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Pulse charging lead-acid batteries to improve performance and reverse the effects of sulfation

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Pulse Charging Lead-Acid Batteries to Improve Performance and Reverse the Effects of Sulfation

Robert B. Cooper

**Thesis submitted to the
College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements
for the degree of**

**Master of Science
in
Electrical Engineering**

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**Morgantown, WV
2002**

**Keywords: EV Battery Charging, Battery Recovery, Discharge Test,
and Battery Impedance**

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Abstract

Pulse Charging Lead-Acid Batteries to Improve Performance and Reverse the Effects of Sulfation

Robert B. Cooper

When lead-acid batteries are improperly charged or discharged, useful power delivered to loads diminishes. One cause for this is a phenomenon generally referred to as sulfation. One possible method that has been proposed by many to reverse the effects of sulfation is to recharge the lead-acid battery using a pulse charger. To gain a better understanding of the possible benefits of this type of charging, a pulse charger / discharger was constructed. Cycle testing was then done on six pairs of batteries to compare the pulse charged batteries to conventional full-wave rectifier charged batteries. The results of the tests showed that pulse charging failed to improve the condition of sulfated batteries. Pulse charging did result in substantial improvements if the battery's condition was classified as fair. However, pulse charging had little effect on the condition of batteries in excellent condition.

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Chapter 1: Introduction

1.1 Overview

Improper charging of lead acid batteries or leaving them in a discharged state for long periods of time often leads to premature failure of the battery. One of the major causes for premature failure is a condition commonly known as battery sulfation. This accounts for 84% of all lead acid battery failures [4]. Sulfation is a condition characterized by the battery not being able to hold the proper voltage, unable to provide useful current, possessing a higher than normal internal impedance, or any combination of the three. Since the premature failure of batteries can add significantly to the maintenance costs of electric vehicles and other systems that use lead-acid batteries, any process that can prevent premature failure is highly desirable.

1.2 Lead-Acid Battery Charging

As a lead acid battery is discharged the following reaction takes place [1]:

In a fully charged battery, there should be no lead sulfate (PbSO_4) present on the battery's plate grids. As can be seen from equations 1.1 and 1.2 when a battery is discharged, lead (Pb) from the negative battery plate and lead oxide (PbO_2) from the positive battery plate are converted to lead sulfate. As the battery discharge process progresses, the electro-chemical reactions will continue until no more lead sulfate can be formed. At this point, the battery will be in a fully discharged state and unable to provide further current to a load.

In order to recharge the lead-acid battery, the reverse electro-chemical reactions to the ones described by equations 1.1 and 1.2 must take place. The reverse processes are implemented by the application of an external electrical power source which provides the energy to overcome the thermodynamically favored direction. The reactions that take place are described by equations shown below [1].

As the battery is recharged, the lead sulfate is converted back into lead and lead oxide.

The lead sulfate that remains after recharging the battery is what is commonly called sulfation. When the sulfation condition occurs, lead sulfate crystals grow on the plates of the lead acid battery. As the crystals grow larger, their solubility within the

electrolyte solution decreases [2], making it very difficult to convert the lead sulfate back to lead and lead-oxide during the next recharge cycle. Eventually, the crystals become hard and chemically inactive [3]. When this happens, the lead sulfate can no longer be converted using conventional charging techniques and the battery's capacity is permanently reduced due to the loss of active material.

Although lead sulfate is a normal product in the discharge / charge cycle of a lead acid battery, subjecting the battery to certain conditions or practices will make the problem of sulfation arise more quickly. By examining equations 1.1, 1.2, 1.3, and 1.4, the two ways that sulfation can occur in a lead acid battery become apparent [3]. If the battery has been discharged to a point where there is mostly lead sulfate present on the battery plates, then it will be difficult to convert all of the lead sulfate back to lead and lead oxide during the recharge process. Although an excessively discharged battery, less than 10% capacity remaining, is more susceptible to the effects of sulfation, leaving any lead-acid battery in a discharged state for an extended period of time will produce sulfation [3]. Equations 1.1 and 1.2 also show how excessive discharge can lead to cell reversal, a condition where the polarity of the battery's individual cells reverse. Also, if the battery has not been recharged completely, thereby leaving a small amount of lead sulfate present on the plates, this lead sulfate will harden over time and become chemically inactive and thereby reducing the overall quantity of active material within the battery. Although there are many reasons for lead sulfate to remain on the plates after recharge, two of the most preventable ones are when a user removes a battery from the charger before it has completely recharged and when a user uses an improper charging technique to recharge the battery.

1.3 Review of Technical Literature

One possible method to reverse the effects of sulfation is to use a pulsed current source to charge the lead-acid battery [3, 8]. Although several commercially available pulse-charging systems exist, such as the “RediPulse Charger” from PulseTech Products Corporation, there have been very few independent tests done to prove their effectiveness [4, 5]. In addition to the lack of independent tests of pulse chargers, there are no published papers dealing with the design parameters of pulse chargers. Most of the information obtained regarding the design of the pulse charger was obtained from relevant patents [11, 12, 13, 14, 15, 16, 17, 18, 19]. While some research has been done with regards to pulse charging techniques, a large portion of this research has dealt with rapid charging of lead-acid batteries [9, 10].

Currently, there are two groups of devices that claim to reverse the effects of lead acid battery sulfation. One group consists of those devices that do not charge the battery but instead apply a pulsed current ranging from a few milliamps up to one amp. They are generally referred to as pulse rejuvenators. These devices are intended to revive the battery and return it to a condition where a conventional constant voltage / constant current charger could be used to recharge the battery to full capacity. The other group consists of devices that are actually battery chargers that use a pulsed current instead of the d. c. constant voltage sources used in conventional chargers. These pulse chargers actually combine the functions of the pulse rejuvenators and conventional chargers into one unit.

Chapter 2: Statement of Problem

A pulse charger and experimental procedure will be developed to determine if pulse charging is useful in reversing the effects sulfation and improving a lead-acid battery's overall condition. The pulse charger parameters will be determined using average parameter values from commercially available pulse chargers and pulse rejuvenators.

Once a pulse charger has been built and tested, charge / discharge tests will be run on several lead-acid batteries of various ages and conditions in order to determine the effectiveness of pulse charging as compared to conventional constant voltage / constant current charging. The test batteries that will be used are Optima "Red Top" Model 800S Absorbed Glass Matt (AGM) lead-acid batteries.

This research will attempt to answer two basic questions regarding pulsed current charging.

- Is pulse charging effective in improving the condition of lead-acid batteries that are in a condition that is significantly lower than that of new lead-acid batteries?
- If pulse charging did not restore the battery, is the battery's discharge test time, internal impedance, or no-load terminal voltage any worse after having been subjected to this type of charging?

Chapter 3: Pulse Charger Design

3.1 Introduction to Pulse Charging

Pulse charging is a process of charging a battery with a current that alternates between the desired charging current, I_{CHRG} , and zero. This differs from standard ‘off-the-shelf’ battery chargers that provide a non-controlled charging current. Example outputs from each type of charger are shown in Figures 3.1 and 3.2.

Figure 3.1: Example of the charging current from a basic pulse charger operating at 1 kHz.

Figure 3.2: Example of the charging current from a standard 'off the shelf' charger.

Although the current from the pulse charger is shown as rectangular pulses, the output waveform can be any shape as long as the current goes to zero for some portion of the oscillation period. Other parameters for the description of the pulse charger output waveform can also be varied from those shown in Figure 3.1. Some of these other parameters are pulse frequency, current amplitude, and pulse duty cycle.

The amplitude of the output current from a standard 'off-the-shelf' charger can also vary from that shown in Figure 3.2. By examining the output current of the standard charger, it appears that the charging current is also pulsed into the battery. However, these current pulses are uncontrolled. They are simply the result of the standard charger using unfiltered unregulated full-wave rectified AC line current as the source of charging current.

3.2 Design Requirements

To test how effective pulse charging is in rejuvenating lead-acid batteries in various conditions, certain parameters of the pulse charger itself needed to be determined before the design and construction of the charger could take place.

3.2.1 Output Waveform Specifications

The following list consists of the design criteria related to the output waveform of the charger. The list includes all the required information to construct the output waveform along with a brief discussion regarding the reasons for each choice. The output waveform consists of a charge pulse, a discharge pulse, a rest period between the charge pulse and the discharge pulse, and a rest period between the discharge pulse and the charge pulse of the next cycle.

- Pulse Frequency (f_p) = 1 kHz

The few pulse chargers that are commercially available use a pulse frequency ranging from a few hertz to 20 kHz. There was no one pulse frequency that all manufacturers and patent holders agreed upon. The decision to use 1 kHz was made based on the fact that this was the highest frequency that the PIC16F877 Microcontroller could provide and still perform other required functions.

- Charge Pulse Time (t_{CHRG}) = $0.2 * f_p^{-1} = 200\mu\text{s}$

A 20% duty cycle was selected in order to achieve the longest possible charge time while leaving enough time to fit in a substantial rest period before a discharge pulse was applied to the battery.

- Rest time between charge pulse and discharge pulse (t_{OFF1}) = $0.6 * f_p^{-1} = 600\mu s$
- Discharge Pulse Time (t_{DCHRG}) = $0.1 * f_p^{-1} = 100\mu s$

Since the length of the discharge pulse was unimportant a 10% duty cycle was selected since this was the minimum time required by the microcontroller to turn on the discharge pulse, read two analog voltages, and then turn off the discharge pulse.

- Rest time until next charge pulse (t_{OFF2}) = $0.1 * f_p^{-1} = 100\mu s$

A second rest period was added to the charger waveform to allow time for the discharge current to turn off before the charge pulse was again applied to the battery.

- Charge Pulse Rise Time (t_{RCP}) = $1\mu s$ or less

The pulse rise time is the one parameter that most manufacturers and patent holders agreed upon. All relevant information that was examined stated that the charge pulse should have as fast a rise time as possible. A time of $1\mu s$ was selected because this was the fastest that could be produced using reasonably priced components and not needing special printed circuit board layouts.

- Charge Pulse Fall Time (t_{FCP}) = $50\mu s$ or less

This is one of the parameters than no one can agree on. A time of $50\mu s$ was selected as a value that could be achieved without special components.

- Discharge Pulse Rise Time (t_{RDP}) = $1\mu s$ or less.

The discharge pulse's rise and fall times were selected for the same reasons that the charge pulse's rise and fall times were selected.

- Discharge Pulse Fall Time (t_{FDP}) = $50\mu s$ or less

The discharge pulse's fall time was one of the most critical design criteria that had to be met. The discharge pulse had to be completely turned off by the time the next charge pulse was applied to the battery or excessive current could flow from the external power supply through the charge pulse controller and discharge resistor.

- Maximum Charge Voltage ($V_{\text{CHRG_MAX}} = 40$ Volts

Both the maximum charge voltage and the maximum charge current were set by the use of the external power supply.

- Maximum Charge Current ($I_{\text{CHRG_MAX}} = 60$ Amps
- Maximum Discharge Current ($I_{\text{DCHRG_MAX}} = 0.1 * I_{\text{CHRG}}$

It was decided that the maximum discharge current should be no more than 10% of the charging current. The battery will still have a net charging current of up to 90%. The prototype pulse charger actually has a discharge current that is about 2% of the charging current.

3.2.2 Embedded Computer Requirements

With the requirements for the output waveform of the pulse charger determined, the next set of design criteria needed relates to generating the specified waveform itself. These criteria are listed below.

- The waveform will be generated using a software control algorithm to minimize stability problems and increase frequency accuracy.
- Required external data that will be needed to monitor and control the output waveform:

- Battery voltage at the end of the first rest period. This voltage will be referred to as the battery open-circuit voltage (V_{BOC}). V_{BOC} is required to make the battery impedance calculation and to assist in the determination of the battery's state of charge.
- Battery voltage during the period when the charge pulse is on. This voltage will be referred to as the battery charging voltage (V_{BCHRG}).
- Battery voltage during the period when discharge pulse is on. This voltage will be referred to as the battery discharge voltage (V_{DCHRG}). The value of V_{DCHRG} along with V_{BOC} are used to calculate the battery's internal impedance. V_{DCHRG} is also used to assist in the determination of the battery's state of charge.
- Charging Current (I_{CHRG}). The value of I_{CHRG} and V_{BCHRG} are used to give the user information on how the pulse charger is charging the battery.
- Discharge Current (I_{DCHRG}). The value I_{DCHRG} is displayed to provide the user with information regarding the battery's ability to supply current.
- Charging Current Power Supply Voltage (V_{PS}). The power supply voltage needs to be monitored so that adjustments can be made if the charging voltage or charging current become too excessive or if either needs to be increased.
- Charger Internal Temperature (T_{INT}). The internal temperature is monitored so that the charger can be safely shutdown before causing damage to the internal components if the charge current control hardware begins to overheat.

- Any microcontroller used for the control of the charge and discharge pulses will need to have a minimum of 5 analog input pins. The three battery voltages, open-circuit, charge, and discharge, can share one analog input pin since these voltages are read at different times from the same connection point in the circuit.
- Any microcontroller used for the control of the charge and discharge pulses will require a minimum of 18 digital output pins. Since 8-bit digital-to-analog converters are used, the charge and discharge pulse are described by 8 bits each. 2 control bits are required for an analog switch used to .
- Any microcontroller used for the control of the charge and discharge pulses will be required to have built-in hardware support for RS232 serial communications. Using the built-in serial hardware of the microcontroller will simplify circuit design and minimize components. A serial communications capability is required so that the pulse charger's two microcontrollers can communicate with each other.
- Minimum operating speed of the pulse control microcontroller will need to be 20 MHz. This is so that the microcontroller will operate at a speed that will allow it to read analog data and at the same time be able to generate and control the pulse charger's output waveform.

3.2.3 User Interface Requirements

The final set of design criteria deals with the user interface aspect of the pulse charger. These requirements are listed below.

- Any microcontroller used for user interface control will be required to have built-in hardware support for RS232 serial communications.

- Any microcontroller used for user interface control will need to have a minimum of 26 digital I/O pins.
 - 8 pins for LCD display data
 - 6 pins for the LCD and elapsed timer control lines
 - 12 pins for keypad data input
- An LCD with a minimum display capability of 2 lines with 20 characters per line.
An LCD is required so that information regarding the pulse charger's operating parameters can be displayed to the user.
- A 12-key keypad for user input to the pulse charger.
A keypad is required so that the user can modify selected charger settings.
- An elapsed timer capable of keeping track of the elapsed time for a minimum of 24 hours.
A timer is required for the 'Timed Charge' feature of the microcontroller.
- The user interface microcontroller will need to operate at a frequency of 4 MHz.
This is to accommodate the timing requirements of the LCD. Although a faster clock could be used, it would have resulted in wasted clock cycles since the LCD is a much slower device than the microcontroller.

3.3 Design Discussion

To facilitate a clear understanding for the design of the pulse charger, the process will be divided into several sections. Overall, the design of the pulse charger can be divided into a hardware element and a software element. The hardware element can be further divided into three general sections: User Interface, Charge / Discharge Pulse

Control, and Pulse Charger Battery Interface. The block diagram in Figure 3.3 shows the interaction between each of these sections. In addition to the three hardware blocks of

Figure 3.3: Hardware block diagram.

Figure 3.3, several power supplies were designed and built to fulfill the different voltage requirements of the pulse charger's electronic components. The power supplies constructed include a +5 volt supply to power the majority of the charger's electronics, a ± 15 volt supply to power to several operational amplifiers and a Hall-effect current sensor, and a +12 volt supply to provide power to the pulse charger's cooling fans. A more detailed explanation of each hardware block and power supply as well as design information will be provided later in this chapter.

The software for the pulse charger was written in C and compiled using the PIC-C Compiler by Custom Computer Services, Inc of Brookfield, WI. Their website is located at www.ccsinfo.com. Two separate programs were produced, one for the Pulse Control Microcontroller and the other for the User Interface Microcontroller. Flowcharts for the programs and a discussion of the code will be presented in the software section of this chapter.

3.4 Hardware Design

The Charge / Discharge Pulse Control Block of Figure 3.3 contains the primary electronic components for the operation of the pulse charger. This block consists of the microcontroller that generates the digital data used to construct the charge and discharge pulse. Since this microcontroller controls the charge and discharge pulses, it will be referred to as the Pulse Control Microcontroller. The Pulse Control Microcontroller also receives data from several external sensors used in the pulse charger. There are also two digital-to-analog converters that transform the digital data from the microcontroller to an analog signal suitable for amplification by operational amplifiers before the signal is applied to the charging and discharge current switching devices. Communication between the Pulse Control Microcontroller and the User Interface Microcontroller, discussed in a later section, is provided by the use of the microcontroller's built-in serial hardware. The serial hardware supports the RS232 communications protocol and so this will be the protocol used by all serial communications.

3.4.1 Charge / Discharge Pulse Control

The block diagram of Figure 3.4 shows the interactions between the hardware of the Charge / Discharge Pulse Control Block. The Charge / Discharge Pulse Control Block Diagram consists of five individual sub-blocks representing the major functions that are performed with regards to generating and controlling the charge and discharge pulses. To better explain the design of the pulse charger, each block will be examined separately with a detailed analysis of the components performing the functions of the block being discussed. This will also be the format used for subsequent discussions concerning the hardware design procedure.

Figure 3.4: Charge / Discharge Pulse Control Hardware Block Diagram.

The first block that will be examined in more detail is the Pulse Control Microcontroller since it is the central block with which all remaining hardware blocks interact with. The schematic representing the electronic components in this block is shown in Figure 3.5. From the design criteria, it was apparent that the best

Figure 3.5: Schematic for the ‘Pulse Control Microcontroller Hardware Block’

microcontroller to use for U3 was the PIC16F877 from Microchip, Inc., www.microchip.com. The PIC16F877 contains a total of 33 multipurpose I/O pins. It also has eight analog input pins and hardware support for the RS232 communications protocol. Using five of the I/O pins for analog input and two for serial communications leaves 26 pins to be used for general I/O, which was more than sufficient. Other advantages of using the PIC16F877 verses other microcontrollers was the PIC’s tolerance to ‘electrically noisy’ conditions, a minimum amount of required support hardware, and

the ability to run at the required operating frequency of 20 MHz. Support hardware for U3 consists of the two 0.1 μ F power supply bypass capacitors, C3 and C5, the pull-up resistor, R13, which is used for resetting the microcontroller, and the 20 MHz oscillator, X1.

The power used by U3 and X1 is provided by a +5 volt supply. The average supply current, I_{DD} , required by microcontroller U3 during standby mode is 6.5 mA at a supply voltage, V_{DD} , of 5 Volts and frequency of oscillation, F_{OSC} , of 20 MHz. Additional power will be required by U3 for the operation of the Port B, C, D and E I/O pins. Each Port A pin will have draw a maximum operating current of 500 nA for a total Port A current of 2 μ A. Therefore, for the purposes of calculating current capacity of the power supply, the Port A pins will be ignored. Each pin of Port B and Port D will need to source a maximum of 100 μ A, resulting in a total current of 1.6 mA, $I_B = 800 \mu A$ and $I_D = 800 \mu A$. The serial transmit and serial receive pins of U3 will source a maximum of 25 mA and sink a maximum of 25 mA, respectively. Like Port A, the I/O pins of Port E will draw a negligible amount of current from the power supply, on the order of 1 μ A, and so will be ignored for the purposes of calculating the required power supply current capacity. At this point, all of U3's current requirements have been determined. Therefore, the maximum value of I_{DD} is 33.1 mA at worst case. This is given by the following equation:

$$I_{DD} = I_{DD\min} + I_B + I_D + I_{RS232} \quad (3.1)$$

The maximum supply current requirement for the oscillator X1 is 25 mA. Pull-up resistor, R13, is used to limit the reset current to a value less than 1 mA. Consequently, the chosen value of R13 must satisfy the following equation:

$$R13 \geq \frac{V_{DD}}{I_{RESET_MAX}} \quad (3.2)$$

With the value of V_{DD} being set at 5 volts and the value of I_{RESET_MAX} set at 1 mA, it can be seen that the value of R13 must be at least 5 k Ω . By choosing a resistance of 47 k Ω , the current drawn from the power supply when the microcontroller is reset will be no more than 0.1 mA.

At this point, all current requirements for the electronic components of the Pulse Controller Microcontroller Block have been calculated. These requirements are summarized in Table 3.1.

PART IDENTIFIER	POWER SUPPLY	CURRENT REQUIREMENT
U3	+5 Volt	33.1 mA
X1	+5 Volt	25.0 mA
R13	+5 Volt	0.10 mA

Table 3.1: Current requirements summary for the ‘Pulse Control Microcontroller Hardware Block’.

The Analog Charge Pulse Block of Figure 3.4 consists of an 8-bit digital-to-analog converter and a precision rail-to-rail operational amplifier. The schematic for this block is shown in Figure 3.6.

Figure 3.6: Schematic for the ‘Analog Charge Pulse Hardware Block’

The function that the components contained in the Analog Charge Pulse Block perform is to convert the digital charge pulse data from microcontroller U3 of Figure 3.5 into an analog voltage pulse of sufficient amplitude to drive the gate of an N-Channel MOSFET. To convert the digital data to an analog signal a microprocessor compatible digital-to-analog convert (DAC) was selected. The AD557 was selected due to its fast settling time and ease with which it could be incorporated into the circuit design. Although the DAC is microprocessor controllable, this feature was not used due to the lack of a common data bus and the total absence of an address bus in the pulse charger’s hardware design. Because of this, the chip select pin, CS, and the chip enable pin, CE, of U4 in Figure 3.6 have been connected to ground. Also, since U4 is to be operated with a full-range output of 0 – 2.56 volts, the voltage output sensor pins have been tied to V_{OUT} . According to the datasheet for the AD557, the output settling time for U4 is typically 0.8 μ s with an error of $\pm \frac{1}{2}$ LSB. Since the settling time of U4 is much shorter than the

slew rate of the op-amp that is driven, U4's settling time will have a minimal effect on the rise times of the charge and discharge pulses that are eventually applied to the battery.

In order to satisfy the design requirements, it was extremely important that the operational amplifier, U2D, have a high slew rate. Therefore, the op-amp chosen was the OP-484. This op-amp was wired in a non-inverting configuration in order to maintain the input and output voltages in phase. Although the OP-484's slew rate of 4 V/ μ s at a load resistance of 2 k Ω was not as fast as desired, it was sufficient to meet the design criteria. The time required for the OP-484's output voltage to transition from minimum to maximum is given by the following equation:

$$t_{SLEW} = \frac{V_{OUT}}{SlewRate} \quad (3.3)$$

With a desired output voltage from the op-amp of 10 volts, the transition time, t_{SLEW} , will be 2.5 μ s. The reason for an output voltage of 10 volts is that a higher voltage will more quickly charge the gate capacitance of the MOSFET being driven by U2D and, thereby, produce a faster rise time for the charge pulse that is applied to the lead-acid battery. Although the output from U2D will require 2.5 μ s to reach 10 volts, the MOSFET will have turned on by the time the voltage has reached the maximum gate threshold voltage of 4 volts. By substituting a value of 4 for V_{OUT} in equation 3.3, it can be seen that the charge pulse will reach the MOSFET's maximum gate threshold voltage in 1.0 μ s.

In order to obtain the correct output voltage from U2D, its gain needs to be adjusted by controlling the values of resistors R10 and R12 of Figure 3.6. With an input voltage of approximately 2.5 volts and a desired output voltage of 10 volts, the required

ideal gain for U2D is 4. The gain for an op-amp in a non-inverting configuration is given by the following equation:

$$\frac{V_{out}}{V_{in}} = 1 + \frac{R_{10}}{R_{12}} \quad (3.4)$$

By using a potentiometer for resistor R10 the gain can be adjusted to account for component tolerances and give the desired value of 4. With the value of resistor R12 set at 10 k Ω , the ideal value for resistor R10 will be 30 k Ω . A 50 k Ω potentiometer was selected for R10 since this is the closest standard value that is higher than the calculated value of R10. The resistance of R10 is given by the equation below.

$$R_{10} = R_{12} \left(\frac{V_{out}}{V_{in}} - 1 \right) \quad (3.5)$$

Since the AD557 DAC, U4, is a low power device, the maximum operating current required from the +5 volt supply is 15 mA. The required output current from the U4 is negligible since its output is connected to the input of the op-amp U2D. The maximum operating current for U2 is 250 μ A in addition to any sourcing currents from the four individual op-amps contained in the complete IC. The output current of U2D is 1 mA, which is calculated by dividing the output voltage by the load resistance. The output voltage is 10 volts and the load resistance is approximately 10 k Ω . U2's supply current will be provided by the +15 volt supply. Table 3.2 summarizes the current

requirements for the Analog Charge Pulse Block and will be used in the power supply design section later in this chapter.

PART IDENTIFIER	POWER SUPPLY	CURRENT REQUIREMENT
U2 + U2D	+15 Volt	1.25 mA
U4	+5 Volt	15.0 mA

Table 3.2: Current requirements summary for the ‘Analog Charge Pulse Hardware Block’.

The Analog Discharge Pulse Block of Figure 3.4 consists of an 8-bit digital-to-analog converter and a precision rail-to-rail operational amplifier. The schematic for this block is shown in Figure 3.7. Since the Analog Discharge Pulse Block contains the same electronic components as the Analog Charge Pulse Block and must satisfy the same design requirements, only a brief description of the operation and design will be provided.

Figure 3.7: Schematic for the ‘Analog Discharge Pulse Hardware Block’

The only difference between the Analog Discharge Pulse Block and the Analog Charge Pulse Block is the op-amp's output current. Since the op-amp of the discharge block connects directly to the gate of the discharge pulse MOSFET, only a small gate leakage current will be required from the op-amp. According to the datasheet for the MOSFET, the gate leakage current, both forward and reverse, will be no more than 100 nA. Because less output current is required from the op-amp and U2's operating current has already been accounted for in Table 3.2, the overall power requirements for this block are lower than those of the Analog Charge Pulse Block as can be seen in Table 3.3.

PART IDENTIFIER	POWER SUPPLY	CURRENT REQUIREMENT
U5	+5 Volt	15.0 mA

Table 3.3: Current requirements summary for the 'Analog Discharge Pulse Hardware Block'.

The Analog Switch Block in Figure 3.4 takes the single current sensor output signal and splits it into a charging current data signal and a discharge current data signal. While separate signals are not required for the direct operation of the pulse charger, they were needed for the LabView interface feature that has been included. Microcontroller U3 will control the analog switch since it will collect and process the data regarding at what times the current sensor output contains charging current data and at what times the sensor output contains discharge current data. The analog switch that was used is a CD4067 Analog Multiplexer / Demultiplexer. The schematic for the Analog Switch Block is shown in Figure 3.8. Since only 2 of the 16 outputs are required address lines, S1, S2, and S3 of U6 are unused and so have been connected to ground. The remaining

Figure 3.8: Schematic for the ‘Analog Switch Hardware Block’

address pin, S0, is used to control the selected output pin. Whenever address line S0 is low the signal on the input pin, CI/O will be connected to output pin I0. When S0 is high, the signal on CI/O will be connected to I1, assuming that U6 is enabled by placing a low signal on pin 15. If the enable pin is high, then the input of U6 is disconnected from all output pins.

To pass the input signal through U6 to one of its outputs results in a maximum propagation delay of 650 ns. A maximum propagation delay of 440 ns results when the any output of U6 is disconnected for the input. Since these delays are much shorter than the 1 ms delays that are imposed by the LabView VI used read the pulse charger’s analog data signals, they will be ignored. It will be assumed that U6’s input is instantaneously connected to and disconnected from its outputs. U6’s operating power requirements are given in Table 3.4.

PART IDENTIFIER	POWER SUPPLY	CURRENT REQUIREMENT
U6	+5 Volt	0.15 mA

Table 3.4: Current requirements summary for the ‘Analog Switch Hardware Block’.

The Pulse Charger Internal Temperature Sensor Block of Figure 3.4 is made up of a temperature sensor and an op-amp to amplify the sensor’s output signal. The schematic for this block is shown in Figure 3.9. The LM35 Precision Centigrade Temperature Sensor was selected because of its ease of use. Using the LM35 in the basic configuration shown in Figure 3.9, the output of U9 will be a voltage that is directly

Figure 3.9: Schematic for the ‘Pulse Charger Internal Temperature Sensor Hardware Block’

proportional to the temperature on the surface of the device. The output voltage and temperature is given by the following equation:

$$T = \frac{V_{OUT}}{0.01} \quad (3.6)$$

The temperature given by equation 3.6 will be in degrees Celsius. The valid sensed temperature range for U9 is from 2 °C to 150 °C. Using equation 3.6, an output voltage range of 0.02 volts to 1.5 volts is obtained. To increase the conversion resolution, U9's output voltage will be amplified to a maximum of 5 volts. If U9's output voltage was 1.5 volts and not amplified, the minimum temperature change, ΔT_{MIN} , that can be detected by the microcontroller using 10-bit analog-to-digital conversion is 0.490 °C. By amplifying the output voltage of U9 to make use of the full input voltage range of 0 – 5 volts, the microcontroller can detect a temperature change as small as 0.147 °C. The equation shown below was used to determine the value of ΔT_{MIN} .

$$\Delta T_{MIN} = \frac{T_{MAX}}{V_{OUT} \left(\frac{1023}{5} \right)} \quad (3.7)$$

The value V_{OUT} in equation 3.7 is the output voltage from U9 and the value of T_{MAX} is the maximum temperature to be sensed.

Signal noise is also a reason to amplify U9's output. When the output voltage from U9 is amplified, its signal-to-noise ratio is increased. This assumes that any noise that may interfere with the desired signal is added after the amplification stage. The chances of signal noise being introduced prior to amplification are reduced by placing the amplifier as close as possible to the output of U9.

To obtain an output voltage of 5 volts from U1A with an input voltage of 1.5 volts, U1A's gain needs to be adjusted by controlling the values of resistors R1 and R5 of Figure 3.9. The required gain for U1A is approximately 3.33. By using a potentiometer for resistor R1, the gain can be precisely adjusted to provided an output of 5 volts with an input voltage of 1.5 volts. Using a resistor with a 1% tolerance for R5 and a value of 28 kΩ, the ideal value for resistor R1 is approximately 65.33 kΩ. A 100 kΩ potentiometer was selected for R1 since this is the closest standard value that is higher than the calculated value of R1. The resistance of R1 is given by the following equation:

$$R_1 = R_5 \left(\frac{V_{OUT}}{V_{IN}} - 1 \right) \quad (3.8)$$

The output current of the temperature sensor, U9, depends on the temperature of the surrounding environment. For the purpose of calculating power supply current requirements, U9's maximum output current of 10 mA will be used. The maximum operating current for U1 will be 0.25 mA. Output current from U1 will be limited to the leakage currents associated with the analog inputs of the microcontroller. The maximum power requirements for the Pulse Charger Internal Temperature Sensor Block are summarized in Table 3.5.

PART IDENTIFIER	POWER SUPPLY	CURRENT REQUIREMENT
U1	+5 Volt	0.25 mA
U9	+5 Volt	10.0 mA

Table 3.5: Current requirements summary for the 'Pulse Charger Internal Temperature Sensor Hardware Block.

3.4.2 Pulse Charger to Battery Interface

The Pulse Charge Battery Interface Block of Figure 3.3 contains the hardware required to interface the low power control signals from the Charge / Discharge Pulse Control Block to the electronic components used to control the charge and discharge current. The components that make up the sensors that monitor all battery related voltages and currents are also contained in this block. The block diagram of Figure 3.10 shows the connections between the hardware contained in the Pulse Charge Battery Interface Block.

Figure 3.10: Pulse Charger to Battery Interface Hardware Block Diagram

The External High Voltage / High Current Power Supply Block of Figure 3.10 is a Sorenson DCR40-60A constant voltage / constant current regulated power supply. The DCR40-60A has over-voltage, over-current, and thermal protection circuitry. It is used to provide the charging current to the battery.

The Battery Block of Figure 3.10 consists of the lead-acid battery that is being charged. All batteries that will be charged during this research will be 12 volt Optima “Red Top” Model 800S Absorbed Glass Matt (AGM) lead-acid batteries.

The Power Supply Voltage Sensor Block in Figure 3.10 contains a resistive voltage divider circuit. The schematic for this block is shown in Figure 3.11. The nominal maximum external power supply voltage is 40 volts. To provide a margin of safety against a higher than normal output voltage from damaging the microcontroller that the sensor output is connected to, it is assumed that the maximum external power supply voltage is 50 volts for design purposes. The voltage divider that is formed by resistors R32 and R33 in Figure 3.11 scales the power supply voltage range of 0 – 50

Figure 3.11: Schematic for the ‘Power Supply Voltage Sensor Hardware Block’

volts down to a range of 0 – 5 volts. Therefore, the sum of the resistances of R32 and the upper portion of potentiometer R33 will need to have a voltage drop of 0.9 times the external power supply voltage and the resistance of the lower portion of R33 will need to drop 0.1 times the external power supply voltage. Another important factor in determining the resistor values is that the voltage sensor should have a minimal current drain from the power supply. It was determined that the sensor should draw less than 1 mA from the power supply while, at the same time, the resistors should not be so large that any noise that may be present in the signal could inundate the desired current flow in the resistors and result in false voltage measurements. Also, the effective output impedance of the voltage sensor needed to be less than 10 k Ω , in order to satisfy the requirement that any component connected to any of the microcontroller's analog inputs have an output impedance of less than 10 k Ω . Using the following equation,

$$V_{out} = \frac{V_{dd} (R_{33B})}{R_{32} + R_{33A} + R_{33B}} \quad (3.9)$$

it was determined that the resistance between the power supply voltage input and the sensor output should be 9 times the value of R_{33B}. A total resistance of no more than 100 k Ω was also chosen. Using standard 1% tolerance resistors, a 20 k Ω potentiometer was selected for R33 and a 71.5 k Ω resistor for R32. Referring to equation 3.9, the wiper position of R₃₃ should be set so that the lower portion's resistance, R_{33B}, is 9.15 k Ω .

The Battery Voltage Sensor Block in Figure 3.10 is also made up of a resistive voltage divider circuit consisting of a fixed resistor and a potentiometer. The schematic for this block is shown in Figure 3.12. This voltage sensor had two conflicting design

Figure 3.12: Schematic for the ‘Battery Voltage Sensor Hardware Block’

constraints with regards to the selection of the resistor values. First, the microcontroller’s source impedance restriction of less than 10 k Ω had to be adhered too. Second, the values for resistors R34 and R35 needed to be large enough so that very little of the charging current would flow through them. For the selection of resistors R34 and R35, it was determined that their the total resistance should be approximately 10,000 times greater than the highest battery impedance that could be expected to minimize their effect on the lead-acid battery. By choosing a total resistance between 900 k Ω and 1 M Ω , the battery’s impedance could be between 90 Ω and 100 Ω . The voltage divider formed by resistors R34 and R35 in Figure 3.12 scales the charging voltage to a range of 0 – 5 volts. Because the maximum charging voltage of 50 volts had already been determined and a maximum sensor output voltage of 5 volts was required, the exact resistor values had to be chosen to provide a scaling factor of 1/10. By choosing resistor values that were 10 times larger than the power supply voltage sensor resistors and referring to the calculations for power supply voltage sensor, it is simple to see that the resistance between R35’s wiper arm and ground would need to be set at 91.5 k Ω . Also, the total

sensor resistance of 915 k Ω limited the current drain from the power supply to a maximum of 54.6 μ A which is insignificant when the total current output from the supply could be as high as 60A.

By choosing such high resistances for R34 and R35 results in an approximate sensor output impedance of 91.5 k Ω . Since this is much greater than the required maximum of 10 k Ω , something was needed to reduce to sensor's output impedance to below 10 k Ω . The chosen solution was to use an operational amplifier wired in a voltage follower configuration. This can be seen in Figure 3.12. When an op-amp is used as a voltage follower, the output voltage will follow the input voltage with no amplification - hence, the name: voltage follower. Using a supply voltage of +15 volts, an operating frequency of less than 1 kHz, a gain of 1, and referring to the datasheet for the OP484 op-amp, it was determined that the new output impedance of the battery voltage sensor is less than 1 Ω , which is definitely less than 10 k Ω .

The Battery Current Sensor Block in Figure 3.10 consists of a Honeywell CSNA111 Hall-Effect Current Sensor and a ½ watt output resistor. The schematic for this block is shown in Figure 3.13. In designing the battery charger, it was determined that data for two current values would be needed, the charge and discharge currents. To accommodate the collection of the required current values, two solutions were examined. The first possible solution was to use two separate Hall-effect sensors. However, this was rejected due to sensor cost. The second solution, which was chosen, was to run two wires through the same current sensor. This was possible because only one of the wires will be conducting current at any one time. The microcontroller that the sensor output is connected to will be able to distinguish between the charge current and discharge

Figure 3.13: Schematic for the 'Battery Current Sensor Hardware Block'

current values because the microcontroller will have information regarding which pulse is turned on at the time. If the microcontroller is sending charge pulse data, then the current sensor is sending charge current data. If the microcontroller is sending discharge pulse data, then the current sensor is sending discharge current data. Even through the current sensor, S1 of Figure 3.13, is capable of both positive and negative output voltages, it is desired that the output from the sensor only consist of positive voltages. This is so that the sensor output can be connected directly to the microcontroller without the need for intermediate circuitry to convert any negative voltages to positive voltages. To accomplish a positive-only output from the current sensor, the wires were run through the sensor in such a way so that the current in each wire flowed in the same direction.

The value of resistor R36 in Figure 3.13 was chosen so that the sensor output current at the maximum sensed current would produce a voltage drop as close to but less than 5 volts. Referring to the datasheet for the CSNA111, the output current from the

sensor is 1 mA for each amp of sensed current. Since the maximum charging current was set at 60 amps, it can be seen that the maximum output current from the sensor will be 60 mA. The discharge current will be much lower than the charge current so it was not used to determine the value of R36. Because the analog input on the microcontroller does not draw any current other than small leakage currents, all of the sensor's output current will flow through R36. Using the following equation and substituting 5 for V_{MAX} and 0.06 for

$$R_{36_MAX} = \frac{V_{MAX}}{I_{OUT}} \quad (3.10)$$

I_{OUT} , it was determined that the resistance of R36 could be no greater than 83.33 Ω .

Therefore, a 82.5 Ω 1% resistor was selected for R36. Using the nominal resistance of 82.5 results in an output voltage from S1 of 4.95 volts. Since this is very close to the maximum input voltage of the microcontroller, the upper tolerance limits for R36 and S1 were examined to determine if the voltage could possibly go over 5 volts. The tolerance for S1 is $\pm 0.5\%$. Using the following equation where the value of I_{NOM} is the nominal

$$V_{OUT} = 1.005(I_{NOM}) * 1.01(R_{36}) \quad (3.11)$$

output current from S1 and the value of R36 is its nominal resistance value, it was determined that at worst case the output voltage from the current sensor will be 5.02 volts.

The CSNA111 current sensor requires operating power from a ± 15 volt power supply. The sensor draws a primary operating current of 10 mA. There is also a

secondary current of up to 60 mA. The secondary current will vary according to the sensed current with a relationship of 1 mA of secondary current for every amp of sensed current.

The next two blocks of Figure 3.10 to be examined will be the Charge Current Switch Block and the Battery Charger Cables Block. They are being discussed together since both contribute to the total charge path resistance. The schematic for both blocks is shown in Figure 3.14. The Battery Charger Cables Block consists of an equivalent resistor, R_{cable} , representing to total resistance of the cable connecting the battery to the charger.

Figure 3.14: Schematic for the ‘Battery Charge Current Hardware Block’ and ‘Battery Charger Cables Hardware Block’

The charging current is switched on and off by turning the P-Channel MOSFETs, Q1 – Q3, on and off. The gate voltages for Q1 – Q3 are derived from the external power supply voltage, Vdd. The gate voltage level is controlled by turning Q4 on and off and by a resistive voltage divider consisting of resistors R29 and R30. To turn Q1 – Q3 on, their gate-to-source voltage must satisfy the following equation:

$$V_{GS} \leq V_{GS(th)} \quad (3.12)$$

At any time when equation 3.12 is not satisfied, Q1 – Q3 will be off and not conducting current. To turn Q4 on, its gate-to source voltage must satisfy the following equation:

$$V_{GS} \geq V_{GS(th)} \quad (3.13)$$

Otherwise, it will be off and not conducting current. When Q4 is turned on by applying a gate voltage that satisfies equation 3.13, current will flow through resistors R29 and R30. The voltage applied to the gate terminals of Q1 – Q3 will then be more negative than Vdd, which is applied to the source terminals of Q1 – Q3, due to the voltage drop across R29. When Q4 is turned back off, no current will flow through resistors R29 and R30 and Q1 – Q3's gate voltage will return to the level of Vdd. This will then violate equation 3.12 and Q1 – Q3 will turn off, allowing no further charging current to flow to the battery.

The values of resistors R29 and R30 were chosen so that the gate voltages of Q1 – Q3 are sufficiently negative to turn the P-Channel MOSFETs on when Vdd is equal to 13

volts and Q1 – Q3’s gate-to-source voltages are less than 20 volts when V_{DD} is equal to 40 volts. Resistors 29 and R30 also had to be small enough to allow sufficient current to flow to the gate terminals of Q1 – Q3 so that the maximum gate charge, Q_G, of 180 nC could charge as quickly as possible. Also, the resistors had to be large enough to keep an excessive amount of current from flowing through Q4, reducing the available current to charge the battery.

The gate voltages of Q1 – Q3 are determined by the resistances of R29 and R30. Referring to the datasheet for the IRF5210, the maximum gate-to-source threshold voltage is –4 volts. This means that the gate must be at least 4 volts more negative than the source before it is certain that the MOSFET has turned on. Although the gate-to-source voltage can be as high as 20 volts, it is undesirable to operate at that level. Therefore, it was decided that the gate-to-source voltage should never go above 15 volts. Using the equation below and setting the values of V_{GS} to 4 volts and V_{DD} to 13 volts, it

$$R_{30} = \left[\frac{V_{DD}}{V_{GS}} - 1 \right] (R_{29}) \quad (3.14)$$

can be seen that the value of R30 must be approximately 2.25 times the value of R29.

Using equation 3.14 again and this time setting the values of V_{GS} to 15 volts and V_{DD} to 40 volts, it can be seen that the value of R30 must be approximately 1.67 times the value of R29. Therefore, to satisfy both conditions simultaneously the value of R30 must satisfy the inequality of equation below.

$$1.67 \leq R_{30} \leq 2.25 \quad (3.15)$$

The value of $R_{DS(on)}$ for Q4 was ignored since it is much smaller than any potential resistor values.

Resistors R29 and R30, in addition to providing a voltage divider function, must also allow sufficient current to flow in order to quickly charge to gate capacitances of Q1 – Q3, thereby turning off the MOSFETs. According to the IRF5210 datasheet, each MOSFET requires a maximum gate charge of 180 nC to switch a drain current, I_D , of 21 amps with a drain-to-source voltage, V_{DS} , of 80 volts and a gate-to-source voltage, V_{GS} , of 10 volts. As a general rule, the value of V_{DS} when Q1 – Q3 are switched off will be between 25 and 30 volts, assuming that a battery is connected to the charger with a terminal voltage between 10 and 15 volts. Referring to Figure 3 contained in International Rectifier's Application Note AN-944, it can be seen that a higher gate charge, Q_G , will be required before the MOSFET can turn off as V_{DS} increases. To complicate matters even further, it can be seen that the relationship between I_D , V_{DS} , and Q_G is not linear. A doubling of the drain current does not produce a doubling of the required gate charge. Faced with this dilemma and aware of the fact that the turn-off time of Q1 – Q3 would only effect the falling edge of the charge pulse, it was decided that the gate current should be between 100 mA and 400 mA. The 400 mA upper limit was selected since this was approximately as large a current that could be safely carried through a 2 watt resistor. The gate charge time would later be calculated from the completed circuit and adjustments made, if needed. Using this current range, the relationship given by equation 3.15, and a table of standard resistors available in power

ratings of 2 watts, it was decided that R29 should be 75 Ω and R30 should be 130 Ω .

Wire-wound type resistors were first selected for R29 and R30, but were later changed to carbon-type resistors. After the circuit was built, it was determined that the inductance of the wire-wound resistors was sufficiently large to cause MOSFETs Q1 – Q3 turn-off time to be extended beyond an acceptable limit. Examining the graph of Q1 – Q3's source-to-drain voltage in Figure 3.15, it can be seen that the time required for the voltage to rise for 0 volts to a constant level of approximately 1 volt is 160 μ s. By replacing the wire-wound resistors with carbon resistors, the problem of the resistor's inductance has been minimized. Figure 3.16 shows the improvement when carbon resistors are used instead of wire-wound resistors. The time required for the voltage to rise for 0 volts to a constant level of approximately 1 volt is now 60 μ s.

As stated earlier, the gate charge time calculations were difficult to make using only the datasheet information. To determine if the chosen values for R29 and R30 would satisfy all design criteria, measurements were made in order to produce a graph of the actual turn-off time of the P-Channel MOSFETs. It was determined that the longest turn-off time would result when the external power supply voltage, V_{PS} , was at its minimum value. This would, also, correspond to a minimum gate drive current flowing through resistors R29 and R30.

Referring to Figure 3.17, it can be seen that at point A Q4 has completely turned off thus allowing Q1 – Q3's gate voltages to start to rise. From point A to point B the P-Channel MOSFET's gate capacitances as well as several undetermined parasitic capacitances are charging. The time required for these capacitances to charge is 78 μ s.

Charge-Discharge Pulse Relationships Using Wire-Wound Resistors for R29 & R30

Charge-Discharge Pulse Relationships Using Carbon Resistors for R29 & R30

MOSFET Turn-off Time
R29 = 75 R30 = 130 Fp = 1kHz Vps = 12V

Since the supply voltage is set at 12 volts, the resulting gate drive current is $12 / (R29 + R30)$ or 58.537 mA. Using the relationship between charge and current given by the following equation,

$$i = \frac{dq}{dt} \quad (3.16)$$

the total charge, C_{TOTAL} , consumed during the period between points A and B of Figure 3.17 is 4.566 μC .

The time required to turn on Q1 – Q3, as well as MOSFETs Q4 – Q6, is controlled extensively by the internal drain inductance, L_D , and the internal source inductance, L_S , of the MOSFETs. Since the switching frequency is relatively low, 1 kHz, the inductances have very little effect on turn-on time. Thus, all MOSFETs in this application can be assumed to turn on instantaneously.

The last part of the design process relating to Q1 – Q3 and Q4 is the required size of the heat sinks. Starting with the P-Channel MOSFETs Q1 – Q3 and referring once again to the IRF5210 datasheet, two parameters relating to thermal resistance are examined. They are the junction-to-case thermal resistance, $R_{\theta JC}$, which has a maximum value of 0.75 $^{\circ}C/W$, and the case-to-sink thermal resistance, $R_{\theta CS}$, with a typical value of 0.5 $^{\circ}C/W$. Additionally, to calculate the maximum thermal resistance of the heat sink, the power dissipated by the device must be known. The maximum peak charging current will be 60 amps with a duty cycle of 0.2, which corresponds to an average of 12 amps. Since the 12 amps will be shared equally between Q1 – Q3, each MOSFET will conduct an average maximum of 4 amps of current. When Q1 – Q3 are turned on, they will have

a maximum drain-to-source resistance, $R_{DS(ON)}$, of 0.06 Ω . Therefore, each MOSFET will dissipate a maximum average power, P_{DAVG} , of 0.96 watts and a maximum peak power, P_{DPEAK} , of 8.64 watts. Assuming a maximum ambient temperature, T_A , of 38 °C and a desired junction temperature, T_J , of no more than 125 °C, enough information is now known to calculate the maximum thermal resistance, $R_{\theta SA}$, of the heat sink. Using the following equation,

$$R_{\theta SA} = \frac{T_J - T_A}{P_{DPEAK}} - (R_{\theta JC} + R_{\theta CS}) \quad (3.17)$$

the heat sink that is required for Q1 – Q3 can have a thermal resistance no greater than 8.8 °C/W. The heat sink requirements for MOSFET Q4 are much lower since it conducts a maximum current of 195 mA. Referring to the datasheet for the IRF3710, the values of $R_{\theta JC}$ is 0.74 °C/W, $R_{\theta CS}$ is 0.5 °C/W, and $R_{DS(ON)}$ is 0.023 Ω . Assuming the same temperature conditions of Q1 – Q3 and using equation 3.17, it can be seen that Q4 will not require a heat sink since the junction-to-ambient thermal resistance, $R_{\theta JA}$, of the TO-220 package style has a maximum value of 62 °C/W which is sufficient to provide the required cooling.

Looking back at Figure 3.14, diode D1 is used to provide protection against an over-voltage condition caused by a failure of Q4. If the drain-to-gate junction of Q4 were to break down, then a voltage as high as 40 volts could be applied to the output of the preceding component. This condition would most likely result in its failure. By adding a diode, this cause for failure can be eliminated. If Q4 were to fail, then D1 would become reversed biased, allowing no current flow back into the devices of the preceding sections.

Because of the presence of D1, a pull-down resistor, R31, was required to insure that Q4's gate would never be in a floating condition. Such as the case when the desired gate voltage is below the junction voltage of D1. In this case, D1 would effectively be reversed biased and no current would flow to Q4 to charge its gate capacitance.

Lastly, the resistance of the cables, R_{CABLE} , connecting the pulse charger to the battery was calculated for two reasons. First, it was desired that the cables have a minimum voltage drop when carrying maximum current to the battery. This allowed more efficient charging since most of the power provided by the pulse charger would actually be delivered to the battery terminals. The second reason for calculating the resistance of the cables was so that the required cable size could accurately be ascertained to satisfy the minimum voltage drop requirement. Knowing that the cable length from the interior of the pulse charger to the battery terminals would be approximately 3 meters per conductor for a total cable length of 6 meters and that copper wire would be used, the value of R_{CABLE} could be calculated. Using the following equation,

$$R = \frac{l}{\sigma S} \quad (3.18)$$

where σ is the resistivity of copper and S is the cross-sectional area of the conductor, it was determined that 8 AWG wire would be the best size to use for the cables. The resistance of 8 AWG wire is 0.0020583 Ω /m. This results in a total cable resistance of 0.01235 Ω . At the maximum current of 60 amps, the cable will have a voltage drop of 0.741 volts, which was deemed to be acceptable. 10 AWG wire would have had a maximum voltage drop of 1.182 volts. It was felt that this amount of voltage drop would

have been too great and would have reduced the charger's ability to provide power to the battery. 6 AWG wire would have had a lower voltage drop, but would have introduced problems in making connections inside the charger due to its physical dimensions.

3.4.3 User Interface

The final block in Figure 3.3 is the User Interface Block. It contains all necessary hardware to provide the user interaction features of the pulse charger. A 12-key keypad was used to acquire user input to the charger. This keypad is a generic non-matrix type which means that one data line is required for each key. Therefore, if all twelve keys are used, then the microcontroller must have twelve available data input pins. Information regarding the operation of the pulse charger is displayed to the user using an Optrex DMC-20261 20x2 LCD. The LCD requires eight data lines and three control lines. Both the keypad and LCD are controlled by a second PIC16F877 microcontroller. The microcontroller receives data from two sources. One source is provided directly from the user via the 12 data inputs from the keypad. The second source, which consists of the battery voltage data, battery current data, and MOSFET temperature data, is received from the Pulse Control Microcontroller over the two serial communication wires connecting the two microcontrollers together. Figure 3.18 shows the relationship between the hardware making up the User Interface Block.

The LCD Block of Figure 3.18 contains only one part, the DMC-20261 LCD. The operation of the LCD is straight forward as long as the initialization procedure given in the datasheet is precisely followed and all timing requirements are met. For more

information regarding the initialization procedure, refer to the source code in section C.1 of Appendix C. The LCD is controlled by three I/O pins, the Enable Pin, which turns

Figure 3.18: User Interface Hardware Block Diagram.

the entire LCD on and off, the RS pin which selects the instruction register of the LCD if low or the data register if high, and the R/W pin which allows data to be written to the LCD if low or read from the LCD if high. The 8-bit data mode of the LCD was used to simplify the LCD related software functions. This allowed each 8-bit instruction of character data to be sent to the LCD at once. However, using the 8-bit mode also requires more I/O pins from the microcontroller. Since the additional I/O pins were available, it was decided that the trade-off between software simplicity and circuit complexity was warranted.

Using the LCD is relatively easy since all control hardware for the display device is built into the LCD module. The schematic for the few external pieces of hardware is shown in Figure 3.19. Resistor Rext2 provides a variable LCD drive voltage, V_D , for the

LCD. By varying the drive voltage, the contrast between the displayed characters and the background can be adjusted. The value of Rext2 was arbitrarily chosen since the current requirements are insignificant. Its only purpose is to provide a variable voltage between

Figure 3.19: Schematic for the ‘LCD Hardware Block’

4.4 and 5.0 volts. No steps were taken to insure that the drive voltage does not go below 4.4 volts since the only effect of a lower voltage would be the inability to read the displayed text. Also, no temperature compensation circuitry was designed since the charger would be primarily operated in a temperature-controlled environment. If the charger is operated in an area where the temperature is below 15 °C, resistor Rext2 will need to be adjusted to provide a higher drive voltage.

The LCD’s backlight intensity is controlled by resistors R14 and Rext1. R14 is used to limit the maximum possible current provided to the backlight LED assembly. Using the equation 3.19 with the values of V_S equal to 5 volts, V_F equal to 4.4 volts,

$$R_{14} + R_{EXT1} = \frac{V_S - V_F}{I_F} \quad (3.19)$$

and I_F equal to 260 mA, the minimum total resistance needed was 2.3 Ω . However, I_F should be limited to a much lower value because the LED assembly can withstand a maximum current of only 152 mA when the ambient temperature increases to 50 °C. Therefore, the value of resistor R14 was selected as 13 Ω in order to limit I_F to no more than 31 mA. This current would provide sufficient illumination to a dark or dimly light area and would minimize power requirements. Resistor Rext1 was added to further limit I_F in order to provide a variable backlight level.

Power requirements for the LCD Hardware Block are summarized in Table 3.6. The LCD module's power requirements are highly dependent on temperature so each calculated value has been doubled to insure adequate current is available from the +5 volt power supply.

PART IDENTIFIER	POWER SUPPLY	CURRENT REQUIREMENT
LCD Drive Current	+5 Volt	3.0 mA
Backlight LED Assembly	+5 Volt	62.0 mA

Table 3.6: Current requirements summary for the 'LCD Hardware Block'.

The keypad consists of 12 individual keys arranged in a 4x3 grid. Each key is a pushbutton-type switch that closes a contact connecting the key's data wire to a common ground when pressed. When the key is released, the electrical connection is broken and is no longer connected to the common ground. Pull-up resistors were used so that +5

volts would be applied to the microcontroller's input pin when a key was not pressed. When the key is pressed, the voltage applied to the microcontroller's input pin would then be connected to ground or 0 volts. Switch de-bouncing is handled in the software for the User Interface Microcontroller, thereby, simplifying the hardware design process. The schematic shown in Figure 3.20 illustrates how the keypad was used with the microcontroller. The values of the pull-up resistors R16 – R22 and R24 – 28 were selected in order to minimize current when a key is pressed. The current required for the Keypad Hardware Block is 0.34 mA, assuming that only one key is pressed at any one time.

Figure 3.20: Schematic for the ‘Keypad Hardware Block’

The User Interface Microcontroller Block in Figure 3.18 consists of a PIC16F877 Microcontroller and a DS1602 Elapsed Timer. The microcontroller performs all user interface functions such as displaying information on the LCD and receiving user input from the keypad. In addition to these tasks, the User Interface Microcontroller also performs all operational-related calculations using battery voltage and current data as well as determining when the selected charge completion condition has been reached.

Values calculated by the microcontroller include battery impedance, MOSFET temperatures, and the state of battery charge. The elapsed timer is used to provide real-time clock data to the microcontroller. This information is used to display elapsed charge time to the user. Figure 3.21 shows the schematic for the User Interface Block.

As with the Pulse Control Microcontroller that was discussed previously, ceramic capacitors, C7 and C8, that are connected between the microcontroller's power supply pins provide a low impedance path to ground for high frequency noise that may be present. The microcontroller's clock signal is provided by the 4 MHz oscillator. The reset signal comes from the reset switch that is also connected to the Pulse Control Microcontroller. Refer to Figure 3.5 for further information regarding how the reset switch is connected to the microcontroller.

Quickly looking at the schematic of Figure 3.21, one would assume that this

Figure 3.21: Schematic for the 'User Interface Microcontroller Hardware Block'

microcontroller would require a large amount of power. However, due to the fact that the LCD module is a CMOS based device, there is very little current flowing in the three LCD control lines as well as the eight LCD data lines DB0 – DB7. The same is also true for the three control lines connected to U8. The keypad data lines do consume some power, but not as much as one might think. Although there are twelve data lines, only one of those data lines that start with KP_ will be active at a time and even then the microcontroller will not need to sink or source any current other than very small leakage currents. The standby current used by U7 will be no more than 6.5 mA. The actual standby current will actually be less since this assumes a frequency of oscillation of 20 MHz instead of U7's frequency of 4 MHz. The largest single power user of U7 is the serial communication lines. They will consume approximately 25 mA of current, according to the PIC16F877 datasheet.

The elapsed timer U8 is operated by three control lines. The RST pin of U8 performs two functions. First, it turns on the serial port to allow the microcontroller to send commands the timer. Second, it is used to terminate timer commands or timer data transfers. The DQ pin is used as the serial transfer line. Timer commands and timer data transfers come through this pin. The CLK pin is the clock signal to the timer. Depending on the state of the RST and DQ pins, the CLK pin will initiate or terminate command and timer data transfers. Table 3.7 summarizes the pin state combinations and the corresponding function the elapsed timer will perform. All DS1602 functions are initiated or terminated when a pin transitions from high-to-low or low-to-high as seen in Table 3.7. For a more complete understanding of the DS1602 operation, refer to the source code for the timer related functions contained in section C.2 of Appendix C. The

power requirements of the DS1602 are very low. According to the datasheet for the DS1602, the device will consume a maximum of 1 mA of current for active operation.

RST	DQ	CLK	FUNCTION
High	Data	Low-to-High	Write Data to DS1602
High	Data	High-to-Low	Read Data from DS1602
High-to-Low	-	High	Terminate DS1602 Data Transfers
Low-to-High	-	-	Initiate DS1602 Data Transfers

Table 3.7: DS1602 control pin states

Resistor R23 in Figure 3.21 is used to limit the RST pin's sink current. The value of R23 was recommended by the DS1602 datasheet. Component X3 is a 32.768 kHz watch crystal. It provides the clock frequency that the DS1602 uses to keep track of the number of seconds that have elapsed since the timer was last reset to zero. Since the DS1602 is used as an event timer while the pulse charger is turned on, the Vbat pin has been grounded. Normally, a battery is connected to the Vbat pin to provide the elapsed timer with power while the main power supply is turned off. That way, the total time in operation can be tracked. However, this feature of the DS1602 was not used.

The power requirements for the User Interface Microcontroller Hardware Block are summarized in Table 3.8. These currents will be used in the section of this chapter dealing with the design of the pulse chargers low voltage power supplies.

PART IDENTIFIER	POWER SUPPLY	CURRENT REQUIREMENT
U7	+5 Volt	31.5 mA
U8	+5 Volt	1.0 mA
X2	+5 Volt	25.0 mA

Table 3.8: Current requirements summary for the ‘User Interface Microcontroller Hardware Block’.

3.4.4 Power Supplies

All low voltage power supplies are built around the 78XX and 79XX series voltage regulators. To provide the correct voltage levels, four individual power supplies were built. These supplies provided voltages of +5, +12, +15, and –15 volts. In the previous sections of this chapter, summaries have been given in tables stating the power requirements for all low voltage electronic components. Table 3.9 restates these power

PART IDENTIFIER	POWER SUPPLY	CURRENT REQUIREMENT
U2	+15 Volt	1.25 mA
S1	+15 Volt	70.0 mA
S1	-15 Volt	70.0 mA
Fans	+12 Volt	140.0 mA
U1	+5 Volt	0.25 mA
U3	+5 Volt	33.1 mA
U4	+5 Volt	15.0 mA
U5	+5 Volt	15.0 mA
U6	+5 Volt	0.15 mA
U7	+5 Volt	31.5 mA
U8	+5 Volt	1.0 mA
U9	+5 Volt	10.0 mA
X1	+5 Volt	25.0 mA
X2	+5 Volt	25.0 mA
R13	+5 Volt	0.10 mA
LCD	+5 Volt	65.0 mA
Keypad	+5 Volt	0.34 mA

Table 3.9: Current requirements for all low voltage power supplies.

requirements so they will be available in a single table. The power requirements of the +12 volt supply are being given for the first time. This is because the +12 volt supply is only used to provide power to the two cooling fans that provide air flow through the charger's interior. Table 3.10 shows the total current requirements for each of the four power supplies. The 'Design for Current' column of Table 3.10 is the current value that is used in the power supply design calculations. These values were determined by adding

POWER SUPPLY	CALCULATED LOAD CURRENT	50% SAFTY MARGIN	DESIGN FOR CURRENT
+15 Volt	71.25 mA	35.63 mA	106.88 mA
-15 Volt	70.0 mA	35.0 mA	105.0 mA
+12 Volt	140.0 mA	70.0 mA	210.0 mA
+5 Volt	221.44 mA	110.72 mA	332.16 mA

Table 3.10: Power supply current and design requirements summary

50% to the calculated current requirements for all power consuming components. The additional 50% was added to account for any possible omissions or incorrect assumptions made during the design process. It is also good engineering practice to design the power supplies to be able to provide more current than the bare minimum.

Since all of the values in the 'Design for Current' column of Table 3.10 are below 1 Amp, the power supplies can use the 78XX and 79XX series voltage regulators. Also, since no special features were required, it was decided that the power supplies would be built using the suggested circuits and component values given in the 78XX and 79XX voltage regulator datasheets. The main consideration in building the power supplies was the voltage rating of the capacitors and bridge rectifiers that were used. These parts were

chosen with voltage ratings of at least 3 times the expected maximum applied voltage. Schematics for all four power supplies are in sections B.4 and B.5 of Appendix B.

3.5 Software

Two microcontrollers were used in the design of the pulse charger, one to handle user interface related functions and the other to generate and control the charging waveform. By using two microcontrollers, there was a need to develop two separate programs, one for each microcontroller. A discussion on the development of these programs will be presented in the next two sections. Emphasis will be placed on describing the logic and coding of functions whose purpose is not readily apparent or contains equations that require a derivation to fully understand. Although each function and many of the individual commands have comments in the source code, some features could not be adequately explained in a limited space or without referring to complicated formulas.

3.5.1 ‘Pulse Control Microcontroller’ Software

The primary purpose of the Pulse Control Microcontroller is to generate the charging waveform. This includes controlling the on-time and amplitude of the charge and discharge pulses, controlling the off-time between the charge and discharge pulses, and read analog data representing the current state of the battery and charger. The flowchart in Figure 3.22 represents the program that was written for the Pulse Control Microcontroller. Source code listings for this microcontroller are contained in Appendix C, sections C.5 and C.6.

Referring to the source code listing of section C.5 and the flowchart of Figure 3.22, the first task that the microcontroller does upon power-up is to initialize all I/O pins

Figure 3.22: Main Program Flowchart for the 'Pulse Control Microcontroller'

as either inputs or outputs. The analog input pins have additional initialization procedures performed on them. The initialization routine is performed by the `init()` function of the file `MASTER.C`.

Once the Pulse Control Microcontroller has completed the initializing communication takes place between it and the User Interface Microcontroller. The user setup procedure is handled by the `user_setup()` function of the file `MASTER.C`. Most of this function is well commented except of where the values of the variables `delay_chrg`, `delay_dchrg`, `delay_off1`, and `delay_off2` are calculated. A segment of code from the `user_setup()` function is shown in Figure 3.23. It performs the necessary calculations to determine the delay length needed to obtain the correct charge pulse on-time.

```
Line 1:  tcp = 0.2 / pulse_freq;  // Charge pulse has 20% on-time
Line 2:
Line 3:  if (pulse_freq > 0x00F9)
Line 4:      If (tcp <= 216.6)
Line 5:          delay_chrg = 0;
Line 6:      else
Line 7:          delay_chrg = (tcp - 0.0000928) / 0.0000034;  // Delay
Line 8:
Line 9:  if (pulse_freq < 0x00FA)
Line 10:      if (pulse_freq > 0x0009)
Line 11:          delay_chrg = (tcp - 0.0000928) / 0.0000804;  // Delay
Line 12:
Line 13:  if (pulse_freq < 0x000A)
Line 14:      delay_chrg = (tcp - 0.0000928) / 0.0008004;      // Delay
```

Figure 3.23: Source code segment that calculates charge pulse delay times.

The code of Line 1 of Figure 3.23 determines the charge pulse on-time that is required for the given pulse frequency, represented by the variable `pulse_freq`. It performs the calculation of equation 3.20. Line 3 of the code segment determines if the

$$tcp = duty_cycle \left(\frac{1}{Frequency} \right) \quad (3.20)$$

pulse frequency is greater than 250 Hertz. If so, then another check is made to determine if the required delay time is less than the minimum delay time that can be provided by the microcontroller. If this is true, then the delay time is set to zero otherwise a delay time is calculated. The values on Lines 7, 11 and 14 of Figure 3.23 were derived by first determining the fixed amount of time that the source code of Figure 3.24 took to execute. The difference between the fixed execution time and the charge pulse time gave a delay that needed to be performed by the code on Lines 6 – 9 of Figure 3.24. The difference between the fixed execution time and the charge pulse time gave a delay that needed to

```

Line 1:  // Charge Pulse portion of charging algorithm.
Line 2:  output_high(PIN_E2);           // Disable cd4067
Line 3:  output_low(PIN_E1);           // Sensor output line 0
Line 4:  output_low(PIN_E2);           // Enable cd4067
Line 5:  cpulse_data.cdata = 0xFF;     // Turn on IRF5210 MOSFETs
Line 6:  for (i = 0; i < delay_chrg; i++)
Line 7:  {
Line 8:      delay_us(1);
Line 9:  }
Line 10: vbc = read_battery_voltage();
Line 11: ic = read_current();
Line 12: cpulse_data.cdata = 0x00;     // Turn off IRF5210 MOSFETs

```

Figure 3.24: Source code segment that generates the charge pulse using the fast charging algorithm.

be performed by the code on Lines 6 – 9 of Figure 3.24. By first compiling the code of Figure 3.24, it was determined that the code on Lines 2, 3, 4, 5, and 12 would take 1.2μs to execute. Each of the instructions on Lines 2, 3, 4, 5, and 12 produce one Assembly language instruction and none alter the program counter of the microcontroller so each

will take only 1 instruction cycle to execute. Each instruction cycle is made up of 4 clock cycles and a clock cycle is equal to 50ns. Instructions that do alter the program counter will take 2 instruction cycles or 8 clock cycles. The code on Lines 10 and 11 of Figure 3.24 each take an estimated 45.2μs. This gives a software-related fixed execution time of 91.6μs. The time of 45.2μs is an estimated time since the time required for analog-to-digital conversions to complete could only be approximated. The analog acquisition time and conversion time were both estimated at 20μs each. The Assembly language instructions then took another 5.2μs to execute. Equations 3.21 and 3.24 given the analog acquisition time and the conversion time respectively. The formulas as well as the values used were obtained from the analog-to-digital conversion section of the PIC16F877 datasheet.

$$T_{ACQ} = T_{AMP} + T_C + T_{COEF} \quad (3.21)$$

$$T_C = \left[C_{HOLD} (R_{IC} + R_{SS} + R_S) \ln \left(\frac{1}{2047} \right) \right] \quad (3.22)$$

$$T_{COEF} = \left[(Temp - 25^{\circ}C) \left(\frac{0.05\mu s}{^{\circ}C} \right) \right] \quad (3.23)$$

$$T_{CONV} = 12 [32 (T_{OSC})] \quad (3.24)$$

Because the turn-off time of the P-Channel MOSFETs was so long, it could not be ignored. Through experimentation, it was determined that the average turn-off time of

the P-Channel MOSFETs was 125 μ s. This value was added to the software-related fixed execution time in order to compensate for the length of time the MOSFETs took to turn off and stop conducting current.

It is now known that the fixed execution time of the charge pulse code segment will take 216.6 μ s to execute. A similar method was followed to calculate the fixed execution times for the discharge pulse code and the code for the first and second rest periods. They are much shorter because these segments of code do not depend on the turn-off time of the p-Channel MOSFETs. The fixed times for all code segments are summarized in Table 3.11. The duty cycles for each code segment are also given in this table.

CODE SEGMENT	FIXED TIME (T_{FIXED})	DUTY CYCLE
Charge Pulse Code	216.6 μ s	0.2
Discharge Pulse Code	91.6 μ s	0.1
1 st Rest Period Code	90.4 μ s	0.6
2 nd Rest Period Code	45.2 μ s	0.1

Table 3.11: Summary of the fixed execution times and duty cycles for the different pulse charger output waveform sections.

It is now known that the code of Figure 3.24 will take 216.6 μ s to execute. The delay loop formed by the code on Lines 6 and 8 of Figure 3.24 will need to have an execution time equal to the charge pulse on-time minus 216.6 μ s. Next, a formula was developed for the execution time of the ‘for loop’ on Line 6. This formula is given in equation 3.25 where the value of ‘i’ is the number of times the ‘for loop’ is to be executed and the value of ‘delay’ is given by the chosen fixed delay time on Line 8 of Figure 3.24. Also, for this formula to be valid, the value of ‘i’ must always be less than

$$t_{FOR_LOOP} = 1.2\mu s + i(1.4\mu s + delay) \quad (3.25)$$

or equal to 255. The reason is that the code for the ‘for loop’ becomes very complicated when ‘i’ becomes large enough to need a 9-bit representation and the execution time for the loop can no longer be given by a single equation.

At this point, enough information has been developed so that the values on Lines 7, 11 and 14 of Figure 3.23 can be calculated. The steps outlined below show how the delay formula coefficients in the user_setup() function of the MASTER.C source code file were calculated.

- Select the desired frequency range of f_L to f_H .
Valid ranges for the charger are $f_L = 251$ Hz & $f_H = 1000$ Hz, $f_L = 10$ Hz & $f_H = 250$ Hz, and $f_L = 1$ Hz & $f_H = 9$ Hz.
- Using Table 3.11, determine the duty cycle that corresponds to the delay being calculated.
- Using equation 3.20, calculate the value of t_{cp} using the value of f_L for frequency
- Using Table 3.11, determine the value of t_{FIXED} that corresponds to the delay being calculated.
- Set t_{FOR_LOOP} to equal $t_{cp} - t_{FIXED}$
- Using equation 3.25, calculate the value of ‘delay’ by setting t_{FOR_LOOP} to the value that was calculated in the previous step and the value of ‘i’ to 250. A value of 250 was used to ensure that the ‘for loop’ will not execute more than 255 times. A floating point number will result for ‘delay’. Round this number up to

the next integer value if greater than 0.8. This will be the number of microseconds to use as the fixed delay inside the 'for loop'. If the value of delay less than or equal to 0.8, then divide the number by 0.2 and round up to the next integer value. This will be the number of instruction cycles to use as the fixed delay inside the 'for loop'.

- Using equation 3.20 once again, calculate the value of t_{cp} using the same duty cycle value previously used and this time using the value of f_H for frequency.
- Set t_{FOR_LOOP} to equal $t_{cp} - t_{FIXED}$
- Using equation 3.25, substitute the value of t_{FOR_LOOP} calculated in the previous step and 'delay' and calculate the value of 'i'. This will be the number of times that the 'for loop' will need to be executed. This will be a floating point number but the compiler will charge it to an integer number when the assignment is made in the equations in Lines 7, 11 and 14 of Figure 3.23.

The next portion of code for the Pulse Control Microcontroller to be examined is the interrupt handler. The relevant code segment is shown in Figure 3.25. The source code of Lines 1 and 2 are what make this the interrupt handler. They signal to the compiler that this function is to be executed anytime an interrupt is triggered by data coming into the microcontroller through the RCV pin of Port C. The compiler, then, generates the appropriate Assembly code. The remaining code of Lines 3 – 37 are simply what is executed according to the data that is received through the RCV pin.

```

Line 1:  #int_rda
Line 2:  rda_handler()
Line 3:  {
Line 4:      int    cmd;
Line 5:
Line 6:      cmd = getc();
Line 7:      switch (cmd)
Line 8:      {
Line 9:          case 0x10:
Line 10:              rs232_send_long_data(vboc);
Line 11:              break;
Line 12:              .
Line 13:              .
Line 14:              .
Line 30:      case 0xFF:
Line 31:          continue_charging = 0;
Line 32:          break;
Line 33:      default:
Line 34:          rs232_send_long_data(0x0000);
Line 35:          break;
Line 36:      }
Line 37:  }

```

Figure 3.25: Interrupt handler routine for the ‘Pulse Control Microcontroller’

Finally, referring back to the flowchart in Figure 3.22, it can be seen that the charging algorithm begins once the charger has completed its setup routines. The flowchart for the charging algorithm is shown in Figure 3.26. This flowchart represents the fast, slow, and very slow charging algorithms since the only difference in these algorithms is the values of the ‘for loop’ delays and the number of times each loop is executed. All analog input voltages to the microcontroller are read at the end of the code sections for the charger pulse, discharge pulse, rest period 1, and rest period 2. This helps to ensure that the correct voltage is present at the analog input pin of the microcontroller before a reading is made. Whenever the charging algorithm’s stopping condition is reached, the microcontroller will enter an endless loop. This is because the Pulse Control Microcontroller is no longer needed for the operation of the charger.

Figure 3.26: Flowchart for the charging algorithm

3.5.2 ‘User Interface Microcontroller’ Software

The User Interface Microcontroller is used to display information to the user via an LCD. It also receives user input from a keypad. Besides the user interface functions

that are performed, the microcontroller is used to control the operation of an elapsed timer, test the initial battery voltage, perform calculations using battery voltage and current data, and to determine when the battery being charged has reached the user-defined stopping condition. Most of the programming techniques and logic that make up the source code for the User Interface Microcontroller should be easily understood by someone knowledgeable with the C programming language. Therefore, only code segments where formulas were developed or where calculations were made prior to writing the C code, in order to simplify the microcontroller's tasks will be discussed.

Figure 3.27 is the main program flowchart for the User Interface Microcontroller source code. The four features of the source code that will be discussed in more detail are three formulas that are part of the functions `get_voltage()`, `get_battery_current()`, and `get_internal_temperature()` as well as a lookup table that was written in simplify the task of converting the 32-bit binary output from the elapsed timer into a human readable time format of hours, minutes, and seconds.

The first function that will be examined is `get_voltage()`. The code for this function is in the `SLAVE.C` source code listing contained in section C.3 of Appendix C. For convenience, it is also shown in Figure 3.28. This function will receive a 10-bit binary representation of the analog voltage that was present at the analog input pin of the microcontroller. Line 7 of Figure 3.28 multiplies this 10-bit number, given by the variable 'data', by an appropriate scaling factor so that the function will return a floating point number representing the actual real world value that will be displayed to the user and used for calculations.

Figure 3.27: Main Program Flowchart for the 'User Interface Microcontroller'

```

Line 1: // Convert the 10-bit battery voltage and power supply
Line 2: // voltage data into a floating point number representing
Line 3: // the actual measured voltage
Line 4: float get_voltage(long data)
Line 5: {
Line 6:     float voltage;
Line 7:     voltage = (float)data * 0.0488758;
Line 8:     return voltage;
Line 9: }

```

Figure 3.28: Code segment for the function get_voltage()

The first step taken to calculate the scaling factor was to determine the maximum input voltage to the microcontroller. In this case, the maximum voltage was 5 volts. Next, a formula was developed that related the 10-bit binary number to the analog input voltage. Knowing the 10-bit number, the developed formula needed to give the original analog input voltage to the microcontroller. The derived formula is shown below.

$$V_{AN} = \frac{data}{1023}(V_{AN_MAX}) \quad (3.26)$$

The value of the variable data is the 10-bit number produced by the analog-to-digital conversion and the variable, V_{AN_MAX} , is the maximum analog input voltage. Since the actual voltage is 10 times greater than the analog input voltage to microcontroller, all that is required at this point is to multiple the value of V_{AN} given by equation 3.26 by 10 in order to know the actual voltage at the power supply or battery terminals. The following equation is the one that was used to determine the scaling factor in the code on Line 7 of Figure 3.28.

$$V = \frac{data(10)}{1023}(V_{AN_MAX}) = data(V_{SCALE}) \quad (3.27)$$

The next function to be examined is `get_battery_current()`. The code for this function is shown in Figure 3.29 as well as in file `SLAVE.C` contained in section C.4 of Appendix C. This function receives a 10-bit binary representation of the voltage applied

```

Line 1: // Convert the 10-bit battery current data into a floating
Line 2: //point number representing the actual measured current
Line 3: float get_battery_current(long data)
Line 4: {
Line 5:     float current;
Line 6:     current = (float)data * 0.0592435;
Line 7:     return current;
Line 8: }
```

Figure 3.29: Code segment for the function `get_battery_current()`

to an analog input pin of the microcontroller. To calculate the scaling factor contained in the code on Line 6, equation 3.26 is, once again, used in order to determine the analog input voltage to the microcontroller. Since this voltage was produced by the output current from the current sensor flowing through a 82.5Ω resistor, dividing the value of V_{AN} given by equation 3.26 by 82.5 will give the value of the scaled current output from the current sensor. This calculation is shown in equation 3.28. Since the current sensor

$$I_{SENSE} = \frac{data}{1023(82.5)}(V_{AN_MAX}) \quad (3.28)$$

scales the actual sensed current by a factor of 1000, multiplying the value of I_{SENSE} by 1000 will give the actual current value flowing into and out of the battery. The actual

current and the scaling factor used in the code of Line 6 of Figure 3.29 was calculated by the following formula.

$$I = \frac{data(1000)}{1023(82.5)}(V_{AN_MAX}) = data(I_{SCALE}) \quad (3.29)$$

The last function to be examined is `get_internal_temperature()`. The code for this function is shown in Figure 3.30 as well as in file `SLAVE.C` contained in section C.4 of

```

Line 1: // Convert the 10-bit temperature data into a floating
Line 2: // point number representing the actual measured
Line 3: // temperature
Line 4: float get_internal_temperature(long data)
Line 5: {
Line 6:     float temp;
Line 7:     temp = ((float)data * 0.2641938) + 32;
Line 8:     return temp;
Line 9: }
```

Figure 3.30: Code segment for the function `get_internal_temperature()`

Appendix C. Like the two previous scaling factor calculations, this one also started with equation 3.26 to give the analog input voltage to the microcontroller. To determine the output voltage from the temperature sensor, the analog input voltage was divided by 3.33 since it was amplified by an operational amplifier with a gain of 3.33 prior to being applied to the microcontroller. This calculation is given by the following equation.

$$V_{TEMP} = \frac{data}{1023(3.33)}(V_{AN_MAX}) \quad (3.30)$$

To convert the voltage output from the temperature sensor, V_{TEMP} , into a temperature in degrees Celsius, the result from equation 3.30 was multiplied by 100 since the temperature sensor's output voltage is 0.01 V/°C. The equation below gives the sensed

$$Temp_C = \frac{data(100)}{1023(3.33)} (V_{AN_MAX}) \quad (3.31)$$

temperature in degrees Celsius in terms of the microcontroller's 10-bit binary representation.

Since a temperature in degrees Fahrenheit was desired, the temperature given by equation 3.31 was modified in order to give a scaling factor and an offset value that could be used in the code on Line 7 of Figure 3.30. Equation 3.32 gives the sensed temperature in degrees Fahrenheit. The final equation used for this code is given by equation 3.33.

$$Temp_F = \frac{data(100)(9)}{1023(3.33)(5)} (V_{AN_MAX}) + 32 \quad (3.32)$$

$$Temp_F = data(T_{SCALE}) + T_{OFFSET} \quad (3.33)$$

The final piece of code that was used with the User Interface Microcontroller to be discussed is the lookup table that was produced to simplify the elapsed time conversion from a 32-bit binary number into a time format of HR:MIN:SEC. This code is in the file SLAVE.H of Appendix C section C.4. The relevant code segment is shown in Figure 3.31 for convenience.

```

Line 1:  // Hr, min, and sec associated with each bit of the 32-bit
Line 2:  // word from the elapsed timer.  Ex: If bits 0 and 12 are
Line 3:  // set then the elapsed time is 1:8:16 + 0:0:1 = 1:8:17
Line 4:  const int time[18][3] = {{ 0, 0, 1}
Line 5:                                     { 0, 0, 2}
Line 6:                                     { 0, 0, 4}
Line 7:                                     { 0, 0, 8}
Line 8:                                     { 0, 0, 16}
Line 9:                                     { 0, 0, 32}
Line 10:                                    { 0, 1, 4}
Line 11:                                    { 0, 2, 8}
Line 12:                                    { 0, 4, 16}
Line 13:                                    { 0, 8, 32}
Line 14:                                    { 0, 17, 4}
Line 15:                                    { 0, 34, 8}
Line 16:                                    { 1, 8, 16}
Line 17:                                    { 2, 16, 32}
Line 18:                                    { 4, 33, 4}
Line 19:                                    { 9, 6, 8}
Line 20:                                    {18, 12, 16}
Line 21:                                    {36, 24, 32}};

```

Figure 3.31: Code segment for the elapsed timer lookup table

The elapsed timer that was used is simply a counter that counts the number of elapsed seconds. The output from the timer is a 32-bit binary number that corresponds to the number of elapsed seconds that the timer has counted. In order to convert the 32-bit number into a human readable form, it was determined that a lookup table should be developed instead of doing the conversion with only equations.

The lookup table of Figure 3.31 is a matrix with 18 rows and 3 columns. Each row of the table represents 1 bit of the 32-bit binary output from the elapsed timer. For example, row 1 corresponds to bit 0 of the output, row 2 corresponds to bit 1 of the output, row 3 corresponds to bit 2 of the output, and so on up to row 18, which corresponds to bit 17 of the elapsed timer's output. Only 17 of the 32 bits were used in order to save processing time and memory. Also, because 17 bits can represent an elapsed time of 72 hours, 49 minutes, and 3 seconds it was decided that this would

provided a sufficiently long timing capability for normal charger operation. The columns of the lookup table represent the elapsed time's hours, minutes, and seconds. The first column of the table represents the number of elapsed hours, the second column represents the number of minutes, and the third column represents the number of seconds.

After the output from the elapsed timer is read by the microcontroller, it tests bits 0 through 17 of the 32-bit output to determine which bits are set and which bits are cleared. If the bit is set, then the row of the lookup table that corresponds to the bit number is accessed and the number of hours, minutes, and seconds are read. The total for the hours, minutes, and seconds corresponding to all set bits is maintained and converted into the time format of HR:MIN:SEC once all 17 bits have been checked.

Chapter 4: Experimentation

Once the pulse charger was designed, built, and tested, battery testing could begin. Several steps were taken prior to starting the test procedure to insure that each battery's condition included in a test set was as closely matched to the others as possible. To explain the testing of the batteries, the experimental procedure will be broken down into steps that correspond to those that were actually taken in the lab. The sections that follow will show how the testing of the batteries progressed from when they were first paired into test sets to the final charge / discharge cycle.

4.1 Charging Algorithms

It was determined that the best method for comparing the effectiveness of using a pulse charger instead of a constant voltage / constant current charger, hereafter referred to as normal charging, was to simultaneously charge two batteries using pulse charging for one battery and normal charging for the other battery.

4.1.1 Pulse Charging

As it was explained in a prior chapter, pulse charging is a process in which the charging current is applied to the battery for a short period of time then removed for a period of time and then applied again and so on. The form of pulse charging used for this experiment also had a discharge pulse as part of the charger's output waveform. Figure 4.1 is a plot of the charger's charge and discharge pulses and the battery's resulting

Pulse Charger Output Measured at Battery Terminals

charging and discharging voltage. The frequency of the charger's output is 1 kHz. This frequency was used throughout the experimental procedure.

4.1.2 Normal Charging

The normal charging method used an EverStart Basic Six Model WM-82-6 manual charger. Since this is a manual charger, it will continue to apply charging current to the battery even after the battery has reached a fully charged state. As someone can infer, this is a very basic charger that applied a constant non-alternating voltage to the battery. The charging current was a pulsating AC sine wave value with periods of zero charging current. While the charging current is referred to as constant, this statement is not entirely accurate. While the peak value of current is constant for some period of time, its magnitude does drop as the battery's state of charge nears 100% and as the internal impedance of the battery changes. Figure 4.2 is a plot of the normal charger's output waveform. As it can be seen from the plot, the normal charger's output is much simpler than the output from the pulse charger.

4.2 Battery Testing Equipment

The equipment that was used in the battery test procedure consisted of six normal chargers, one custom designed pulse charger, and a discharge test apparatus. Five of the six normal charges were used to give the lead-acid batteries their top-off charge before the first discharge test was run. The remaining normal charger also perform the top-off charge task. But, as the batteries were grouped into test sets, this charger was given the task of performing the normal charge on one of the batteries in a test set.

EverStart Basic Six Model WM-82-6
Battery Charger Output Measured at Battery Terminals

The discharge test apparatus that was used consisted of a 0.1 Ω resistive load, Hall-effect current sensor, voltage sensor, a hold-in circuit breaker, a data acquisition card, and a computer with LabView software. The discharge test apparatus and the LabView virtual instrument program were not created specifically for this research. They were made by another individual for another project.

4.3 Test Procedure

The test procedure used in this research can actually be divided into two phases, each with a different goal. The first test phase was used to determine the subject battery's initial condition. This information was needed so that test sets could be formed for the second test phase. The second test phase consisted of collecting data by repeatedly charging and discharging the batteries of each test set. This second phase data was used to make the final determination regard the benefits and usefulness of pulse charging as compared to normal charging.

4.3.1 Initial Condition Test

The testing procedure that will be discussed in this section was used to determine a subject battery's initial condition and, so, will be referred to as the Initial Condition Test. The data resulting from the Initial Condition Test was not used in the comparison between pulse charging and normal charging. This test procedures only purpose was to enable the pairing of batteries with similar conditions into test sets.

The testing of the pulse charging technique began with randomly selecting a battery. This battery's pre-charge terminal voltage was measured and recorded. The battery was

then given a top-off charge using one of several constant voltage / constant current chargers. Once the battery had been charged, its post-charge terminal voltage was measured and recorded. The battery was then placed aside for 24 hours. After the 24 hour period had past, the battery's post-charge + 24 terminal voltage was measured and recorded. At this point, the battery's weight was also measured and recorded. The battery was, then, immediately subjected to a discharge test to determine its current condition. The discharge test continued until the battery's terminal voltage reached 10.765 volts for at least 0.4 seconds. At this point, the discharge test was halted and the resulting data file saved for future use. A segment of a discharge test data file is shown in Figure 4.3. The first column of data represents the battery's voltage and the second column represents the battery's current. Each row represents one data sample taken at 0.2 second intervals. The data values in the file have been scaled by the LabView VI. To obtain the actual measured values, the voltage data values need to be multiplied by 10.07 and the current data values multiplied by 149.9.

LabView Volts	LabView Amps	Actual Voltage	Actual Current
1.128	0.725	11.359	108.678
1.125	0.725	11.329	108.678
1.125	0.725	11.329	108.678
.	.	.	.
.	.	.	.
.	.	.	.
1.128	0.725	11.359	108.678
1.125	0.725	11.329	108.678
1.128	0.725	11.359	108.678

Figure 4.3: Segment of a discharge test data file with scaled and actual voltage and current data.

After the discharge test had completed, the battery was again charged using a normal charger. The pre-charge, post-charge, and post-charge + 24 terminal voltages were again measured and recorded at the appropriate times during charging. The battery was, then, placed in a storage area to wait for possibly use as a member of a test set.

Using the data file resulting from the discharge test, the battery's discharge time was determined and recorded. The discharge time is defined as the elapsed time starting when the battery is first connected to the load resistor and ending when the battery's terminal voltage reaches 10.765 volts for 0.4 seconds.

Data from the discharge test was used to calculate the battery's impedance. The following equation was used for this task.

$$Z = \frac{V_{t=0s} - V_{t=0.2s}}{I_{t=0.2s}} \quad (4.1)$$

The process of randomly selecting batteries and subjecting them to a charge-discharge-charge cycle continued as the availability of normal chargers permitted. As each battery was finished, certain parameters concerning its condition were added to a table. The data placed in this table consisted of the battery's identifying number, the most recent post-charge + 24 terminal voltage, the discharge time, and the impedance calculated using equation 4.1. As data was added to this table, the batteries were grouped together so that their voltage, impedance, and discharge time were as closely matched as possible. Once two batteries were found with similar characteristics, they became designated as a test set.

4.3.2 Charger Comparison Test

Once two batteries had been grouped into a test set, one of the batteries was designated to be recharged using the normal charger and the other battery was designated to be recharged using the pulse charger. Each battery's pre-discharge terminal voltage was measured and recorded. They were, then, subjected to the discharge test to determine the length of time that they could provide current to a $0.1\ \Omega$ resistive load before the terminal voltage reached 10.765. The resulting time was designated as the Test 0 Discharge Time. After a discharge test had been run on both batteries of the test set, their pre-charge terminal voltages were measured and recorded. The discharge test data, along with equation 4.1, were then used to determine the battery's internal impedance. They were recharged using the appropriate charging technique. When each battery had reached a fully charged state, it was removed from the charger and a record was made of its post-charge terminal voltage. The batteries were, then, left undisturbed for 24 hours. At the end of the 24 hour period, their post-charge + 24 terminal voltages were measured and recorded. Another discharge test was performed, resulting in the Test 1 Discharge Time. The batteries were charged as had previously been done with records being made of terminal voltages at the designated times. The same discharge / charge cycle repeated until the Test 8 Discharge Time had been measured. When this time had been determined, the Charger Comparison Test for the battery test set was complete.

4.4 Test Results

Six battery tests set were used to test the pulse charging technique. Each test set used had slightly different characteristics in order to test pulse charging on as wide a

range of battery conditions as possible. Table 4.1 summarizes the characteristics that each battery test set possessed at the start of the Charger Comparison Test.

TEST SET DESIGNATION	NORMALLY CHARGED BATTERY ID	PULSE CHARGED BATTERY ID	TEST SET CHARACTERISTICS
A	161	177	Batteries that were more than 4 years old and had a discharge test time of 10 minutes or more.
B	437	438	Batteries that were less than 4 years old and had a discharge test time of 10 minutes or more.
C	43	116	Batteries that had a discharge test time between 3 and 5 minutes.
D	120	129	Batteries that had a discharge test time between 5 and 6 minutes and had an internal impedance of less than 0.006 ohms.
E	144	148	Batteries that had a discharge test time between 5 and 6 minutes and had an internal impedance of greater than 0.006 ohms.
F	132	324	Batteries that still had a terminal voltage of less than 12 volts when charged for 24 hours using a normal charger.

Table 4.1: Distinguishing characteristics of the battery tests sets.

4.4.1 Battery Discharge Tests

The results from the discharge tests of the Charge Comparison Test for each battery test set are summarized in Tables 4.2, 4.3, and 4.4. The graphs used to determine the information in these tables are contained in Appendix A. The discharge data has also been included as an embedded attachment in the pdf version of this document. The graph of Figure 4.4 is a compilation of all battery test set discharge data.

Figure 4.4: Comparison between pulse charged and normally charged batteries.

Table 4.2 shows the initial and final discharge test times for each battery in the test sets that was charged normally as well as the change in the discharge test times. The time changes are presented in seconds and as a percentage. Table 4.3 shows the same information as Table 4.2, but for the batteries that were charged using the pulse charging technique. Table 4.4 shows a side-by-side comparison of the discharge test time charges. It is from the data in Table 4.4 that most conclusions will be drawn regarding pulse charging. These conclusions will be presented and discussed in Chapter 5.

TEST SET	Test 0 Discharge Time (seconds)	Test 8 Discharge Time (seconds)	Discharge Time Change (seconds)	Discharge Time Change (percentage)
A	654.8	717.2	62.4	9.530 %
B	883.0	1158.2	275.2	31.166 %
C	222.6	315.0	92.4	41.509 %
D	353.2	362.4	9.2	2.605 %
E	322.4	284.2	-38.2	-11.849 %
F	0.2	0.2	0.0	0.000 %

Table 4.2: Summary of the changes in the discharge test times for batteries the were charged normally.

TEST SET	Test 0 Discharge Time (seconds)	Test 8 Discharge Time (seconds)	Discharge Time Change (seconds)	Discharge Time Change (percentage)
A	598.6	591.8	- 6.8	- 1.136 %
B	1053.0	1157.8	104.8	9.953 %
C	251.6	382.6	131.0	52.067 %
D	351.4	373.4	22.0	6.261 %
E	306.8	260.2	- 46.6	-15.189 %
F	0.2	0.2	0.0	0.000 %

Table 4.3 Summary of the changes in the discharge test times for batteries that were pulse charged.

TEST SET	Discharge Test Time Change Using Normal Charging	Discharge Test Time Change Using Pulse Charging	How much better or worse was pulse charging as compared to normal charging?
A	9.530 %	- 1.136 %	-111.920 %
B	31.166 %	9.953 %	-68.065 %
C	41.509 %	52.067 %	25.435 %
D	2.605 %	6.261 %	140.345 %
E	-11.849 %	-15.189 %	-28.188 %
F	0.000 %	0.000 %	0.000 %

Table 4.4: Comparison between discharge test time changes using normal charging and pulse charging

4.4.2 Battery Discharge Voltages

For each discharge test that was performed, a series of voltage data points were produced. The times required for the battery voltage to reach the test termination voltage of 10.765 have already been presented. Although the discharge test times reveals a significant amount of information regarding the condition of the battery, it is only part of the overall picture. The other important part of the discharge test data is the voltage curves that were produced. The voltage curves that were obtained for the initial discharge test, test 0, and the final discharge test, test 8, for each battery test set are shown in Figures 4.5, 4.6, 4.7, 4.8, 4.9, and 4.10. An important fact about these graphs is the voltage that is maintained at the beginning of each discharge test has risen, even if the discharge time has decreased as in the pulse charge voltage curves of Figure 4.5.

Test Set A Battery Discharge Voltages

Test Set B Battery Discharge Voltages

Test Set C Battery Discharge Voltages

Test Set D Battery Discharge Voltages

Test Set E Battery Discharge Voltages

Test Set F Battery Discharge Voltages

4.4.3 Battery Impedance Calculations

The discharge tests also provided the information needed to calculate battery internal impedance. Initially, it was thought that some useful information concerning any changes in battery condition could be seen by examining the impedance history of the battery. Upon completion of the Charger Comparison Tests, it was determined that the impedances that were calculated using equation 4.1 varied unpredictably. The impedance history graphs for the batteries in each test set are included for reference in Appendix A.

4.4.4 Battery Post-Charge + 24 Hours Voltage Measurements

The post-charge + 24 hour voltages for all batteries used in the Charge Comparison Tests were plotted in order to keep a record of the battery's approximate state of charge. It was assumed that a battery that had a terminal voltage of at least 12.8 volts 24 hours after the charging process had completed would have been charged to between 90 – 100 % capacity. Ideally, the post-charge + 24 hours voltage would not vary by large amounts unless the terminal voltage was unable to hold a satisfactory voltage initially. By keeping the post-charge + 24 hours voltage of each battery of a test set closely matched, it was estimated that each battery was charged to approximately the same capacity point. The graphs that show these voltage relationship are given for reference in Appendix A.

4.4.5 Miscellaneous Battery Test Data

In the process of matching batteries into test sets, it was desired to have a set that contained batteries that appeared to be usable by examination of their terminal voltage

and internal impedance measurement, but were unable to provide useful current during the discharge test. Two such batteries were found and the first discharge test of the Charger Comparison Test procedure was carried out. During the discharge test, it was found that the batteries were now providing useful current for at least one minute. Table 4.5 lists the discharge times for each battery. Neither battery was pulse charged since the Charger Comparison Test was not carried out to that point.

BATTERY ID	INITIAL CONDITION TEST	CHARGER COMPARISON TEST #0	Discharge Time Increase (seconds)	Discharge Time Increase (percentage)
110	14.8 sec.	337.4 sec.	322.6	2179.730 %
160	16.6 sec.	108.2 sec.	91.6	551.807 %

Table 4.5: Discharge time comparison of two initially unusable batteries.

Chapter 5: Conclusions and Recommendations

Using the data obtained from the series of discharge / charge tests on the six sets of batteries, several conclusions were reached. These conclusions are presented in section 5.1 of this document. Also, in the process of using the pulse charger, several areas where design improvements could be made were noticed. These design changes are summarized in section 5.2.

5.1 Conclusion on the Benefits of Pulse Charging

By examining the data that was presented in chapter 4 of this document, it was concluded that a battery charged using the pulse technique and one charged using the normal technique showed nearly identical changes in their discharge test characteristics. While the pulse charging technique did not offer any additional advantages over the normal charging technique, it also did not offer any disadvantages. Therefore, when charging an Optima “Red Top” Model 800S Absorbed Glass Matt (AGM) lead-acid battery, it can be said that using the pulse charging technique developed for this research was not better or no worse than using a standard charger. It was also concluded that the process of cycling the batteries provided the best chance for improving a battery’s condition.

The pulse charging technique was better for two test sets. The pulse charged batteries of Test Set C and Test Set D showed superior improvements in discharge test time over those that were charged normally, although the normally charged batteries of these test sets also show some improvement. Using the normal charging technique was

better for Test Set A. Both batteries of Test Set E had a decrease in their discharge test times, although the normally charged battery had less of a decrease. For Test Set B, the normally charged battery had the greatest discharge time increase. It should be noted that the pulse charged battery of Test Set B began the test series with discharge time of 1053 seconds, which is near the maximum possible discharge time for the tested batteries and, so, had little room for improvement. The normally charged battery of Test Set B began the test series with a discharge time of 883 seconds, so had a much greater chance for an increase in discharge test time. Neither battery of Test Set F showed any improvements through the discharge test series.

The battery pulsed charged in Test Set D had the greatest discharge time improvement over the normally charged battery, when measured as a percentage. The pulse charged battery's discharge time improved by 22 seconds, an increase of 6.261 %. The battery from this test set that was charged normally improved only 9.2 seconds, an increase of 2.605%. This resulted in a pulse charging vs. normal charging improvement of 140.345%. Although this seems large, the actual improvement in discharge time was below 10% for both the pulsed and normally charged batteries. Therefore, no clear advantage for pulse charging could be seen in this test set.

The battery pulse charged in Test Set C also showed a greater improvement over the battery that was normally charged. The pulse charged battery's discharge time improvement was 131.0 seconds. However, the normally charged battery's discharge time improvement was 92.4 seconds. This Test Set showed the largest improvement of any pulse charged battery and clearly indicates an advantage of using pulse charging for this particular pair of batteries.

With Test Sets A, B and E, the batteries that were normally charged showed greater improvements over those that were pulse charged. These two sets negate any advantages of pulse charging that resulted in Test Sets C and D. Since Test Set A and B consisted of batteries that had an initial discharge time of 10 minutes or longer and Test Set E's batteries had high initial impedances, it can be concluded that performing charge / discharge cycling provided the improvements in discharge time and not any particular charging algorithm.

Another bit of data that supports the fact that performing charge / discharge cycling provides greater benefits than pulse charging is shown in Table 4.5 of Chapter 4. Although these batteries were not part of any test set, they do show the improvements that can be obtained by simply cycling batteries as a normal part of usage.

The last conclusion to be reached is with regards to reversing the sulfation of lead-acid batteries. The batteries of Test Set F shows most clearly that pulse charging AGM batteries did not reverse sulfation. While it can not be ascertained that sulfation was the only problem that these batteries suffered from, it is reasonable to believe that the batteries were badly sulfated due to their inability to hold a charged voltage greater than 12 volts. The lack of any improvement in the discharge test times of either the pulsed charged or normally charged batteries shows that, at least for the tested AGM batteries, pulse charging was ineffective.

5.2 Recommendations for Pulse Charger Design Improvements

Overall, the pulse charge, as designed, works well. However, there are minor areas of the design that could be modified to improve the operational characteristics of

the charger. If another pulse charger were to be built, it is recommended that the following four modifications be made to the design.

1. Improve power supply filtering in order to reduce AC power line noise, which caused the pulse charger's microcontrollers to reset. This occurred when the external power supply tried to limit the charging current, causing high frequency noise to appear in the AC voltage coming into the pulse charger.
2. Modify the input line of the battery voltage sensor by connecting its inputs directly to the battery with 18 AWG wire. As designed, the battery voltage sensor is placed on the same board as the MOSFETs and its input is connected to the drain of the P-Channel MOSFETs. This results in a sensed voltage that is lower than the actual battery voltage when high charging currents are being used and, thus, causing errors in the calculations made by the microcontrollers.
3. Provide a temperature sensing capability for all three P-Channel MOSFETs. As designed, only one temperature sensor is used to detect unsafe operating temperatures. The sensor is placed on one heat sink of one P-Channel MOSFET. This configuration leaves the remaining two P-Channel MOSFETs unprotected.
4. Change the N-Channel MOSFET Q4 shown on the schematic in Appendix B, section B.3 to an audio or other linear type MOSFET. The MOSFET that is currently used is a switching type. It is very difficult to have the MOSFET control the P-Channel gate voltage with sufficient precision to provide a controlled charging voltage.

5.3 Future Work

- Since only six test sets were used, it can be argued that the test results were inconclusive. Therefore, using Optima “Red Top” Model 800S Absorbed Glass Matt (AGM) lead-acid batteries and the same pulse charger setup, perform the same discharge / charge tests on a greater number of battery sets to obtain a more definite data pattern.
- Modify the charger pulse frequency and repeat the discharge / charge tests to determine if a different frequency will work better.
- Repeat the discharge / charge tests using flood-cell type lead acid batteries to determine if the type of battery has any effect on the test results.

Appendix A: Battery Data Files

A.1 Battery Test Set A - Discharge Time

Test Set A Data: Click icon to access file.

Battery 161 Discharge Test Data: Click icon to access file.

Battery 177 Discharge Test Data: Click icon to access file.

A.2 Battery Test Set B - Discharge Time

Test Set B Data: Click icon to access file.

Battery 437 Discharge Test Data: Click icon to access file.

Battery 438 Discharge Test Data: Click icon to access file.

A.3 Battery Test Set C - Discharge Time

Test Set C Data: Click icon to access file.

Battery 43 Discharge Test Data: Click icon to access file.

Battery 116 Discharge Test Data: Click icon to access file.

A.4 Battery Test Set D - Discharge Time

Test Set D Data: Click icon to access file.

Battery 120 Discharge Test Data: Click icon to access file.

Battery 129 Discharge Test Data: Click icon to access file.

A.5 Battery Test Set E - Discharge Time

Test Set E Data: Click icon to access file.

Battery 144 Discharge Test Data: Click icon to access file.

Battery 148 Discharge Test Data: Click icon to access file.

A.6 Battery Test Set F - Discharge Time

Test Set F Data: Click icon to access file.

Battery 132 Discharge Test Data: Click icon to access file.

Battery 324 Discharge Test Data: Click icon to access file.

A.7 Miscellaneous Battery Tests - Discharge Voltage Curves

Battery 110 Discharge Test Data: Click icon to access file.

Battery 160 Discharge Test Data: Click icon to access file.

A.8 Battery Test Set A – Battery Impedance

A.9 Battery Test Set B – Battery Impedance

A.10 Battery Test Set C – Battery Impedance

A.11 Battery Test Set D – Battery Impedance

A.12 Battery Test Set E – Battery Impedance

A.13 Battery Test Set F – Battery Impedance

A.14 Battery Test Set A – Post-Charge + 24 Hours Voltage

A.15 Battery Test Set B – Post-Charge + 24 Hours Voltage

A.16 Battery Test Set C – Post-Charge + 24 Hours Voltage

A.17 Battery Test Set D – Post-Charge + 24 Hours Voltage

A.18 Battery Test Set E – Post-Charge + 24 Hours Voltage

A.19 Battery Test Set F – Post-Charge + 24 Hours Voltage

Lead Acid Battery Pulse Charger

Title
Printed Circuit Board #4: +5 Volt Supply

Size Document Number

Rev
A

Date: Monday, March 18, 2002

Sheet 1 of 1

Lead Acid Battery Pulse Charger			
Title Printed Circuit Board #4: +/-15 Volt, +12 Volt Supply			
Size	Document Number		Rev A
Date:	Monday, March 18, 2002	Sheet 1 of 1	

B.6 Schematic for Components Not Mounted on a Printed Circuit Board.

Appendix C: Pulse Charger Source Code

C.1 User Interface Microcontroller Source Code File LCD_FUNC.C

```

/*****
FILE:          LCD_FUNC.C
WRITTEN BY:    Robert B. Cooper

LCD module related functions

Pulse Battery Charger: PIC16F877 - B

Functions were written for a DMC-20261 LCD Module

Most functions are modified forms of those contained in
the file LCD.C provided with the CCS C Compiler.
*****/

#include <slave.h>

// Send an 8 bit command or display data to LCD module.
void lcd_send_byte(byte n)
{
    lcd_data.data = n;          // Place data on LCD data port defined in
                                // file SLAVE.H
    delay_cycles(2);            // Wait until output has settled
    control.enable = 1;         // Initiate data transfer to LCD module
    delay_us(5);                // Wait until data has transferred
    control.enable = 0;         // Finish data transfer
}

// Read data from LCD module
byte lcd_read_data()
{
    byte n;

    set_tris_d(LCD_READ);      // Change LCD data port direction to inputs
    control.rw = 1;            // Tell LCD module that data will be read
                                // from module
    delay_cycles(2);
    control.enable = 1;         // Initiate data transfer from LCD module
    delay_cycles(2);
    n = lcd_data.data;          // Read data from LCD data port
    control.enable = 0;         // Finish data transfer
    set_tris_d(LCD_WRITE);     // Change LCD data direction to outputs

    return n;
}

```

```

// Prepare LCD module to receive a command or data instruction
// ADDRESS: 0 - Instruction Register
//          1 - Data Register
// DATA:    8 bit command or data value
void lcd_send_data(byte address, byte data)
{
    control.rs = 0;

    // Wait until the busy flag is cleared
    while (bit_test(lcd_read_data(), 7));

    control.rs = address;    // Set the current LCD register
    delay_cycles(2);
    control.rw = 0;          // Set write data to LCD module
    delay_cycles(2);
    control.enable = 0;
    lcd_send_byte(data);     // Send data to selected LCD register
}

// Initialize LCD module according to steps specified in data sheet.
void lcd_init()
{
    byte i;

    set_tris_c(CONTROL_WRITE);
    set_tris_d(LCD_WRITE);
    control.rs = 0;
    control.rw = 0;
    control.enable = 0;
    delay_ms(200);

    for(i=1; i <= 3; i++)
    {
        // LCD busy flag cannot be checked at this point so send byte
        // directly to LCD and wait long enough to be sure command was
        // received.
        lcd_send_byte(0x30);
        delay_ms(5);
    }

    // Busy flag can now be checked so send byte indirectly to LCD
    lcd_send_data(0, 0x38);
    lcd_send_data(0, 0x08);
    lcd_send_data(0, 0x01);
    lcd_send_data(0, 0x06);
    lcd_send_data(0, 0x0C);
}

// Place LCD cursor at the position specified by x and y
void lcd_moveto_xy(byte x, byte y)
{
    byte address;

    if (y != 1)

```

```

        address = LCD_LINE_2;    // Move cursor to line 2
    else
        address = 0;

    // Move the cursor to the specified x position on the current line.
    address += x-1;
    lcd_send_data(0, 0x80|address);
}

// Send a character or text format command to LCD module
void lcd_putc(char c)
{
    switch(c)
    {
        // Clear the display and return the cursor to the home position
        case '\f':
            lcd_send_data(0, 1);
            delay_ms(2);
            break;

        // Move the cursor to the beginning of the second line
        case '\n':
            lcd_moveto_xy(1, 2);
            break;

        // Move the cursor back 1 position, the contents of the LCD
        // display remains the same
        case '\b':
            lcd_send_data(0, 0x10);
            break;

        // Send a single 8 bit character to the LCD
        default:
            lcd_send_data(1, c);
            break;
    }
}

```

C.2 User Interface Microcontroller Source Code File TMR_FUNC.C

```

/*****
FILE:          TMR_FUNC.C
WRITTEN BY:    Robert B. Cooper

Elapsed time related functions

Pulse Battery Charger: PIC16F877 - B

Functions were written for the DS1602 Elapsed Time Counter
*****/

```



```

// Send an 8 bit instruction to the timer
void timer_send_byte(byte data)
{
    int i;

    set_tris_c(CONTROL_WRITE);
    for(i=0; i < 8; i++)
    {
        // Send least significant bit first
        control.dq = data & 0x01;

        // Toggle DS1602 clock to shift data into DS1602
        control.clk = 1;
        delay_us(2);
        control.clk = 0;

        // Move the next bit of data to the right-most position
        data = data >> 1;
    }
}

// Read 8-bits of data from the timer
int timer_read_byte()
{
    int i, data;

    set_tris_c(CONTROL_READ_DQ);

    for (i=0; i < 8; i++)
    {
        control.clk = 1;

        // Receive data from timer, least significant bit first
        if(control.dq)
            data = (data >> 1) | 0x80;
        else
            data = data >> 1;

        control.clk = 0;
    }

    set_tris_c(CONTROL_WRITE);

    return data;
}

// Begin a new data transfer cycle for the DS1602
void timer_begin_data_transfer()
{
    control.rst = 0;
    control.clk = 0;
    control.rst = 1;
}

```

```

// End the data transfer cycle
void timer_end_data_transfer()
{
    control.clk = 1;
    control.rst = 0;
}

// Read the 32-bit value representing the number of seconds the timer
// has been operating.
void read_timer_data()
{
    int    lo_byte_hi_word, lo_byte_lo_word;
    int    hi_byte_hi_word, hi_byte_lo_word;
    long   hi_word, lo_word;

    timer_begin_data_transfer();

    timer_send_byte(0x41); // Read the 32 bit value of the active
                          // counter.

    // Read each of the four bytes from the 32 bit word starting with
    // the least significant bit first.
    lo_byte_lo_word = timer_read_byte();
    hi_byte_lo_word = timer_read_byte();
    lo_byte_hi_word = timer_read_byte();
    hi_byte_hi_word = timer_read_byte();

    // Combine high and low bytes of the low word into a single 16 bit
    // number;
    timer_data.lo_word = ((long)hi_byte_lo_word << 8) | lo_byte_lo_word;

    // Combine high and low bytes of the high word into a single 16 bit
    // number;
    timer_data.hi_word = ((long)hi_byte_hi_word << 8) | lo_byte_hi_word;
}

void write_timer_data()
{
    timer_begin_data_transfer();

    timer_send_byte(0x40);

    timer_send_byte(timer_data.lo_word & 0xFF);
    timer_send_byte((timer_data.lo_word) >> 8);
    timer_send_byte(timer_data.hi_word & 0xFF);
    timer_send_byte((timer_data.hi_word) >> 8);

    timer_end_data_transfer();
}

// Initialize the DS1602 timer

```

```

void setup_timer()
{
    timer_begin_data_transfer();

    // Set ocsillator trim value to a default value of 3, see DS1602
    // datasheet
    timer_send_byte(0xD8);

    timer_end_data_transfer();
}

// Reset the stored times to zero.
void reset_timer()
{
    timer_begin_data_transfer();
    timer_send_byte(0x02);    // Clear Vcc active counter
    timer_end_data_transfer();

    timer_begin_data_transfer();
    timer_send_byte(0x04);    // Clear continuous counter
    timer_end_data_transfer();
}

```

C.3 User Interface Microcontroller Source Code File SLAVE.C

```

/*****

FILE:          SLAVE.C
WRITTEN BY:    Robert B. Cooper

Main source code file for microcontroller #2 (Slave).
User Interface Microcontroller

Pulse Battery Charger: PIC16F877 - B

*****/

#include <LCD_FUNC.C>
#include <TMR_FUNC.C>
#include <stdio.h>

#use rs232(baud=9600, xmit=PIN_C6, rcv=PIN_C7, errors)

// Main program function
main()
{
    // Define Local Variables

```

```

short battery_charged = 0;
int cmd, count = 0;
long data;
float value, vboc, vbc, vbd, id;

// Setup microcontroller
init();

// Tell user to turn on external power supply
vdd_powerup();

// Tell user to connect a battery
battery_connect();

// Determine user definable settings
user_setup();

// Send user desired pulse frequency
rs232_send_long_data(pulse_frequency);
if (rs232_get_short_data() != 0xC0)
{
    charger_error(0x03);    // Pulse Frequency was sent incorrectly
}

// Send start charging command to master microcontroller
rs232_send_short_data(0xF0);
if (rs232_get_short_data() != 0xC0)
{
    charger_error(0x01);    // Communication error
}

// Display start message
lcd_putc("\f Charging Has Begun\n");
delay_ms(DISPLAY_DELAY);

// Display charger and battery parameters until the stop condition
// is reached. Valid stop conditions are end of timed charge or
// battery fully charged.
while (!battery_charged)
{
    // Display the value of the open circuit battery voltage
    rs232_send_short_data(0x10);    // Send request for data
    data = rs232_get_long_data();    // Receive 10-bit battery
    // voltage data
    vboc = get_voltage(data);        // Convert to floating point
    // value
    display_oc_battery_voltage(vboc); // Display battery voltage

    // Display the value of the battery voltage when charging
    rs232_send_short_data(0x20);
    data = rs232_get_long_data();
    vbc = get_voltage(data);
    display_chrg_battery_voltage(vbc);

    // Display the value of the battery voltage when discharging
    rs232_send_short_data(0x30);
    data = rs232_get_long_data();
}

```

```

vbd = get_voltage(data);
display_dischrg_battery_voltage(vbd);

// Display the value of the battery charging current
rs232_send_short_data(0x40);
data = rs232_get_long_data();
value = get_battery_current(data);
display_battery_charging_current(value);

// Display the value of the battery discharge current
rs232_send_short_data(0x50);
data = rs232_get_long_data();
id = get_battery_current(data);
display_battery_discharge_current(id);

// Display the value of the power supply voltage
rs232_send_short_data(0x60);
data = rs232_get_long_data();
value = get_voltage(data);
display_power_supply_voltage(value);

// Display the value of the internal temperature
rs232_send_short_data(0x70);
data = rs232_get_long_data();
value = get_internal_temperature(data);
display_internal_temperature(value);
if (value > shutdown_temp)
{
    rs232_send_short_data(0xFF); // Tell MASTER to stop charging
                                // algorithm
    charger_error(0x04);        // Display error message
}

// Display estimated battery impedance
value = calculate_battery_impedance(vboc, vbd, id);
display_battery_impedance(value);

// Display the elapsed time
read_elapsed_time();
display_elapsed_time();
delay_ms(DISPLAY_DELAY);

// Check if the stop condition has been reached
if (timed_charge)
{
    if (hr >= charge_time_hrs) // Desired charging hours have
    {                          // been reached
        if (min >= charge_time_min) // Desired charging mins have
        {                          // been reached
            battery_charged = 1;    // Battery charge time has
        }                          // been reached
    }
}
else if (constantVoltage)
{
    if (vbc > vboc)
    {

```

```

    old_DvDt = DvDt;
    DvDt = vbc - vbd;

    if (DvDt > old_DvDt)
    {
        if (DvDt - old_DvDt < 0.1)
        {
            dvdt_count += 1;
        }
        else
        {
            dvdt_count = 0;
        }
    }
    else
    {
        if (old_DvDt - DvDt < 0.1)
        {
            dvdt_count += 1;
        }
        else
        {
            dvdt_count = 0;
        }
    }

    if (dvdt_count > 10)
    {
        battery_charged = 1;
    }
}
else if (constantCurrent)
{
    // This has not been implemented.
}
// End: while (!battery_charged)

// Complete charging
rs232_send_short_data(0xFF); // Tell master to stop charging
                               // algorithm

// Display finished message and total charge time
read_elapsed_time();          // Hr, min, sec data is stored in
                               // global variables
while (1)
{
    lcd_putc("\f Charging Complete\n");
    delay_ms(DISPLAY_DELAY);
    display_elapsed_time();
    delay_ms(DISPLAY_DELAY);
}

// Setup the microcontroller's ports

```

```

void init()
{
    // Initialize LCD
    lcd_init();

    // Initialize microcontroller I/O pins
    set_tris_a(0x3F);    // All port A pins configured as inputs
    set_tris_b(0xFF);    // All port B pins configured as inputs
    set_tris_e(0x7);     // All port E pins configured as inputs

    // Setup the elapsed timer
    setup_timer();        // Enable the timer
    reset_timer();        // Reset time to 00:00:00
}

```

```

void vdd_powerup()
{
    short continue_loop = 1;
    long  data;
    int   key = 99;

    while (continue_loop)
    {
        lcd_putc("\fTurn External Power\n");
        lcd_putc("Supply On & Press #");
        key = scan_keypad();

        if (key == 11)
        {
            rs232_send_short_data(0xD0);
            data = rs232_get_long_data();

            if (data > 2)
            {
                rs232_send_short_data(0xC0);
                continue_loop = 0;
                delay_ms(500);
            }
        }
    }
}

```

```

void battery_connect()
{
    short continue_loop = 1, valid_battery = 0;
    long  data;
    int   key = 99;

    while (continue_loop)
    {
        lcd_putc("\fConnect Battery To\n");
        lcd_putc("Charger & Press #");
        key = scan_keypad();

        if (key == 11)

```

```

    {
        rs232_send_short_data(0xA0);
        data = rs232_get_long_data();

        valid_battery = test_battery_voltage(data);

        if (valid_battery)
        {
            rs232_send_short_data(0xC0);
            continue_loop = 0;
            delay_ms(500);
        }
    }
}

// Receive 2 bytes of data from the master microcontroller.
long rs232_get_long_data()
{
    int    data_hi, data_lo;
    long   data;

    data_hi = getc();
    data_lo = getc();

    data = data_hi;
    data = (data << 8) + data_lo;

    return data;
}

// Receive 1 byte of data from the master microcontroller.
long rs232_get_short_data()
{
    int    data;

    data = getc();

    return data;
}

// Send a 1 byte of data to the master microcontroller
void rs232_send_long_data(long data)
{
    int    data_hi, data_lo;

    // Break long data into two separate bytes of data
    data_hi = data >> 8;    // Move the upper byte to the lower 8 bits
    data_lo = data;        // Upper byte is lost in this assignment

    // Send high byte first;
    putc(data_hi);
    delay_us(2);           // Delay needed for data to be sent correctly.
    putc(data_lo);
}

```



```

}

// Send a 1 byte of data to the master microcontroller
void rs232_send_short_data(int data)
{
    putc(data);
}

// Determine if a battery is connected to the charger and if its open
// circuit voltage is within a valid range.
short test_battery_voltage(long data)
{
    // No battery is connected to the charger
    if (data < 10)
    {
        lcd_putc("\fNo Battery Connected\n");
        lcd_putc(" Press RESET button");
        delay_ms(2000);
        return 0;
    }

    // Battery voltage is less than 5 volts.
    if(data < 102)
    {
        lcd_putc("\fBad Battery Voltage\n");
        lcd_putc(" Voltage < 5 Volts");
        delay_ms(2000);
        return 0;
    }

    // Battery voltage is greater than 15 volts.
    if(data > 307)
    {
        lcd_putc("\f Batt. Fully Charged\n");
        lcd_putc("  Voc > 15 Volts");
        delay_ms(2000);
        return 0;
    }

    // Battery voltage is within the valid range of 5 - 15 volts
    return 1;
}

// Determine any special user settings.
void user_setup()
{
    int    key, i, j;
    boolean continue_loop = 1;

    // Display Setup Message
    lcd_putc("\f  Charger Setup\n");
    lcd_putc("Press # to Continue");

    while (continue_loop)

```

```

    {
        key = scan_keypad();

        if (key == 11)          // Enter key was pressed
        {
            enter_user_settings();
            continue_loop = 0;
        }
    }
}

// Enter user definable settings
void enter_user_settings()
{
    int    key = 0, menu = 1, continue_loop = 1;

    while (continue_loop)
    {
        if (menu == 1)
        {
            lcd_putc("\f1: Timed Charge\n");
            lcd_putc("2: Pulse Freq.      ");
            lcd_send_data(1, 0x7E);    // Display the right arrow

            key = scan_keypad();
            delay_ms(250);    // Adjust delay in order to avoid
                             // unintentional key presses.

            if (key == 1)
            {
                enter_charge_time();
            }
            else if (key == 2)
            {
                enter_pulse_frequency();
            }
            else if (key == 9)
            {
                menu = 2;
            }
        }

        if (menu == 2)
        {
            lcd_putc("\f3: Stop: dv/dt=0\n");
            lcd_putc("4: Stop: di/dt=0  ");
            lcd_send_data(1, 0x7F);    // Display the left arrow
            lcd_send_data(1, 0x7E);    // Display the right arrow

            key = scan_keypad();
            delay_ms(250);    // Adjust delay in order to avoid
                             // unintentional key presses.

            if (key == 3)
            {
                constantVoltage = 1;
            }
        }
    }
}

```

```

        constantCurrent = 0;
        timed_charge = 0;
    }
    else if (key == 4)
    {
        constantCurrent = 1;
        constantVoltage = 0;
        timed_charge = 0;
    }
    else if (key == 7)
    {
        menu = 1;
    }
    else if (key == 9)
    {
        menu = 3;
    }
}

if (menu == 3)
{
    lcd_putc("\f5: Begin Charging\n");
    lcd_send_data(1, 0x7F);    // Display the left arrow

    key = scan_keypad();
    delay_ms(250);    // Adjust delay in order to avoid
                     // unintentional key presses.

    if (key == 5)
    {
        continue_loop = 0;
    }
    else if (key == 7)
    {
        menu = 2;
    }
}
}

// Enter the total charge time for the battery
void enter_charge_time()
{
    short continue_loop = 1;
    int key, j;
    int digit[4] = {0, 0, 0, 0};

    lcd_putc("\f Total Charge Time?\n");
    lcd_putc("      00:00");

    while (continue_loop)
    {
        key = scan_keypad();

        if (key <= 9)    // A digit was pressed
        {

```

```

    for (j=0; j<3; j++)
    {
        digit[j] = digit[j+1];        // Shift each number to the left
                                      // 1 position.
    }
    digit[3] = key;
    lcd_putc("\f Total Charge Time?\n");
    printf(lcd_putc, "      %U%U:%U%U", digit[0], digit[1],
        digit[2], digit[3]);
    delay_ms(250);        // Adjust delay in order to avoid
                          // unintentional key presses.
}

if (key == 10)          // Reset key was pressed
{
    lcd_putc("\f Total Charge Time?\n");
    lcd_putc("      00:00");
    digit[0] = 0;
    digit[1] = 0;
    digit[2] = 0;
    digit[3] = 0;
}

if (key == 11)          // Enter key was pressed
{
    charge_time_hrs = digit[0] * 10 + digit[1];
    charge_time_min = digit[2] * 10 + digit[3];

    if (charge_time_min > 59)
    {
        lcd_putc("\fEntered Time Invalid\n");
        delay_ms(2000);

        lcd_putc("\f Total Charge Time?\n");
        lcd_putc("      00:00");
        digit[0] = 0;
        digit[1] = 0;
        digit[2] = 0;
        digit[3] = 0;
    }
    else
    {
        if (charge_time_hrs != 0 && charge_time_min != 0)
        {
            timed_charge = 0;        // Time entered was 00:00, charging
                                      // not timed
        }
        else
        {
            timed_charge = 1;
            constantVoltage = 0;
            constantCurrent = 0;
        }
        continue_loop = 0;
    }
}
} // End: while (continue_loop)

```

```

printf(lcd_putc, "\f hrs = %U\n", charge_time_hrs);
printf(lcd_putc, " min = %U", charge_time_min);
delay_ms(2000);
}

// Enter the pulse frequency to use.
void enter_pulse_frequency()
{
    short continue_loop = 1;
    int    key, j;
    int    digit[4] = {0, 0, 0, 0};

    lcd_putc("\fFrequency 1Hz - 1kHz\n");
    lcd_putc("      Fp = 0000");

    while (continue_loop)
    {
        key = scan_keypad();

        if (key <= 9)          // A digit was pressed
        {
            for (j=0; j<3; j++)
            {
                digit[j] = digit[j+1];    // Shift each number to the left
                                           // 1 position.
            }
            digit[3] = key;
            lcd_putc("\fFrequency 1Hz - 1kHz\n");
            printf(lcd_putc, "      Fp = %U%U%U%U", digit[0], digit[1],
                    digit[2], digit[3]);
            delay_ms(250);    // Adjust delay in order to avoid
                               // unintentional key presses.
        }

        if (key == 10)        // Reset key was pressed
        {
            lcd_putc("\fFrequency 1Hz - 1kHz\n");
            lcd_putc("      Fp = 0000");
            digit[0] = 0;
            digit[1] = 0;
            digit[2] = 0;
            digit[3] = 0;
        }

        if (key == 11)        // Enter key was pressed
        {
            pulse_frequency = digit[0]*1000 + digit[1]*100 + digit[2]*10 +
                               digit[3];

            if (pulse_frequency < 1 || pulse_frequency > 1000)
            {
                lcd_putc("\f Entered Frequency\n");
                lcd_putc("      was Invalid\n");
                delay_ms(2000);
            }
        }
    }
}

```

```

        lcd_putc("\fFrequency 1Hz - 1kHz\n");
        lcd_putc("      Fp = 0000");
        digit[0] = 0;
        digit[1] = 0;
        digit[2] = 0;
        digit[3] = 0;
    }
    else
    {
        continue_loop = 0;
    }
}
} // End: while (continue_loop)
}

// Scan the pins the keypad is attached to until a key is pressed
int scan_keypad()
{
    int key, kp = 1;

    while(kp)
    {
        key = 99;

        if(!keypad_b.three) key = 3;
        if(!keypad_b.six)   key = 6;
        if(!keypad_b.pound) key = 11;
        if(!keypad_b.two)   key = 2;
        if(!keypad_b.five)  key = 5;
        if(!keypad_b.one)   key = 1;
        if(!keypad_b.four)  key = 4;
        if(!keypad_b.star)  key = 10;
        if(!keypad_e.seven) key = 7;
        if(!keypad_e.eight) key = 8;
        if(!keypad_e.nine)  key = 9;
        if(!input(PIN_A4))  key = 0;

        if(key < 99)
        {
            delay_ms(50);

            if(key == 1)  kp = keypad_b.one;
            if(key == 2)  kp = keypad_b.two;
            if(key == 3)  kp = keypad_b.three;
            if(key == 4)  kp = keypad_b.four;
            if(key == 5)  kp = keypad_b.five;
            if(key == 6)  kp = keypad_b.six;
            if(key == 7)  kp = keypad_e.seven;
            if(key == 8)  kp = keypad_e.eight;
            if(key == 9)  kp = keypad_e.nine;
            if(key == 0)  kp = input(PIN_A4);
            if(key == 10) kp = keypad_b.star;
            if(key == 11) kp = keypad_b.pound;
        }
    }
}

```

```

    return key;
}

// Read the elapsed time from the timer
void read_elapsed_time()
{
    int    ihr, imin, isec, i;

    // Reset variables
    hr = 0;
    min = 0;
    sec = 0;

    read_timer_data();

    for(i = 0; i < 16; i++)
    {
        if (bit_test(timer_data.lo_word, i))
        {
            hr = hr + (long)time[i][0];
            min = min + (long)time[i][1];
            sec = sec + (long)time[i][2];
        }
    }

    for(i = 16; i < 18; i++)
    {
        if (bit_test(timer_data.hi_word, i))
        {
            hr = hr + time[i][0];
            min = min + time[i][1];
            sec = sec + time[i][2];
        }
    }

    imin = sec / 60;           // Number of minutes if their are more
                              // then 60 secs total
    sec = sec - (imin * 60);

    min = imin + min;
    ihr = min / 60;           // Number of hours if their are more then
                              // 60 min total
    min = min - (ihr * 60);

    hr = hr + ihr;
}

// Display the elapsed time in 00:00:00 format
void display_elapsed_time()
{
    lcd_putc("\fCharge Time Elapsed\n");

    if ((hr < 10 && min < 10) && sec < 10)
        printf(lcd_putc, "    0%lu:0%lu:0%lu", hr, min, sec);
    else if ((hr < 10 && min < 10) && sec >= 10)

```

```

    printf(lcd_putc, "      0%lu:0%lu:%lu", hr, min, sec);
else if ((hr < 10 && min >= 10) && sec < 10)
    printf(lcd_putc, "      0%lu:%lu:0%lu", hr, min, sec);
else if ((hr < 10 && min >= 10) && sec >= 10)
    printf(lcd_putc, "      0%lu:%lu:%lu", hr, min, sec);
else if ((hr >= 10 && min < 10) && sec < 10)
    printf(lcd_putc, "      %lu:0%lu:0%lu", hr, min, sec);
else if ((hr >= 10 && min < 10) && sec >= 10)
    printf(lcd_putc, "      %lu:0%lu:%lu", hr, min, sec);
else if ((hr >= 10 && min >= 10) && sec < 10)
    printf(lcd_putc, "      %lu:%lu:0%lu", hr, min, sec);
else if ((hr >= 10 && min >= 10) && sec >= 10)
    printf(lcd_putc, "      %lu:%lu:%lu", hr, min, sec);
}

```

// Display error messages and take appropriate actions

```

void charger_error(int code)
{
    switch (code)
    {
        case 1:
            lcd_putc("\fCommunication Error\n");
            lcd_putc("  Restart Charger ");
            while(1);
            break;
        case 2:          // Battery voltage was not valid, error msg
                        // has already been displayed
            while(1);
            break;
        case 3:
            lcd_putc("\f Pulse Freq. Error\n");
            lcd_putc("  Restart Charger ");
            while(1);
            break;
        case 4:
            lcd_putc("\f MOSFET Temperature\n");
            lcd_putc("Exceeded 150 ");
            lcd_send_data(1, 0xDF);    // Display the degree symbol
            lcd_putc("F");
            while(1);
            break;
        default:
            lcd_putc("\f  Unknown Error\n");
            lcd_putc("  Restart Charger ");
            while(1);
            break;
    }
}

```

// Convert the 10-bit battery voltage and power supply voltage data
// into a floating point number representing the actual measured
// voltage

```

float get_voltage(long data)
{
    float voltage;

```



```

    voltage = (float)data * 0.0488758;

    return voltage;
}

// Convert the 10-bit battery current data into a floating point number
// representing the actual measured current
float get_battery_current(long data)
{
    float current;

    current = (float)data * 0.0592435;

    return current;
}

// Convert the 10-bit temperature data into a floating point number
// representing the actual measured temperature
float get_internal_temperature(long data)
{
    float temp;

    temp = ((float)data * 0.2641938) + 32;

    return temp;
}

// Display the open circuit battery voltage and pause
void display_oc_battery_voltage(float data)
{
    lcd_putc("\fOpen Battery Voltage\n");
    printf(lcd_putc, "Vboc = %2.3f Volts", data);
    delay_ms(DISPLAY_DELAY);
}

// Display the battery voltage when charging and pause
void display_chrg_battery_voltage(float data)
{
    lcd_putc("\f Charging Voltage\n");
    printf(lcd_putc, " Vbc = %2.3f Volts", data);
    delay_ms(DISPLAY_DELAY);
}

// Display the battery voltage when discharging and pause
void display_dischrg_battery_voltage(float data)
{
    lcd_putc("\f Discharge Voltage\n");
    printf(lcd_putc, " Vbd = %2.3f Volts", data);
    delay_ms(DISPLAY_DELAY);
}

```

```

// Display the battery charging current and pause
void display_battery_charging_current(float data)
{
    lcd_putc("\f Charging Current\n");
    printf(lcd_putc, " Ic = %2.3f Amps", data);
    delay_ms(DISPLAY_DELAY);
}

// Display the battery discharge current and pause
void display_battery_discharge_current(float data)
{
    lcd_putc("\f Discharge Current\n");
    printf(lcd_putc, " Id = %2.3f Amps", data);
    delay_ms(DISPLAY_DELAY);
}

// Display the battery discharge current and pause
void display_power_supply_voltage(float data)
{
    lcd_putc("\fPower Supply Voltage\n");
    printf(lcd_putc, " Vdd = %2.3f Volts", data);
    delay_ms(DISPLAY_DELAY);
}

// Display the battery discharge current and pause
void display_internal_temperature(float data)
{
    lcd_putc("\fInternal Temperature\n");
    printf(lcd_putc, " T = %2.3f ", data);
    lcd_send_data(1, 0xDF); // Display the degree symbol
    lcd_putc("F");
    delay_ms(DISPLAY_DELAY);
}

// Display the battery impedance and pause
void display_battery_impedance(float data)
{
    lcd_putc("\f Battery Impedance\n");

    if (data == -1) // Battery impedance is infinite
    {
        lcd_putc(" Zb = infinite");
    }
    else
    {
        printf(lcd_putc, " Zb = %4.4f ", data);
        lcd_send_data(1, 0xF4); // Display the omega symbol
    }
    delay_ms(DISPLAY_DELAY);
}

```

```

// Calculate the battery impedance during the charge period
float calculate_battery_impedance(float vboc, float vbd, float id)
{
    float impedance, vd;

    if (id <= 0)
    {
        impedance = -1;          // Signify that the battery impedance is
                                // infinite
    }
    else
    {
        vd = vboc - vbd;
        if (vd < 0)
        {
            impedance = minImpedance; // Voltage error so show the
                                      // previous impedance value.
        }
        else
        {
            impedance = vd / id;
            if (impedance < minImpedance)
            {
                minImpedance = impedance; // Save the value of the new
                                          // minimum impedance.
            }
            else
            {
                impedance = minImpedance; // Since impedance will not go
                                          // up a voltage error occurred
                                          // so return the minimum
                                          // previous impedance value.
            }
        }
    }

    return impedance;
}

```

C.4 User Interface Microcontroller Source Code File SLAVE.H

```

/*****

FILE:          SLAVE.H
WRITTEN BY:    Robert B. Cooper

Main header file for microcontroller #2.
USER INTERFACE MICROCONTROLLER
Pulse Battery Charger: PIC16F877 - B

*****/

```

```

#device PIC16F877
#use delay(clock=4000000)      // 4 MHz oscillator
#nolist
#fuses HS,NOWDT,NOPROTECT,NOBROWNOUT,NOPUT

#define PORTB 0x06             // Port B Address
#define PORTC 0x07             // Port C Address
#define PORTD 0x08             // Port D Address
#define PORTE 0x09             // Port E Address

#define LCD_LINE_2 0x40        // Starting address of LCD Line 2

#define FALSE 0
#define TRUE 1

#define BYTE int
#define BOOLEAN short int

#define DISPLAY_DELAY 3000     // Default delay between display updates
                                // is (3 secs.)

// Define global variables
int  charge_time_hrs   = 0x00; // Default time for charge, Charger
                                // will shut off when
int  charge_time_min   = 0x00; // stop condition is reached
                                // regardless of elapsed time

float minImpedance      = 10000; // Variable to hold the minimum
                                // battery impedance.
float minCurrent        = 0;     // Minimum value of charging current.
float old_DvDt          = 100;   // Previous difference between Vboc
                                // and Vbc
float DvDt              = 100;   // Current difference between Vboc and
                                // Vbc
long  pulse_frequency   = 1000; // Default pulse frequency of 1 kHz.
int   dvdt_count        = 0;     // Number of consecutive times that
                                // DvDt is within 0.1 volts

boolean rs232_data      = 0;     // True if data is in the rs232 rcv
                                // buffer
boolean timed_charge     = 0;     // True if the user wants to limit the
                                // charging time
boolean constantCurrent  = 0;     // True if current is used to
                                // determine charge completion.
boolean constantVoltage  = 1;     // True if voltage is used to
                                // determine charge completion.
                                // This is the default condition.

float shutdown_temp     = 150;   // Shut the charger off if the
                                // MOSFET temperature is warmer than
                                // this value.

long  hr = 0, min = 0, sec = 0; // Elapsed time variables

// Hr, min, and sec associated with each bit of the 32-bit word from
// the elapsed timer. Ex: If bits 0 and 12 are set then the elapsed

```

```

// time is 1:8:16 + 0:0:1 = 1:8:17
const int time[18][3] = {{ 0, 0, 1}
                        { 0, 0, 2}
                        { 0, 0, 4}
                        { 0, 0, 8}
                        { 0, 0, 16}
                        { 0, 0, 32}
                        { 0, 1, 4}
                        { 0, 2, 8}
                        { 0, 4, 16}
                        { 0, 8, 32}
                        { 0, 17, 4}
                        { 0, 34, 8}
                        { 1, 8, 16}
                        { 2, 16, 32}
                        { 4, 33, 4}
                        { 9, 6, 8}
                        {18, 12, 16}
                        {36, 24, 32}};

// Define the structure for a 32 bit long word used to store timer
// data.
struct word32
{
    long    hi_word;    // Upper 16 bits
    long    lo_word;    // Lower 16 bits
} timer_data;

struct control_pins
{
    boolean rs;        // LCD register select
    boolean rw;        // LCD Read/Write
    boolean enable;    // LCD Enable
    boolean rst;       // DS1602 reset
    boolean dq;        // DS1602 data i/o
    boolean clk;       // DS1602 clock
    boolean xmit;      // RS-232 transmit pin, hardware control
    boolean rcv;       // RS-232 receive pin, hardware control
} control;

// Define a structure so that all pins assigned to the LCD data output
// can be written to with a single command.
struct lcd_data_pins
{
    int      data : 8;  // Pins D0 - D7
} lcd_data;

struct keypad_pins_portb
{
    boolean star;      // Pin B0
    boolean four;      // Pin B1
    boolean one;       // Pin B2
    boolean five;      // Pin B3
    boolean two;       // Pin B4

```

```

    boolean pound;        // Pin B5
    boolean six;          // Pin B6
    boolean three;        // Pin B7
} keypad_b;

struct keypad_pins_porte
{
    boolean seven;        // Pin E0
    boolean eight;        // Pin E1
    boolean nine;         // Pin E2
} keypad_e;

// Assign structures to microcontroller ports
#define keypad_b = PORTB // Assign the keypad_b structure to PORTB
#define control = PORTC  // Assign the control structure to PORTS
#define lcd_data = PORTD // Assign the lcd_data structure to PORTD
#define keypad_e = PORTE // Assign the keypad_e structure to PORTE

// I/O port direction constants
STRUCT control_pins const CONTROL_WRITE = {0,0,0,0,0,0,0,1};
STRUCT control_pins const CONTROL_READ_DQ = {0,0,0,0,1,0,0,1};
STRUCT lcd_data_pins const LCD_WRITE = {0x00}; // All pins are outputs
STRUCT lcd_data_pins const LCD_READ = {0xFF};  // All pins are inputs

// Keypad symbols
char const keypad_sym[12] = {'1', '2', '3', '4', '5', '6', '7', '8',
                             '9', '0', '*', '#'};

/*****
Function prototypes
*****/

// LCD related functions
void lcd_send_byte(byte n);           // Send a byte of data to the LCD
byte lcd_read_data();                 // Read a byte of data from the LCD
void lcd_send_data(byte address, byte data); // Send data to LCD once
                                           // it is initialized
void lcd_init();                       // Initialize the LCD
void lcd_moveto_xy(byte x, byte y);    // Move the LCD cursor to the x,y
                                           // position
void lcd_putc(char c);                 // Write characters to the LCD

// Elapsed time related functions
void timer_send_byte(byte data);       // Send a single byte of data to
                                           // the timer
int timer_read_byte();                 // Read a single byte of data from
                                           // the timer
void timer_begin_data_transfer();      // Start the transfer of data from
                                           // the timer
void timer_end_data_transfer();        // End the transfer of data from
                                           // the timer
void read_timer_data();                 // Read a 32-bit word from the
                                           // timer
void write_timer_data();                // Write command data to the timer

```

```

void setup_timer();           // Setup the timer and choose
                              // features to use
void reset_timer();           // Reset the timer to time 00:00:00
void read_elapsed_time();     // Read the elapsed time from the
                              // timer

// Setup and Initialization functions
void init();                  // Initialize microcontroller pins and
                              // special features
void user_setup();            // Handle startup and user preferences
void enter_user_settings();   // Preference Menu display and calls
                              // "enter_" functions
void enter_pulse_frequency(); // User can choose the pulse frequency
                              // to use
void enter_charge_time();     // User can set a specific amount of
                              // time to charge
short test_battery_voltage(long data); // Tests the initial battery
                                      // condition

void vdd_powerup();
void battery_connect();

// User interface functions not related to the LCD
int scan_keypad();            // Return key pressed on keypad and
                              // provides a de-bouncing function

// Functions that handle error conditions
void charger_error(int code); // Display errors messages and take
                              // appropriate action

// Functions that convert 10-bit long variable data to float point
// numbers representing the actual measured value at the source
float get_voltage(long data);
float get_battery_current(long data);
float get_internal_temperature(long data);

// Display related functions
void display_oc_battery_voltage(float data);
void display_chrg_battery_voltage(float data);
void display_dischrg_battery_voltage(float data);
void display_battery_charging_current(float data);
void display_battery_discharge_current(float data);
void display_power_supply_voltage(float data);
void display_internal_temperature(float data);
void display_battery_impedance(float data);
void display_elapsed_time();

// Communications related functions
long rs232_get_long_data();    // Receive 2 bytes of data from
                              // master
int rs232_get_short_data();    // Receive 1 byte of data from
                              // master

```

```

void rs232_send_long_data(long data); // Send 2 bytes of data to
                                       // master
void rs232_send_short_data(int data); // Send 1 byte of data to master

// Functions that do calculations on battery parameters
float calculate_battery_impedance(float vboc, float vbd, float id);

/*****
 *
 *   All code beyond this point was compiler generated
 *
 *****/

// PORT A pin definitions
#define PIN_A0  40
#define PIN_A1  41
#define PIN_A2  42
#define PIN_A3  43
#define PIN_A4  44
#define PIN_A5  45

// PORT B pin definitions
#define PIN_B0  48
#define PIN_B1  49
#define PIN_B2  50
#define PIN_B3  51
#define PIN_B4  52
#define PIN_B5  53
#define PIN_B6  54
#define PIN_B7  55

// PORT C pin definitions
#define PIN_C0  56
#define PIN_C1  57
#define PIN_C2  58
#define PIN_C3  59
#define PIN_C4  60
#define PIN_C5  61
#define PIN_C6  62
#define PIN_C7  63

// PORT D pin definitions
#define PIN_D0  64
#define PIN_D1  65
#define PIN_D2  66
#define PIN_D3  67
#define PIN_D4  68
#define PIN_D5  69
#define PIN_D6  70
#define PIN_D7  71

// PORT E pin definitions
#define PIN_E0  72
#define PIN_E1  73

```



```

#define PIN_E2 74

// Constants used for RESTART_CAUSE()
#define WDT_FROM_SLEEP 0
#define WDT_TIMEOUT 8
#define MCLR_FROM_SLEEP 16
#define NORMAL_POWER_UP 24

// Constants used for SETUP_COUNTERS()
#define RTCC_INTERNAL 0
#define RTCC_EXT_L_TO_H 32
#define RTCC_EXT_H_TO_L 48
#define RTCC_DIV_2 0
#define RTCC_DIV_4 1
#define RTCC_DIV_8 2
#define RTCC_DIV_16 3
#define RTCC_DIV_32 4
#define RTCC_DIV_64 5
#define RTCC_DIV_128 6
#define RTCC_DIV_256 7
#define WDT_18MS 8
#define WDT_36MS 9
#define WDT_72MS 10
#define WDT_144MS 11
#define WDT_288MS 12
#define WDT_576MS 13
#define WDT_1152MS 14
#define WDT_2304MS 15
#define L_TO_H 0x40
#define H_TO_L 0
#define RTCC_ZERO 0x0B20 // Used for ENABLE/DISABLE INTERRUPTS
#define RB_CHANGE 0x0B08 // Used for ENABLE/DISABLE INTERRUPTS
#define EXT_INT 0x0B10 // Used for ENABLE/DISABLE INTERRUPTS
#define GLOBAL 0x0BC0 // Used for ENABLE/DISABLE INTERRUPTS

// Constants used for Timer1 and Timer2
#define T1_DISABLED 0
#define T1_INTERNAL 5
#define T1_EXTERNAL 7
#define T1_EXTERNAL_SYNC 3
#define T1_CLK_OUT 8
#define T1_DIV_BY_1 0
#define T1_DIV_BY_2 0x10
#define T1_DIV_BY_4 0x20
#define T1_DIV_BY_8 0x30
#define T1_DIV_BY_16 0x40
#define T1_DIV_BY_32 0x50
#define T1_DIV_BY_64 0x60
#define T1_DIV_BY_128 0x70
#define T1_DIV_BY_256 0x80
#define T1_DIV_BY_512 0x90
#define T1_DIV_BY_1024 0xA0
#define T1_DIV_BY_2048 0xB0
#define T1_DIV_BY_4096 0xC0
#define T1_DIV_BY_8192 0xD0
#define T1_DIV_BY_16384 0xE0
#define T1_DIV_BY_32768 0xF0
#define T1_DIV_BY_65536 0x100
#define T1_DIV_BY_131072 0x200
#define T1_DIV_BY_262144 0x300
#define T1_DIV_BY_524288 0x400
#define T1_DIV_BY_1048576 0x500
#define T1_DIV_BY_2097152 0x600
#define T1_DIV_BY_4194304 0x700
#define T1_DIV_BY_8388608 0x800
#define T1_DIV_BY_16777216 0x900
#define T1_DIV_BY_33554432 0xA00
#define T1_DIV_BY_67108864 0xB00
#define T1_DIV_BY_134217728 0xC00
#define T1_DIV_BY_268435456 0xD00
#define T1_DIV_BY_536870912 0xE00
#define T1_DIV_BY_1073741824 0xF00
#define T1_DIV_BY_2147483648 0x1000
#define T1_DIV_BY_4294967296 0x2000
#define T1_DIV_BY_8589934592 0x3000
#define T1_DIV_BY_17179869184 0x4000
#define T1_DIV_BY_34359738368 0x5000
#define T1_DIV_BY_68719476736 0x6000
#define T1_DIV_BY_137438953472 0x7000
#define T1_DIV_BY_274877906944 0x8000
#define T1_DIV_BY_549755813888 0x9000
#define T1_DIV_BY_1099511627776 0xA000
#define T1_DIV_BY_2199023255552 0xB000
#define T1_DIV_BY_4398046511104 0xC000
#define T1_DIV_BY_8796093022208 0xD000
#define T1_DIV_BY_17592186044416 0xE000
#define T1_DIV_BY_35184372088832 0xF000
#define T1_DIV_BY_70368744177664 0x10000
#define T1_DIV_BY_140737488355328 0x20000
#define T1_DIV_BY_281474976710656 0x30000
#define T1_DIV_BY_562949953421312 0x40000
#define T1_DIV_BY_1125899906842624 0x50000
#define T1_DIV_BY_2251799813685248 0x60000
#define T1_DIV_BY_4503599627370496 0x70000
#define T1_DIV_BY_9007199254740992 0x80000
#define T1_DIV_BY_18014398509481984 0x90000
#define T1_DIV_BY_36028797018963968 0xA0000
#define T1_DIV_BY_72057594037927936 0xB0000
#define T1_DIV_BY_144115188075855872 0xC0000
#define T1_DIV_BY_288230376151711744 0xD0000
#define T1_DIV_BY_576460752303423488 0xE0000
#define T1_DIV_BY_1152921504606846976 0xF0000
#define T1_DIV_BY_2305843009213693952 0x100000
#define T1_DIV_BY_4611686018427387904 0x200000
#define T1_DIV_BY_9223372036854775808 0x300000
#define T1_DIV_BY_18446744073709551616 0x400000
#define T1_DIV_BY_36893488147419103232 0x500000
#define T1_DIV_BY_73786976294838206464 0x600000
#define T1_DIV_BY_147573952589676412928 0x700000
#define T1_DIV_BY_295147905179352825856 0x800000
#define T1_DIV_BY_590295810358705651712 0x900000
#define T1_DIV_BY_1180591620717411303424 0xA00000
#define T1_DIV_BY_2361183241434822606848 0xB00000
#define T1_DIV_BY_4722366482869645213696 0xC00000
#define T1_DIV_BY_9444732965739290427392 0xD00000
#define T1_DIV_BY_18889465931478580854784 0xE00000
#define T1_DIV_BY_37778931862957161709568 0xF00000
#define T1_DIV_BY_75557863725914323419136 0x1000000
#define T1_DIV_BY_151115727451828646838272 0x2000000
#define T1_DIV_BY_302231454903657293676544 0x3000000
#define T1_DIV_BY_604462909807314587353088 0x4000000
#define T1_DIV_BY_1208925819614629174706176 0x5000000
#define T1_DIV_BY_2417851639229258349412352 0x6000000
#define T1_DIV_BY_4835703278458516698824704 0x7000000
#define T1_DIV_BY_9671406556917033397649408 0x8000000
#define T1_DIV_BY_19342813113834066795298816 0x9000000
#define T1_DIV_BY_38685626227668133590597632 0xA000000
#define T1_DIV_BY_77371252455336267181195264 0xB000000
#define T1_DIV_BY_154742504910672534362390528 0xC000000
#define T1_DIV_BY_309485009821345068724781056 0xD000000
#define T1_DIV_BY_618970019642690137449562112 0xE000000
#define T1_DIV_BY_1237940039285380274899124224 0xF000000
#define T1_DIV_BY_2475880078570760549798248448 0x10000000
#define T1_DIV_BY_4951760157141521099596496896 0x20000000
#define T1_DIV_BY_9903520314283042199192993792 0x30000000
#define T1_DIV_BY_19807040628566084398385987584 0x40000000
#define T1_DIV_BY_39614081257132168796771975168 0x50000000
#define T1_DIV_BY_79228162514264337593543950336 0x60000000
#define T1_DIV_BY_158456325028528675187087900672 0x70000000
#define T1_DIV_BY_316912650057057350374175801344 0x80000000
#define T1_DIV_BY_633825300114114700748351602688 0x90000000
#define T1_DIV_BY_1267650600228229401496703205376 0xA0000000
#define T1_DIV_BY_2535301200456458802993406410752 0xB0000000
#define T1_DIV_BY_5070602400912917605986812821504 0xC0000000
#define T1_DIV_BY_10141204801825835211973625643008 0xD0000000
#define T1_DIV_BY_20282409603651670423947251286016 0xE0000000
#define T1_DIV_BY_40564819207303340847894502572032 0xF0000000
#define T1_DIV_BY_81129638414606681695789005144064 0x100000000
#define T1_DIV_BY_162259276829213363391578010288128 0x200000000
#define T1_DIV_BY_324518553658426726783156020576256 0x300000000
#define T1_DIV_BY_649037107316853453566312041152512 0x400000000
#define T1_DIV_BY_1298074214633706907132624082305024 0x500000000
#define T1_DIV_BY_2596148429267413814265248164610048 0x600000000
#define T1_DIV_BY_5192296858534827628530496329220096 0x700000000
#define T1_DIV_BY_10384593717069655257060992658440192 0x800000000
#define T1_DIV_BY_20769187434139310514121985316880384 0x900000000
#define T1_DIV_BY_41538374868278621028243970633760768 0xA00000000
#define T1_DIV_BY_83076749736557242056487941267521536 0xB00000000
#define T1_DIV_BY_166153499473114484112975882535043072 0xC00000000
#define T1_DIV_BY_332306998946228968225951765070086144 0xD00000000
#define T1_DIV_BY_664613997892457936451903530140172288 0xE00000000
#define T1_DIV_BY_1329227995784915872903807060280344576 0xF00000000
#define T1_DIV_BY_2658455991569831745807614120560689152 0x1000000000
#define T1_DIV_BY_5316911983139663491615228241121378304 0x2000000000
#define T1_DIV_BY_10633823966279326983230456482242756608 0x3000000000
#define T1_DIV_BY_21267647932558653966460912964485513216 0x4000000000
#define T1_DIV_BY_42535295865117307932921825928971026432 0x5000000000
#define T1_DIV_BY_85070591730234615865843651857942052864 0x6000000000
#define T1_DIV_BY_170141183460469231731687303715884105728 0x7000000000
#define T1_DIV_BY_340282366920938463463374607431768211456 0x8000000000
#define T1_DIV_BY_680564733841876926926749214863536422912 0x9000000000
#define T1_DIV_BY_1361129467683753853853498429727072845824 0xA000000000
#define T1_DIV_BY_2722258935367507707706996859454145691648 0xB000000000
#define T1_DIV_BY_5444517870735015415413993718908291383296 0xC000000000
#define T1_DIV_BY_10889035741470030830827987437816582766592 0xD000000000
#define T1_DIV_BY_21778071482940061661655974875633165533184 0xE000000000
#define T1_DIV_BY_43556142965880123323311949751266331066368 0xF000000000
#define T1_DIV_BY_87112285931760246646623899502532662132736 0x10000000000
#define T1_DIV_BY_174224571863520493293247799005065324265472 0x20000000000
#define T1_DIV_BY_348449143727040986586495598010130648530944 0x30000000000
#define T1_DIV_BY_696898287454081973172991196020261297061888 0x40000000000
#define T1_DIV_BY_1393796574908163946345982392040522594123776 0x50000000000
#define T1_DIV_BY_2787593149816327892691964784081045188247552 0x60000000000
#define T1_DIV_BY_5575186299632655785383929568162090376495104 0x70000000000
#define T1_DIV_BY_11150372599265311570767859136324180752990208 0x80000000000
#define T1_DIV_BY_22300745198530623141535718272648361505980416 0x90000000000
#define T1_DIV_BY_44601490397061246283071436545296723011960832 0xA0000000000
#define T1_DIV_BY_89202980794122492566142873090593446023921664 0xB0000000000
#define T1_DIV_BY_178405961588244985132285746181186892047843328 0xC0000000000
#define T1_DIV_BY_356811923176489970264571492362373784095686656 0xD0000000000
#define T1_DIV_BY_713623846352979940529142984724747568191373312 0xE0000000000
#define T1_DIV_BY_1427247692705959881058285969449495136382746624 0xF0000000000
#define T1_DIV_BY_2854495385411919762116571938898990272765493248 0x100000000000
#define T1_DIV_BY_5708990770823839524233143877797980545530986496 0x200000000000
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#define T1_DIV_BY_22835963083295358096932575511191922182123945984 0x400000000000
#define T1_DIV_BY_45671926166590716193865151022383844364247891968 0x500000000000
#define T1_DIV_BY_91343852333181432387730302044767688728495783936 0x600000000000
#define T1_DIV_BY_182687704666362864775460604089535377456991567872 0x700000000000
#define T1_DIV_BY_365375409332725729550921208179070754913983135744 0x800000000000
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#define T1_DIV_BY_2923003274661805836407369665432566039311865085952 0xB00000000000
#define T1_DIV_BY_5846006549323611672814739330865132078623730171904 0xC00000000000
#define T1_DIV_BY_11692013098647223345629478661730264157247460343808 0xD00000000000
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#define T1_DIV_BY_46768052394588893382517914646921056628989841375232 0xF00000000000
#define T1_DIV_BY_93536104789177786765035829293842113257979682750464 0x1000000000000
#define T1_DIV_BY_187072209578355573530071658587684226515959365500928 0x2000000000000
#define T1_DIV_BY_374144419156711147060143317175368453031918731001856 0x3000000000000
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#define T1_DIV_BY_95780971304118053647396689196894323976171195136475136 0xB000000000000
#define T1_DIV_BY_191561942608236107294793378393788647952342390272950272 0xC000000000000
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#define T1_DIV_BY_766247770432944429179173513575154591809369561091801088 0xE000000000000
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#define T1_DIV_BY_6129982163463555433433388108601236734474956488734408704 0x20000000000000
#define T1_DIV_BY_12259964326927110866866776217202473468949912977468817408 0x30000000000000
#define T1_DIV_BY_24519928653854221733733552434404946937899825954937634816 0x40000000000000
#define T1_DIV_BY_49039857307708443467467104868809893875799651909875269632 0x50000000000000
#define T1_DIV_BY_98079714615416886934934209737619787751599303819750539264 0x60000000000000
#define T1_DIV_BY_196159429230833773869868419475239575503198607639501078528 0x70000000000000
#define T1_DIV_BY_392318858461667547739736838950479151006397215279002157056 0x80000000000000
#define T1_DIV_BY_784637716923335095479473677900958302012794430558004314112 0x90000000000000
#define T1_DIV_BY_1569275433846670190958947355801916604025588861116008628224 0xA0000000000000
#define T1_DIV_BY_3138550867693340381917894711603833208051177722232017256448 0xB0000000000000
#define T1_DIV_BY_6277101735386680763835789423207666416102355444464034512896 0xC0000000000000
#define T1_DIV_BY_12554203470773361527671578846415332832204710888928069025792 0xD0000000000000
#define T1_DIV_BY_25108406941546723055343157692830665664409421777856138051584 0xE0000000000000
#define T1_DIV_BY_50216813883093446110686315385661331328818843555712276103168 0xF0000000000000
#define T1_DIV_BY_100433627766186892221372630771322662657637687111424552206336 0x100000000000000
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#define T1_DIV_BY_401734511064747568885490523085290650630550748445698208825344 0x300000000000000
#define T1_DIV_BY_803469022129495137770981046170581301261101496891396417650688 0x400000000000000
#define T1_DIV_BY_1606938044258990275541962092341162602522202993782792835301376 0x500000000000000
#define T1_DIV_BY_3213876088517980551083924184682325205044405987565585670602752 0x600000000000000
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#define T1_DIV_BY_25711008708143844408671393477458601640355247900524685364822016 0x900000000000000
#define T1_DIV_BY_51422017416287688817342786954917203280710495801049370729644032 0xA00000000000000
#define T1_DIV_BY_102844034832575377634685573909834406561420991602098741459288064 0xB00000000000000
#define T1_DIV_BY_205688069665150755269371147819668813122841983204197482918576128 0xC00000000000000
#define T1_DIV_BY_411376139330301510538742295639337626245683966408394965837152256 0xD00000000000000
#define T1_DIV_BY_822752278660603021077484591278675252491367932816789931674304512 0xE00000000000000
#define T1_DIV_BY_1645504557321206042154969182557350504982735865633579863348609024 0xF00000000000000
#define T1_DIV_BY_3291009114642412084309938365114701009965471731267159726697218048 0x1000000000000000
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#define T1_DIV_BY_13164036458569648337239753460458804039861886925068638906788872192 0x3000000000000000
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#define T1_DIV_BY_52656145834278593348959013841835216159447547700274555627155488768 0x5000000000000000
#define T1_DIV_BY_105312291668557186697918027683670432318895095400549111254310977536 0x6000000000000000
#define T1_DIV_BY_210624583337114373395836055367340864637790190801098222508621955072 0x7000000000000000
#define T1_DIV_BY_421249166674228746791672110734681729275580381602196445017243910144 0x8000000000000000
#define T1_DIV_BY_842498333348457493583344221469363458551160763204392890034487820288 0x9000000000000000
#define T1_DIV_BY_1684996666696914987166688442938726917102321526408775780068975640576 0xA000000000000000
#define T1_DIV_BY_3369993333393829974333376885877453834204643052817551560137951281152 0xB000000000000000
#define T1_DIV_BY_6739986666787659948666753771754907668409286105635103120275902562304 0xC000000000000000
#define T1_DIV_BY_13479973333575319897333507543509815336818572211270206240551805124608 0xD000000000000000
#define T1_DIV_BY_26959946667150639794667015087019630673637144422540412481103610249216 0xE000000000000000
#define T1_DIV_BY_53919893334301279589334030174039261347274288845080824962207220498432 0xF000000
```

```

#define CCP_CAPTURE_FE                0x4
#define CCP_CAPTURE_RE                0x5
#define CCP_CAPTURE_DIV_4             0x6
#define CCP_CAPTURE_DIV_16           0x7
#define CCP_COMPARE_SET_ON_MATCH     0x8
#define CCP_COMPARE_CLR_ON_MATCH     0x9
#define CCP_COMPARE_INT               0xA
#define CCP_COMPARE_RESET_TIMER      0xB
#define CCP_PWM                       0xC
#define CCP_PWM_PLUS_1                0x1c
#define CCP_PWM_PLUS_2                0x2c
#define CCP_PWM_PLUS_3                0x3c
#define CCP_1_LOW=                    0x15
#define CCP_1_HIGH=                   0x16
#define INT_CCP1                      0x8C04 // Used for ENABLE/DISABLE INTERRUPTS

// Constants used for SETUP_CCP2()
#define CCP_2_LOW=                    0x1B
#define CCP_2_HIGH=                   0x1C
#define INT_CCP2                      0x8D01 // Used for ENABLE/DISABLE INTERRUPTS

// Constants used for SETUP_PSP()
#define PSP_ENABLED                    0x10
#define PSP_DISABLED                  0
#define PSP_DATA=                     8
#define INT_PSP                       0x8C80 // Used for ENABLE/DISABLE INTERRUPTS

// Constants used in SETUP_SSP()
#define SPI_MASTER                    0x20
#define SPI_SLAVE                     0x24
#define SPI_L_TO_H                    0
#define SPI_H_TO_L                    0x10
#define SPI_CLK_DIV_4                 0
#define SPI_CLK_DIV_16                1
#define SPI_CLK_DIV_64                2
#define SPI_CLK_T2                    3
#define SPI_SS_DISABLED               1
#define INT_SSP                       0x8C08 // Used for ENABLE/DISABLE INTERRUPTS
#define INT_RDA                       0x8C20 // Used for ENABLE/DISABLE INTERRUPTS
#define INT_TBE                       0x8C10 // Used for ENABLE/DISABLE INTERRUPTS

// Constants used for SETUP_ADC()
#define ALL_ANALOG                    0x80
#define ANALOG_RA3_REF                0x81
#define A_ANALOG                     0x82
#define A_ANALOG_RA3_REF              0x83
#define RA0_RA1_RA3_ANALOG            0x84
#define RA0_RA1_ANALOG_RA3_REF        0x85
#define NO_ANALOGS                    0x86
#define ANALOG_NOT_RE1_RE2            0x89
#define ADC_OFF                       0x00
#define ADC_CLOCK_DIV_2                0x01
#define ADC_CLOCK_DIV_8                0x41
#define ADC_CLOCK_DIV_32               0x81
#define ADC_CLOCK_INTERNAL             0xc1
#define ADC_DONE                      0x8C40 // Used for ENABLE/DISABLE INTERRUPTS
#define list

```

C.5 Pulse Control Microcontroller Source Code File MASTER.C

```
/******  
  
    FILE:                MASTER.C  
    WRITTEN BY:          Robert B. Cooper  
  
    Main source code file for microcontroller #1.  
    PULSE CONTROL MICROCONTROLLER  
  
    Pulse Battery Charger: PIC16F877 - A  
  
*****/  
  
#include <master.h>  
#include <stdio.h>  
  
#use rs232(baud=9600, xmit=PIN_C6, rcv=PIN_C7, errors)  
  
// RS-232 Interrupt event handler, triggered when data is received on  
// the rcv pin  
#int_rda  
rda_handler()  
{  
    int      cmd;  
  
    cmd = getc();  
  
    switch (cmd)  
    {  
        case 0x10:          // Send open circuit battery voltage value  
            rs232_send_long_data(vboc);  
            break;  
        case 0x20:          // Send charging battery voltage value  
            rs232_send_long_data(vbc);  
            break;  
        case 0x30:          // Send discharge battery voltage value  
            rs232_send_long_data(vbd);  
            break;  
        case 0x40:          // Send most recent charging current value  
            rs232_send_long_data(ic);  
            break;  
        case 0x50:          // Send most recent discharge current value  
            rs232_send_long_data(id);  
            break;  
        case 0x60:          // Send most recent power supply voltage value  
            rs232_send_long_data(vdd);  
            break;  
        case 0x70:          // Send most recent internal temperature value  
            rs232_send_long_data(int_temp);  
            break;  
        case 0xFF:  

```

```

        continue_charging = 0;
        break;
    default:
        rs232_send_long_data(0x0000);
        break;
    }
}

// Main program function
main()
{
    long    data;

    // Setup the microcontroller's features
    init();

    // Complete charger and user setup.
    user_setup();

    // Wait for start code from slave microcontroller
    data = rs232_get_short_data();
    if (data == 0xF0)
    {
        rs232_send_short_data(0xC0); // Send continue command to
                                     // SLAVE pic

        // Setup RS-232 Interrupts
        enable_interrupts(GLOBAL);
        enable_interrupts(INT_RDA);

        if (pulse_freq > 0x00FA)
        {
            exec_fast_charging_algorithm();
        }
        if (pulse_freq <= 0x00FA)
        {
            if (pulse_freq >= 0x000A)
            {
                exec_slow_charging_algorithm();
            }
        }
        if (pulse_freq < 0x000A)
        {
            exec_very_slow_charging_algorithm();
        }
    }
    else
    {
        rs232_send_short_data(0xE0); // An error occurred, do not
                                     // start charging
    }

    while (1);
}

```

```

// Initialize the microcontroller
void init()
{
    // Setup ADC Pins
    setup_adc_ports(ANALOG_NOT_RE1_RE2);    // Activate all analog
                                            // enabled pins except
                                            // for E1 and E2.
    setup_adc(ADC_CLOCK_DIV_32);            // Set clock division for an
                                            // operating frequency of 20
                                            // MHz.

    // Setup Charge Pulse Data Output (Port B)
    set_tris_b(0x00);                       // All port B pins configured as outputs
    cpulse_data.cdata = 0x00;               // Output 0 to D/A

    // Setup Discharge Pulse Data Output (Port D)
    set_tris_d(0x00);                       // All port D pins configured as outputs
    dpulse_data.ddata = 0x00;               // Output 0 to D/A

    // Setup Control Pins (Port C)
    set_tris_c(0x80);                       // Configure pin C7 (rs232 rcv) as an
                                            // input, other Port C pins as outputs

    // Setup Analog Switch Control Pins (Port E)
    set_tris_e(0x01);                       // A/D pin configured as an input, all
                                            // others output
    output_high(PIN_E2);                     // Disable the CD4067 analog switch
    output_low(PIN_E1);                      // Default analog switch channel is 0
    delay_ms(1000);                          // Delay to give SLAVE microcontroller
                                            // time to power up.
}

// Get any special user settings that have been entered by the user.
// This data is contained in the slave microcontroller.
void user_setup()
{
    short    continue_loop = 1;
    int      cmd;
    float    tcp, trp1, tdp, trp2;

    // Send value of external power supply voltage
    while (continue_loop)
    {
        cmd = rs232_get_short_data(); // Receive 8-bit data from SLAVE.

        if (cmd == 0xD0)               // Command sent by SLAVE to read power
        {                               // supply voltage
            vdd = read_vdd();
            rs232_send_long_data(vdd);
        }

        cmd = rs232_get_short_data(); // Receive 8-bit data from SLAVE.

        if (cmd == 0xC0)               // Data received by SLAVE, OK to
        {                               // continue otherwise MASTER will
            continue_loop = 0;         // enter an endless loop here and
    }
}

```

```

    } // will need to be reset.
}

// Send initial battery voltage to the slave microcontroller
continue_loop = 1;
while (continue_loop)
{
    cmd = rs232_get_short_data(); // Receive 8-bit data from SLAVE.

    if (cmd == 0xA0) // Command sent by SLAVE to read battery
    { // voltage

        vboc = read_battery_voltage();
        rs232_send_long_data(vboc); // Send 16-bit voltage data
    } // to SLAVE

    cmd = rs232_get_short_data(); // Receive 8-bit data from
    // SLAVE.

    if (cmd == 0xC0) // Data received by SLAVE, OK to continue
    { // otherwise MASTER will enter an endless
        continue_loop = 0; // loop here and will
    } // need to be reset.
}

pulse_freq = rs232_get_long_data(); // Retrieve desired pulse
// frequency from SLAVE

if (pulse_freq != 0)
{
    rs232_send_short_data(0xC0); // Pulse frequency received ok

    // Charge pulse period
    tcp = 0.2 / pulse_freq; // Charge pulse is on 20% of
    // the time

    if (pulse_freq > 0x00FA)
        if (tcp <= 216.6)
            delay_chrg = 0;
        else
            delay_chrg = (tcp - 0.0000928) / 0.0000034;

    if (pulse_freq <= 0x00FA)
        if (pulse_freq >= 0x000A)
            delay_chrg = (tcp - 0.0000928) / 0.0000804;

    if (pulse_freq < 0x000A)
        delay_chrg = (tcp - 0.0000928) / 0.0008004;

    // First rest period
    trp1 = 0.6 / pulse_freq;
    if (pulse_freq > 0x00FA)
        delay_off1 = (trp1 - 0.0000916) / 0.0000094;

    if (pulse_freq <= 0x00FA)
        if (pulse_freq >= 0x000A)
            delay_off1 = (trp1 - 0.0000916) / 0.0002364;

```

```

    if (pulse_freq < 0x000A)
        delay_off1 = (trp1 - 0.0000916) / 0.0023614;

    // Discharge period
    tdp = 0.1 / pulse_freq;
    if (pulse_freq > 0x00FA)
    {
        delay_dchg = (tdp - 0.0000928) / 0.0000016;
    }
    if (pulse_freq <= 0x00FA)
    {
        if (pulse_freq >= 0x000A)
        {
            delay_dchg = (tdp - 0.0000928) / 0.0000394;
        }
    }
    if (pulse_freq < 0x000A)
    {
        delay_dchg = (tdp - 0.0000928) / 0.0003934;
    }

    // Second rest period
    trp2 = 0.1 / pulse_freq;
    if (pulse_freq > 0x00FA)
    {
        delay_off2 = (trp2 - 0.0000464) / 0.0000016;
    }
    if (pulse_freq <= 0x00FA)
    {
        if (pulse_freq >= 0x000A)
        {
            delay_off2 = (trp2 - 0.0000464) / 0.0000394;
        }
    }
    if (pulse_freq < 0x000A)
    {
        delay_off2 = (trp2 - 0.0000464) / 0.0003934;
    }
}

}

// Send a 1 byte of data to the slave microcontroller
void rs232_send_long_data(long data)
{
    int    data_hi, data_lo;

    // Break long data into two seperate bytes of data
    data_hi = data >> 8;    // Move the upper byte to the lower 8 bits
    data_lo = data;         // Upper byte is lost in this assignment

    // Send high byte first;
    putc(data_hi);
    delay_us(2);            // Delay needed for data to be sent correctly.
    putc(data_lo);
}

```

```

// Send a 1 byte of data to the slave microcontroller
void rs232_send_short_data(int data)
{
    putc(data);
}

// Receive 2 bytes of data from the slave microcontroller.
long rs232_get_long_data()
{
    int    data_hi, data_lo;
    long   data;

    data_hi = getc();           // Get high byte
    data_lo = getc();           // Get low byte

    data = data_hi;
    data = (data << 8) + data_lo;

    return data;
}

// Receive 1 byte of data from the slave microcontroller.
long rs232_get_short_data()
{
    int    data, i;

    data = getc();

    return data;
}

// Read the current value from the current sensor
long read_current()
{
    long   current;

    // Read the analog voltage on channel 3 (charge current data)
    set_adc_channel(3);           // Set the microcontroller to read the
                                   // analog voltage from pin AN3
    delay_us(20);                 // Delay needed before data can be read from
                                   // analog input when the channel has been
                                   // changed.
    current = read_adc();

    return current;
}

// Read the output voltage from the battery voltage sensor
long read_battery_voltage()
{
    long   voltage;

```



```

    // Read the analog voltage on channel 4 (battery voltage data)
    set_adc_channel(4);      // Set the microcontroller to read the
                             // analog voltage from pin AN4
    delay_us(20);           // Delay needed before data can be read from
                             // analog input when the channel has been
                             // changed.

    voltage = read_adc();

    return voltage;
}

// Read the output voltage from the High-Current Power Supply voltage
// sensor
long read_vdd()
{
    long voltage;

    // Read the analog voltage on channel 2 (power supply voltage data)
    set_adc_channel(2);      // Set the microcontroller to read the
                             // analog voltage from pin AN2
    delay_us(20);           // Delay needed before data can be read from
                             // analog input when the channel has been
                             // changed.

    voltage = read_adc();

    return voltage;
}

// Read the output voltage from the internal temperature sensor
long read_internal_temp()
{
    long temp;

    //Read the analog voltage on channel 1 (internal temperature data)
    set_adc_channel(1);      // Set the microcontroller to read the
                             // analog voltage from pin AN1
    delay_us(20);           // Delay needed before data can be read from
                             // analog input when the channel has been
                             // changed.

    temp = read_adc();

    return temp;
}

// Main function that controls the charging algorithm when the pulse
// frequency is greater than 250Hz.
void exec_fast_charging_algorithm()
{
    long data;
    int i;

    while (continue_charging)
    {
        // Charge Pulse portion of charging algorithm.

```

```

    output_high(PIN_E2);          // Disable cd4067 before changing
                                  // channels
    output_low(PIN_E1);          // Sensor output to the charge
                                  // current data line
    output_low(PIN_E2);          // Enable cd4067 to pass current
                                  // data through
    cpulse_data.cdata = 0xFF;    // Turn on IRF5210 MOSFETs
    for (i = 0; i < delay_chrg; i++)
    {
        delay_us(1);
    }
    vbc = read_battery_voltage(); // Battery voltage during charge
                                  // period
    ic = read_current();          // Charging current
    cpulse_data.cdata = 0x00;    // Turn off IRF5210 MOSFETs

    // 1st Rest Period portion of charging algorithm
    for (i = 0; i < delay_off1; i++)
    {
        delay_us(9);
    }
    int_temp = read_internal_temp(); // MOSFET temperature
    vdd = read_vdd();               // External power supply
                                  // voltage

    // Discharge Pulse portion of charging algorithm
    output_high(PIN_E2);          // Disable cd4067 before changing
                                  // channels
    output_high(PIN_E1);          // Sensor output to the discharge
                                  // current data line
    output_low(PIN_E2);          // Enable cd4067 to pass current
                                  // data through
    dpulse_data.ddata = 0xFF;    // Turn on IRF3710 MOSFETs
    for (i = 0; i < delay_dchg; i++)
    {
        delay_cycles(1);
    }
    vbd = read_battery_voltage(); // Discharge battery voltage
    id = read_current();          // Discharge Current
    dpulse_data.ddata = 0x00;    // Turn off IRF3710 MOSFETs

    // 2nd Rest Period portion of charging algorithm
    for (i = 0; i < delay_off2; i++)
    {
        delay_cycles(1);
    }
    vboc = read_battery_voltage(); // Open circuit battery
                                  // voltage
}

}

// Main function that controls the charging algorithm when pulse
// frequency is between 10Hz and 250Hz.
void exec_slow_charging_algorithm()
{
    long data;

```

```

int    i;

while (continue_charging)
{
    // Charge Pulse portion of charging algorithm.
    output_high(PIN_E2);          // Disable cd4067 before changing
                                  // channels
    output_low(PIN_E1);           // Sensor output to the charge
                                  // current data line
    output_low(PIN_E2);           // Enable cd4067 to pass current
                                  // data through
    cpulse_data.cdata = 0xFF;     // Turn on IRF5210 MOSFETs
    for (i = 0; i < delay_chrg; i++)
    {
        delay_us(76);
    }
    vbc = read_battery_voltage(); // Battery voltage during charge
                                  // period
    ic = read_current();          // Charging current
    cpulse_data.cdata = 0x00;     // Turn off IRF5210 MOSFETs

    // 1st Rest Period portion of charging algorithm
    for (i = 0; i < delay_off1; i++)
    {
        delay_us(235);
    }
    int_temp = read_internal_temp(); // MOSFET temperature
    vdd = read_vdd();                // External power supply
                                    // voltage

    // Discharge Pulse portion of charging algorithm
    output_high(PIN_E2);          // Disable cd4067 before changing
                                  // channels
    output_high(PIN_E1);          // Sensor output to the discharge
                                  // current data line
    output_low(PIN_E2);           // Enable cd4067 to pass current
                                  // data through
    dpulse_data.ddata = 0xFF;     // Turn on IRF3710 MOSFETs
    for (i = 0; i < delay_dchg; i++)
    {
        delay_us(38);
    }
    vbd = read_battery_voltage(); // Discharge battery voltage
    id = read_current();          // Discharge Current
    dpulse_data.ddata = 0x00;     // Turn off IRF3710 MOSFETs

    // 2nd Rest Period portion of charging algorithm
    for (i = 0; i < delay_off2; i++)
    {
        delay_us(38);
    }
    vboc = read_battery_voltage(); // Open circuit battery
                                    // voltage
}
}

```

```

// Main function that controls the charging algorithm when pulse
// frequency is less than 10Hz.
void exec_very_slow_charging_algorithm()
{
    long data;
    int i;

    while (continue_charging)
    { // Charge Pulse portion of charging algorithm.
        output_high(PIN_E2); // Disable cd4067 before changing
                             // channels
        output_low(PIN_E1); // Sensor output to the charge
                             // current data line
        output_low(PIN_E2); // Enable cd4067 to pass current
                             // data through
        cpulse_data.cdata = 0xFF; // Turn on IRF5210 MOSFETs
        for (i = 0; i < delay_chrg; i++)
        {
            delay_us(785);
        }
        vbc = read_battery_voltage(); // Battery voltage during charge
                                     // period
        ic = read_current(); // Charging current
        cpulse_data.cdata = 0x00; // Turn off IRF5210 MOSFETs

        // 1st Rest Period portion of charging algorithm
        for (i = 0; i < delay_off1; i++)
        {
            delay_us(2360);
        }
        int_temp = read_internal_temp(); // MOSFET temperature
        vdd = read_vdd(); // External power supply
                        // voltage
        // Discharge Pulse portion of charging algorithm
        output_high(PIN_E2); // Disable cd4067 before changing
                             // channels
        output_high(PIN_E1); // Sensor output to the discharge
                             // current data line
        output_low(PIN_E2); // Enable cd4067 to pass current
                             // data through
        dpulse_data.ddata = 0xFF; // Turn on IRF3710 MOSFETs
        for (i = 0; i < delay_dchg; i++)
        {
            delay_us(392);
        }
        vbd = read_battery_voltage(); // Discharge battery voltage
        id = read_current(); // Discharge Current
        dpulse_data.ddata = 0x00; // Turn off IRF3710 MOSFETS

        for (i = 0; i < delay_off2; i++)
        {
            delay_us(392);
        }
        vboc = read_battery_voltage(); // Open circuit battery
                                     // voltage
    }
}

```

C.6 Pulse Control Microcontroller Source Code File MASTER.H

```
/******  
  
FILE:          MASTER.H  
WRITTEN BY:    Robert B. Cooper  
  
Main header file for microcontroller #1.  
PULSE CONTROL MICROCONTROLLER  
  
Pulse Battery Charger: PIC16F877 - A  
  
*****/  
  
#device PIC16F877  
#use delay(clock=20000000)  
#fuses HS,NOWDT,NOPROTECT,NOBROWNOUT,NOPUT  
#nolist  
  
#define PORTB 0x06  
#define PORTC 0x07  
#define PORTD 0x08  
#define PORTE 0x09  
  
#define FALSE 0  
#define TRUE 1  
  
#define BYTE int  
#define BOOLEAN short int  
  
// Define global variables  
short continue_charging = 1; // True until the battery stop condition  
                             // is reached.  
long pulse_freq = 1000;     // Desired pulse frequency, 1 kHz is the  
                             // default  
long vboc = 0x0000;         // Open circuit battery voltage  
long vbc = 0x0000;          // Charging battery voltage  
long vbd = 0x0000;          // Discharge battery voltage  
long vdd = 0x0000;          // Power supply voltage  
long ic = 0x0000;           // Charging current  
long id = 0x0000;           // Discharge current  
long int_temp = 0x0000;     // Internal temperature  
int delay_chrg = 0x00;      // Number of 'for loops' to execute  
                             // during charge pulse  
int delay_off1 = 0x00;      // Number of 'for loops' to execute  
                             // during rest period 1  
int delay_dchg = 0x00;      // Number of 'for loops' to execute  
                             // during discharge pulse  
int delay_off2 = 0x00;      // Number of 'for loops' to execute  
                             // during rest period 2
```

```

// Define a structure so that all pins assigned to the charge pulse
// output can be written to with a single command.
struct charge_pulse_pins
{
    int      cdata : 8;
} cpulse_data;

// Define a structure so that all pins assigned to the discharge pulse
// output can be written to with a single command.
struct discharge_pulse_pins
{
    int      ddata : 8;
} dpulse_data;

#byte cpulse_data = PORTB    // Assign cpulse_data structure to PORTB
#byte dpulse_data = PORTD    // Assign dpulse_data structure to PORTD

/*****
Function prototypes
*****/

// Functions related to the hardware operation of the charger
void init();
void user_setup();
void exec_fast_charging_algorithm();
void exec_slow_charging_algorithm();
void exec_very_slow_charging_algorithm();

// Functions related to communications between the microcontrollers
void rs232_send_short_data(int data);    // Send 1 byte of data
void rs232_send_long_data(long data);    // Send 2 bytes of data
long rs232_get_long_data();              // Receive 2 bytes of data
int rs232_get_short_data();              // Receive 1 byte of data

// Functions that read physical charger parameters from the analog
// input channels of the microcontroller.
long read_current();
long read_battery_voltage();
long read_vdd();
long read_internal_temp();

/*****
*
*   All code beyond this point was compiler generated
*
*****/

// PORT A pin definitions
#define PIN_A0  40
#define PIN_A1  41
#define PIN_A2  42
#define PIN_A3  43
#define PIN_A4  44
#define PIN_A5  45

```

```

// PORT B pin definitions
#define PIN_B0  48
#define PIN_B1  49
#define PIN_B2  50
#define PIN_B3  51
#define PIN_B4  52
#define PIN_B5  53
#define PIN_B6  54
#define PIN_B7  55

// PORT C pin definitions
#define PIN_C0  56
#define PIN_C1  57
#define PIN_C2  58
#define PIN_C3  59
#define PIN_C4  60
#define PIN_C5  61
#define PIN_C6  62
#define PIN_C7  63

// PORT D pin definitions
#define PIN_D0  64
#define PIN_D1  65
#define PIN_D2  66
#define PIN_D3  67
#define PIN_D4  68
#define PIN_D5  69
#define PIN_D6  70
#define PIN_D7  71

// PORT E pin definitions
#define PIN_E0  72
#define PIN_E1  73
#define PIN_E2  74

// Constants used for RESTART_CAUSE()
#define WDT_FROM_SLEEP  0
#define WDT_TIMEOUT      8
#define MCLR_FROM_SLEEP 16
#define NORMAL_POWER_UP 24

// Constants used for SETUP_COUNTERS()
#define RTCC_INTERNAL      0
#define RTCC_EXT_L_TO_H 32
#define RTCC_EXT_H_TO_L 48
#define RTCC_DIV_2         0
#define RTCC_DIV_4         1
#define RTCC_DIV_8         2
#define RTCC_DIV_16        3
#define RTCC_DIV_32        4
#define RTCC_DIV_64        5
#define RTCC_DIV_128       6
#define RTCC_DIV_256       7
#define WDT_18MS           8
#define WDT_36MS          9
#define WDT_72MS          10

```

```

#define WDT_144MS      11
#define WDT_288MS      12
#define WDT_576MS      13
#define WDT_1152MS     14
#define WDT_2304MS     15
#define L_TO_H         0x40
#define H_TO_L         0

#define RTCC_ZERO      0x0B20    // Used for ENABLE/DISABLE INTERRUPTS
#define RB_CHANGE      0x0B08    // Used for ENABLE/DISABLE INTERRUPTS
#define EXT_INT        0x0B10    // Used for ENABLE/DISABLE INTERRUPTS
#define GLOBAL         0x0BC0    // Used for ENABLE/DISABLE INTERRUPTS
#define INT_RTCC       0x0B20    // Used for ENABLE/DISABLE INTERRUPTS
#define INT_RB         0x0B08    // Used for ENABLE/DISABLE INTERRUPTS
#define INT_EXT        0x0B10    // Used for ENABLE/DISABLE INTERRUPTS

// Constants used for Timer1 and Timer2
#define T1_DISABLED     0
#define T1_INTERNAL     5
#define T1_EXTERNAL     7
#define T1_EXTERNAL_SYNC 3
#define T1_CLK_OUT      8
#define T1_DIV_BY_1     0
#define T1_DIV_BY_2     0x10
#define T1_DIV_BY_4     0x20
#define T1_DIV_BY_8     0x30
#define T1_DIV_BY_16    0x40
#define T1_DIV_BY_32    0x50
#define T1_DIV_BY_64    0x60
#define T1_DIV_BY_128   0x70
#define T1_DIV_BY_256   0x80
#define T1_DIV_BY_512   0x90
#define T1_DIV_BY_1024  0xA0
#define T1_DIV_BY_2048  0xB0
#define T1_DIV_BY_4096  0xC0
#define T1_DIV_BY_8192  0xD0
#define T1_DIV_BY_16384 0xE0
#define T1_DIV_BY_32768 0xF0
#define T2_DISABLED     0
#define T2_INTERNAL     5
#define T2_EXTERNAL     7
#define T2_EXTERNAL_SYNC 3
#define T2_CLK_OUT      8
#define T2_DIV_BY_1     0
#define T2_DIV_BY_2     0x10
#define T2_DIV_BY_4     0x20
#define T2_DIV_BY_8     0x30
#define T2_DIV_BY_16    0x40
#define T2_DIV_BY_32    0x50
#define T2_DIV_BY_64    0x60
#define T2_DIV_BY_128   0x70
#define T2_DIV_BY_256   0x80
#define T2_DIV_BY_512   0x90
#define T2_DIV_BY_1024  0xA0
#define T2_DIV_BY_2048  0xB0
#define T2_DIV_BY_4096  0xC0
#define T2_DIV_BY_8192  0xD0
#define T2_DIV_BY_16384 0xE0
#define T2_DIV_BY_32768 0xF0
#define TIMER_1_LOW=    0x0e
#define TIMER_1_HIGH=   0x0f
#define INT_TIMER1      0x8C01    // Used for ENABLE/DISABLE INTERRUPTS
#define INT_TIMER2      0x8C02    // Used for ENABLE/DISABLE INTERRUPTS

// Constants used for SETUP_CCP1()
#define CCP_OFF          0
#define CCP_CAPTURE_FE   4
#define CCP_CAPTURE_RE   5
#define CCP_CAPTURE_DIV_4 6
#define CCP_CAPTURE_DIV_16 7
#define CCP_COMPARE_SET_ON_MATCH 8
#define CCP_COMPARE_CLR_ON_MATCH 9
#define CCP_COMPARE_INT   0xA
#define CCP_COMPARE_RESET_TIMER 0xB
#define CCP_PWM           0xC
#define CCP_PWM_PLUS_1    0x1c
#define CCP_PWM_PLUS_2    0x2c
#define CCP_PWM_PLUS_3    0x3c
#define CCP_1_LOW=        0x15
#define CCP_1_HIGH=       0x16
#define INT_CCP1          0x8C04    // Used for ENABLE/DISABLE INTERRUPTS

// Constants used for SETUP_CCP2()
#define CCP_2_LOW=        0x1B

```



```

#byte    CCP_2_HIGH=          0x1C
#define  INT_CCP2              0x8D01    // Used for ENABLE/DISABLE INTERRUPTS

// Constants used for SETUP_PSP()
#define  PSP_ENABLED           0x10
#define  PSP_DISABLED          0
#byte    PSP_DATA=            8
#define  INT_PSP               0x8C80    // Used for ENABLE/DISABLE INTERRUPTS

// Constants used in SETUP_SSP()
#define  SPI_MASTER            0x20
#define  SPI_SLAVE             0x24
#define  SPI_L_TO_H            0
#define  SPI_H_TO_L            0x10
#define  SPI_CLK_DIV_4         0
#define  SPI_CLK_DIV_16        1
#define  SPI_CLK_DIV_64        2
#define  SPI_CLK_T2            3
#define  SPI_SS_DISABLED       1
#define  INT_SSP               0x8C08    // Used for ENABLE/DISABLE INTERRUPTS
#define  INT_RDA               0x8C20    // Used for ENABLE/DISABLE INTERRUPTS
#define  INT_TBE               0x8C10    // Used for ENABLE/DISABLE INTERRUPTS

// Constants used for SETUP_ADC()
#define  ALL_ANALOG             0x80
#define  ANALOG_RA3_REF         0x81
#define  A_ANALOG              0x82
#define  A_ANALOG_RA3_REF       0x83
#define  RA0_RA1_RA3_ANALOG     0x84
#define  RA0_RA1_ANALOG_RA3_REF 0x85
#define  NO_ANALOGS             0x86

#define  ANALOG_RA3_RA2_REF      0x88
#define  ANALOG_NOT_RE1_RE2      0x89
#define  ANALOG_NOT_RE1_RE2_REF_RA3 0x8A
#define  ANALOG_NOT_RE1_RE2_REF_RA3_RA2 0x8B
#define  A_ANALOG_RA3_RA2_REF    0x8C
#define  RA0_RA1_ANALOG_RA3_RA2_REF 0x8D
#define  RA0_ANALOG              0x8E
#define  RA0_ANALOG_RA3_RA2_REF 0x8F

#define  ADC_OFF                0
#define  ADC_CLOCK_DIV_2        1
#define  ADC_CLOCK_DIV_8        0x41
#define  ADC_CLOCK_DIV_32       0x81
#define  ADC_CLOCK_INTERNAL     0xc1
#define  ADC_DONE               0x8C40    // Used for ENABLE/DISABLE INTERRUPTS
#define  INT_ADC                0x8C40    // Used for ENABLE/DISABLE INTERRUPTS

#list

```

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