Department of Electronic and Telecommunication Engineering

University of Moratuwa, Sri Lanka

EN2091 -Laboratory Practices II

LEAD ACID BATTERY CHARGER

Group members

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Abstract

This report briefly describes the methodology to design an Lead acid battery charger to charge a 12v Lead acid battery, with a maximum charging current of 1A. We achieve that, using a 230V AC input voltage source and PWM (Pulse width modulation) techniques. In this project, we use resistors, capacitors, inductors and OPAMPs in order to build various functional blocks and collectively combine them. We primely use Ltspice software to design the circuit parts and visualize the simulations. Solidworks software used to design the enclosure and Altium software used to design the PCB.

0.1 Introduction

0.1.1 Lead Acid Battery

This is a kind of rechargeable battery which contains 6 cells in it. Each cells are made up of lead and lead oxide plates which are sunk in the sulphuric acid. when load is connected, the chemical reaction among the substances produce the electricity. During charging the electrode plates are being charged by the external sources. Nominal voltage (Open circuit) of a single cell is around 2.2v. When operating it will change around 1.8v - 2.1v.

0.1.2 Charging methodologies

Charging profile for a battery is unique. To maintain the healthy battery while restoring the charging capacity and maintaining the level without self-discharge, that profile should be strictly followed. Lead acid battery uses 3 major ways.

1. Constant Current mode (CC)
2. Constant Voltage mode (CV)
3. Floating Charging mode

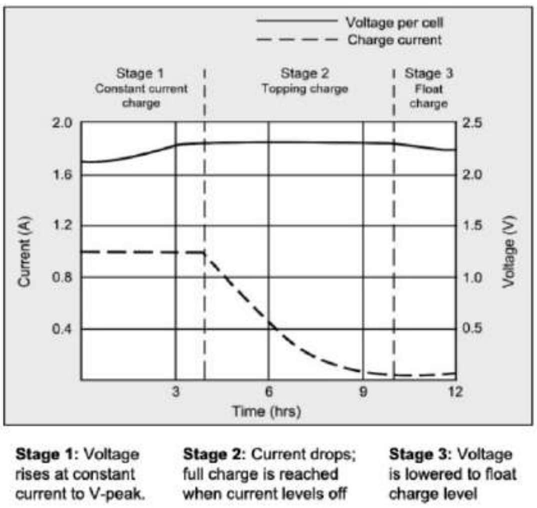

Figure1: Charging modes of the Lead acid battery

Here constant current mode roundly consume half charge time and battery get charges up to 70%. After reaching the set voltage limit, current starts to decrease while keep the voltage constant. Finally the floating charging mode occurs when current level drops to zero, which expiate the self discharging losses is important to maintain the battery at full charge. Otherwise, battery will loss the capability of maintain the full charge due to the sulfation.

0.2 Functional Block Diagram

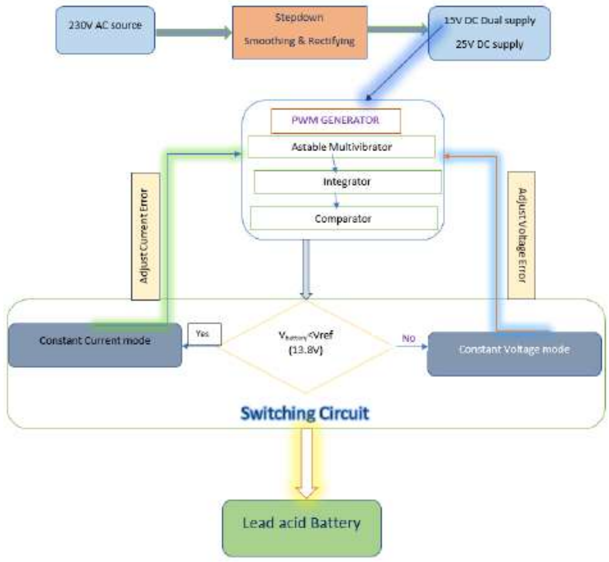

Figure2: Functional Block Diagram

Lead acid battery charger can be directly connected to 230V AC source. So, it is necessary to step down it to the required value. Then we do the rectification and smoothing using the appropriate circuits. Here we need both 15V DC dual supply voltage and 25V DC voltage to power PWM generator and Buck converter respectively

Our design is based on **P control** method. 25V Dc voltage is controlled by a PWM signal and the duty cycle of the PWM signal will be adjusted automatically depending on a feedback. During the constant current mode, the current passes through the Buck converter is being sensed by a sense resistor. Then that current will be compared with a reference value (1A) and the error will be given as a feedback and duty cycle of the PWM signal will be changed accordingly.

During constant voltage mode, battery voltage is measured using a resistor divider and Voltage error between output of the resistor divider and a reference value is given to the PWM generator circuit as a feedback for it to change the duty cycle of the PWM signal.

While charging the battery, voltage between battery terminals is continuously measured and if it becomes higher than 13.7V, charging method will be changed from Constant current (CC) to Constant voltage (CV).

0.3 Pulse Width Modulated signal generation (PWM)

Here we have created a PWM signal generator circuit where we can adjust the pulse width (Duty cycle) using a external voltage level. This circuit includes 3 main parts. They are,

1. Astable Multi-Vibrator
2. Integrator
3. Comparator

0.3.1 Astable Multi-Vibrator

Astable multi-vibrator is used for creating a square wave. In the astable multi-vibrator an RC timing circuit is connected to inverting terminal of the op-amp while voltage divider circuit is connected to the non-inverting terminal which acts as a Schmitt comparator. Schmitt comparator compares the RC circuit's charging and discharging curves with its two reference voltages and generates square wave.

T = Time period of the square wave is given by ,

$$T = 2\times \text{ (R6) } \times \text{ (C3) } \ln\left(\frac{1+\beta}{1-\beta}\right)$$

and the feedback factor β is given by,

$$\beta = \left(\frac{R5}{R4+R5}\right)$$

In our circuit, we have chosen $R4 = 35k\Omega$ *and* $R5 = 30k\Omega$, therefore β is around 0.462. Then $ln(\frac{1+\beta}{1-\beta})$ term becomes 1. So the time period of the PWM signal becomes just $2 \times R6 \times C3$. In the design $R6 = 40k\Omega$ and $C3 = 0.01\mu F$. So we can get a square wave which has 0.8ms time period or simply 1250Hz frequency.

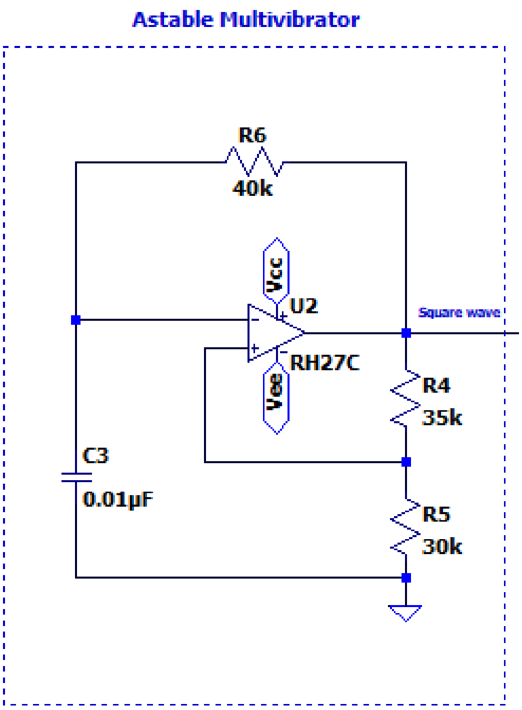

Figure3: As-table Multi-Vibrator

0.3.2 Integrator

Integrator circuit is used to create the triangular waveform. Output of the astable multi-vibrator is connected to the inverting terminal of the integrator circuit.A Triangular wave is generated by integrating the square wave.

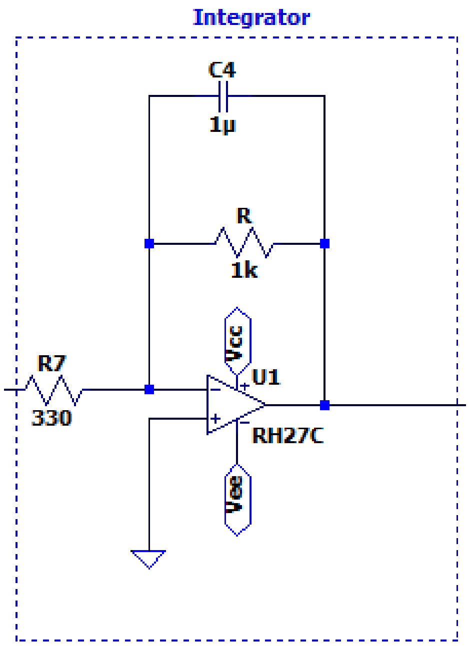

Figure4: Integrator

0.3.3 Comparator

In this comparator, Op amp non-inverting terminal is connected to the CC/CV error Voltage through a Switching circuit and inverting terminal is connected to the output of the Integrator (Triangle Wave). If the error voltage is higher than the Triangle wave, comparator Opamp will output -15V and otherwise +15V. So the duty cycle of the output PWM is controlled by the error voltages.[2]

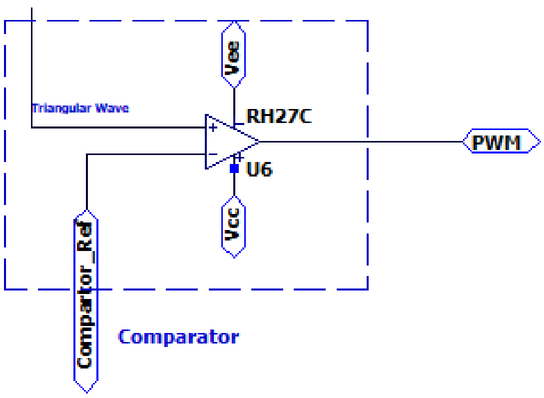

Figure5: Comparator

0.4 Buck Converter

Buck converter is a circuit which can reduce the input voltage to it using PWM. It converts the input voltage to a PWM signal and changes its pulse width to get the required output voltage. Initially input voltage is given to a Drain of a N channel mosfet. Gate of the mosfet is driven by a small low current PWM signal. After that source of the mosfet will produce a High current PWM signal which is required to charge the battery. Before that, PWM signal is filtered using a LC filter and DC component of the PWM is extracted for fed into the battery.

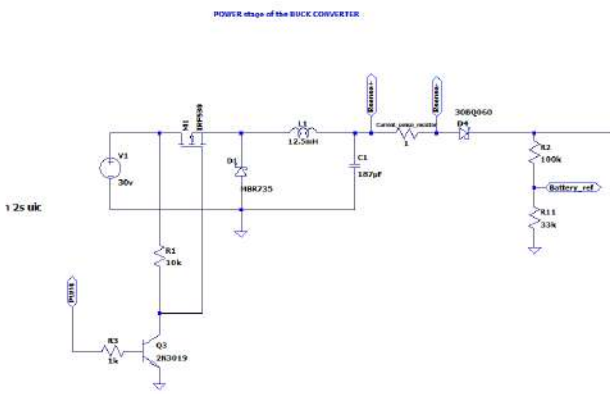

Figure6: Buck converter

Mosfet Gate driver is a NPN transistor. Low power pwm signal is connected to the base of the transistor. Transistor switches between Cutoff and Saturate states at the frequency of PWM signal (1250Hz).

0.5 Feedback Control (P control)

Controlling the duty cycle is completely based on feed backs. To give the feed backs, we have used differential amplifiers.[3]

0.5.1 Constant Current Control

We need to provide constant current less than 1A to the charging battery to the proper functionality. To measure the current going into the battery, we have connected a 1Ω $5W$ sense resistor series with the LC filter. Since that resistor is 1Ω, voltage across the resistor is always equal to current passing through it.

$$\Delta V = \Delta I \times 1$$

The voltage across the sense resistor is calculated using the 1st differential amplifier. output of the 1st differential amplifier is given by following equation.

$$V_{out1} = \frac{33k\Omega}{10k\Omega}\ \Delta V = 3.3\ \Delta V$$

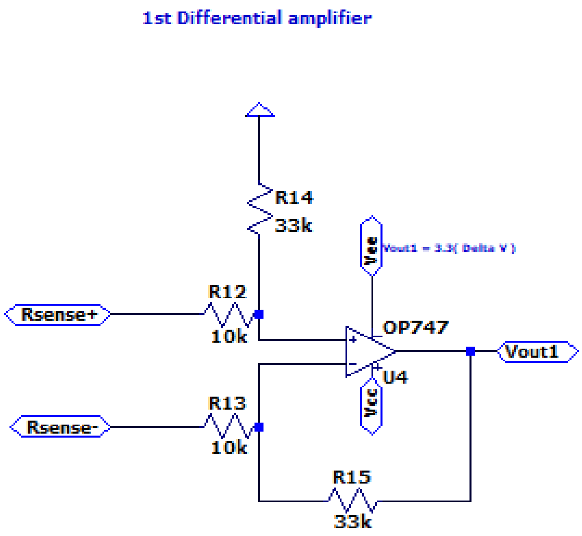

Figure7: 1st Differential amplifier

The output of the 1st differential amplifier is sent to the 2nd differential amplifier's input. It is comparing ΔV with a reference value and Generates the current error which is to be given as the feedback. Output of the 2nd differential amplifier is given by the following equation.

$$V_{out2} = 3.3\ (5.1\ -\ 3.3\Delta V)$$

To get 5.1V reference, we used a 5.1V Zener diode. V_{out2} is the current error feedback.

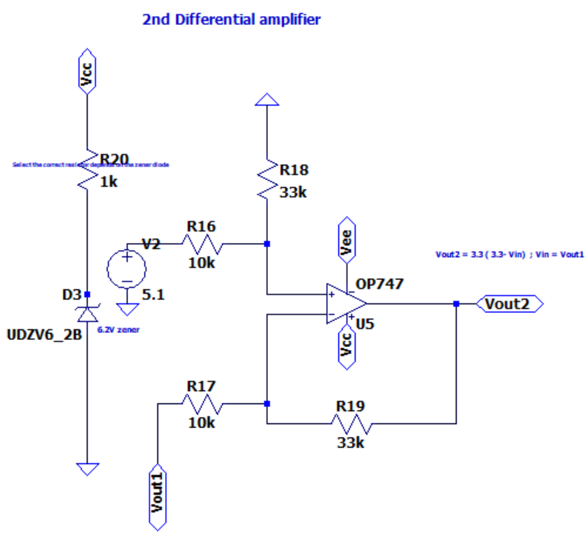

Figure8: 2nd differential amplifier

0.5.2 Constant Voltage Control

Constant voltage control is used to keep the battery voltage below 13.8V. Once the battery reaches certain voltage level current will reduce and voltage is maintained below a 13.8V so that battery can be left connected to charger till we use it. We have used a resistor divider to get a reference value which indicates the battery voltage. Resisters are selected in high values to minimize the current flow through the divider and get an accurate reference value.

$$V_{\text{IN}} = \frac{R1}{R1+R2} \cdot V_{\text{battery}}$$

This above output is connected as input of the 3rd differential amplifier. This differential amplifier is used for calculating the error in constant voltage mode.. According to the differential amplifier resistor values, output is given by

$$V_{out3} = (3.3 - BatteryRef)$$

V_{out3} is used as the voltage error. V_{error} decreases with the battery voltage and PWM width reduces with increasing battery voltage. V_{error} and $\text{Current}_{\text{error}}$ is swapping between them from a switching circuit to change from CC mode to CV mode.

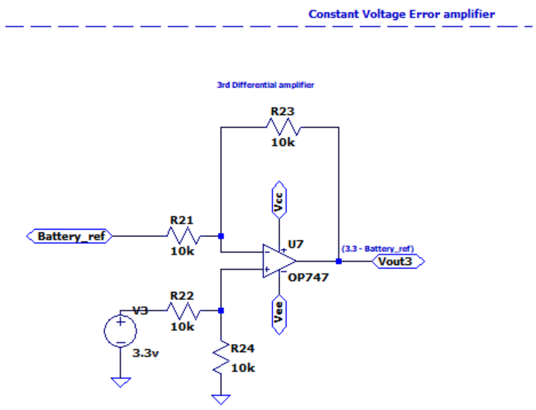

Figure9: Constant Voltage Circuit

0.6 Switching from CC to CV

When the battery voltage is higher than 13.8v, Charging mode should be changed to from constant current to constant voltage and current into the battery should be decreased gradually. Switching from CC to CV is achieved using a comparator. Reference voltage 13.8v is connected to inverting input of a opamp and positive terminal of the battery is connected to the non inverting input. Output of the comparator is connected to the base of a NPN transistor which drives the relay and change the CC/CV mode.[4]

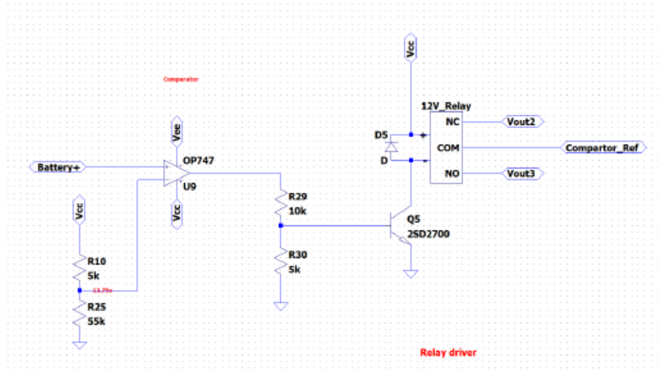

Figure10: Switching Circuit from CC to CV

Initially battery voltage is less than 13.8V, So output of the comparator is -15V and relay driver transistor will not turn on. Then relay remains turn off and Common pin of the relay will stay in Normally closed (NC) contact, which is V_{out2} the current error.

After battery voltage goes beyond 13.8V, relay will turn on and Common pin will be switched to Normally open contact, which is V_{out3} the voltage error.

0.7 Power supply circuit

We need +15V and -15V dual supply to power up the Opamp ICs and another 25V High current supply to charge the battery through the buck converter. We have added a step down transformer to step down 230Ac. It has two center tapped secondary coils, which output 12V - 0V - 12V and 18V - 0V - 18V. 12V secondary outputs are connected to a Diode full wave rectifier and positive and negative voltage regulators. 18V secondary outputs are connected to 2 diodes and a Large smoothing capacitor to reduce the ripple and voltage drop when drawing high current.

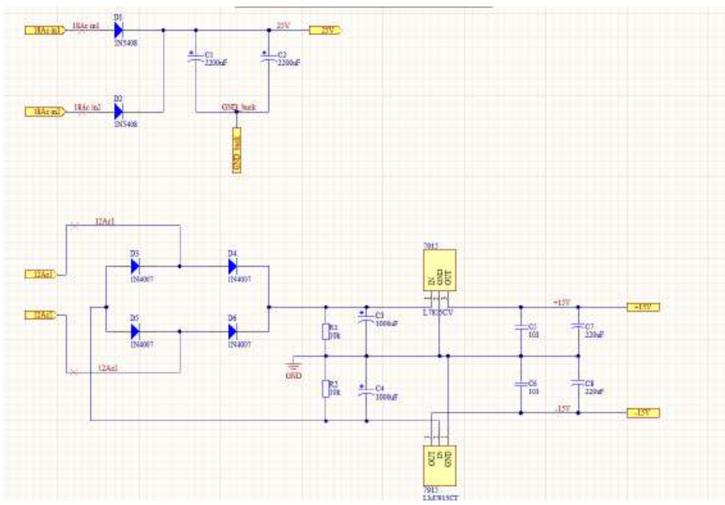

Fig11: Power supply circuit

0.8 Components Selection and Calculations

0.8.1 PWM Generation

Frequency of the PWM signal is around 1kHz, So we used **TL071** opamp ICs which has $20V/\mu s$ slew rate.

Square wave

Time period of the square wave (Output of the astable multivibrator) is given by ,

$$T = 2RC\ ln(\frac{1+\beta}{1-\beta})$$

$where\ \beta = \frac{R2}{R1+R2}$

$R = 40k\Omega,\ C = 0.01\mu F,\ R1 = 35k\Omega\ and\ R2 = 30k\Omega,$

This gives T = 1.25ms, or simply 1250Hz frequency.

Triangular Wave

Integrator is acting as a Active low pass filter. Therefore in high frequencies output signal could be attenuated. Bode plot of the opamp integrator is shown below.

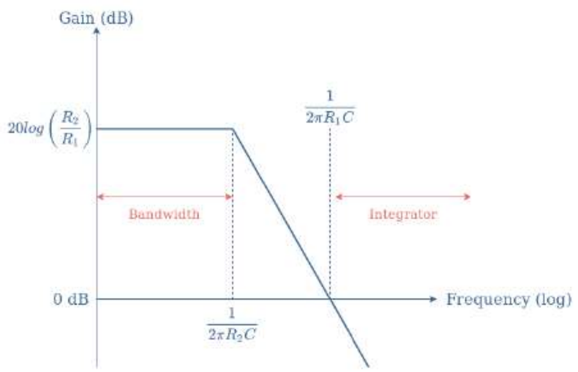

Fig12: Bode plot of the integrator

We selected $R2 = 1k\Omega$ and $C = 1\mu F$, therefore cut-off frequency $\frac{1}{2\pi CR2}$ is higher than the frequency of the Square Wave.

0.8.2 Error calculation using Differential amplifiers

We used high resistor values for all resistors in differential amplifiers to reduce current flowing into them. To make voltage references, we used zener diodes with appropriate resistors series with them.

0.8.3 Switching circuit

To get a 13.8V voltage level as a reference, we used a resistor voltage divider with $5k\Omega\ and\ 55k\Omega$.

Voltage across the $55k\Omega$ resistor is equal to $\frac{55k}{55k+5k} = 13.8V$.

When the relay is ON, it draws a typically high current rather than other electronic components. So the relay can't be driven directly from the switching opamp output. Therefore we put a **D400** NPN transistor which can handle high current to drive the relay.

0.8.4 Buck converter

Buck converter is the main part which maintains the current or the voltage of the battery in required levels. All the parts in buck converter circuit should be able to handle higher currents and voltages.

Mosfet selection

We used **IRF530N** N Channel mosfet in the buck converter.Its continuous drain current I_D is 12A and it has very low drain to source resistance R_{DS} which is $90m\Omega$. It supports fast switching applications.

Inductor selection

PWM signal's duty cycle is important to control the output given to the load. Inductor plays a vital role in providing stable current to the load as PWM signal switches. Value of the inductance depends the expected ripple current that device is able to work as expected and the duty cycle. According to the inductor current buck converter varies within one of the following conduction modes:

Inductance value depends on the following parameters.

- Maximum input voltage
- Output voltage
- Duty cycle
- Maximum ripple current
- Frequency

First we have to calculate the maximum duty cycle of the buck converter.

$$Maximum\ duty\ cycle\ (D) = \frac{V_{out}(max)}{V_{in} \cdot \eta}$$

where η is the efficiency of the buck converter. We have assumed $\eta = 90\%$, $V_{in} = 25V$ and $V_{out}(max) = 15V$. Then the maximum duty cycle is ,

$$D = \frac{15V}{25V \times 0.9} = 66.7\%$$

Current through the inductor oscillates around the steady state current, therefore there is a ripple in Inductor current. In our design we have assumed the inductor ripple current is around 30% of the maximum current 1A.

$$Inductor\ ripple\ current = \Delta I_L = 0.3A$$

For the inductor, we have to choose high power inductor because it should be able to handle 1A or higher values. Required inductance for the buck converter is given by,

$$Inductance\ (L) = \frac{V_{out} \times (V_{in}\ -\ V_{out})}{\Delta I_L\ \times\ f_s\ \times\ V_{in}}$$

where f_s = Switching frequency

From the equation we get ,

$$L = \frac{15V\ \times (25V\ -\ 15V)}{0.3A\ \times\ 1250Hz\ \times\ 25V} = 16mH$$

Therefore we used a **20mH Power inductor** for our buck converter.

Capacitor selection

Output capacitor in a buck converter is used for output regulation. When PWM is high, capacitor is charging and discharging when PWM is low. During low PWM, output capacitor prevents regulations from falling too much. So, output capacitance must be high enough to maintain the ripple voltage. Output capacitance depends on the following parameters.

1. Inductor ripple current
2. Ripple output voltage
3. Switching frequency

Equation used to calculate the required value of the capacitance is :

ΔV_{out} = Desired output voltage ripple

This ripple voltage is around 3V.

$$C_{out(min)} = \frac{\Delta I_L}{8\ \times\ f_s\ \times\ \Delta V_{out}}$$

From the equation we get,

$$C_{out(min)} = \frac{0.3A}{8 \times 1250Hz \times 3V} = 10\mu F$$

So we have added a $220\mu F$ 50V capacitor in the buck converter.

Diode selection

When the current flows through the inductor, capacitor get charged and stores the energy. When there is no current through the inductor, this diode provides a path to the charge in capacitor to flow into output. So this increases the efficiency of the buck converter. However this diode should be operate in high frequencies and voltage drop through it should be less as much as possible. As Schottky diodes have low voltage drop and supports fast switching, we used a **1N5817 schottky diode** in the buck converter which has a 1A average forward current. Since the voltage drop is low , power dissipation is also very low in schottky diodes.[5] [1]

Current sense resistor

Current sense resistor in the buck converter is 1Ω, therefore it heats up and resistance could be changed. To reduce that, we used 5W cement type resistor.

0.8.5 Supply circuit

We used **1N5821 rectifier diodes** to rectifythe 18V AC rms output from the 18V secondary of the transformer. They can handle continuous current around 3A.

Smoothing capacitor value can be calculated using following equation,

$$C = \frac{I_{Load}}{2 \times f \times V_{(p-p)}}$$

Here $V_{(p-p)}$ is the ripple of the output voltage after the smoothing.

To get the high current we need to increase the capacitance of the smoothing capacitor. So we used two $2200\mu F$ 63V capacitors in parallel as the smoothing capacitors.

0.9 Testing and Simulation

For the simulation purposes, we used **LTspice** software. we choose that particular software because we can visualize the voltage and current waveforms more conveniently. We tested our circuits in the Breadboard implementation before the designing of the PCB.

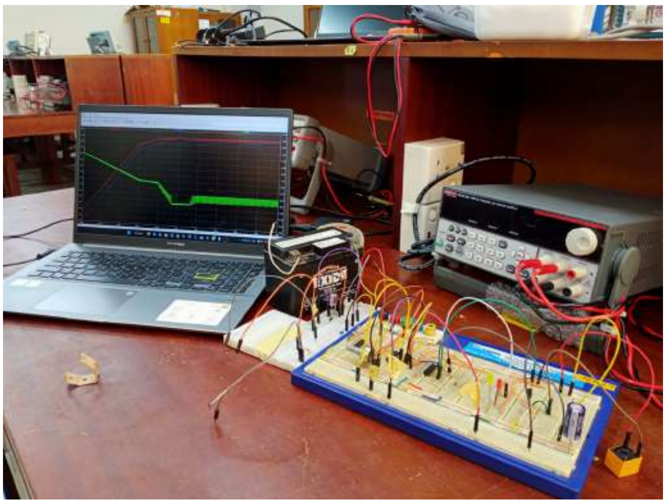

Fig13: Breadboard Implementation

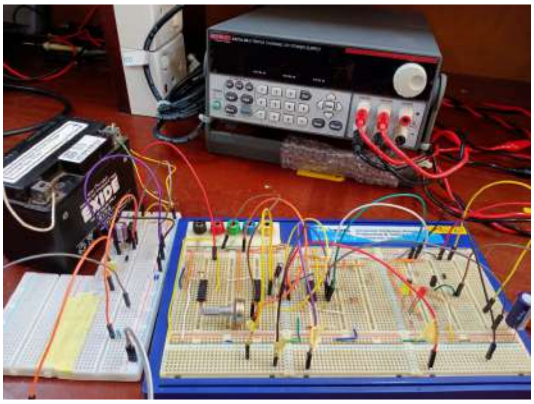

Fig14: Breadboard Implementation

0.9.1 Simulation results

These are the voltage and current waveforms from the LTSPICE software.

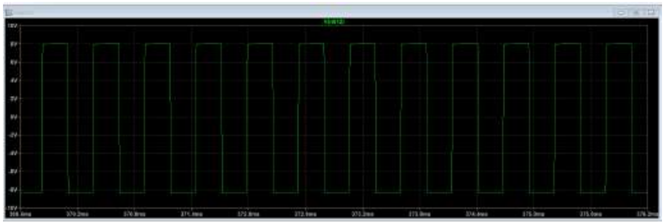

Fig15: Square Wave from Astable multivibrator

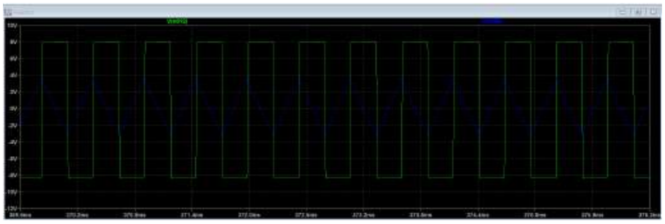

Fig16:Integrator output (Blue color Wave)

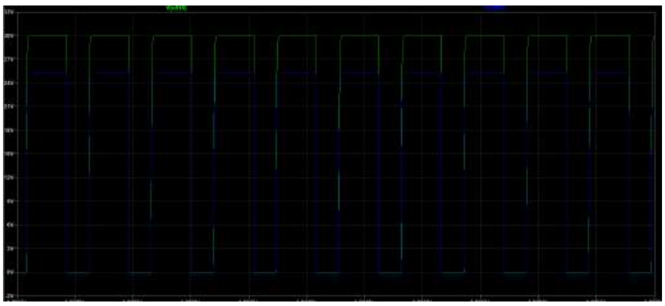

Fig17:Mosfet output Voltage

Here the green color wave is the mosfet gate driving signal and the blue color signal is the mosfet source voltage. 25V input to the drain of the mosfet has become a PWM wave.

Battery voltage and charging current

Battery voltage and the E.M.F of the battery increase parallel, therefore current remains almost constant less than 1A. In the constant voltage mode current starts to drop.

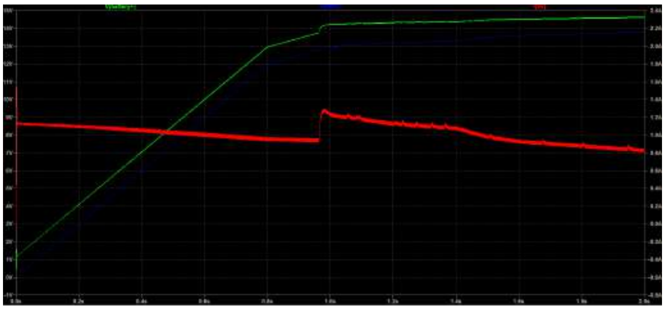

Fig:18
Green - battery voltage
Blue - E.M.F of the battery
Red -charging current

0.10 PCB Design

We designed the PCB for our project using the **ALTIUM** software and printed in a copper board using toner transfer method by ourselves. We designed two PCBs in order to overcome the complexity. One for the power circuit and another for all the other parts. We made single Layer PCBs and their dimensions are,

Main circuit - 10cm X 11cm.
Supply circuit - 6cm X 7.5cm

Traces of the power lines are 1.4mm width while all the other traces are 1mm width. In the main circuit, large copper areas (Copper polygons) are connected to ground. Drill hole size in the PCB is 1mm. We placed the components in such a way to overcome the complexity in the routing and thermal heating issues.

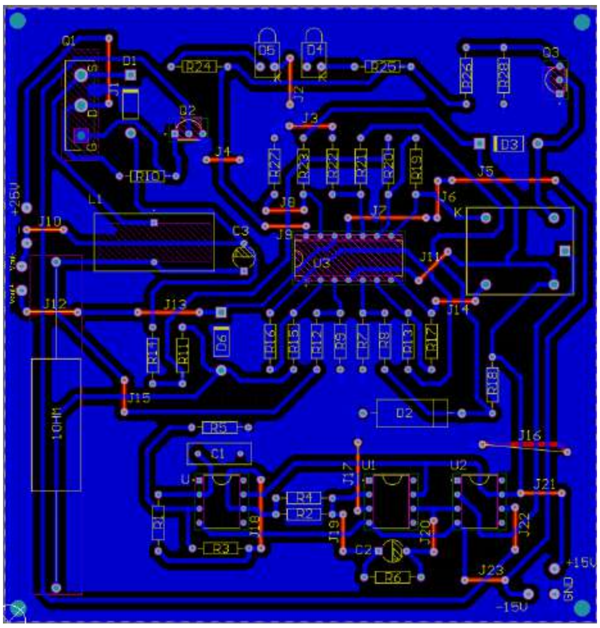

Fig19: PCB layout of the main circuit

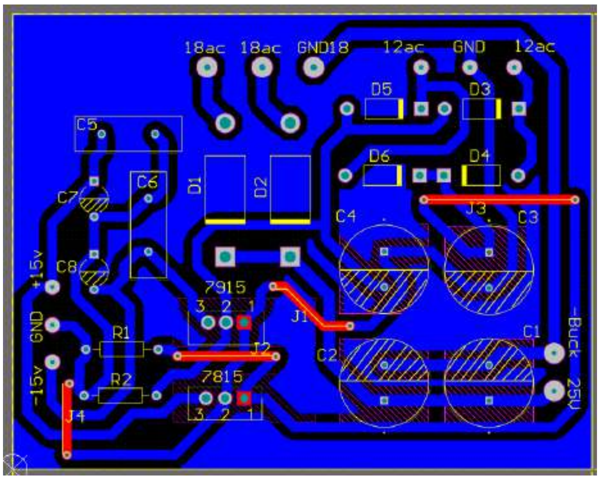

Fig20: PCB layout of the supply circuit

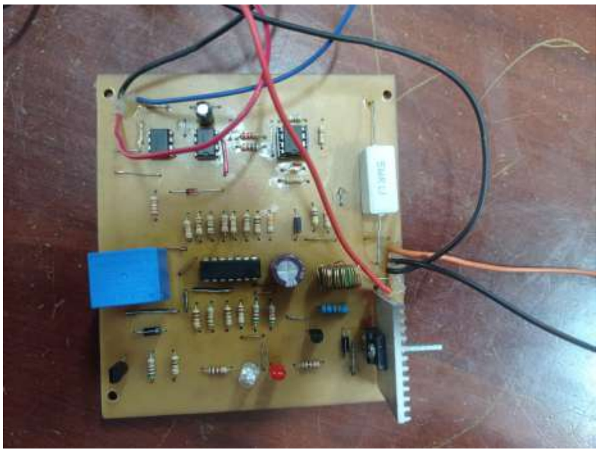

Fig21: Main circuit PCB soldered

Since the mosfet is heating, heat sink is attached to it using a bolt. We added thermal paste for better thermal conductivity.

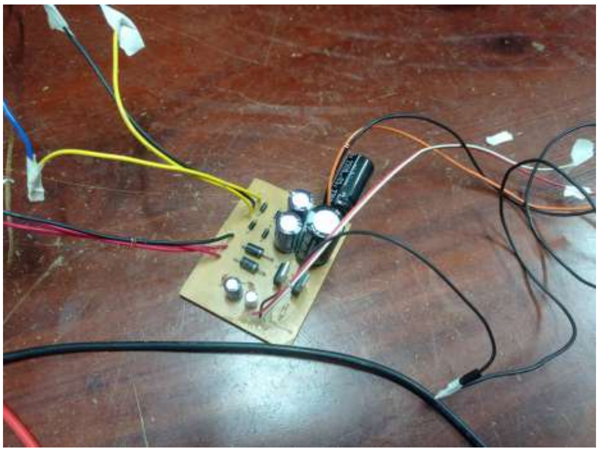

Fig22: Supply circuit PCB soldered

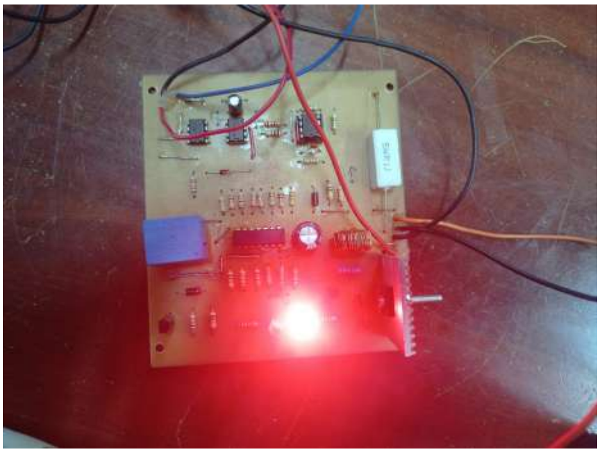

Fig23: Testing the Soldered PCB board

0.11 Enclosure

The enclosure for the Lead acid battery charger was designed using **SOLID-WORKS** software.It is a simple rectangular shape box. The skeleton structure and all the faces are made separately.. Screws and reverts are used to combine the parts and holes are made in order to provide the ventilation to the product. Cladding boards and aluminium frames are used to making the enclosure. Due to the high cost for the laser printing we self-made the enclosure.

center tapped transformer is placed at the bottom part

for the safety. outside of the enclosure face has the switch. There are 2 LED (green, red) to indicate the CC,CV modes respectively. The dimensions of the enclosure are **13cm X 20cm X 25cm**

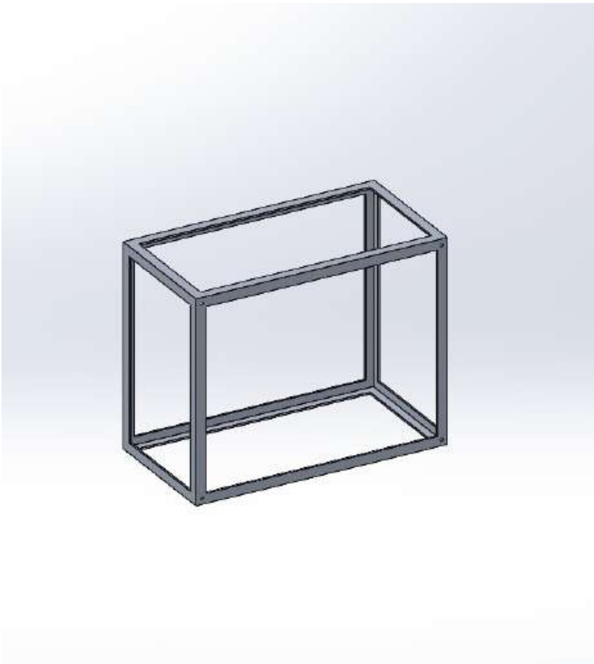

Fig24: Skeleton Frame Structure

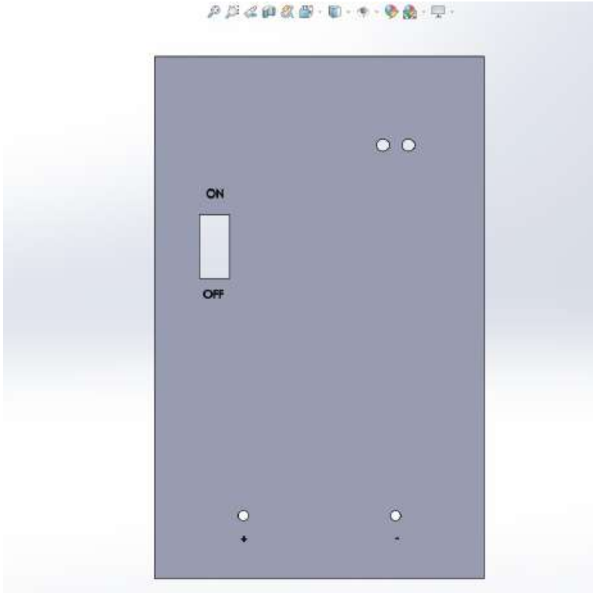

Fig25: Face containing the Switch and indicators

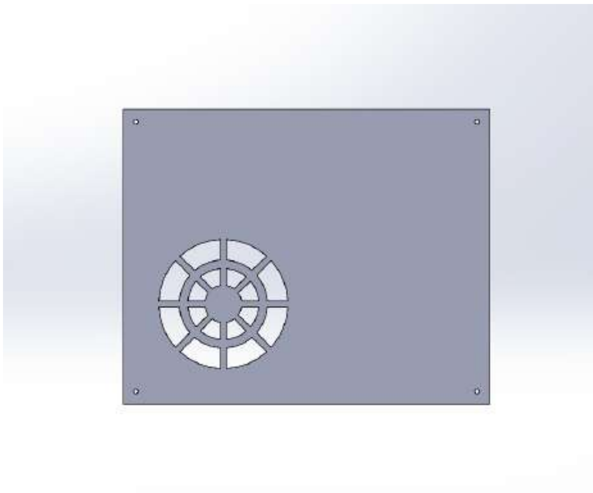

Fig26: Holes for the ventilation

Fig27: Lateral view of the product

Fig28: Front view of the product

0.12 Results

Following are the readings obtained during the testing of the circuit in the laboratory. Waveform readings were obtained from oscilloscope and the voltage and current values were obtained from the Multimeter.

When we observed the out of the Astable multi-vibrator, it gave a square wave of 1KHz

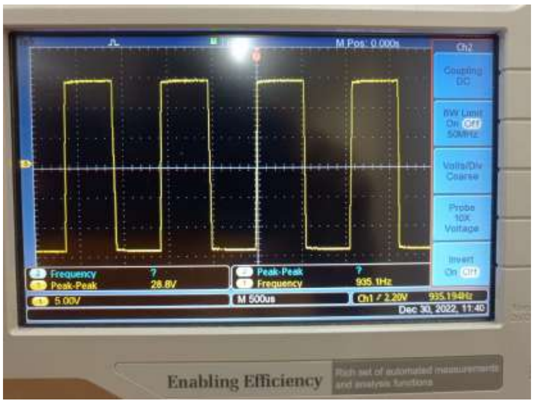

Fig29: Square Wave obtained from Astable multi-vibrator

In the following diagram yellow waveform and blue waveform show the outputs of the Integrator and comparator respectively. comparator produce the PWM waveform according to the feedback from the inverting input terminal.

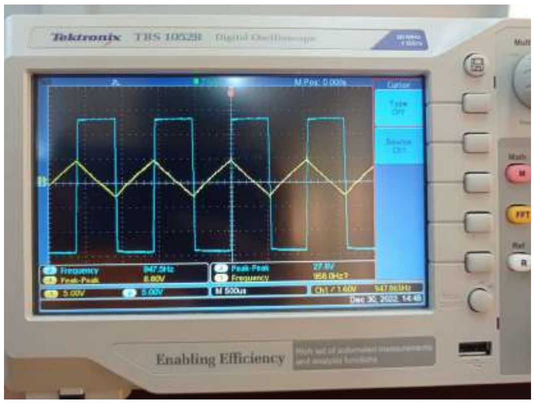

Fig30: Outputs of Comparator and Integrator

Following Figures show the MOSFET gate driving signal (PWM) and the source voltage of the MOSFET (which is to be filtered using LC filter) in the yellow and blue waveforms respectively. Those figures indicate the changes of the duty cycle of the PWM signals in both cases along with the source voltage.

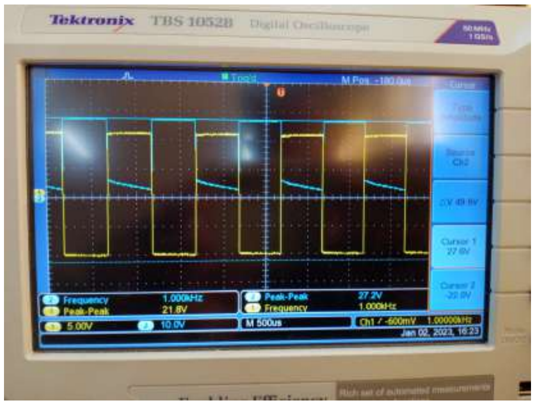

Fig31: Mosfet source voltage $V_{p\text{-}p}$=27.6V

0.13 Discussion

This project fulfills almost all the requirements. But there are some constraints that we couldn't overcome. Main problem was the switching frequency in the buck converter. After some search we found that for a effective buck converter switching frequency should be very high like 100kHz. But couldn't achieve that much high frequency due to unavailability of required opamps with very high slew rates. We used the highest possible **TL071** opamp with $20V/\mu s$.

Second drawback in our design is there is no way to change the charging current or switching voltage. At least we should have mounted a display to show the charging current and the battery voltage. In this case we need a external multi meter to measure those parameters.

0.14 Future Works

1. Adding a display to show current and voltages.
2. Including the adjustable current and switching voltage functionality.
3. Increasing the buck converter switching frequency for high efficient.
4. Adding a reverse polarity protection circuit with a fuse.
5. Mounting cooling fans inside the enclosure.
6. Replacing PCB with high quality imported multi layer PCB.
7. Auto cutoff circuit with a timer.

0.15 Task allocation

BANDARA H.M.S.D	Enclosure design, Breadboard implementation, PCB soldering, circuit building
JATHURSHAN.S	Documentation, Enclosure making , Circuit building
MITHUSHAN.K	Documentation, Breadboard implementation, Circuit design soldering
H.M.K SHEHAN	PCB design, Circuit design, PCB printing, Bread broad implementation, PCB soldering, Enclosure making

Table 1: Specifications

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Appendix A

Appendix A

A.1 Lead-Acid Battery charger Data sheet

A.1.1 Overview

This is the Lead acid battery charger with high efficiency. This charger ensures the high power delivery and healthy battery life.

A.1.2 Description

Each battery has their own charging habit. This battery uses the CC/CV charging method based on the PWM technique. Following Block diagram describe the functionality of the charger. It uses the feedback gather from the battery and switching between the CC/CV mode charging and adjust the PWM width.

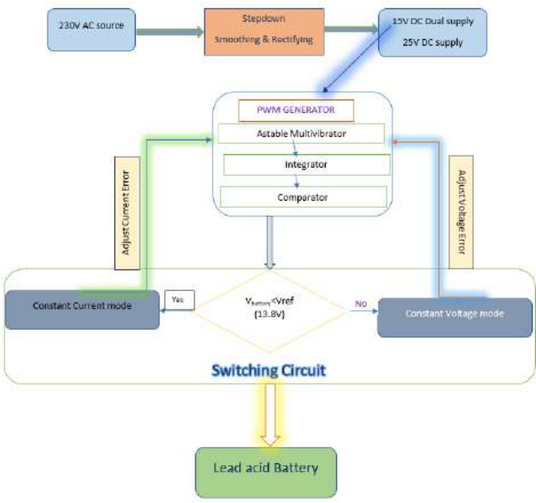

Fig1: Functional Block diagram

A.1.3 Features and Options

- Charges 12V Lead acid battery
- CC/CV charging with indicators
- Ventilation
- Shockproof casing
- Can operate in domestic supply

A.1.4 Specifications

Battery Voltage	0-12V
CC to CV transformation voltage	13.8V
Supply voltage of the Buck converter	25V
PWM signal frequency	1KHz

Table A.1: Specifications

A.1.5 Circuit Diagram

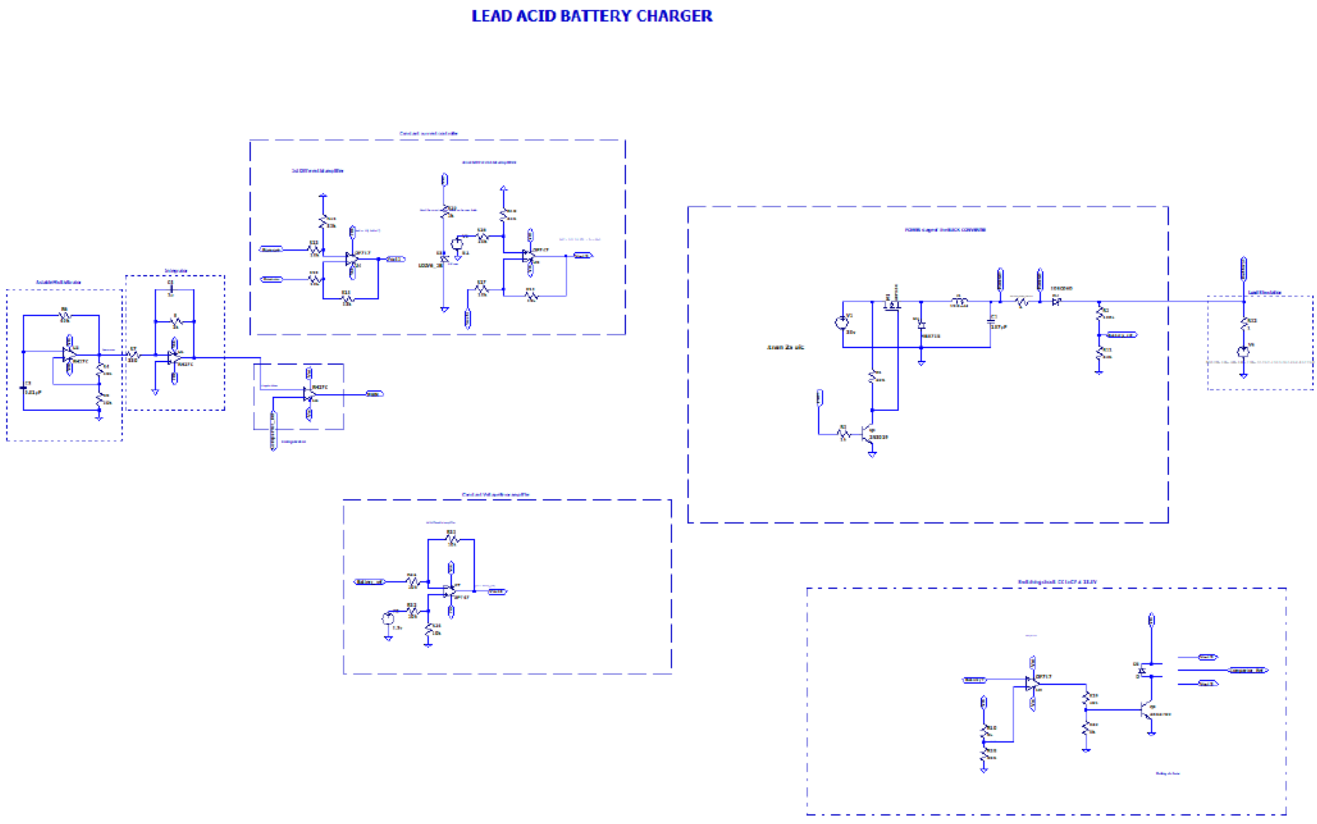

Fig2: Circuit Diagram