Design Details

Figure 3-1 below shows the entire system block diagram, including the controller, power stage, and load-share controller. Each sub-section is contained on its own printed circuit board (PCB). Figure 3-2 shows the power distribution and the 0 V references within the system. An explanation of each sub-section follows.

Figure 3-1. System Block Diagram

Figure 3-4. Voltage Sense Circuit

To calculate the resistor divider (R18 and R19), input and output voltage swings were determined based on manufacturer datasheets. Since the A/D has a reference voltage of 3.3 VDC, the desired voltage divider output was set to 3 VDC at maximum input and output voltage. This value was set to give maximum A/D range while still allowing for some small voltage overshoot. To reduce power loss through the sense circuit, a current of 500 μ A through the voltage divider was chosen. Table 3-1 below summarizes the values used for the voltage divider calculations, where V_{IN} and V_{OUT} represent the input and output voltages of the DC-DC, respectively.

Table 3-1. Resistor Divider Voltage Set Values

Parameter	Minimum	Typical	Maximum
V_{IN} (V)	46	48	50
V_{OUT} (V)	4.85	5.00	5.15
V_{SET} (V)	N/A	3	N/A
I_{SET} (μ A)	N/A	500	N/A

Using the values from Table 3-1, (3-1) shows the total desired resistance. Choosing $R_{19} = 6 \text{ k}\Omega$ and using (3-2), the desired resistor values are set.

$$R_{18} + R_{19} = \frac{V_{IN-MAX}}{I_{SET}} = \frac{50V}{500\mu A} = 100k\Omega \quad (3-1)$$

$$R_{18} = (R_{18} + R_{19}) - R_{19} = 100k\Omega - 6k\Omega = 94k\Omega \quad (3-2)$$

Choosing standard available resistor values gives $R_{18} = 93.1 \text{ k}\Omega$ and $R_{19} = 6.04 \text{ k}\Omega$. These values show the resistor divider for input voltage sensing. Using the same equations and V_{OUT} values from Table 3-1 gives resistor values of $R_{18} = 4.3 \text{ k}\Omega$ and $R_{19} = 6 \text{ k}\Omega$ for the output voltage sensing. Calculations and more design values for this resistor divider can be found in Table A-2 in Appendix A. Following the resistor divider there is an isolation circuit. This is one of a few means of isolating the control logic/sensing from the main power rails.

The isolation circuit for this voltage sensing is based around a linear optocoupler manufactured by Clare, part number LOC110. As shown in Figure 3-4, the LOC110 requires two op-amps, three resistors, and some filter capacitors for proper operation. The operation of the LOC110 relies on the input voltage being converted into a current which drives an LED, which in turn shines on two phototransistors, one providing feedback and the second driving the output (the LED and phototransistors are integrated in the LOC110). To determine the resistor values, some constants are needed, which can be found in the LOC110 datasheet [8], and are shown in Table 3-2 below. An example design process is provided by Clare in Application Note AN-107 [9]. For both the input and output voltage sense circuits, the LOC110 design will be the same since both resistor dividers can range from 0 V to 3 V. Since this is the case, the input and output voltage spans for the LOC110 will be set to 0 V to 3 V.

Table 3-2. LOC110 Device Characteristics

Parameter	Symbol	Minimum	Typical	Maximum	Units
LED Voltage Drop	V_F	0.9	1.2	1.4	V
K1, Servo Gain (I_{C1}/I_F)	K1	0.004	0.007	0.03	-
K2, Forward Gain (I_{C2}/I_F)	K2	0.004	0.007	0.03	-
Input-Side Supply Voltage	V_{CC1}	5	5	5	V

Using this information and choosing an LED current (I_F) of 15 mA, R_{35} from Figure 3-4 is calculated in (3-3) and rounded to 274 Ω .

$$R_{35} = \frac{V_{CC1max.} - V_{Fmin.}}{I_F} = \frac{5V - 0.9V}{15mA} = 273.3\Omega \quad (3-3)$$

Next the input (R_{39}) and output (R_{40}) gain resistors are calculated to be 50 k Ω as shown in (3-4) and (3-5).

$$R_{39} = \frac{Input\ Span\ Max.}{K1_{min.} * I_F} = \frac{3V}{0.004 * 15mA} = 50k\Omega \quad (3-4)$$

$$R_{40} = \frac{Output\ Span\ Max.}{K2_{min.} * I_F} = \frac{3V}{0.004 * 15mA} = 50k\Omega \quad (3-5)$$

The above values completely define the necessary external resistors for the LOC110 to operate, in this case as a one-to-one isolator. The output of the op-amp on the output of the LOC110 is now a properly scaled and isolated voltage ready for use by the A/D of the microcontroller.

Also contained on the microcontroller PCB are three power supplies used to power various components on the board. The main input power supply is an off-the-shelf isolated DC-DC manufactured by TI, part number PTMA402050N2AD. This converts an input voltage of 48 VDC to 5 VDC. This 5 VDC feeds a linear voltage regulator, part number LM1117 to supply 3.3 VDC to the microcontroller. A second linear voltage regulator, manufactured by Linear Technology, part number LT3012, is fed by the input 48 VDC and drops this down to 5 VDC. The reason for this second 5 VDC regulator is to supply a non-isolated voltage to the input-side op-amps of the optocouplers.

The remaining components on the control PCB are three momentary push buttons, three LEDs, the In-Circuit Serial Programming (ICSP) circuit for programming the microcontroller, a reset button for the microcontroller, and a USB to Serial converter circuit. The buttons and LEDs provide general purpose input/output (GPIO) for the microcontroller. The complete control board schematic can be found in Appendix A.

3.2.2 Power Stage

The power stage of this thesis consists of three DC-DC converters manufactured by TI, part number PTEA415050N2AD. This part was chosen for its input/output voltages and load capacity. Typical input/output characteristics are shown below in Table 3-3. These values meet the design requirements of 48 V input voltage, 5 V output voltage, and 9 A maximum current for each DC-DC in the system. More characteristics of the PTEA415050N2AD can be found in the device datasheet [10]. Figure 3-5 below shows the typical efficiency curves of the PTEA415050N2AD at various input voltages. In this thesis, only an input voltage of 48 V is considered.

Table 3-3. PTEA415050N2AD Input/Output Characteristics

Parameter	Symbol	Minimum	Typical	Maximum	Units
Input Voltage	V_I	35	48	75	V
Output Voltage	V_O	4.95	5	5.05	V
Output Current	I_O	0	-	15	A

Figure 3-5. Efficiency vs. Output Current for the PTEA415050N2AD (Source: www.ti.com)

The PTEA415050N2AD is a fully isolated DC-DC converter, with the standard application circuit shown in Figure 3-6 below. As shown, pins 1 and 3 are input voltage, pins 8 and 4 are output voltage, 7 and 5 are output voltage remote sense, 6 is output voltage adjust, and 2 is an enable line. In Figure 3-6 the enable line, pin 3, is permanently tied to $-V_I$ which doesn't allow for dynamic on/off control of the DC-DC. In order for the microcontroller to control whether each DC-DC is on or off, and isolated connection was required between the two. Figure 3-7 shows the circuit used to tie an output of the microcontroller to the enable line of the DC-DC, while maintaining proper isolation. As shown, the microcontroller drives a solid-state relay (SSR) via the "EN_1" line, which in turn controls an n-channel MOSFET. When the MOSFET turns on the DC-DC enable line is pulled to $-V_I$ and the DC-DC switches on. In Figure 3-6, the remote sense

pins are tied to the load, but in this thesis these lines are used by the load-share controller, discussed further in the next section of this document.

Figure 3-6. Standard Application Circuit for the PTEA415050N2AD (Source: www.ti.com)

Figure 3-7. Isolated Enable Circuit for PTEA415050N2AD

In order to sense input and output currents of the DC-DC converters (and eventually calculate efficiency), integrated hall effect-based linear current sensors were added to the circuit, one each on the input and output of the DC-DC. Figure 3-8 shows one current sensor and its support circuitry. The sensor is manufactured by Allegro MicroSystems, part number ACS713. The

ACS713 was chosen for its linearity and low conduction path resistance of 1.2 mΩ, as shown in the datasheet [11]. The ACS713 converts the measured current into a voltage on the output pin (pin 7) with a scale factor of 0.185 V/A and an offset of 0.5 V at a measured 0 A. Also shown in Figure 3-8 is an op-amp connected to the output of the ACS713 in a non-inverting setup. This provides buffering and scaling between the ACS713 and the microcontroller.

Figure 3-8. ACS713 Current Sense Circuit

In order to obtain maximum resolution of the sensed current, the op-amp was set up to scale the maximum output of the ACS713 up to around 3 V (similar to the voltage sensing discussed above, this leaves some overhead at the A/D input which can sense up to 3.3 V). In order to set the proper gain on the input side, the maximum input current was calculated as shown in (3-6) below.

$$I_{IN-max} = \frac{I_{O-max} * V_{O-typ}}{V_{I-typ}} = \frac{9A * 5V}{48V} = 0.94A \quad (3-6)$$

Adding in a 15% overhead factor results in $I_{IN-max} = 1.1$ A. Table 3-4 shows these design values, used to calculate the op-amp gain below.

Table 3-4. ACS713 Design Values

Parameter	Symbol	Value	Units
ACS713 Gain	ACS_{GAIN}	0.185	V/A
ACS713 Offset	ACS_{OFFSET}	0.5	V
Set Voltage	V_{SET}	3	V
Max. Input Current	I_{IN-max}	1.1	A
Max. Output Current	$I_{OUT-max}$	9	A

$$\begin{aligned}
 \text{Desired Input Gain} &= \frac{V_{SET}}{(I_{IN-max} * ACS_{GAIN}) + ACS_{OFFSET}} \\
 &= \frac{3V}{(1.1A * 0.185V/A) + 0.5V} = 4.26
 \end{aligned} \tag{3-7}$$

$$\text{Desired Input Op - Amp Gain} = 1 + \frac{R_2}{R_1} = 4.26 \tag{3-8}$$

Setting $R_2 = 10$ k Ω and solving (3-8) gives $R_1 = 3.07$ k Ω . In order to increase the A/D resolution and choosing a standard resistor value gives $R_1 = 3.01$ k Ω . (3-9) and (3-10) show the calculations for the output circuit.

$$\begin{aligned}
 \text{Desired Output Gain} &= \frac{V_{SET}}{(I_{OUT-max} * ACS_{GAIN}) + ACS_{OFFSET}} \\
 &= \frac{3V}{(9A * 0.185V/A) + 0.5V} = 1.39
 \end{aligned} \tag{3-9}$$

$$\text{Desired Output Op - Amp Gain} = 1 + \frac{R_2}{R_1} = 1.39 \tag{3-10}$$

In this case setting $R_1 = 10$ k Ω and solving (3-10) gives $R_2 = 3.86$ k Ω . In order to increase the A/D resolution and choosing a standard resistor values gives $R_2 = 4.02$ k Ω . Using these resistor values, input and output op-amp gain are calculated in (3-11) and (3-12).

$$\text{Input Op - Amp Gain} = 1 + \frac{R_2}{R_1} = 1 + \frac{10k\Omega}{3.01k\Omega} = 4.32 \tag{3-11}$$

$$Output\ Op - Amp\ Gain = 1 + \frac{R_2}{R_1} = 1 + \frac{4.02k\Omega}{10k\Omega} = 1.40 \quad (3-12)$$

Using this data, the total current to voltage (as seen at the microcontroller) gain can be calculated as shown in (3-13), where I represents either the input or output current through the DC-DC and the respective input or output *Op-Amp Gain* is used.

$$Gain = [(I * ACS_{GAIN}) + ACS_{OFFSET}] * Op - Amp\ Gain \quad (3-13)$$

The op-amp gain values are summarized in Table 3-5 below. Using the values from Table 3-4 and Table 3-5 the current sense resolution can be calculated. One last value, the number of counts in the A/D is needed. Since the A/D uses 10 bits, there are $2^{10}-1 = 1023$ counts. It is then shown in (3-14) through (3-16) that the input current reading has a resolution of 4.03 mA/count of the A/D. Similarly, the output current resolution can be calculated and the result of 12.44 mA/count results.

Table 3-5. Current Sensor Op-Amp Gain Values

Parameter	Symbol	Value	Units
Input Op-Amp Gain	GAIN _{IN}	4.32	V/V
Output Op-Amp Gain	GAIN _{OUT}	1.40	V/V

$$\begin{aligned} V_{I_{IN-max}} &= [(I_{IN-max} ACS_{GAIN}) + ACS_{OFFSET}] GAIN_{IN} \\ &= [(1.1A * 0.185V/A) + 0.5V] 4.32 = 3.04V \end{aligned} \quad (3-14)$$

$$\begin{aligned} V_{I_{IN-min}} &= [(I_{IN-min} ACS_{GAIN}) + ACS_{OFFSET}] GAIN_{IN} \\ &= \left[\left(0A * \frac{0.185V}{A} \right) + 0.5V \right] 4.32 = 2.16V \end{aligned} \quad (3-15)$$

Input Resolution

$$\begin{aligned} &= \frac{I_{IN-max}}{\left[V_{I_{IN-max}} * \left(\frac{1023Counts}{3.3V} \right) \right] - \left[V_{I_{IN-min}} * \left(\frac{1023Counts}{3.3V} \right) \right]} \\ &= \frac{1.1A}{\left(3.04V * \frac{1023Counts}{3.3V} \right) - \left(2.16V * \frac{1023Counts}{3.3V} \right)} \\ &= 4.03mA/count \end{aligned} \quad (3-16)$$

The final design value for the ACS713 circuit is the filter capacitor, C_F , connected between pins 5 and 6 as shown in Figure 3-8. This filter capacitor determines the bandwidth of the ACS713 as well as the peak-to-peak noise levels. Setting $C_F = 47 \text{ nF}$ sets a good trade-off between noise suppression and bandwidth. The ACS713 datasheet shows that with a C_F of this value, peak-to-peak noise will be approximately 100 mA and rise time (t_r) (the time interval between when the device reaches 10% of its full scale value and when it reaches 90% of its full scale value) to be $88.2 \mu\text{s}$ [11]. According to the datasheet, the rise time to a step response determines the bandwidth, shown in (3-17). This C_F is used in both input and output current sense circuits. This completes the power stage details. Figure 3-9 shows one complete sub-section of the power stage. This sub-section is repeated three times to form a complete power stage.

$$f(-3 \text{ dB}) = 0.35/t_r = 0.35/88.2\mu\text{s} = 3.97\text{kHz} \quad (3-17)$$

Figure 3-9. Completed Power State Sub-Section

3.2.3 Load-Share Controller

As discussed earlier, paralleled DC-DC converters may not equally share the current being delivered to a load. To remedy this, a load-share controller can be used. The load-share controller in this thesis is based around the TI UCC39002 integrated circuit. The UCC39002 is used to ensure equal currents through multiple paralleled DC-DC converters, as seen in this thesis. It senses the output current of each DC-DC and uses the remote sense lines of the DC-DC to adjust the voltage up or down to fine-tune current. Each DC-DC being paralleled must have a UCC39002 on its output line, and each UCC39002 must communicate (via the Load Share Bus) with the others in order to set equal currents.

In order for the load-share controller to properly work with a given DC-DC, supporting circuitry must be designed to the parameters of the specific DC-DC. One important parameter required is the unity gain crossover frequency of the DC-DC. This is not a parameter given in the datasheet of the PTEA415050N2AD, and so a test was needed to find this value. In the User's Guide of the UCC39002 a method is given to measure unity gain crossover frequency [12]. The setup shown in Figure 3-10 was used, and a Frequency Response Analyzer was used in place of the Network Analyzer shown.

Figure 3-10. Setup to Measure Unity Gain Crossover Frequency of DC-DC (Source: www.ti.com)

The Frequency Response Analyzer used for the test is manufactured by Venable Instruments and is a model 3120 Analyzer. Accompanying instrument software provided a means to capture data during the test. Multiple tests were performed on three PTEA415050N2AD units, each with the test settings shown in Table 3-6. The Bode Plots of each test are shown in Figure 3-11, Figure 3-12, and Figure 3-13, with the unity gain values compiled in Table 3-7. The unity gain crossover frequency used for the design of the load-share controller takes the average of these three values and is $f_{\text{COMOD}} = 21.59 \text{ kHz}$.

Table 3-6. Test Parameters Used To Find Unity Gain Crossover Frequency of PTEA415050N2AD

Parameter	Symbol	Value	Units
Input Voltage	V_{IN}	48.3	V
Output Voltage	V_{OUT}	4.87	V
Input Current	I_{IN}	1.09	A
Output Current	I_{OUT}	8.99	A
Start Frequency	f_{START}	10	Hz
Stop Frequency	f_{STOP}	240	kHz

Figure 3-11. Unity Gain Crossover Frequency Bode Plot: Unit 1

Figure 3-12. Unity Gain Crossover Frequency Bode Plot: Unit 2

Figure 3-13. Unity Gain Crossover Frequency Bode Plot: Unit 3

Table 3-7. Unity Gain Crossover Frequency Results

Parameter	Symbol	Value	Units
Unity Gain Crossover Frequency Unit 1	f_{COMOD1}	22.73	kHz
Unity Gain Crossover Frequency Unit 2	f_{COMOD2}	21.24	kHz
Unity Gain Crossover Frequency Unit 3	f_{COMOD3}	20.8	kHz
Unity Gain Crossover Frequency	f_{COMOD}	21.59	kHz

For this thesis, an evaluation board for the UCC39002 was chosen. The board, part number UCC39002EVM, provides connections for three DC-DC converters and the corresponding space for the UCC39002 support circuitry. Figure 3-14 shows the schematic for the evaluation board. All components labeled “TBD” required design and population; the remaining components were included on the board. The UCC39002EVM User’s Guide provides a generic design example, followed here as a groundwork for component values, and available for further design detail [12]. The circuits for all three ICs are the same, so the values were calculated for the first one and copied to the remaining two.

Figure 3-14. UCC39002EVM Load-Share Schematic (Source: www.ti.com)

A number of constants were required to perform the calculations needed for the circuit design. These constants were gathered from the PTEA415050N2AD datasheet, the UCC39002EVM user's guide, and the design requirements of this thesis. These constants are compiled in Table 3-8, and some are discussed further here. Since the board allows for two 1 W sense resistors in parallel, TI recommends de-rating the total power and limiting it to 1 W combined power dissipation, giving $P_{\text{RSENSE(max)}}$. The resistors R_{CSA1} and R_{CSA2} set the gain of the current sense amplifier on the UCC39002, and were chosen to set a gain which will be calculated shortly. f_{POLE} is an added high frequency pole TI suggests adding to the system for noise roll off, and is set at over twice the unity gain crossover frequency. The gain of the module at the compensation frequency (22 Hz), $G_{\text{MOD}}(f_{\text{ZERO}})$, was read off of Figure 3-11. The remaining values in Table 3-8 appear in the sources discussed above.

Table 3-8. Load-Share Controller Design Constants

Parameter	Symbol	Value	Units
Nominal Output Voltage of the Modules to be Paralleled	V_{OUT}	5	V
Max. Output Current of Each Module to be Paralleled	$I_{\text{OUT(max)}}$	9	A
Max. Output Voltage Adj. Range of Modules to be Paralleled	ΔV_{ADJ}	0.015	% V_{O}
Max. Output Voltage Adj. Range of Modules to be Paralleled	$V_{\text{OUTADJ(max)}}$	0.075	V
Number of Modules	N	3	-
IC Supply Voltage	V_{DD}	5	V
Unity Gain Crossover Frequency of Modules to be Paralleled	f_{COMOD}	21.59	kHz
Max. Power Dissipation of the Sense Resistor	$P_{\text{RSENSE(max)}}$	1	W
Resistor to Set Current Sense Amplifier Gain	R_{CSA1}	324000	Ω
Resistor to Set Current Sense Amplifier Gain	R_{CSA2}	1000	Ω
Added High Frequency Pole for Noise Roll Off	f_{POLE}	50	kHz
Internal Resistance of the LS Pin	R_{LS}	100	k Ω
Maximum Current that the Internal Adjust Amplifier can Sink	$I_{\text{ADJ(max)}}$	6	mA
Gain in dB of Module at Compensation Zero Frequency	$G_{\text{MOD}}(f_{\text{ZERO}})$	35.3	dB
Transconductance of the Internal Error Amplifier	G_{M}	0.014	S

To avoid cumbersome, mostly simple equations, this paper will not show all the equations required for the component design of the UCC39002EVM, as they can all be found in the design example in the user's guide discussed above. Instead only the results are shown in Table 3-9. With these results the UCC39002EVM was fully populated and connected to the

power stage, completing the hardware design of this thesis. The following section will discuss the hardware design and how the circuits designed in this section were implemented.

Table 3-9. Load-Share Controller Design Values

Parameter	Symbol	Value	Units
Maximum value of the current sense resistor for the given allowable power dissipation	$R_{SENSE(max)}$	12.3	m Ω
Actual resistor value based on available standard values (2512 size, 1W, room for two in parallel)	R_{SENSE}	1	m Ω
Calculated power dissipation of the actual resistor	P_{RSENSE}	81	mW
Voltage drop across R_{SENSE} (should be much less than ΔV_{ADJ})	V_{RSENSE}		mV
Absolute maximum voltage of the CSO pin	$V_{CSO(max)}$	3	V
Absolute maximum allowable current sense gain before saturation	$A_{CSA(max)}$	333.3	-
Actual current sense amplifier gain chosen for this design	A_{CSA}	324	-
Resultant output voltage of the current sense amplifier and approximate voltage of load share bus	V_{CSO}	2.916	V
Calculated capacitor for high frequency pole	$C_{CSA(calc)}$	9.8	pF
Actual value capacitor for high frequency pole	C_{CSA}	10	pF
Actual high frequency pole	f_{POLE}	49.12	kHz
Increase in master supply current due to R_{LS}	$I_{MASTERINCREASE(max)}$	90	μ A
Increase in master power dissipation due to R_{LS}	$P_{MASTERINCREASE}$	0.45	mw
Calculated resistor used to set voltage at Sense+ terminal of power module	$R_{ADJ(calc)}$	11	Ω
Actual resistor used to set voltage at Sense+ terminal of power module	R_{ADJ}	11	Ω
Voltage at ADJ pin ($V_{ADJ} \geq V_{EAO} + 1$ V)	V_{ADJ}	4.934	V
Error amplifier output voltage	V_{EAO}	3	V
Minimum to prevent saturating internal adjust amplifier transistor	$R_{ADJ(min)}$	8.4	Ω
Desired frequency of the error amplifier compensation zero (placed two decades before the modules crossover frequency)	f_{ZERO}	215.9	Hz
Absolute value of gain of power module (estimated from gain frequency measurement, unit less, not in dB)	$ G_{MOD}(f_{ZERO}) $	58.21	-
Load resistance	R_{LOAD}	0.56	Ω
Voltage gain	A_V	0.0018	-
Adjustment amplifier gain	A_{ADJ}	0.022	-
Calculated capacitor for compensation	$C_{EAO(calc)}$	1.32	nF
Actual capacitor used for compensation	C_{EAO}	120	nF
Calculated series resistor used in the error amplifier compensation	$R_{EAO(calc)}$	6.143	k Ω
Actual series resistor used in the error amplifier compensation	R_{EAO}	6.19	k Ω

Chapter 4. Hardware Design

This section will describe the physical implementation of the schematic discussed in the Design Details section of this document. As already discussed, the design was broken up into a controller PCB, a power PCB, and a load-share controller PCB, with wires interconnecting everything. An original design combined the controller and power sections and was not fully isolated, and this proved to be a faulty approach. Noise on the ground caused unwanted results, and thus the newer design discussed here was implemented. The following sections discuss specific details of each board.

4.1 Controller PCB

The controller PCB was designed using the EAGLE suite of software. Common-practice rules for PCB design were followed, including minimum trace spacing and trace width. The PCB was designed as a two-layer board using 1-ounce copper and an FR-4 substrate. A top power (+3V3) plane and a bottom ground (VSS) plane were added to improve noise suppression on the PCB. Figure 4-1 and Figure 4-2 show the top and bottom copper layers respectively, while Figure 4-3 and Figure 4-4 show the top and bottom silkscreen layers respectively. The components on the board are grouped in functional sections as drawn on the schematic. The PCB interfaces with the rest of the system via a 24-pin connector and wire harness. A mini-USB port is available for serial connection to a host computer, and there are three general-purpose buttons and LEDs. Test points were added for ease of testing and diagnosis, and a reset provides a means to reboot the system. Two LEDs show the status of the 5 V and 3.3 V power rails, and there is a 5-pin header for programming the microcontroller. Finally, there is a jumper, which if removed cuts power to the PCB disabling all functionality. All these features are shown in Figure 4-5.

Figure 4-1. Controller PCB Top Copper

Figure 4-2. Controller PCB Bottom Copper

Figure 4-3. Controller PCB Top Silkscreen

Figure 4-4. Controller PCB Bottom Silkscreen (Mirrored)

Figure 4-5. Control PCB Photo with Features Labeled

4.2 Power Stage PCB

The Power Stage PCB was designed using the EAGLE suite of software. Common-practice rules for PCB design were followed, including minimum trace spacing and trace width. The PCB was designed as a two-layer board using 1-ounce copper and an FR-4 substrate. Special care was taken sizing the input and output power traces going to and from the DC-DC converters, since they are capable of carrying 9 A each. An online trace width calculator using IPC-2221 standards was used for properly sizing the trace width [13]. As an example, for sizing the DC-DC output traces the parameters in Table 4-1 were input into the online calculator, giving the trace width shown in Table 4-1. In the PCB design, a trace width of over 9.5 mm on both the top and bottom layers was used, giving an effective trace width of 19 mm, well above the recommended width.

Table 4-1. Example Trace Width Calculation

Parameter	Value	Units
Current	10	A
Copper Thickness	1	oz/ft ²
Temperature Rise	10	°C
Ambient Temperature	25	°C
Trace Length	2.54	mm
Required Trace Width (External Layer)	7.19	mm

The power PCB connects to the controller PCB via a 24-pin connector and wire harness. Figure 4-6 and Figure 4-7 show the top and bottom copper layers of the PCB respectively, and Figure 4-8 and Figure 4-9 show the top and bottom silkscreen layers of the PCB, respectively. Bolt holes were added for a 48 V supply hook-up, and also for connection to the load-share controller PCB. Three 2-pin connectors also allow for the load-share controller to connect to the remote sense lines of the three DC-DC converters. Test points provide a means to measure different signals on the board during testing and debugging. Figure 4-10 shows a photograph of the top of the power PCB, labeled with the features just discussed.

Figure 4-6. Power PCB Top Copper

Figure 4-7. Power PCB Bottom Copper

Figure 4-8. Power PCB Top Silkscreen

Figure 4-9. Power PCB Bottom Silkscreen (Mirrored)

Figure 4-10. Power PCB Photo with Features Labeled

4.3 Load-Share PCB

Since the UCC39002EVM was purchased from TI, this thesis did not focus on its design. The UCC39002EVM User's Guide contains information regarding the load-share controller PCB design and layout [12]. Using the component values from the design section above, the UCC39002EVM PCB was populated and is shown in Figure 4-11 below.

Figure 4-11. UCC39002EVM PCB

Chapter 5. Software Design

In order for this thesis to function, various systems had to be programmed with custom software. Embedded firmware running on the microcontroller allowed for system data sampling and DC-DC converter control via a control algorithm. This firmware was programmed to send data to an accompanying piece of software running on a personal computer. This software displayed real-time data to an operator and also logged all data values. The sections below discuss in more detail both of these programs.

5.1 Embedded Firmware

The embedded firmware in this thesis runs on the PIC24FJ128GA006 microcontroller on the control PCB. It is written in the C programming language and compiled in Microchip's MPLAB IDE using the C30 compiler. The core firmware is contained within *main.c*, with supporting files *adc.c*, and *uart1.c* used to configure some of the microcontroller peripherals. The PIC24FJ128GA006 datasheet [14] was referenced for all peripheral configurations. The complete firmware code can be found in Appendix C.

5.1.1 Analog-to-Digital Converter (ADC) Configuration

Section 17 of the PIC24F Reference Manual [15] was used for reference when configuring the ADC. The file *adc.c* contains all the register configurations for the ADC. The ADC uses six status and control registers, and *adc.c* sets them to function properly in the hardware setup of this thesis. AD1CON1, AD1CON2 and AD1CON3 control the general operation of the ADC, AD1CHS selects which pins are passed into the ADC, AD1PCFG sets the ADC pins as analog (as oppose to digital), and AD1CSSL sets the pins to be included in an automatic scan. The AD1CON1 register controls whether the ADC is enabled or not, and in order for the ADC to be configured it must be disabled. In this thesis, the ADC is set up to auto-convert all selected channels according to a timing sequence set by bits in AD1CON3. The PIC24FJ128GA006 has

an analog module clock with a period defined as T_{AD} . As defined in the reference manual, an ADC conversion takes $12 T_{AD}$. In order to calculate T_{AD} , the device instruction cycle clock period, T_{CY} must be calculated. T_{CY} is derived from the system clock defined earlier as 20 MHz, and is given in (5-1) below. Defining the ADC conversion clock period select bits in the AD1CON3 register as 0x0F (or $16 T_{CY}$) and using (5-2) gives T_{AD} .

$$T_{CY} = \frac{2}{F_{OSC}} = \frac{2}{20MHz} = 0.1\mu s \quad (5-1)$$

$$T_{AD} = T_{CY}(ADCS + 1) = 0.1\mu s(15 + 1) = 1.6\mu s \quad (5-2)$$

Another important parameter in the ADC settings involves the SAMC bits in the AD1CON3 register. These bits control the length of time between the start of sampling and the start of conversion (essentially the sample time). Setting SAMC to 15 results in a sample time of $15 T_{AD}$ or $24 \mu s$.

5.1.2 Serial Port (UART) Configuration

The UART peripheral module in the PIC24FJ128006 is configured in *uart1.c*, which was adapted from code found in a PIC24 tutorial [16]. This configuration file also provides the serial communication functions used in *main.c*, including UART initiation, transmit and receive, along with some others. The serial port will be configured with the settings shown in Table 5-1.

Table 5-1. Serial Port Settings

Parameter	Value
Baud Rate	9600
Data Bits	8
Stop Bits	1
Parity	None
Flow Control	None

5.1.3 Main

The overall control of the system in this thesis is implemented in *main.c*. This file deals with reading in and averaging different voltages and currents across the system, enabling and

disabling DC-DC converters, and sending data over a serial line to a personal computer. Within *main.c* the majority of interesting code appears in the functions `calibACS()`, `runA2D()`, and `railControl()`. The remainder of the code deals with setting up the microcontroller ports, initializing peripherals, and other background tasks. After settings are made and variables are declared, *main.c* enters an endless `while()` loop, where it stays until power is removed or a reset is detected. Just prior to entering the `while()` loop, *main.c* calls `calibACS()`. `calibACS()` is set up to determine the exact value of the offset voltages of the six ACS713 current sensors in the thesis. It does this by disabling all three DC-DC converters (to assure 0 A through the DC-DC), and then calling `runA2D()` and logging the measured offset voltages.

When the function `runA2D()` is run, it reads all enabled ADC channels and records the results. Depending on the value of `ADC_avg`, a running average of these values is calculated. The current setting of `ADC_avg` is 16, meaning each value output from `runA2D()` to the rest of the program is an average of 16 consecutive readings. Once an averaged value of each enabled channel is acquired, `runA2D()` outputs all the data to the serial port (which the PC software will read in, discussed in the next section). With this information available, `railControl()` can now be called in the `while()` loop.

The function `railControl()` looks at the real-time current (averaged) of each DC-DC, and determines how many DC-DC converters should be enabled. At the time of this report, the control scheme is simple; if the current through the first DC-DC is over 9 A, turn on the next converter. Similarly, if the current through the first or second DC-DC is over 9 A, turn on the third converter. Similarly, if all three DC-DCs are on and the total current is 18 A, turn off the third converter, etc. In the future work section below, a more sophisticated control scheme is proposed.

5.2 PC Software

The PC software developed for this thesis provides a graphical user interface (GUI) and a means to record data from the system. The software was developed using the C# programming language in Microsoft Visual C# 2010 Express. The complete software code can be found in Appendix D. Figure 5-1 shows the GUI before it is populated with any data. The GUI allows the user to select a COM port that the hardware is connected to, open or close the serial connection, and override the ACS713 current sensor op-amp gain values used to calculate current. The GUI also displays input and output voltage and current for the system and for each DC-DC, as well as efficiency. ACS713 offset voltages and gains are displayed, and a check-box indicates whether or not a certain DC-DC is enabled. Bar graphs also display the output current of each converter as well as the total system output current, to give a visual of where the system is operating in relation to minimum and maximum load. In the background, the software records all data into a *.csv file for later use. All data is displayed and recorded once a second.

Figure 5-1. PC Software GUI

As mentioned, the GUI displays the ACS713 gain (gain of the op-amp at the output of the ACS713) and provides a means to override the gain with user-selectable values. This enables tuning of the system, where-in the proper value can be found and entered back into the microcontroller firmware for a more accurate system. Any data that is displayed in the GUI can later be retrieved from a file, located in the root directory of the system hard drive, called TestFile.csv. This file is only available once the serial port has been closed or the GUI has been terminated. The file contains appropriate field headers and time-stamps (taken from the computer system clock) of when the data was taken.

Chapter 6. Hardware Results and Analysis

In order to perform tests on the hardware in this thesis, first bring-up and calibration of the system was required, then load-testing and tuning. For all of this work, some test instruments were required. A 48 VDC power supply was needed to power the system, an electronic load was required to draw power from the system, a personal computer was needed to run the software and compile data, and an oscilloscope and digital multimeter (DMM) were used for general diagnosis. Table 6-1 shows the details of the instruments used.

Table 6-1. Test Equipment Used for System Analysis

Instrument	Manufacturer	Part Number	Information
DC Power Supply	Densei-Lambda	JWS240P-48	48V, 5A (10A Peak)
Electronic Load	Kikusui	PLZ-152W	150W Load Max.
Personal Computer	HP and Dell	N/A	Windows XP
Oscilloscope	Tektronix	TPS2024	4-Channel, Isolated
Digital Multimeter	Fluke	287	Full-function DMM

6.1 Calibration

Since the hardware in this thesis has many sensors, both current and voltage, there are design constants in the firmware which, when implemented in hardware, are slightly different and must be measured. As discussed in the firmware section above, the 0A offset voltage of the ACS713 is measured by the firmware each time the system is powered up or reset. Other values, such as the op-amp gain of the output stage following the ACS713 had to be measured for verification. This was done running the system with different loads and measuring the gains with the DMM. Once these values were measured, the firmware was updated to reflect the actual gains, rather than the ideal. Another calibration needed was on the linear optocoupler used to isolate the input and output voltage measurements from the microcontroller. In order for this isolation to work, a linear relationship had to exist between the input and output of the optocoupler. To show this relationship, the input to the optocoupler was varied from 0 V to 3 V and the output voltage was recorded. Table 6-2 and Figure 6-1 show the data taken during calibration. As can be seen from

Figure 6-1, the LOC110 linear optocoupler has a very linear relationship between its input and output voltage.

Table 6-2. LOC110 Linear Optocoupler Linearity Check

V_{IN} (V)	V_{OUT} (Calculated) (V)	V_{OUT} (Measured) (V)
0	0	0.02
0.2	0.2	0.22
0.4	0.4	0.41
0.6	0.6	0.61
0.8	0.8	0.80
1	1	0.99
1.2	1.2	1.17
1.4	1.4	1.36
1.6	1.6	1.55
1.8	1.8	1.73
2	2	1.92
2.2	2.2	2.11
2.4	2.4	2.30
2.6	2.6	2.50
2.8	2.8	2.68
3	3	2.88

Figure 6-1. LOC110 Linear Optocoupler Linearity Calibration

6.2 Load Testing and Tuning

After calibration and firmware tweaking was performed, the system was ready for various tests, including full-load testing. Enabling the control system on the microcontroller and running the electronic load on the output of the load-share controller, the output current was increased from 0 A to 26 A (1 A below full system capability). During this test, the software was running on a computer and logging hardware data. After this test, the data was analyzed and produced the following graphs. Figure 6-2 shows the load currents of each DC-DC converter as compared to the total system output current. As shown, from 0 A to 9 A only one converter was enabled and the current ramps up as expected. At around the 9 A mark the second converter was enabled and the current was evenly shared by the two converters. Similarly, just before the total load current reached 18 A the third converter was enabled and the current was shared by all three converters. This was all done under the control of the microcontroller and shows that the system was acting as expected; the microcontroller was reading in values correctly and sending proper control signals, and the load-share controller was commanding the converters to share the load evenly.

Figure 6-2. Load Currents of Each DC-DC Converter During Full-Load Test

From this same data, an efficiency curve was generated as shown in Figure 6-3. As in the simulation results, the switch points in Figure 6-3 are evident by the step decreases in efficiency near 9 A and 18 A (because of the graph scale they look less pronounced). Adjusting the switch points to 12 A and 24 A (as in the simulation improved parallel converter) gives a smoother efficiency curve without the steps in efficiency. This is also shown in Figure 6-3 below.

Figure 6-3. Efficiency Curve for Generated from Full-Load Test

Figure 6-4 and Figure 6-5 show the single DC-DC converter used a control case and the complete digitally-controlled parallel DC-DC converter designed and built for this thesis. Figure 6-6 and Figure 6-7 show the test bench setup used during testing and data collection.

Figure 6-4. Single DC-DC Converter Used as Control Case

Figure 6-5. Complete Digitally-Controlled Parallel DC-DC Converter System

Figure 6-6. Test Bench Setup with Thesis System Attached

Figure 6-7. Testing Single DC-DC Converter (Control Case)

Chapter 7. Conclusion

Given the need for especially improved low-load efficiency in DC-DC converters, a digitally-controlled parallel DC-DC converter system was proposed. A MATLAB Simulink model was developed to simulate a system with an arbitrary converter topology. This model simply required the efficiency curve of a DC-DC converter and some desired operating characteristics to run. The results of the simulation showed that indeed the proposed parallel system out-performed a control-case single converter in the low-load case while maintaining full-load efficiency. The Simulink model provided a tool to develop a control algorithm which could later be implemented in a hardware design.

Following the successful simulation, a hardware implementation was proposed, based around three off-the-shelf DC-DC converters. The design implemented digital control via a microcontroller and used various current and voltage sensors to feed information to the control scheme. A load-share controller was designed into the output of the paralleled DC-DC converters to ensure equal load on all enabled converters. Along with the hardware system a software interface was developed to provide real-time information to a user as well as to record system data.

The efficiency results of the hardware system showed an improvement over the single converter control case, and performed close to what simulations predicted. Figure 7-1 shows the efficiency results of the simulation (improved parallel and control) and the hardware (with an averaged trendline for the improved parallel system). The slight efficiency gain of the improved parallel hardware results over the simulated improved parallel system appear to be from a small offset error introduced in the hardware, and could be corrected with further development. From Figure 7-1 a comparison of the parallel hardware system can be made to the single control DC-DC converter hardware. At lower loads (between 4.5 A and 8 A), the parallel systems shows

approximately a 2.2 % increase in efficiency over the control case. At the higher end, again the parallel system shows an improvement of approximately 1.6 %. In the mid-range load, the systems are quite comparable with the parallel system showing a slight improvement overall. As just mentioned, the parallel system measurements appear to be slightly high compared to what was expected, but even with corrections this system should still outperform the control case.

Figure 7-1. Efficiency Curves from Simulation and Hardware

Through the design of the hardware many issues arose in relation to an isolated system. Initial ground noise proved devastating for the design, and the redesigned system showed much improvement. PCB layout considerations in regards to trace width, trace spacing, and noise shielding played an important role in the correct workings of this thesis.

7.1 Future Work

There are a few areas where further development could improve this thesis and make it more useful for the real world. To start with, sensed voltage and current values appeared to vary over time as the system was used, and this led to some erroneous data. To mitigate this in the current design, manual calibrations were performed, but this proved tedious and not always accurate. In a future design a more robust calibration would allow for more accuracy and tighter control of the system. Another issue that arose in hardware testing was a problem with converters shutting down when not specifically commanded to do so. This would arise when a different converter was shut down, and appeared to be caused by some noise levels on the output voltage line feeding back into the enable lines of the converter not commanded to shut down. Finding solutions to these two issues would greatly improve the reliability of the system as a whole.

Another area for future work involves adding stress considerations into the control algorithm. This could include DC-DC converter temperature (temperature sensors would need to be added in hardware), converter on-time, and also lifetime converter on-time. This level of control would allow for all the converters to be equally utilized and for improved robustness and durability. Additionally, a spare converter could be designed into the system and could be brought automatically online in the case of a failure of an operating converter. One possible control scheme bringing these metrics together could be Fuzzy Logic. This scheme would allow for a completely defined system over variable temperature, load, and on-time conditions. This scheme could also improve the efficiency curve by choosing the proper number of converters to enable to achieve maximum efficiency (in a more adaptable way than the currently employed control scheme). With further developments, this system can show improvements in reliability and efficiency over a conventional DC-DC converter.

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Appendix A: Additional Hardware Design Information

Table A-1 and Table A-2 show calculation results for the voltage sense resistor dividers.

Table A-1 shows the set parameters, while Table A-2 shows the results of calculations to determine the resistor values, as well as the filter capacitors used. The switching frequency for V_{IN} was taken from the power supply evaluation datasheet [17] and the switching frequency for V_{OUT} was taken from the DC-DC converter datasheet [10].

Table A-1. Input and Output Voltage Ranges

Parameter	Symbol	Minimum	Typical	Maximum	Units
Input Voltage	V_{IN}	46	48	50	V
Output Voltage	V_{OUT}	4.85	5	5.15	V
Desired Set Voltage	V_{SET}	-	3	-	V

Table A-2. Calculation Results for Input and Output Voltage Sense Resistor Dividers

Parameter	V_{IN}	V_{OUT}	Units
Desired Current	0.5	0.5	mA
Actual Current	0.504	0.498	mA
R1+R2 Desired	100000	10300	Ω
R1 Desired	94000	4300	Ω
R2 Desired	6000	6000	Ω
R1 Actual	93100	4300	Ω
R2 Actual	6040	6040	Ω
Max. sense voltage	3.05	3.01	V
Sense at V_{TYP}	2.924	2.921	V
Sense Ratio	0.061	0.584	-
Parallel resistance R_p	5672	2512	Ω
Switching Frequency F_{SW}	297	290	kHz
Filter Capacitor Desired	270	624	pF
Filter Capacitor Actual	270	620	pF

Table A-3 and Table A-4 below show the LOC110 characteristics and support circuitry calculation results, respectively. The information in Table A-3 was taken from the LOC110 datasheet [8] and the calculations used for the results in Table A-4 were taken from the LOC110 Application Note [9].

Table A-3. LOC110 Device Characteristics

Parameter	Symbol	Minimum	Typical	Maximum	Units
LED Voltage Drop	V_F	0.9	1.2	1.4	V
K1, Servo Gain (I_{C1}/I_F)	K1	0.004	0.007	0.03	-
K2, Forward Gain (I_{C2}/I_F)	K2	0.004	0.007	0.03	-
K3, Transfer Gain ($K2/K1=I_{C2}/I_{C1}$)	K3	0.668	1	1.179	-
Input-Side Supply Voltage	V_{CC1}	5	5	5	V
Output-Side Supply Voltage	V_{CC2}	3.267	3.3	3.333	V

Table A-4. Calculation Results for LOC110 Support Circuitry

Parameter	Symbol	Minimum	Typical	Maximum	Units
Input Voltage Span	$V_{IN-SPAN}$	0	-	3	V
Output Voltage Span	$V_{OUT-SPAN}$	0	-	3	V
LED Current	I_F	-	0.015	-	A
Input Resistor (Calculated)	R_{1C}	-	50000	-	Ω
Output Resistor (Calculated)	R_{2C}	-	50000	-	Ω
Input Resistor (Actual)	R_{1A}	-	50000	-	Ω
Output Resistor (Actual)	R_{2A}	-	50000	-	Ω
LED Resistor (Calculated)	R_{FC}	-	273.3333	-	Ω

Figure A-1, Figure A-2, and Figure A-3 below show the complete controller board schematic. Likewise, Figure A-4, Figure A-5, and Figure A-6 show the complete power board schematic. These schematics were created in EAGLE schematic editor. For details on the design shown here, refer to the Hardware Design section above.

Figure A-1. Controller Schematic – 5V, 3.3V, Non-Isolated 5V, Connector, and Test Points

Figure A-2. Controller Schematic – USB, ISCP, Microcontroller, GPIO LEDs and Buttons

Figure A-3. Controller Schematic – Input and Output Voltage Sense Circuits

Figure A-4. Power Schematic – Test Points, Connectors, and RAIL 1

Figure A-5. Power Schematic – RAIL 2

Figure A-6. Power Schematic – RAIL 3

Appendix B: Simulation Model Code

Below is a listing of the code used to run the Simulink model discussed in this thesis. See the Simulation section above for an explanation of each file.

```
%EfficiencyVariables.m

% Define simulation to run
% If you wish to run EE527 paper simulation, set to 1
% If you wish to run Thesis hardware simulation, set to 2
SIM = 2;

% Output voltage
Vo = 48;

% Load current range for parallel-connected converters
if (SIM == 1)
    INPUT_VECTOR = xlsread('Efficiency Lookup Table Data_2.xlsx',
        'A3:A42');
elseif (SIM == 2)
    INPUT_VECTOR = xlsread('Efficiency Lookup Table Data_2.xlsx',
        'G3:G30');
end

% Efficiency for parallel-connected converters
if (SIM == 1)
    EFFICIENCY = xlsread('Efficiency Lookup Table Data_2.xlsx',
        'B3:B42');
elseif (SIM == 2)
    EFFICIENCY = xlsread('Efficiency Lookup Table Data_2.xlsx',
        'H3:H30');
end

global maxEta;          % Maximum efficiency
global maxEtaIndex;    % Index of maximum efficiency
global maxI;           % Load current at maximum efficiency

% Find maximum efficiency
[maxEta,maxEtaIndex] = max(EFFICIENCY);

% Find load current at maximum efficiency
maxI = INPUT_VECTOR(maxEtaIndex);

% Load current range for equivalent single converter
if (SIM == 1)
    INPUT_VECTOR_CONTROL = xlsread('Efficiency Lookup Table
        Data_2.xlsx', 'D3:D42');
elseif (SIM == 2)
    INPUT_VECTOR_CONTROL = xlsread('Efficiency Lookup Table
        Data_2.xlsx', 'J3:J33');
```

```

end

% Efficiency for equivalent single converter
if (SIM == 1)
    EFFICIENCY_CONTROL = xlsread('Efficiency Lookup Table Data_2.xlsx',
    'E3:E42');
elseif (SIM == 2)
    EFFICIENCY_CONTROL = xlsread('Efficiency Lookup Table Data_2.xlsx',
    'L3:L33');
end

% controller.m

function output = controller(input)
% input format: efficiency, efficiency1, efficiency2, efficiency3

% output format: number of active converters, control, controll1,
%               control2,control3

convNum = 0;
control = 0;
controll1 = 0;
control2 = 0;
control3 = 0;

global maxEta;
global maxI;

controller_9amps = 12;
controller_peak_eta = maxI;
controller_type = controller_9amps;

%{
if ( input > (3 * controller_type))
    control = 1;
    controll1 = 1;
    control2 = 1;
    control3 = 1;
%}
if ( input > (2 * controller_type))
    control = 1;
    controll1 = 1;
    control2 = 1;
    control3 = 0;
elseif ( input > controller_type)
    control = 1;
    controll1 = 1;
    control2 = 0;
    control3 = 0;
else
    control = 1;
    controll1 = 0;

```

```
        control2 = 0;
        control3 = 0;
    end

    % Determine number of enabled converters
    convNum = control + control1 + control2 + control3;

    % Output results
    output = [convNum, control, control1, control2, control3];
```

Appendix C: Embedded Firmware Code

Below is a listing of the firmware code used to run the hardware discussed in this thesis. See the Software Design – Embedded Firmware section above for an explanation of each file. The code is written in C and was compiled using the Microchip C30 compiler in MPLAB IDE.

```
//adc.c

#include <adc.h>

void ADCInit ( void )
{
    AD1CON1 = 0x00E4;    // integer format, auto-convert, auto-start
    AD1CON2 = 0x042C;    // AVdd/AVss, scan inputs, interrupt after 12th read
    AD1CON3 = 0x0F0F;    // system clock, Tsamp = 15 Tad, ADCS = 16*Tcy
    AD1CHS  = 0x0000;    // defaults
    AD1PCFG = 0x0033;    // configure pins as analog
    AD1CSSL = 0xFFCC;    // configure pins to scan

    AD1CON1bits.ADON = 1; // turn ADC ON
}

//“uart1.c”

/*
Engscope
UART
April 16, 2008
Author: JL
*/

#include <p24FJ128GA006.h>
#include "uart1.h"

//Initiation function, parameter BAUDRATEREG1 determines baud speed
void UART1Init(int BAUDRATEREG1)
{
    //Set up registers
    U1BRG = BAUDRATEREG1;    //set baud speed
    U1MODE = 0x8000;          //turn on module
    U1STA = 0x8400;           //set interrupts

    //reset RX interrupt flag
    IFS0bits.U1RXIF = 0;
}

//UART transmit function, parameter Ch is the character to send
void UART1PutChar(char Ch)
{
    //transmit ONLY if TX buffer is empty
    while(U1STAbits.UTXBF == 1);
    U1TXREG = Ch;
}
```



```

}

//UART receive function, returns the value received.
char UART1GetChar()
{
    char Temp;

    //wait for buffer to fill up, wait for interrupt
    while(IFS0bits.U1RXIF == 0);
    Temp = U1RXREG;

    //reset interrupt
    IFS0bits.U1RXIF = 0;

    //return my received byte
    return Temp;
}

//UART transmit function, parameter sendInt is the int to send (4-digit DEC)
//MAX: DEC-9999, HEX-270F
void UART1PutInt(unsigned int sendInt)
{
    UART1PutChar((sendInt/1000) + 0x30);
    UART1PutChar(((sendInt%1000)/100) + 0x30);
    UART1PutChar(((sendInt%100)/10) + 0x30);
    UART1PutChar((sendInt%10) + 0x30);
}

//UART transmit string function, paramater stringUART is the string to send
void UART1PutString(const char *stringUART)
{
    while(*stringUART != '\0')
    {
        UART1PutChar(*stringUART++);
    }
}

/*
main.c

(c) Daniel Forbes 2011

Ver.      Date      Notes
0.0        04-18-2011  Created
0.1        04-29-2011  Set up UART
0.2        05-07-2011  Set up ADC (need to test) and LEDs/buttons/enables
0.3        05-20-2011  Added debounce function, RAILS tested
0.4        05-23-2011  Testing ADC
0.5        05-24-2011  ADC working, sending data to C# app.
0.6        06-06-2011  Adding ADC averaging
0.7        06-14-2011  Added Timer1 w/ interrupt for delays
0.8        09-22-2011  Now using V2 PCBs, adding sensor gains
0.9        10-14-2011  Adding ACS offset/calibration function - DONE

```

```

1.0          10-24-2011    Modifying railControl() - less frequent in main()
1.1          05-03-2012    Changing to 12A switch points

```

```

TODO:
*/

```

```

// INCLUDES #####

```

```

#include <p24FJ128GA006.h>
#include "uart1.h"
#include "adc.h"
#include "timer1.h"

```

```

#define LED0 0x0008      // LED0 port
#define LED1 0x0010      // LED1 port
#define LED2 0x0020      // LED2 port
#define SW2  0x0040      // SW2 port
#define SW3  0x0080      // SW3 port
#define SW4  0x0100      // SW4 port
#define EN1  0x0001      // enable rail 1 port
#define EN2  0x0002      // enable rail 2 port
#define EN3  0x0004      // enable rail 3 port

```

```

// ADC array index locations

```

```

#define VIN1  0
#define VIN2  4
#define VIN3  8
#define VOUT1 2
#define VOUT2 6
#define VOUT3 10
#define IIN1  1
#define IIN2  5
#define IIN3  9
#define IOUT1 3
#define IOUT2 7
#define IOUT3 11

```

```

// Control values

```

```

#define NINE 886
#define AMP_LIMIT_AMPS      9

```

```

// Sensor Gain Values

```

```

#define VIN_GAIN      1
#define VOUT1_GAIN    1
#define VOUT2_GAIN    1
#define VOUT3_GAIN    1
#define IIN1_GAIN     432      // All current gain values are x10
#define IIN2_GAIN     432      // These values are passed through to the GUI
#define IIN3_GAIN     432      // for calculations.
#define IOUT1_GAIN    110      // (Old value 132)
#define IOUT2_GAIN    110      //
#define IOUT3_GAIN    110      //

```

```

// System Constants

```

```

#define VOLT_REF      33      // 3.3V ADC reference voltage (x10)
#define ADC_COUNT     1023    // ADC counts
#define ACS_GAIN       185     // 0.185 V/A current gain (x1000)

```

```

// PROTOTYPES #####
void RepeaterProcessEvents();
void calibACS();
int debounce(int button);
void runA2D();
void railControl();
void testA2D();

// GLOBAL VARIABLES #####
int ADCValue_global[12];           // holds latest averaged ADC readings
unsigned char state = 1;           // control state of rails
unsigned int timerInc = 0;         // increments on timer match
unsigned char one_sec = 0;         // one second has elapsed when = 1
int offsetACS[6];                 // array of ACS713 0A offset voltages
unsigned int ampLimit = 0;         // Current limit for each rail (converted to
                                   // ADC counts), also the automatic switching
                                   // point.
unsigned int control_count = 1;    // using to delay railControl

// CONFIGURATION #####
// Watchdog timer disabled
// Two Speed Start-up: Disabled
// Oscillator Selection: Primary Oscillator (XT, HS, EC)
// Clock switching and clock monitor: Both disabled
// Oscillator Selection: HS oscillator
_CONFIG1( JTAGEN_OFF & FWDTEN_OFF & ICS_PGx1 )
_CONFIG2( IESO_OFF & FNOSC_PRI & FCKSM_CSDCMD & POSCMOD_HS )

int main (void)
{
    CLKDIV = 0x0000;    // Don't divide clock

    // Data direction registers
    //TRISA = 0b;
    TRISB = 0b1111111111111111; // Analog inputs
    //TRISC = 0b;
    TRISD = 0b0000000111000000; // RD5=LED2, RD4=LED1, RD3=LED0
                                   // RD8=SW4, RD7=SW3, RD6=SW2
                                   // RD2=EN3, RD1=EN2, RD0=EN1

    //TRISE = 0b;
    TRISF = 0b0000000000010100; // UART1 and UART2
    //TRISG = 0b;

    // Disable all converters
    PORTD &= 0xFFF8;
    //PORTD |= 0x0007;

    // Clear LEDs
    PORTD &= 0xFFC7;

    // CONFIGURE PERIPHERALS #####
    UART1Init(65);           // Initiate UART1 to 9600 at 20MHz OSCI
    ADCInit();               // Initiate ADC
    //#####

    // Read in 0A ACS713 voltage offset

```

```

calibACS();

while ( 1 )
{
    // Test buttons, LEDs, Rails
    if (debounce(SW4))
    {
        if(PORTD & EN1)
            PORTD &= 0xFFFF6;
        else
            PORTD |= LED0 | EN1;
    }
    if (debounce(SW3))
    {
        if(PORTD & EN2)
            PORTD &= 0xFFED;
        else
            PORTD |= LED1 | EN2;
    }
    if (debounce(SW2))
    {
        if(PORTD & EN3)
            PORTD &= 0xFFDB;
        else
            PORTD |= LED2 | EN3;
    }

    runA2D();

    // Turn on automatic RAIL control
    if(control_count >= 5)
    {
        railControl();
        control_count = 0;
    }

    control_count++;
}
return 0;
}

//Read ACS713 0A offset
void calibACS()
{
    //disable all rails to ensure 0A
    PORTD &= (~EN1 & ~EN2 & ~EN3);

    //read all ADC ports
    runA2D();

    //store offset voltages
    offsetACS[0] = ADCValue_global[IIN1];
    offsetACS[1] = ADCValue_global[IIN2];
    offsetACS[2] = ADCValue_global[IIN3];
    offsetACS[3] = ADCValue_global[IOOUT1];
    offsetACS[4] = ADCValue_global[IOOUT2];
    offsetACS[5] = ADCValue_global[IOOUT3];
}

```

```

        return;
    }

    //Button debounce function
    int debounce(int button)
    {
        int pressed = 0;
        int i = 0;

        if (!(PORTD & button))
        {
            for(i = 0; i < 10000; i++){

                if (!(PORTD & button))
                {
                    pressed = 1;
                }
                else
                {
                    pressed = 0;
                }
            }

            return pressed;
        }
    }

    //Run A2D - Read in all 12 A2D channels, apply averaging, and send to UART
    void runA2D()
    {
        int ADCValue, count, count_avg;
        int *ADC16Ptr;                // pointer to ADC buffer
        int ADCValue_avg[12];         // ADC accumulator
        int ADC_avg = 16;              // number of ADC samples to average

        UART1PutString("\n\r");       // carriage return

        // clear ADC accumulator
        for (count = 0; count < 12; count++)
        {
            ADCValue_avg[count] = 0;
        }

        // average readings
        for (count_avg = 0; count_avg < ADC_avg; count_avg++)
        {
            ADCValue = 0;              // clear value
            ADC16Ptr = &ADC1BUF0;      // initialize ADC1BUF pointer
            IFS0bits.AD1IF = 0;        // clear ADC interrupt flag
            AD1CON1bits.ASAM = 1;      // auto start sampling for ?TAD
                                      // then go to conversion
            while (!IFS0bits.AD1IF){}; // conversion done?
            AD1CON1bits.ASAM = 0;      // yes then stop sample/convert

            // read ADC and add to accumulator for averaging
            for (count = 0; count < 12; count++)
            {

```

```

        ADCValue = *ADC16Ptr++;
        ADCValue_avg[count] = ADCValue_avg[count] + ADCValue;
    }
}

// populate array for use elsewhere in the program
for (count = 0; count < 12; count++)
{
    ADCValue_global[count] = ADCValue_avg[count] / ADC_avg;
}

// print ADC accumulator values to UART
for (count = 0; count < 12; count++) // print the 12 ADC values
{
    UART1PutInt(ADCValue_avg[count] / ADC_avg);
    UART1PutString(",");
    ADCValue_avg[count] = 0;
}

// send which rails are enabled to UART
if (PORTD & EN1)
    UART1PutString("1");
else
    UART1PutString("0");

UART1PutString(",");

if (PORTD & EN2)
    UART1PutString("1");
else
    UART1PutString("0");

UART1PutString(",");

if (PORTD & EN3)
    UART1PutString("1");
else
    UART1PutString("0");

// send ACS713 0A offset voltages to UART
for (count = 0; count < 6; count++)
{
    UART1PutString(",");
    UART1PutInt(offsetACS[count]);
}

// send ACS713 gain values
UART1PutString(",");
UART1PutInt(IIN1_GAIN);
UART1PutString(",");
UART1PutInt(IIN2_GAIN);
UART1PutString(",");
UART1PutInt(IIN3_GAIN);
UART1PutString(",");
UART1PutInt(IOUT1_GAIN);
UART1PutString(",");

```

```

        UART1PutInt(IOUT2_GAIN);
        UART1PutString(",");
        UART1PutInt(IOUT3_GAIN);
    }

    // control algorithm for rails
    void railControl()
    {
        if((ADCValue_global[IOUT1] > NINE) && (state == 1))
            state = 2;
        else if(((ADCValue_global[IOUT1] > NINE) || (ADCValue_global[IOUT2] >
NINE)) && (state == 2))
            state = 3;

        UART1PutString(",*");

        switch(state)
        {
            case 0:                // all converters disabled
                PORTD &= 0xFFF8;
                UART1PutString("0");
                break;

            case 1:                // RAIL 1 enabled
                PORTD &= (~EN2 & ~EN3);
                PORTD |= EN1;
                UART1PutString("1");
                break;

            case 2:                // RAIL 1 and RAIL 2 enabled
                PORTD &= ~EN3;
                PORTD |= EN1 | EN2;
                UART1PutString("2");
                break;

            case 3:                // RAIL 1 and RAIL 2 and RAIL 3 enabled
                PORTD |= EN1 | EN2 | EN3;
                UART1PutString("3");
                break;

            default:
                PORTD |= EN1 | EN2 | EN3;
                break;
        }

        return;
    }

    //Test different A2D functions
    void testA2D()
    {
        int ADCValue, count, count_avg;
        int *ADC16Ptr;                // pointer to ADC buffer
        int ADCValue_avg[12];         // ADC accumulator
        int ADC_avg = 16;             // number of ADC samples to average
    }

```

```

UART1PutString("\n\r");           // carriage return

ADCValue = 0;                     // clear value
ADC16Ptr = &ADC1BUF0;             // initialize ADC1BUF pointer
IFS0bits.AD1IF = 0;               // clear ADC interrupt flag
AD1CON1bits.ASAM = 1;             // auto start sampling for ?TAD
                                   // then go to conversion
while (!IFS0bits.AD1IF){};        // conversion done?
AD1CON1bits.ASAM = 0;             // yes then stop sample/convert

for(count = 0; count < 2; count++)
{
    ADCValue = ADCValue + *ADC16Ptr++;
}
ADCValue = ADCValue >> 1;
UART1PutString("0,0,0,0,");
UART1PutInt(ADCValue);
UART1PutString(",0,0,0,0,0,0,0,0,0,0");
}

```


Appendix D: PC Software Code

Below is a listing of the software code used to run on a PC. See the Software Design – PC Software section above for an explanation of the code. The code is written in *C#* and was compiled using Microsoft Visual C# 2010 Express.

```
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Drawing;
using System.Linq;
using System.Text;
using System.Windows.Forms;
using GraphLib;
using System.IO;

namespace Test_1
{
    public partial class Form1 : Form
    {
        string message;
        public Form1()
        {
            InitializeComponent();

            //create variables used in file writing
            string[] data1 = new string[200]; // buffer 1 used for .csv file writing
            string[] data2 = new string[200]; // buffer 2 used for .csv file writing
            int countData1 = 0; // buffer 1 index counter
            int countData2 = 0; // buffer 2 index counter
            bool use_buffer1 = true; // which buffer is in use?
            FileInfo a = new FileInfo(@"C:\TestFile.csv"); // create a new FileInfo
            object for .csv file to write to

            // open/close serial port on specified COM port and write header line to
            .csv file
            private void serial_open_CheckedChanged(object sender, EventArgs e)
            {
                if (serial_open.Checked)
                {
                    textBox1.Text = "OPEN";
                    serialPort1.PortName = comPort_list.Text;
                    serialPort1.Open();

                    StreamWriter storeData;
                    storeData = a.CreateText();
                    try
                    {
                        storeData.WriteLine("Vin1 (V),Iin1 (A),Vout1 (V),Iout1
                        (A),Vin2 (V),Iin2 (A),Vout2 (V),Iout2 (A),Vin3 (V),Iin3
```

```

        (A),Vout3 (V),Iout3 (A),EN1,EN2,EN3,Time,Eta1 (%),Eta2
        (%),Eta3 (%),Iin_Total (A),Iout_total (A),Pin (W),Pout
        (W),Eta_Total(%),Gain_IN1,Gain_IN2,Gain_IN3,
        Gain_OUT1,Gain_OUT2,Gain_OUT3");
        storeData.Close();
    }
    finally
    {
        storeData.Dispose();
    }
}
else
{
    textBox1.Text = "CLOSED";
    serialPort1.Close();
}

}

// read in line of data from serial port
private void serialPort1_DataReceived(object sender,
System.IO.Ports.SerialDataReceivedEventArgs e)
{
    message = serialPort1.ReadLine();
}

// most things happen in here: parse string, display data, write to .csv
file
private void timer1_Tick(object sender, EventArgs e)
{
    // total resistance on input voltage resistor divider
    double rTotalIn = 99140;
    // total resistance on output voltage resistor divider
    double rTotalOut = 10340;
    // resistance to ground on input and output voltage resistor dividers
    double rBottom = 6040;
    // ADC reference voltage
    double vRef = 3.3;
    // number of ADC counts = (2^10) - 1
    double counts = 1023;
    // gain of ACS713 (V/A)
    double hallGain = 0.185;
    // gain of isolation circuit - Input Voltage
    double vGain_in = 1.05;
    double vGain_out1 = 1.075; // gain of isolation circuit - Output 1
    double vGain_out2 = 1.06; // gain of isolation circuit - Output 2
    double vGain_out3 = 1.065; // gain of isolation circuit - Output 3
    double iInGain1 = 0;
    double iInGain2 = 0;
    double iInGain3 = 0;
    double iOutGain1 = 0;
    double iOutGain2 = 0;
    double iOutGain3 = 0;

    if (serialPort1.IsOpen)
    {
        // data parser separator

```

```

char[] csv = new char[] { ',' };
// parse input string into separate components
string[] splitData = message.Split(csv);

if (splitData.Length >= 27)
{
    System.Diagnostics.Debug.WriteLine(splitData.Length.ToString());

    if (checkBox_gainOverride.Checked)
    {
        iInGain1 = Convert.ToDouble(numericUpDown_IIN1.Value);
        iInGain2 = Convert.ToDouble(numericUpDown_IIN2.Value);
        iInGain3 = Convert.ToDouble(numericUpDown_IIN3.Value);
        iOutGain1 = Convert.ToDouble(numericUpDown_IOUT1.Value);
        iOutGain2 = Convert.ToDouble(numericUpDown_IOUT2.Value);
        iOutGain3 = Convert.ToDouble(numericUpDown_IOUT3.Value);
    }

    else
    {
        iInGain1 = double.Parse(splitData[21]) / 100;
        iInGain2 = double.Parse(splitData[22]) / 100;
        iInGain3 = double.Parse(splitData[23]) / 100;
        iOutGain1 = double.Parse(splitData[24]) / 100;
        iOutGain2 = double.Parse(splitData[25]) / 100;
        iOutGain3 = double.Parse(splitData[26]) / 100;
    }

    double iOffset_in1 = double.Parse(splitData[15]) * (vRef / counts) / iInGain1;
    double iOffset_in2 = double.Parse(splitData[16]) * (vRef / counts) / iInGain2;
    double iOffset_in3 = double.Parse(splitData[17]) * (vRef / counts) / iInGain3;
    double iOffset_out1 = double.Parse(splitData[18]) * (vRef / counts) / iOutGain1;
    double iOffset_out2 = double.Parse(splitData[19]) * (vRef / counts) / iOutGain2;
    double iOffset_out3 = double.Parse(splitData[20]) * (vRef / counts) / iOutGain3;
    double Vin = double.Parse(splitData[4]) * (vRef / counts) * (rTotalIn / rBottom) * vGain_in;
    double Vout1 = double.Parse(splitData[2]) * (vRef / counts) * (rTotalOut / rBottom) * vGain_out1;
    double Vout2 = double.Parse(splitData[6]) * (vRef / counts) * (rTotalOut / rBottom) * vGain_out2;
    double Vout3 = double.Parse(splitData[10]) * (vRef / counts) * (rTotalOut / rBottom) * vGain_out3;
    double Iin1 = ((double.Parse(splitData[1]) * (vRef / counts) / iInGain1) - iOffset_in1) / hallGain;
    double Iin2 = ((double.Parse(splitData[5]) * (vRef / counts) / iInGain2) - iOffset_in2) / hallGain;
    double Iin3 = ((double.Parse(splitData[9]) * (vRef / counts) / iInGain3) - iOffset_in3) / hallGain;
    double Iout1 = ((double.Parse(splitData[3]) * (vRef / counts) / iOutGain1) - iOffset_out1) / hallGain;

```

```

double Iout2 = ((double.Parse(splitData[7]) * (vRef / counts)
/ iOutGain2) - iOffset_out2) / hallGain;
double Iout3 = ((double.Parse(splitData[11]) * (vRef / counts)
/ iOutGain3) - iOffset_out3) / hallGain;
double Iin = Iin1 + Iin2 + Iin3;
double Iout = Iout1 + Iout2 + Iout3;
double Pin1 = Vin * Iin1;
double Pin2 = Vin * Iin2;
double Pin3 = Vin * Iin3;
double Pin = Pin1 + Pin2 + Pin3;
double Pout1 = Vout1 * Iout1;
double Pout2 = Vout2 * Iout2;
double Pout3 = Vout3 * Iout3;
double Pout = Pout1 + Pout2 + Pout3;
// output voltage used to calculate total efficiency
double Vout;
double Eta1 = 0;
double Eta2 = 0;
double Eta3 = 0;
double EtaTotal = 0;

// choose which Voutx to use for Vout
if (Vout1 > 4)
    Vout = Vout1;
else if (Vout2 > 4)
    Vout = Vout2;
else if (Vout3 > 4)
    Vout = Vout3;
else
    Vout = 5;

// calculate efficiencies
if (Convert.ToBoolean(int.Parse(splitData[12])))
    Eta1 = (Pout1 / Pin1) * 100;
else
    Eta1 = 0;
if (Convert.ToBoolean(int.Parse(splitData[13])))
    Eta2 = (Pout2 / Pin2) * 100;
else
    Eta2 = 0;
if (Convert.ToBoolean(int.Parse(splitData[14])))
    Eta3 = (Pout3 / Pin3) * 100;
else
    Eta3 = 0;

// total efficiency
//EtaTotal = ((Vout * Iout) / (Vin * Iin)) * 100;

// Three rails ON
if (Convert.ToBoolean(int.Parse(splitData[14])))
    EtaTotal = ((Vout * Iout) / (Vin * Iin)) * 100;
// Two rails ON
else if (Convert.ToBoolean(int.Parse(splitData[13])))
    EtaTotal = ((Pout1 + Pout2) / (Pin1 + Pin2)) * 100;
// One rail ON

```

```

else
    EtaTotal = (Pout1 / Pin1) * 100;

// display converted data in GUI
textBox_Vin.Text = Vin.ToString("N2");
textBox_Vout1.Text = Vout1.ToString("N2");
textBox_Vout2.Text = Vout2.ToString("N2");
textBox_Vout3.Text = Vout3.ToString("N2");
textBox_Iin1.Text = Iin1.ToString("N2");
textBox_Iin2.Text = Iin2.ToString("N2");
textBox_Iin3.Text = Iin3.ToString("N2");
textBox_Iout1.Text = Iout1.ToString("N2");
textBox_Iout2.Text = Iout2.ToString("N2");
textBox_Iout3.Text = Iout3.ToString("N2");
textBox_Eta1.Text = Eta1.ToString("N2");
textBox_Eta2.Text = Eta2.ToString("N2");
textBox_Eta3.Text = Eta3.ToString("N2");
textBox_EtaTotal.Text = EtaTotal.ToString("N2");
textBox_Iin_Total.Text = Iin.ToString("N2");
textBox_Iout_Total.Text = Iout.ToString("N2");
textBox_offsetIN1.Text = iOffset_in1.ToString("N2");
textBox_offsetIN2.Text = iOffset_in2.ToString("N2");
textBox_offsetIN3.Text = iOffset_in3.ToString("N2");
textBox_offsetOUT1.Text = iOffset_out1.ToString("N2");
textBox_offsetOUT2.Text = iOffset_out2.ToString("N2");
textBox_offsetOUT3.Text = iOffset_out3.ToString("N2");
textBox_Iin_gain.Text = iInGain1.ToString("N2") + "/" +
    iInGain2.ToString("N2") + "/" + iInGain3.ToString("N2");
textBox_Iout_gain.Text = iOutGain1.ToString("N2") + "/" +
    iOutGain2.ToString("N2") + "/" + iOutGain3.ToString("N2");

// populate progress bars
if (Iout1 > 9)
{
    progressBar_Iout1.Value = 9;
    progressBar_Iout1.ForeColor = Color.Red;
}

else if ((Iout1 >= 0) && (Iout1 <= 9))
{
    progressBar_Iout1.Value = (int)Iout1;
    progressBar_Iout1.ForeColor = Color.Blue;
}

if (Iout2 > 9)
{
    progressBar_Iout2.Value = 9;
    progressBar_Iout2.ForeColor = Color.Red;
}

else if ((Iout2 >= 0) && (Iout2 <= 9))
{
    progressBar_Iout2.Value = (int)Iout2;
    progressBar_Iout2.ForeColor = Color.Blue;
}

if (Iout3 > 9)

```

```

{
    progressBar_Iout3.Value = 9;
    progressBar_Iout3.ForeColor = Color.Red;
}

else if ((Iout3 >= 0) && (Iout1 <= 9))
{
    progressBar_Iout3.Value = (int)Iout3;
    progressBar_Iout3.ForeColor = Color.Blue;
}

if ((Iout1 >= 0) && (Iout2 >= 0) && (Iout3 >= 0))
{
    progressBar_Iout_Total.Value = (int)Iout1 + (int)Iout2 +
        (int)Iout3;
    progressBar_Iout_Total.ForeColor = Color.Blue;
}

// show which rails are enabled
checkBox_Rail1.Checked =
    Convert.ToBoolean(int.Parse(splitData[12]));
checkBox_Rail2.Checked =
    Convert.ToBoolean(int.Parse(splitData[13]));
checkBox_Rail3.Checked =
    Convert.ToBoolean(int.Parse(splitData[14]));

// read current system time for use in .csv file
string time = DateTime.Now.TimeOfDay.ToString();

// format data string to be stored in buffer
// "Vin1,Iin1,Vout1,Iout1,Vin2,Iin2,Vout2,Iout2,Vin3,
    Iin3,Vout3,Iout3,EN1,EN2,EN3,Time,
    Eta1,Eta2,Eta3,Iin_Total,Iout_total,
    Pin,Pout,Eta_Total,Gain_IN1,Gain_IN2,Gain_IN3,
    Gain_OUT1,Gain_OUT2,Gain_OUT3"
string decodedMessage = Vin.ToString("N2") + "," +
    Iin1.ToString("N2") + "," + Vout1.ToString("N2")
        + "," +
    Iout1.ToString("N2") + "," + Vin.ToString("N2")
        + "," +
    Iin2.ToString("N2") + "," + Vout2.ToString("N2")
        + "," +
    Iout2.ToString("N2") + "," + Vin.ToString("N2")
        + "," +
    Iin3.ToString("N2") + "," + Vout3.ToString("N2")
        + "," +
    Iout3.ToString("N2") + "," + splitData[12]
        + "," +
    splitData[13] + "," + splitData[14]
        + "," +
    time
        + "," +
    Eta1.ToString("N2")
        + "," +
    Eta2.ToString("N2")
        + "," +
    Eta3.ToString("N2")

```

```

Iin.ToString("N2")
Iout.ToString("N2")
Pin.ToString("N2")
Pout.ToString("N2")
EtaTotal.ToString("N2")
iInGain1.ToString("N2")
iInGain2.ToString("N2")
iInGain3.ToString("N2")
iOutGain1.ToString("N2")
iOutGain2.ToString("N2")
iOutGain3.ToString("N2");

```

```

+ "," +
+ "," +
+ "," +
+ "," +
+ "," +
+ "," +
+ "," +
+ "," +
+ "," +
+ "," +
+ "," +
+ "," +

```

```

// fill buffers for .csv file writing
int buffer_Size = 10;

if (use_buffer1)
{
    data1[countData1] = decodedMessage;
    countData1++;

    if (countData1 > buffer_Size)
    {
        use_buffer1 = false;
    }
}
else
{
    data2[countData2] = decodedMessage;
    countData2++;

    if (countData2 > buffer_Size)
    {
        use_buffer1 = true;
    }
}

// write full buffer to file
StreamWriter storeData;
storeData = a.AppendText();
try
{
    // don't write empty buffer at program start
    if (data2[0] == null)

```

```

    {
    }
    else
    {
        // make sure to only write buffer once
        if (use_buffer1 && (countData2 > buffer_Size))
        {
            for (int i = 0; i < buffer_Size; i++)
                storeData.WriteLine(data2[i]);
            storeData.Close();
            countData2 = 0;
        }
        else if (countData1 > buffer_Size)
        {
            for (int i = 0; i < buffer_Size; i++)
                storeData.WriteLine(data1[i]);
            storeData.Close();
            countData1 = 0;
        }
    }
}
finally
{
    storeData.Dispose();
}
}

// make sure to close serial port when form is closed
private void Form1_FormClosing(object sender, FormClosingEventArgs e)
{
    serialPort1.Close();
}
}

```