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Simulation of Automatic Cut-Off 12V Battery Charger

Metropolia University of Applied Sciences

Bachelor of Engineering

Electronics Engineering

Bachelor’s Thesis

21 November 2019

Author Title Number of Pages Date	Nikita Karna Simulation of Automatic Cut-Off 12V Battery Charger 35 pages 21 November 2019
Degree	Bachelor of Engineering
Degree Programme	Electronics
Professional Major	-
Instructors	Janne Mäntykoski, Senior Lecturer, Metropolia UAS

The objective of this project was to simulate a charger for 12V battery which will have the function to automatically cut-off the charging when the battery is fully charged. When the battery is fully charged to its capacity, the charging voltage must be disconnected, otherwise the battery will be overcharged. Overcharging a battery shortens the lifetime of the battery severely, and there is risk of excessive gas forming inside the battery which warps the casing of the battery. Such battery should not be used, as this may cause an operational hazard.

The main components used in this automatic battery charger are the bridge rectifier circuit, the LM317 linear voltage regulator and the LM311 voltage comparator. The LM317 voltage regulator was used to convert the rectified DC voltage to a constant output voltage which is used to charge the battery. Once the battery is completely charged the LM311 voltage comparator is used to drive the circuitry which will cut-off the charging voltage and protect the battery from overcharging.

While working on this project the circuit was first divided into small individual ‘modules’, such as AC to DC conversion, producing constant steady output voltage, creating the cut-off logic to turn off the charging when the battery is full. These ‘modules’ was created in Multisim simulation tool to verify that each component was working as expected. Finally, all the ‘modules’ were assembled to create a battery charging circuit with automatic cut-off.

This project has simulated the automatic charging cut-off of the battery when it was fully charged by comparing the voltage of the battery with a reference voltage, preventing the overcharging of the battery.

Keywords	Rectifier, Battery charger, Voltage Regulator, Voltage Comparator, Multisim

Contents

List of Abbreviations

AC	Alternating Current
B	Base
C	Collector
CVCC	Constant Voltage / Constant Current Charger
DC	Direct Current
E	Emitter
FET	Field Effect Transistor
FWB	Full Wave Bridge Rectifier
I	Current
IC	Integrated Circuit
I-V	Current-Voltage Characteristic
LED	Light Emitting Diode
LDO	Low Drop Out
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PN-junction	Positive-Negative Junction
PWM	Pulse Width Modulation
SMPS	Switched Mode Power Supply
V	Voltage
V_i	Input Voltage
V_O	Output Voltage

1 Introduction

Modern day electronics use a lot of active components that are very sensitive to change in voltage applied across the terminal. Any change in the voltage for these components can result in malfunction which may lead to erratic results and may even permanently damage the component. To overcome this fluctuation in voltage, modern day advancements in integrated circuit technology have produced IC based Voltage regulators that can produce constant non-varying voltage. A Voltage regulator can regulate the voltage by using electronic components such as transistors, diodes etc.

Voltage regulators are used in various applications where the voltage needs to be constant for example in switched mode power supply (SMPS) for powering computers or for regulating the voltage used for home appliances etc. Voltage regulators can be either fixed voltage regulators or adjustable voltage regulators which can maintain constant output voltage within the given range.

The purpose of this project was to simulate an automatic cut-off voltage charger with an LM317 voltage regulator which can charge the battery with a constant voltage, until the battery is fully charged. When the battery is fully charged to its capacity, the charging voltage is stopped, thereby preventing the overcharging of the battery. During the charging process the circuit shows that the battery is being charged by turning on a green LED. When the charging is complete, the circuit turns off the green LED and glows the red LED on, indicating that the charging process is complete and the battery can be removed.

2 Theoretical Background

2.1 Introduction to Voltage Regulators

The electricity available to almost all homes or industry are AC supply. The electronic components cannot work on the AC supply and hence AC must be converted to steady constant DC voltage.

The block diagram of a AC to DC power supply is shown in figure 1 below. The AC mains voltage (230V 50Hz in Finland) is first converted to a suitable voltage using a step-down transformer, which is fed to a rectifier circuit. The rectifier circuit converts the input AC voltage to rectified DC voltage. The rectifier circuit can either be half wave, full wave or full wave bridge rectifier. The rectifier produces a pulsated DC voltage which is not suitable for input to the electronic components. A filter circuit is used to reduce ripples from the output rectified DC voltage. The ripple free rectified DC voltage is converted to a constant output voltage using the voltage regulator. [1,3.39.]

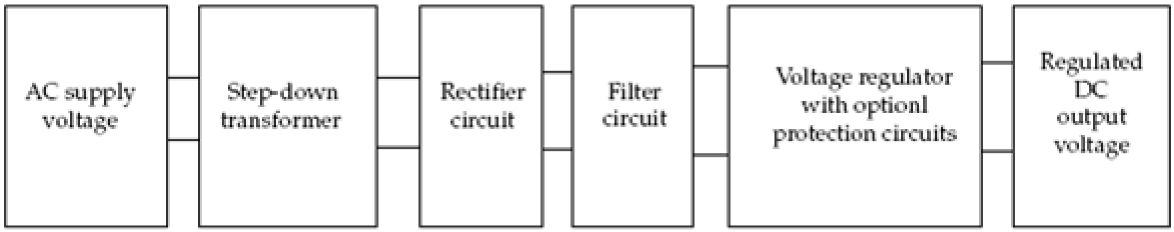


Figure 1. Building Blocks of AC to DC Power Supply [1, 3.40]

A voltage regulator is a device with simple feed-forward design and utilizes negative feedback control loops that gives constant DC output voltage, irrespective of variation in Input voltage, or the current drawn by the load. A voltage regulator consists of a voltage reference Vref and a high gain error amplifier. The error amplifier is used to compare the reference voltage with the feedback of the output voltage. The output voltage V_O is equal or multiple of V_{ref}. [2,6]. When the output voltage V_O is lower than the reference voltage, the error amplifier allows more current to pass through to increase the output voltage. Similarly, when the output voltage V_O is higher than the reference voltage, the error amplifier reduces the current flowing through, as a result of which the output voltage decreases.

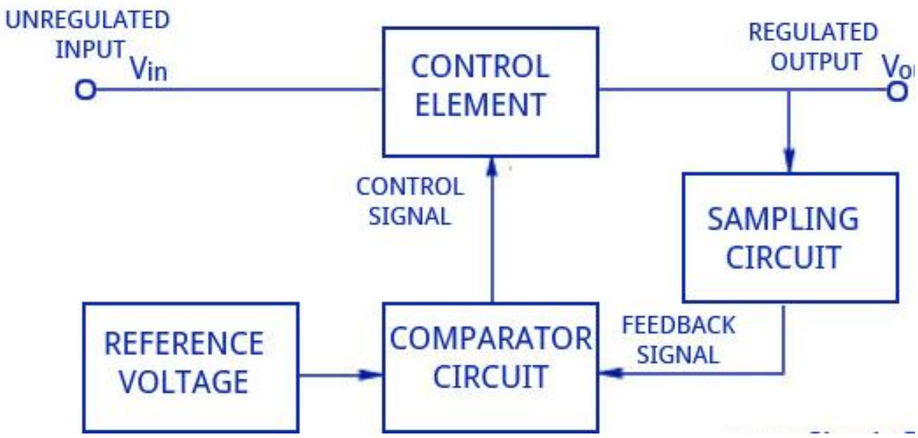


Figure 2. Block Diagram of Series Voltage Regulator [3]

From the block diagram in figure 2, it is seen that the unregulated input voltage is fed into the control element which changes the magnitude of the voltage and gives as output. The output voltage is sampled and feedback to the comparator circuit which compares the output voltage with the reference voltage. When the output voltage increases than the required output voltage the control element reduces the magnitude of the output voltage by using the control signal [3]. But when the output voltage begins to drop below the required output voltage, the comparator circuit senses this and uses control signal to increase the output voltage from the control element.

2.2 Types of Voltage Regulator

2.2.1 Zener Diode as Voltage Regulator

A PN-junction diode is a P-type semiconductor fused with a N-type semiconductor. A normal PN-junction diode works properly when it is forward biased, that is P-junction is connected to the positive terminal and the N-junction is connected to the negative terminal. However, if the PN-junction diode is reverse biased, that is its P-junction is connected to the negative terminal and N-junction is connected to the positive terminal, then the diode stops conducting. But if the reverse voltage is sufficiently high, the diode will suffer a premature breakdown and becomes damaged.

The Zener diode is a special kind of diode that uses the breakdown properties to maintain voltage regulation. A Zener diode is used in reverse bias mode for voltage regulation.

When sufficient reverse voltage is applied, the Zener diode goes into reverse breakdown avalanche mode. As seen in the I-V characteristic of the Zener diode in figure 3, the Zener diode has nearly constant negative voltage, V_Z regardless of the value of current flowing through the diode. The Zener value remains constant even with large variation in reverse current as long as Zener diode current remains between its breakdown current, I_z(min) and its maximum current handling rating I_z(max). This property of Zener diode to maintain constant voltage is an important characteristic of Zener diode. [4.]

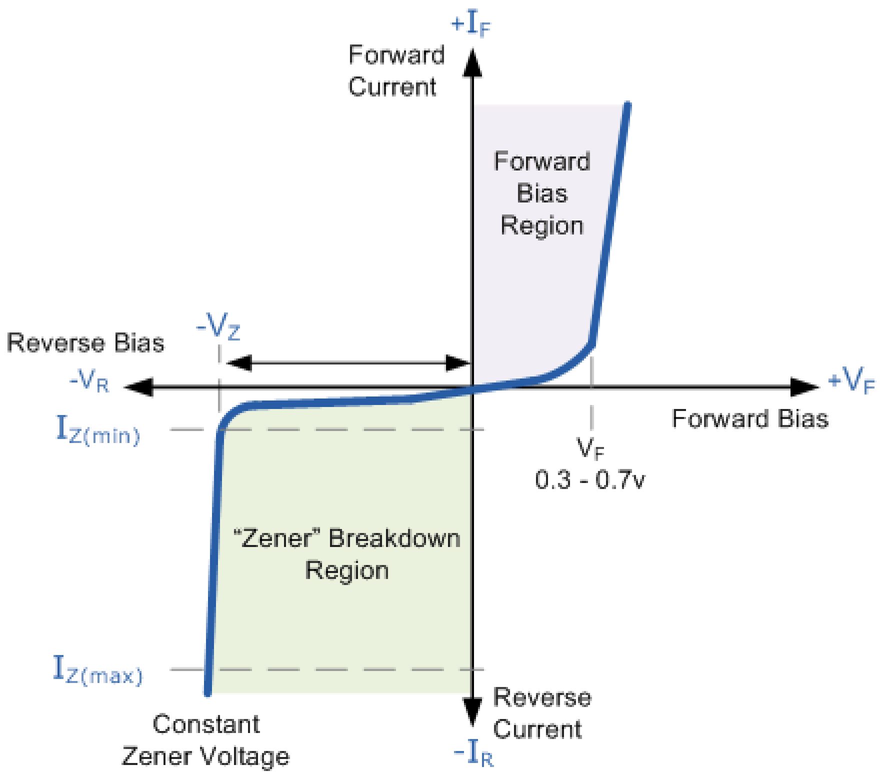


Figure 3. I-V Characteristics of a Zener Diode [4]

Zener diodes are used in shunt regulators. As seen in figure 4, the resistor R is connected in series with Zener diode to limit the current flow through the diode. Constant voltage V_{out} is taken across the Zener diode. When there is no load, the load current I_{load} is zero, all current passes through Zener diode as a result maximum power is dissipated. The load is connected in parallel with the Zener diode, so the voltage across load R_{load} is the same as Zener voltage. [4.]

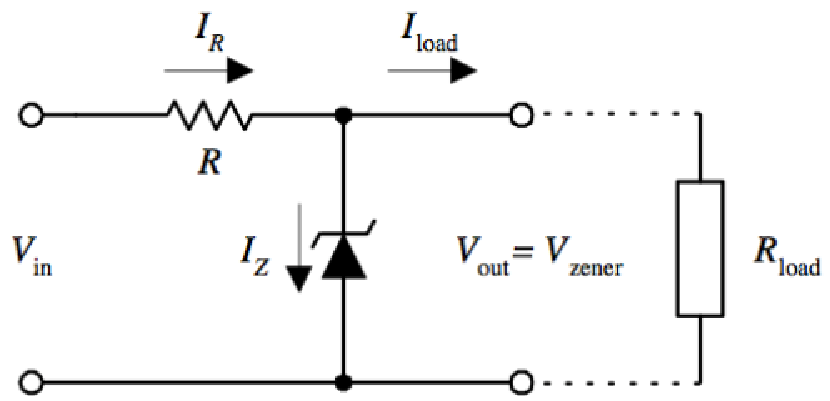


Figure 4. Zener Diode Voltage Regulator [5]

2.2.2 Linear Regulators

Linear regulators are more suitable for applications where the voltage difference between input and output is small. They are easy to use and very simple in design. For the linear regulators the difference between the input voltage and the output voltage is dissipated in form of heat which needs to be removed otherwise permanent damage will occur. It is because of this excess heat generated that Linear regulators are generally very inefficient. A proper heat sink is required for the operation of Linear regulators. The efficiency of linear regulators can be given as [6,3]:

$$Efficiency(\%) = \frac{Pout}{Pin} \times 100\% \tag{1}$$

$$Efficiency\ (\%) = \frac{Vo \times Io}{Vo \times Io + (Vi - Vo) \times Io} \tag{2}$$

Linear regulators are always step-down regulator, that is the output voltage of linear regulator is always less than the input voltage.

Power dissipated by linear regulator is [7,4]:

$$Power\ Dissipation = (Input\ Voltage - Output\ Voltage)\ \times Load\ Current \tag{3}$$

There are two variants of linear type regulators:

- Standard Linear Regulator
- Low Drop-out Linear Regulator

2.2.2.1 Standard Linear Regulator

In the standard linear regulator, the pass elements are a Darlington NPN or PNP transistor. The drop-out voltage for these transistors is at least 1.5V to 2V. This is because the Darlington transistor has high collector to emitter voltage drop and before producing output gate drive voltage encounters two base to emitter drops [8, 2]. For example, LM7805 is 3 terminal linear regulator which has a constant output voltage of 5V. To maintain the constant output of 5V, its input has to be minimum of 7V or higher. Thus, the drop out voltage of LM7805 regulator is 2V

2.2.2.2 Low Drop-out Linear Regulator

Low drop-out linear regulator or LDO have drop out voltage that is less than the standard drop-out regulators. The drop-out voltage for LDO regulators are usually much less. For full loads the drop-out voltage is less than 500mV, and for lighter loads this can fall even up to 10 to 20mV. Figure 5 shows an LDO block diagram that uses either a N-channel or P-channel FET as the pass element. This pass element produces the output voltage by dropping the input voltage linearly until the required output voltage is reached. The output voltage is constantly being sensed by the error amplifier and compared with reference voltage. The error amplifier constantly drives the pass element to keep adjusting the output voltage. In steady operating conditions, the LDO acts like a simple resistor. [8, 3.]

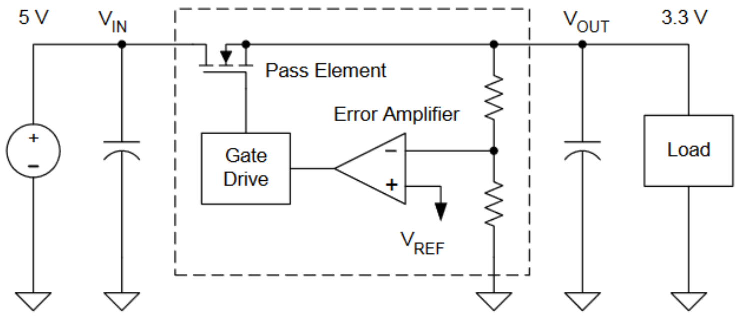


Figure 5. Pass Element in Low drop-out linear regulator [5, 3]

For example, LT1965 series of regulator has a drop-out voltage as low as 300mV. For fixed output voltage of 1.5V, the minimum input voltage required is 1.8V only.

2.2.3 Switching Regulators

Switching regulators are highly efficient and are available in IC which are compact and reliable. Switching regulator does not dissipate energy in the form of heat like linear regulators. They rapidly turn on and off the switching elements to change the magnitude of the output voltage. They can operate with both synchronous and non-synchronous switches (FETs). The FETs are switched rapidly by pulse width modulated signal. The capacitor and inductor elements of the switching regulator store energy temporarily and release energy producing a different magnitude voltage level.

A switching regulator uses switching elements to transform the incoming power supply into pulsated voltage. This pulsated voltage is then converted to continuous regulated DC voltage by using a series of capacitors, inductors and other elements. In switching regulators, the input voltage is supplied to the output by using a MOSFET switch until the required constant output voltage is reached. When the output voltage reaches the required output value, the switch element is turned off and no input power is consumed. By switching off the input power, there is no dissipation of energy in form of heat, and hence it is highly efficient compared to linear regulators. This operation of switching on and off the switching element at very high speed produces the regulated output voltage. [9.]

Unlike the linear voltage regulators which can only provide step-down voltage regulation a switched mode voltage regulator can provide step-up or step-down voltage regulation as well as voltage inversion.

The switching regulator uses two switching elements which can either be Diode or FET switches. Depending upon the type of switching element that is switched, the switching regulators can be Synchronous or Asynchronous switching regulator.

2.2.3.1 Non-Synchronous Switching Regulator

In non-synchronous switching regulator the top switch S1 is a MOSFET switch and the bottom switch D1 is a diode element. This is also known as diode rectification.

In the figure 6 below, when the MOSFET switch S1 is turned on the input voltage charges the inductor L1 and supplies the load current. Switch S1 is on until the output voltage is the required constant output voltage. Once the required output voltage is reached the switch S1 is turned off. As there is no path for current the inductor will produce a dangerously high voltage. To avoid this situation a diode is placed in place of switch S2 so that when switch S1 is turned off, the diode is forward biased allowing current to flow through. When the output voltage drops below the required output voltage, the switch S1 is turned on again. This process is run continually to provide a constant regulated output voltage. [10.]

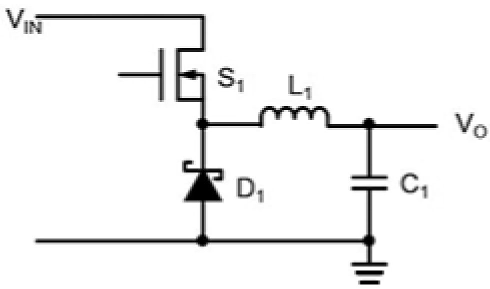


Figure 6. Non-synchronous Switching Regulator Principle [10]

The diode used in nonsynchronous has a significant forward voltage drop which leads to inefficiency when compared to synchronous voltage regulator, especially when the load voltage is low, the voltage drop across the diode alone may be signifcant proportion of the total [9].

2.2.3.2 Synchronous Switching Regulator

Synchronous switching regulators uses MOSFET switches for both switching elements. As there is no diode used, this type of regulators are highly efficient even in low load conditions.

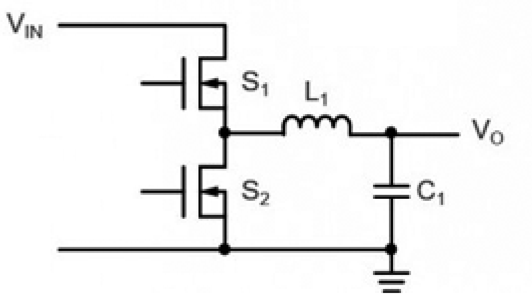


Figure 7. Synchronous Switching Regulator Principle [10]

In synchronous regulators of figure 7, when the switch S1 is on the other switch S2 is turned off, and when switch S1 is turned off the switch S2 is turned on. The two switches work in compliment to each other, thus these regulators are called synchronous switching regulators [9]. Synchronous regulators require complex circuitry as two controller circuits are needed to switch both the MOSFET switches.

2.2.4 Types of Switching Regulators

There are three basic modes of Switched mode voltage regulation

- Buck Switching Regulator
- Boost Switching Regulator
- Buck-Boost Switching Regulator

2.2.4.1 Buck Switching Regulator

A buck switching regulator is a step-down switching voltage regulator. As shown in figure 8, it uses a MOSFET as upper switching element and the lower switching element is mostly a diode, although modern buck switching regulator uses MOSFET for both switching elements. The operation of switch is controlled by pulse width modulated signal.

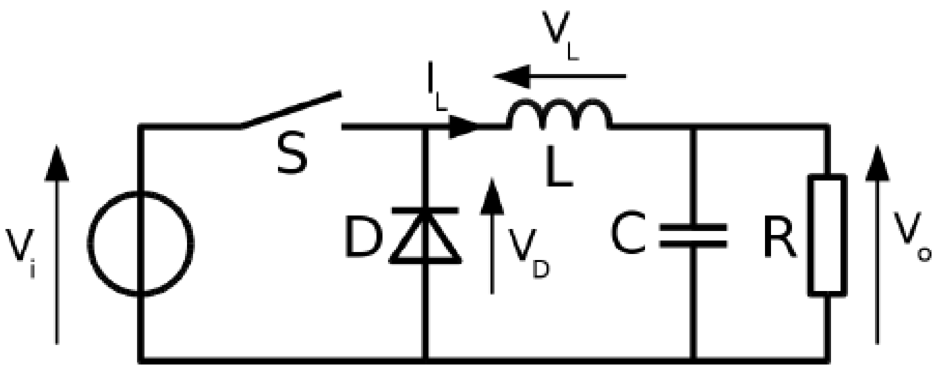


Figure 8. Buck Switching Regulator [11]

Figure 9 shows the operation of Buck regulator during switching. When the upper swtiching element S is closed the input voltage is connected to the inductor L and the load, the current I_L through the inductor increases. The inductor absorbs energy from the source and stores in the form of magnetic field. This increase in current causes voltage V_L to be induced across the inductor, which is opposite to the input load as a result of which the voltage across load decreases. When the switching elemet S is opened, the input voltage is disconnected. Because of the lower switching element diode, the current through the inductor flows throughs the diode. The induced voltage across the inductor changes direction and the inductor becomes the source to supply the load by releasing its stored magnetic energy. [12,213.]

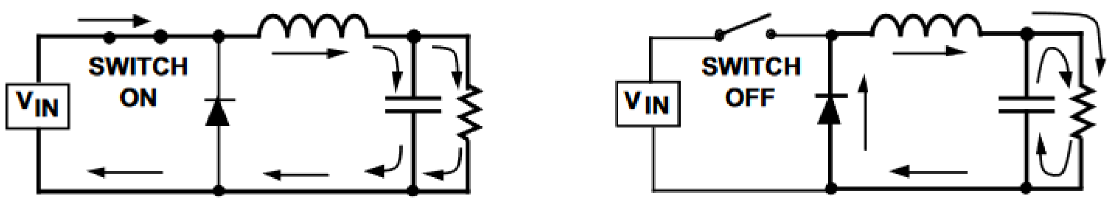


Figure 9. Buck Switching Regulator operation during switch on and off [13,5]

The buck converter decreases the output voltage by continuously switching on and off the switching element S.

Buck converter can operate in two modes. When the current through the inductor never falls to zero the buck converter operates in continuos mode and if the current falls to zero, it is said to be operating in discontinuos mode [11].

2.2.4.2 Boost Switching Regulator

Boost switching regulator are step-up voltage regulators as its output voltage is greater than the input voltage. The increase in output voltage causes the decrease in current at the output. It also uses MOSFET and diode as its two switching elements.

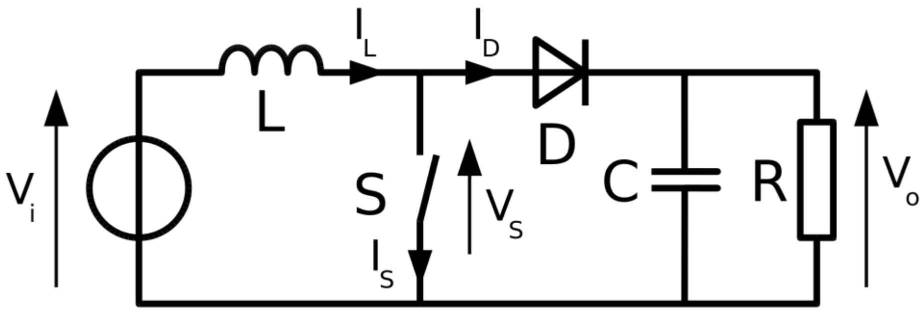


Figure 10. Boost Switching Regulator [14]

The operation of boost regulator is shown in figure 11. When the switching element S is on, the current from the source flows through the inductor. The flow of current through the inductor causes the increase in magnetic field across the inductor. The polarity on the left side of indicator is positive which is opposite to the input source. When the switch is turned off, the magnetic field that was generated across the inductor collapses. The polarity of the voltage across the inductor is also reversed. So now the input voltage and the voltage through inductor are in series which increases the charging voltage to the capacitor through the diode D. [14.]

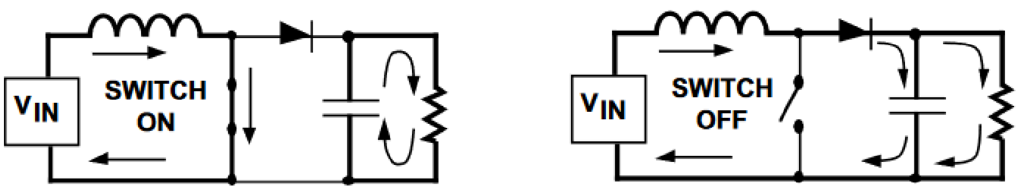


Figure 11. Boost Switching Regulator operation during switch on and off [13,6]

When the switch is cycled fast, the inductor is not discharged completely between the switching cycle, and the voltage across the load is higher than the input voltage when the switching element is off. Similar to the buck regulator, the boost regulator also operates in continuos and discontinuos mode. When the currrent through the inductor never falls to zero, it is said to be operating in continuous mode, but when the current falls to zero level and then again increases in another cycle, it is said to be operating in discontinuos mode. [14.]

2.2.4.3 Buck-Boost Switching Regulator

The buck-boost switching regulator is a combination of the buck regulator and boost regulator which produces an inverted ouput voltage (to that of input voltage) which can be higher or lesser than the input voltage depending upon the duty cycle. So this regulator can operate in both step-up or step-down mode.This is also called inverting regulator.

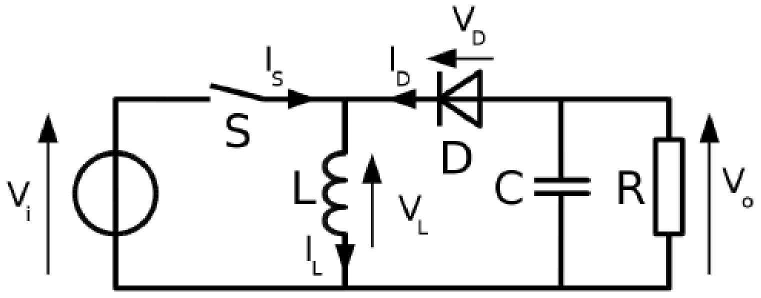


Figure 12. Buck-Boost Switching Regulator [15]

In the figure 13 below, when the switch is turned on the voltage across the inductor is equal to the input voltage. The input voltage is fed to the inductor only and the load does not get the any current from input voltage. There is no current flow through the diode because the diode stops the current as it is reverse biased when the switch is turned on. But when the switch is turned off, the energy stored in the inductor is transferred to the load. But this voltage from inductor is of the opposite polarity to that of the input voltage. So, the load sees the inverted voltage. [15.]

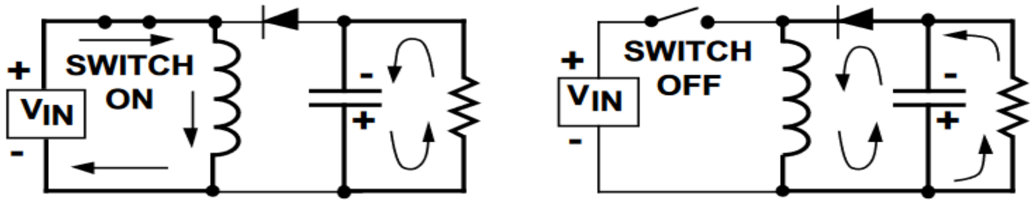


Figure 13. Buck-Boost Switching Regulator operation during switch on and off [13,7]

The magnitude of the output voltage can be higher or lower than the input voltage depending on the duty cycle, but it is inverted. Similar to buck and boost regulator, buck-boost regulators also operate in continuos and discontinuos mode.

2.2.5 Properties of Regulator

In an ideal voltage regulator, the output voltage is constant irrespective of the changes in the input voltage. But the voltage regulators are not ideal and there will be some changes in the output if the input voltage or the current drawn by the load changes. The ability to maintain the constant output voltage within specified limits are given by the line and load regulation.

2.2.5.1 Line Regulation

Line regulation or source regulation of a voltage regulator is the ability to maintain specified output voltage when the input voltage changes, with the load current being the same [16].

Line regulation can be expressed as [16]:

$$Line\ Regulation = \frac{Changes\ in\ Output\ Voltage}{Changes\ in\ Input\ Voltage} \times 100\% \quad (4)$$

Line regulation becomes an important factor when the input voltage is unregulated or fluctuating. A good voltage regulator can have line regulation of less than 0.1% [16].

2.2.5.2 Load Regulation

Load regulation is the ability to maintain constant output when there are changes in the load current. Variation in load current may be because of several factors, such as increasing the speed of fan or increasing the brightness of the Television set [17].

Load regulation can be mathematically expressed as [17]:

$$Load\ Regulation = \frac{Voltage(no\ load) - Voltage(full\ load)}{Voltage(full\ load)} \times 100\% \qquad (5)$$

2.2.5.3 Switching Noise

Switching regulators are much more efficient compared to linear regulators, however they have an inherent problem of switching noise, which is generated by switching inside the DC-DC regulators. The noise is reflected on the output voltage as spikes at switching frequency. Switching regulators have built in internal filtering which is limited but adequate for most applications. However when the noise is very high, then an LC filter or an output filter capacitor may be required to filter out the noise. [18, 1]

2.3 Safety Features of Voltage Regulators

Modern voltage regulators have some safeguards built in for protecting the regulator IC itself, in case the operating conditon goes out of the threshold values or the voltage regulator is connected incorrectly [19].

Voltage regulators can generate a lot of heat, especially when the difference between input voltage and output voltage is high. So a proper heat sink is required in these conditions. Also the IC itself can perform thermal shutdown when the temprature inside the IC exceeds normal operating conditions. [19.]

Voltage regulators also has protective circuitry built inside to prevent the IC from damage due to incorrect polarity such as when the negative battery voltage is connected across input pins. This causes unwanted current flow depending on type of regulator or loads.

Voltage regulators have built in overvoltage protection which protects the regulator from high input voltage beyond the normal input voltage range of the regulator. Protection circuits are built inside so that high input voltage does not damage the IC. When the output of circuit is shorted to ground this can cause high output current which may damage the IC. To prevent itself from damage the IC limits the output current within the specified limit when the short circuit is detected. [19.]

3 Battery Charging

A cell is an electrochemical system whose chemical reactions create a flow of current in a circuit. A cell consists of three components – an anode, a cathode and an electrolyte. A battery is combination of one or more cells in either series or parallel. A battery can be a non-rechargeable battery such as Alkaline or Zinc-Carbon batteries, which needs to be discarded when they are discharged, or it can be a recharegeable battery which can be reused again after recharging the batteries, such as Lead-Acid batteries, Lithium Polymer batteries etc.

A lead-acid battery uses Lead plates for its two electrodes submerged in an Sulphuric acid electrolyte. It has a nominal cell voltage of 2.1V per cell. When a lead-acid cell is charged, the sulphuric acid reacts with lead and forms a layer of lead dioxide on the anode plate and lead sulphate is deposited on the cathode plate. During this reaction hydrogen and oxygen gas are released, but most of these gases is recombined inside the battery itself as the battery is sealed. But over longer periods of time, these gases may leak slowly.

The graph in figure 14 below shows the relation between battery voltage V_b and current I. For each state of charge (level of current charge relative to full capacity), the battery voltage or the charging current can be found if one of them is known [20].

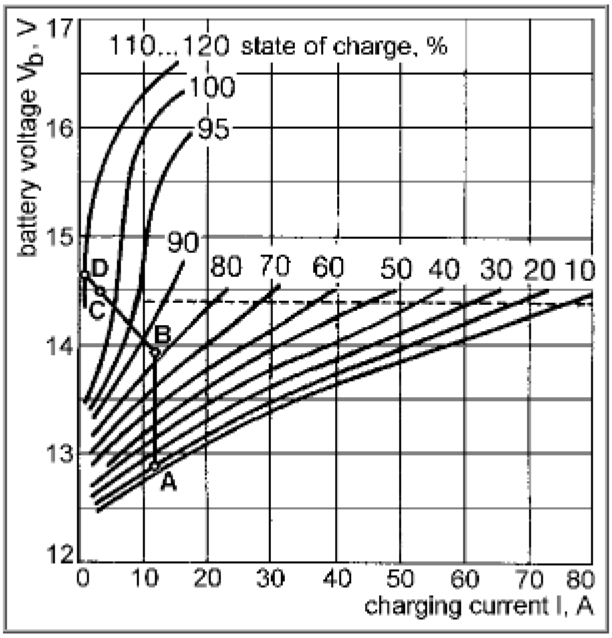


Figure 14. Relation between charging current, voltage and state of charge [20]

Charging the batteries may be done by following any of the below charging implementation methods.

- Constant Voltage Charger
- Constant Current Charger
- Constant Voltage / Constant Current Charger (CVCC)

3.1 Constant Voltage Charger

Constant voltage charging method uses a constant voltage applied across the battery terminals, which does not change with the state of battery charged. Initially when the battery is completely discharged, a large current flows through the battery as the charging potential is high compared to battery voltage, but with the battery voltage gradually increasing, the charging current slowly tapers off. In the figure 15 below, for 12V battery, when the battery voltage reaches around 13.8V, the battery maintains float voltage level and the charger starts trickle charging to compensate for self discharge of the battery. Thus the battery is maintained to its full capacity until the battery is disconnected from the charger.

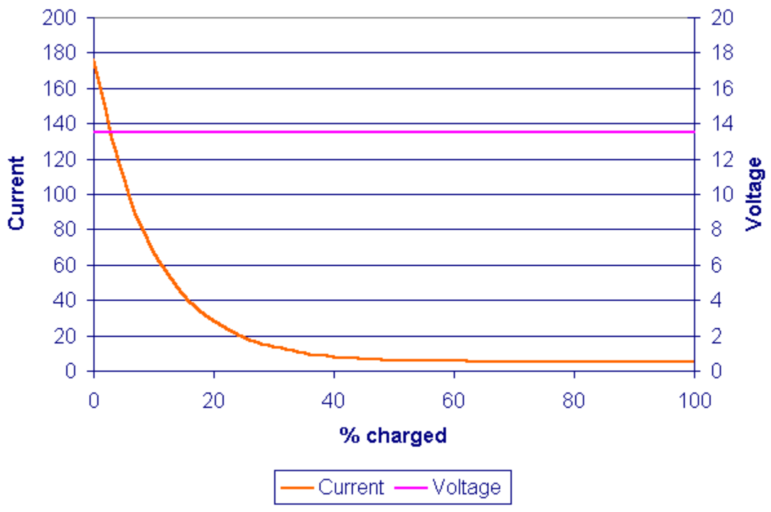


Figure 15. Constant Voltage Charging Method [21]

This implementation of battery charger has advantages that it allows fast charging of the battery, but it also has disadvantage that when the battery is completely discharged high current flows which may overheat the battery. Also, allowing large current flow of battery may reduce the lifetime of the battery. This method is suitable for lead-acid type batteries, but not for Nickel Metal Hydride (Ni-MH) batteries or Lithium-ion (Li-ion) batteries.

3.2 Constant Current Charger

Constant current charger charges batteries which have the current level predefined for 10% of the battery capacity. For 70AH batteries the current level is set at 7A per hour, so the total charging time is 10 hours.

The major drawback of this charging method is that charging time is very slow, and also since the current is constantly being pushed to the battery even when the battery is fully charged to its capacity, there is chance of the battery being overcharged, which may

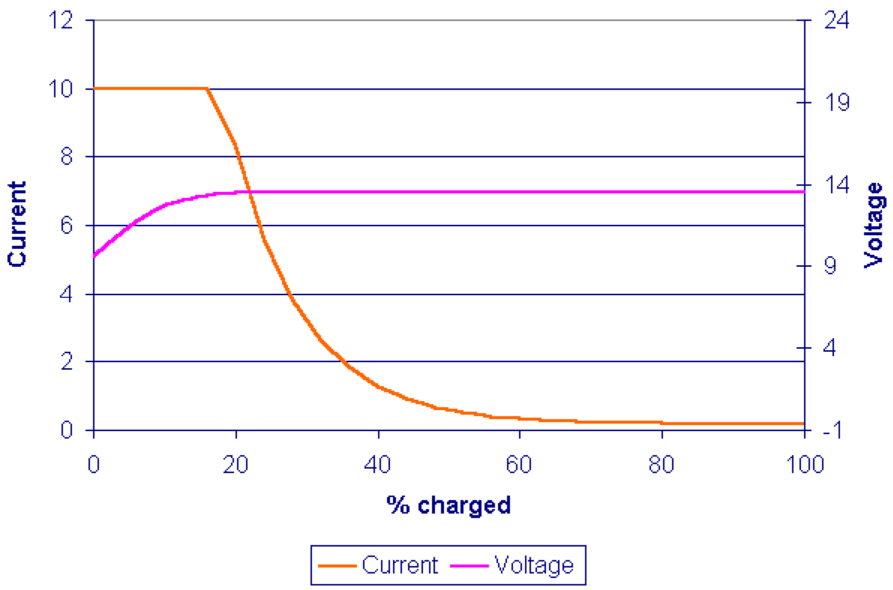


Figure 16. Constant Current Charging Method [21]

overheat the battery and shorten its lifetime.So the battery has to be disconnected from the charger once the battery is completely charged. This method is suitable for Ni-MH type batteries.

3.3 Constant Voltage / Constant Current Charger (CVCC)

CVCC charging method is combination of both constant voltage and constant current charging methods. This method improves on drawback of both the methods mentioned above providing a fast charge time with minimum damage to the battery from overcharging.

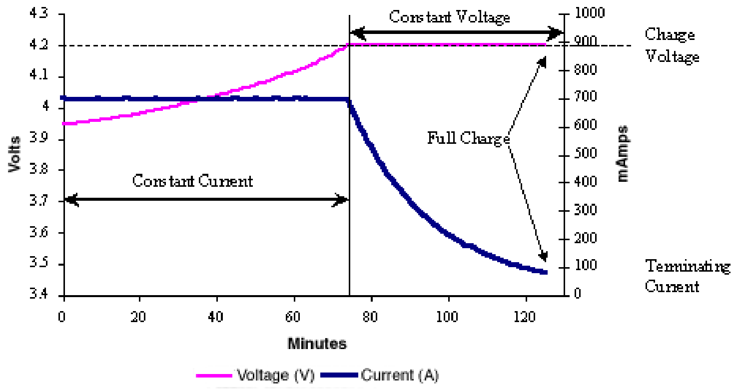


Figure 17. Constant Voltage Constant Current Charging Method [22]

As seen in the graph of figure 17, initially the charger starts charging with constant current method by charging current that is limited to a set level until the battery reaches a predefined voltage level. When that voltage level is reached, the charging method switches to constant voltage method, after which the current is reduced and the the battery starts charging with constant voltage until the battery is fully charged.

CVCC charging methods are best for charging the batteries but because of the complexity in implementing this method, we are using constant voltage method to charge the battery in this project.

4 Components of the Battery Charger

The design of this battery charger with automatic cutoff was simulated in the Multisim simulator to check for the working of individual components and to validate the design.

4.1 Hardware and IC Required

This battery charger uses major components listed below

4.1.1 Full Wave Bridge Rectifier

This battery charger uses a full wave bridge rectifier which uses four diodes in bridge, so that it can rectify both positive and negative half cycles of the input. For positive half the cycle only two diodes D1 and D2 are forward biased and thus conducting, whereas the other two diodes are reverse biased and do not conduct. For the negative half cycle of the input diodes D3 and D4 conduct whereas diodes D1 and D2 do not conduct. On each half cycle of the input there are two diodes performing the rectification, so the output voltage is two voltage drops of the diode (2*0.7 = 1.4V) less than the input voltage.

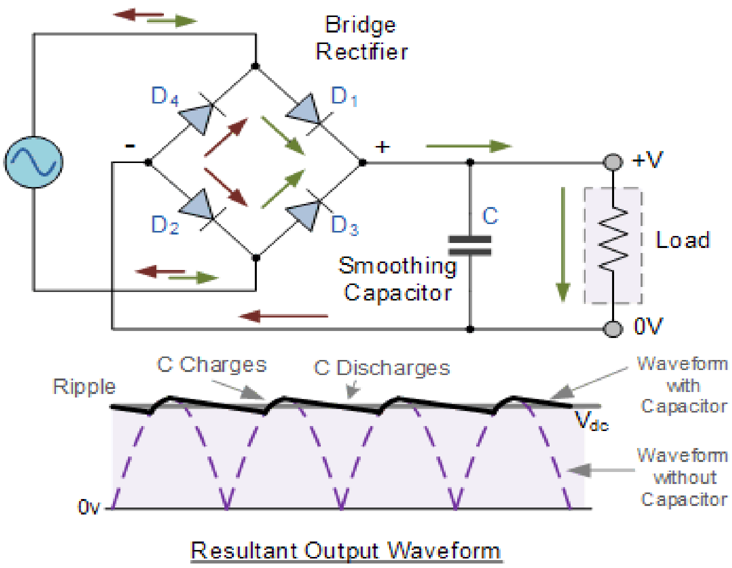


Figure 18. Full wave bridge rectifier with smoothing capacitor [23]

Figure 18 shows the bridge rectifier circuit and its output waveform. The output of the bridge rectifier produces a pulsating DC signal which is not appropriate for operating components requiring DC voltage, so a smoothing capacitor is required to filter the output to provide a DC voltage without any ripples.

Although full wave bridge rectifiers are available in a single IC form which has all the diodes built in the IC itself, it can also be built using four diodes in a ‘bridge’ to do the full wave rectification

4.1.2 Transformer

A transformer is an electromagnetic electrical device that is used to change the amplitude of the input AC voltage. A transformer can either increase or decrease voltage levels without changing its frequency.

Figure 19 shows a single-phase transformer consists of two electricals coils called primary and secondary winding placed in close proximity of each other. Through the process of mutual induction, the voltage in one coil is magnetically induced on the other coil. The primary winding of the transformer is connected to the AC supply voltage as the secondary winding produces the step-up or step-down AC voltage. If the number of windings in the primary coil is higher than the secondary coils, then the transformer steps down the voltage. But if the number of windings in secondary coil is higher than the primary coil then output voltage is increased. The ratio of number of turns between primary and secondary coil gives the output voltage of the transformer.

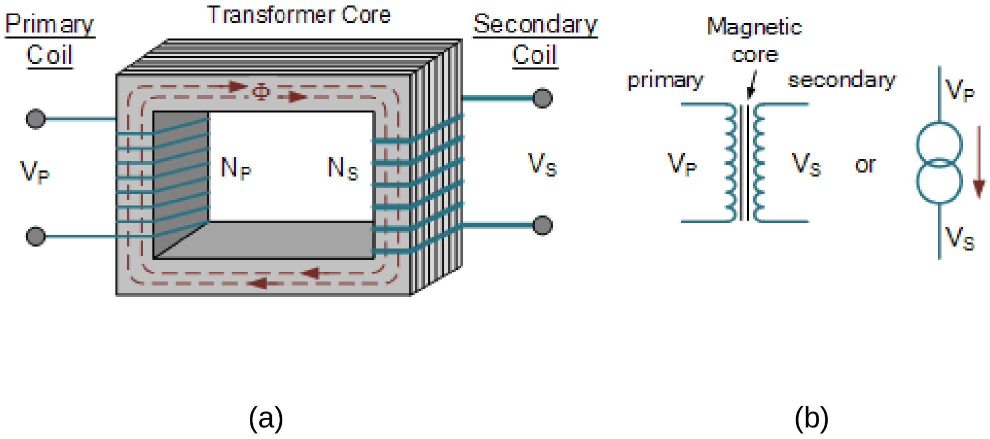


Figure 19. A Single Phase Transformer (a) Construction of Transformer (b) Symbolic representation of Transformers [24]

$$Turn\ Ratio, n = \frac{Vp}{Vs} \tag{6}$$

For this project, we are using a step-down transformer to convert the AC mains voltage in Finland which is 230V AC to step-down to 18V AC. So, the turn ration of this transformer is approximately 13.

$$Turn\ Ratio = \frac{230}{18} = approx. 13 \tag{7}$$

4.1.3 Voltage Regulator

A voltage regulator provides a constant output voltage even when the input voltage is fluctuating within the operating range of the voltage regulator IC.

We are using LM317 linear voltage regulator IC which is a three terminal adjustable voltage regulator. It consists of the input, output and the adjust pin. The adjust pin is used to adjust the output voltage. It can supply output adjustable voltage from 1.2V to 37V. This IC can supply up to 1.5A of current to the load. The dropout voltage of LM317 regulators is about 3V, that is the output should be at least 3V less than input voltage.

In figure 20, the voltage across the feedback resistor R_1 is constant reference voltage V_{ref} produced between output and adjust pins. Since the reference voltage across resistor R_1 is constant, a constant current flow through the resistor R_2, which gives output voltage of

$$V_{out} = V_{ref} \times (1 + \frac{R2}{R1}) \tag{8}$$

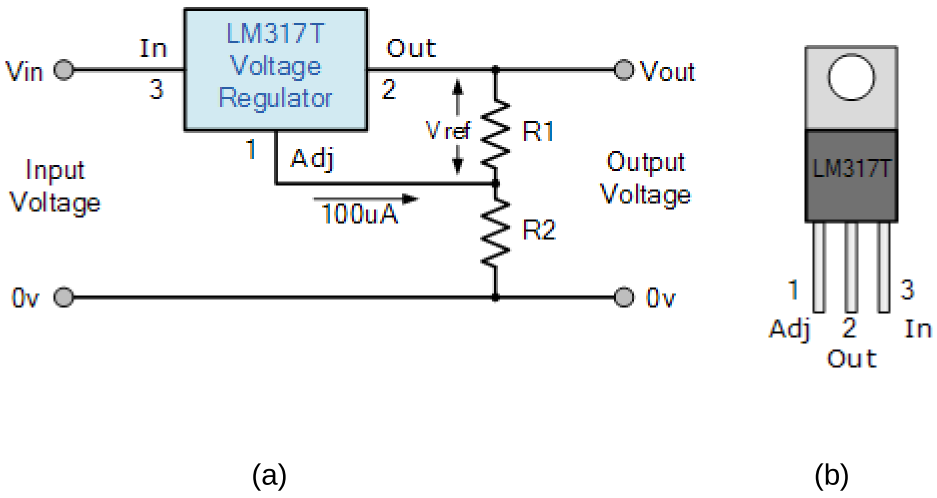


Figure 20. LM317 Regulator (a) LM317 adjustable voltage output circuit (b) LM317 Pinout [25]

For the LM317 regulator the reference voltage is 1.25V. So the output voltage is given by the expression

$$V_{out} = 1.25V \times (1 + \frac{R2}{R1}) \tag{9}$$

Adjustable output voltage is achieved by using a fixed resistor R1 and a potentiometer in place of resistor R_2, by adjusting the resistance of the potentiometer, appropriate output voltage given by expression 9 is achieved.

The difference in input and output voltage is dissipated in form of heat, so for proper operation of LM317 the difference between input and output voltage should not be very high. To dissipate the heat generated during the operation, a proper heat sink must be attached to prevent thermal shutdown or permanent damage to the regulator.

4.1.4 Voltage Comparators

A voltage comparator is used to compare two input voltages to know which voltage is greater. An operational amplifier is used to compare voltages.

For this project, we are using the LM311 voltage comparator to compare the reference voltage with the battery voltage to perform automatic charging voltage cutoff. LM311 is an 8-pin single comparator. The pin out of the LM311 is shown in figure 21. It has two inputs for power V_{EE} and V_{CC} on pins 4 and 8 respectively. Pin 1 is used for ground. Pins 2 and 3 are the non-inverting input and inverting input of the comparator and pin 7 is the output pin of this comparator. This pin is the open collector pin, so to produce the appropriate output voltage level, a pull-up or pull-down resistor circuit is used on pin 7. Pins 5 and 6 are used for balance and strobe functions. [26.]

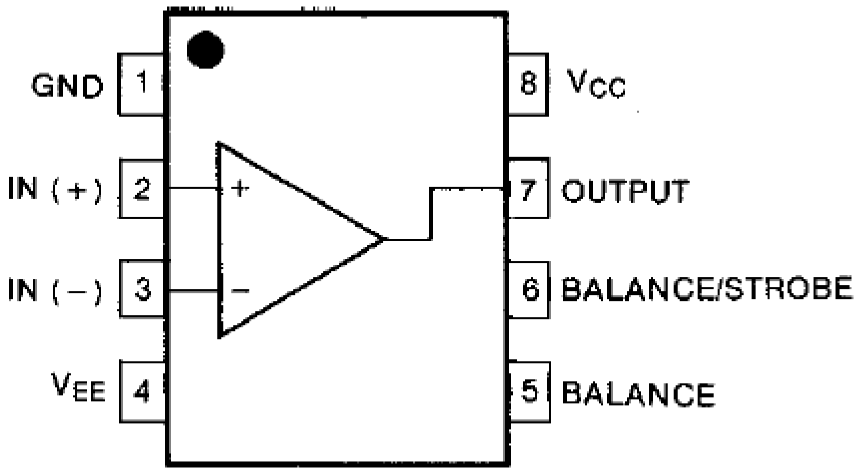


Figure 21. Voltage Comparator LM311 Pinout [26]

When the non-inverting terminal voltage is greater than the inverting terminal voltage, the output is the voltage that is applied on the pin V_{CC}. When the inverting terminal voltage is lower than the non-inverting terminal voltage, then the output will be the voltage applied to pin V_{EE}. The logic high output is the voltage on the pin V_{CC} and the logic low output is the voltage on the pin V_{EE}. Pin V_{EE} can be connected to ground as well. [26.]

5 Working Mechanism of the Battery Charger

The flow chart of automatic cut-off battery charger is shown in figure 22.

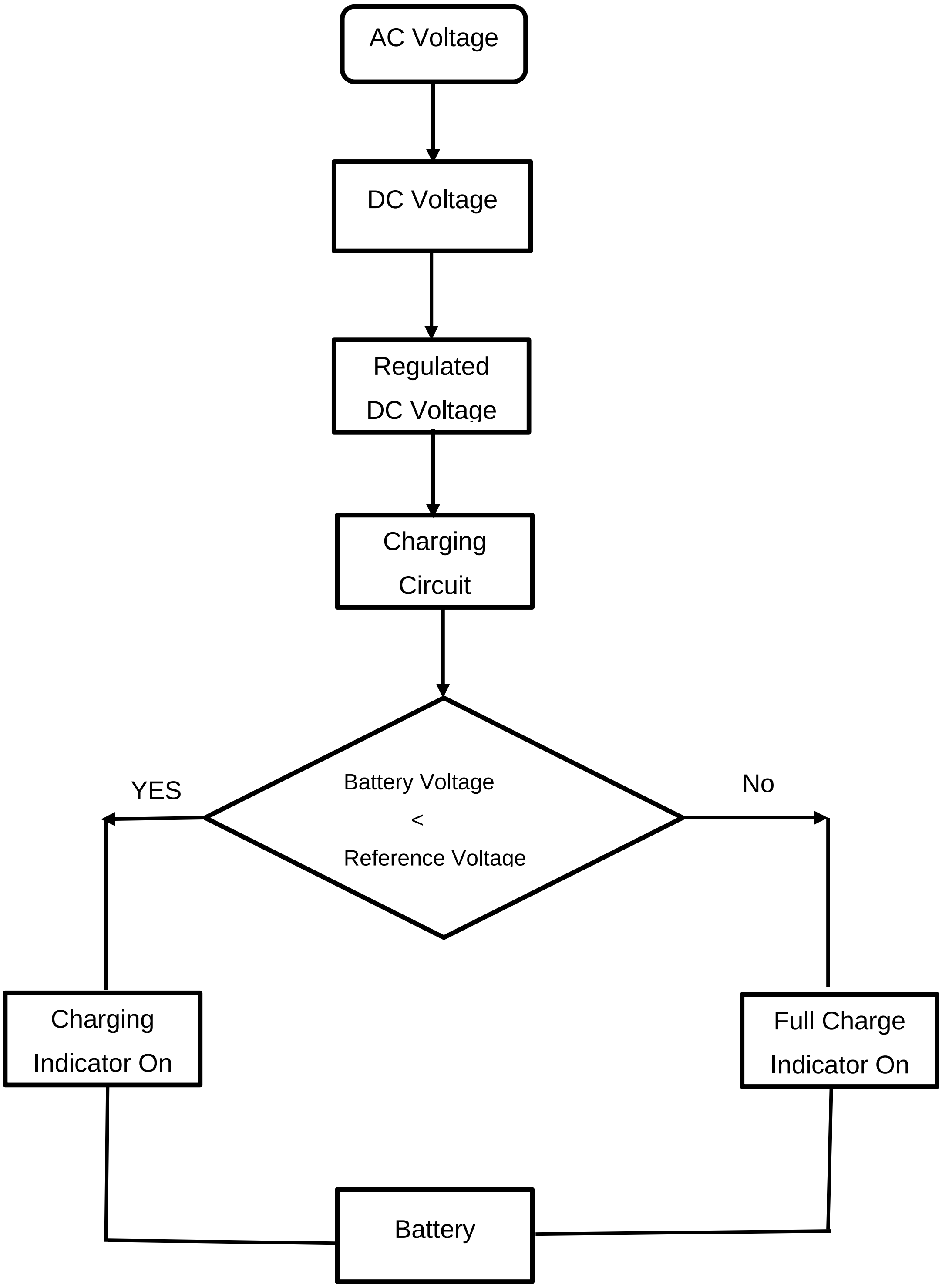


Figure 22. Flow Chart of the charger

This battery charger is used to charge 12V battery until its fully charged to its capacity. After the battery has been fully charged, the charger automatically cuts-off the charging voltage preventing the overcharging of the battery.

Firstly, the input AC Voltage from the AC mains supply is step down using transformer to a lower AC voltage. The step-down AC voltage is then rectified to DC voltage using a full wave bridge rectifier. The rectified voltage from the bridge rectifier still contains ripples, so a smoothing capacitor is used to filter out the ripples. The DC voltage from the rectifier circuit is not constant voltage so a voltage regulator is used to produce a constant output voltage for battery charging which charges the battery to its full capacity. While the battery is being charged an indicator turns on which indicates that battery is being charged. When the battery is fully charged, then the circuit detects the state of the battery and turns off the charging voltage and battery completely charged indicator is turned on.

6 Modelling and Simulation

6.1 Halfwave Rectifier

A half wave bridge rectifier uses a single diode to perform rectification that is convert AC voltage into DC voltage. In the figure 23 below, the diode converts pulsating AC waveform into DC voltage. Even though this is converted into DC signal, there are still ripples. This can be removed by using a smoothing capacitor of appropriate value.

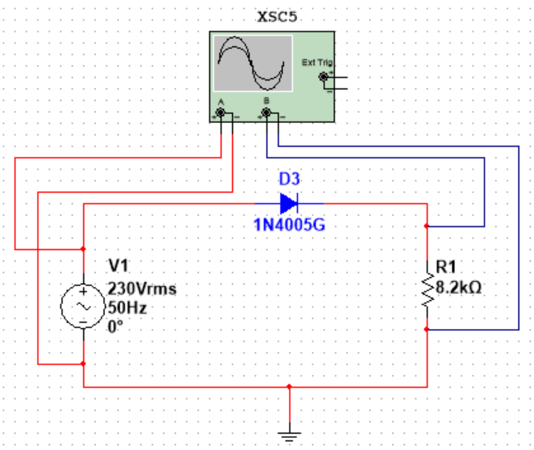
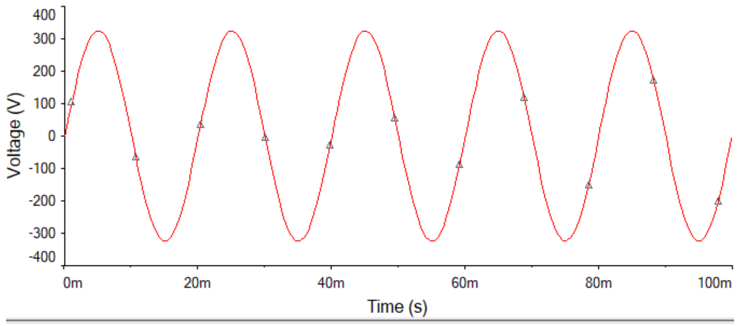
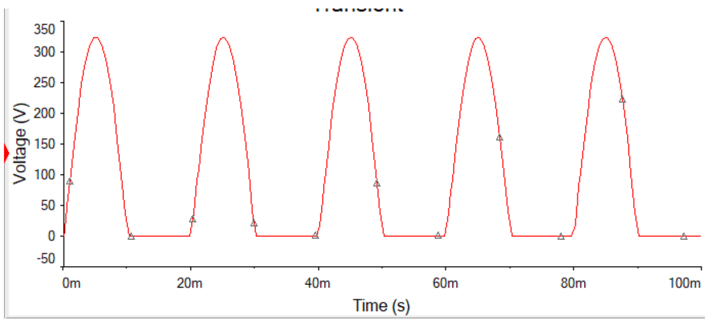


Figure 23. Half Wave Rectifier Simulation Model

As seen in the output of half wave rectifier in figure 24, the half wave rectifier converts only half cycle of the input to DC voltage, the other half is cutoff, because of which half of the power is wasted and the output has too many ripples.



(a)



(b)

Figure 24. Half Wave Rectifier (a) Input AC Voltage Waveform (b) Output Waveform from Half Wave rectifier (no smoothing capacitor)

6.2 Full Wave Bridge Rectifier

A full wave bridge rectifier uses four diodes in a closed loop bridge configuration to perform rectification from AC voltage to DC voltage. Full wave bridge rectifier uses both positive and negative cycle of input to produce the DC output, hence it is more efficient than half wave rectifiers.

The four diodes are arranged in such way that only two diodes are conducting (forward biased) for each half cycle. In the figure 25 below, for positive half cycle of input only diodes D1 and D2 are conducting while D3 and D4 are not conducting (reverse biased). Similarly, for the negative half cycle of input D3 and D4 are forward biased and D1 and D2 are reverse biased. A smoothing capacitor is used across the output of bridge rectifier to further remove ripples and produce a constant DC supply voltage.

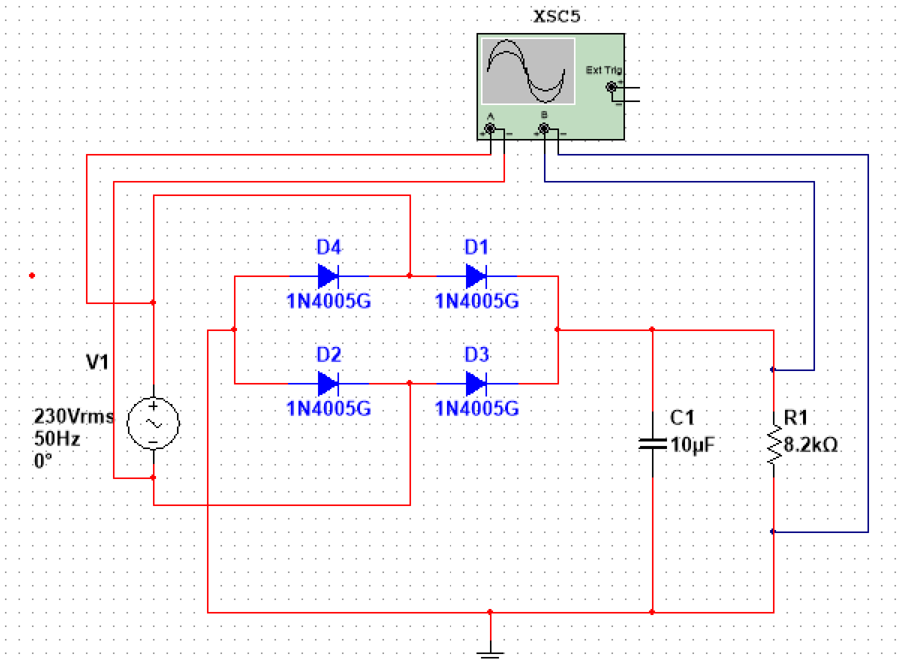
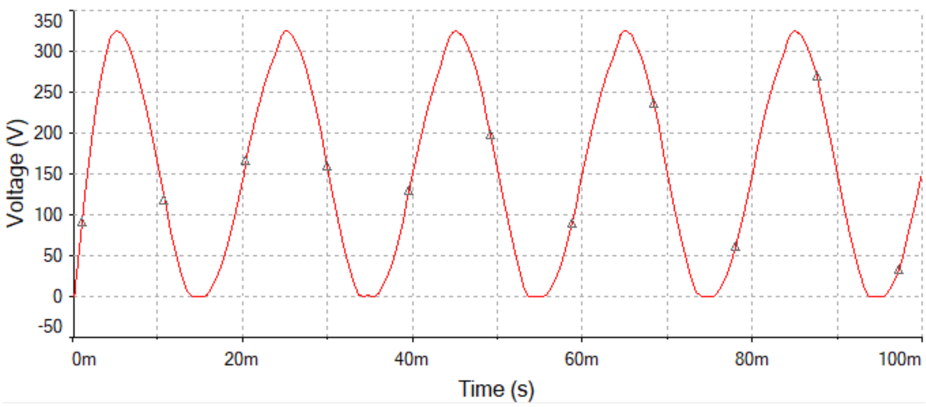
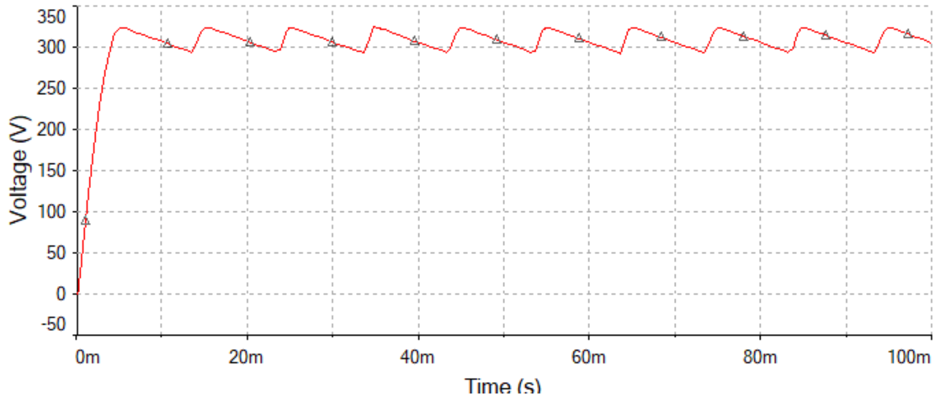


Figure 25. Full Wave Bridge Rectifier Simulation Model

Figure 26 shows the effect of the smoothing capacitor on the rectified DC signal.



(a)



(b)

Figure 26. Full Wave Bridge Rectifier (a) Input AC Voltage Waveform (b) Output Waveform from Full Wave Bridge Rectifier with Smoothing capacitor

6.3 Battery Charger with Automatic Cutoff

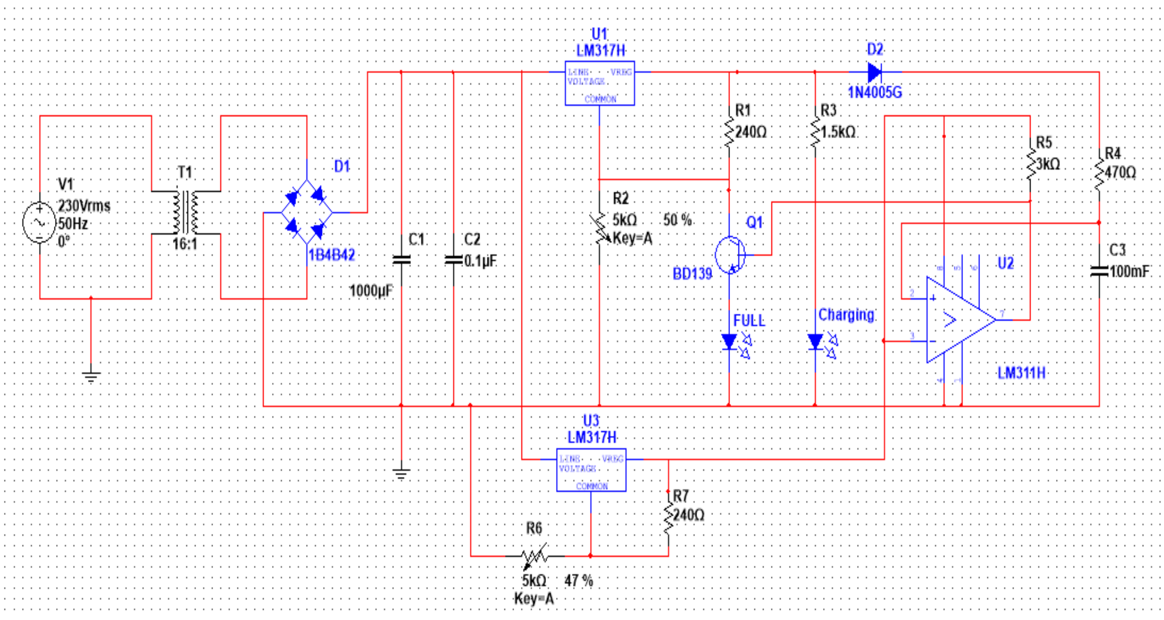


Figure 27. Schematic of the Automatic Battery Charger (Battery modelled as capacitor) [27]

In the above schematic of the battery charger in figure 27, the AC mains supply of 230V 50 Hz is step down to 18V AC using a step-down transformer. The 18V AC is rectified to DC voltage using a full wave bridge rectifier. Full wave bridge rectifier is used for converting from AC voltage to DC voltage because it is more efficient way of converting AC voltage to DC voltage because it uses the complete AC cycle to convert from AC to DC.

Since for each cycle, there are two diodes conducting, so the output voltage would be two voltage drops (2 * 0.7 = 1.4V) less than the input voltage which is approximately 16.6V.

The rectified voltage from full wave bridge rectifier still is not constant steady DC voltage as it contains ripples from which is removed using smoothing capacitor C1 and C2. The smoothing capacitor provides a ripple free DC voltage which is suitable for the operation of voltage regulator IC.

The rectified DC voltage is then connected to the input pin of the LM317 regulator. LM317 is an adjustable linear voltage regulator that regulates the fluctuating input voltage to provide a constant steady DC voltage with no change in output voltage even when there are changes in the input voltage within the operating range of the LM317 regulator. The output voltage of the LM317 can be adjusted by changing the resistor connected on the adjust pin of the regulator.

In the above schematic, the value of R1 is 240Ω and R2 is potentiometer, the value of which is adjusted so that the output voltage of the LM317 regulator is 14.4V. The output voltage from the LM317 regulator is the charging voltage that is used to charge the battery. Due to unavailability of a rechargeable battery on the Multisim simulation software, we are using a RC circuit to model the battery [28]. This voltage is also fed to a green LED through a resistor to indicate that the battery is being charged. The diode D2 is used so that the current can flow only from the output of LM317 to the battery and the reverse current does not flow back from the battery to the circuit.

12V battery will be fully charged when the voltage across battery reaches a float voltage of 13.6V. To prevent the overcharging of the battery, the charging voltage must cease when the voltage on battery reaches 13.6V. For this we are using a voltage comparator LM311 to automatically cut-off the charging voltage.

The V_{CC} terminal is connected to the reference voltage rail to power the LM311 comparator. V_{EE} and GND terminal are connected to the ground. The battery voltage is connected as a feedback to the non-inverting input of the LM311 comparator. The inverting terminal is connected to a reference voltage of 13.6V. The reference voltage is produced by a second LM317 voltage regulator.

When the voltage of the battery is below the reference voltage of 13.6V, the output of the LM311 is off. But as soon as the battery voltage reaches 13.6V, the output of LM311 comparator is high. A pull up resistor is used to turn on the transistor Q_1 which is connected to LM311 output pin. When the transistor is on, it creates a shorter resistance path on the adjust pin of the charging LM317 regulator, as a result of which the adjust pin is shorted to the ground. When the adjust pin is shorted to the ground the output of the charging LM317 regulator drops to the reference voltage of the LM317 regulator which is 1.25V, which is not sufficient to charge the battery any further. Diode D2 is used so that the current does not flow back from battery to the charging circuit. A red LED is also turned on to indicate that the battery charging is complete. The green LED turns off as there is no voltage to drive this LED.

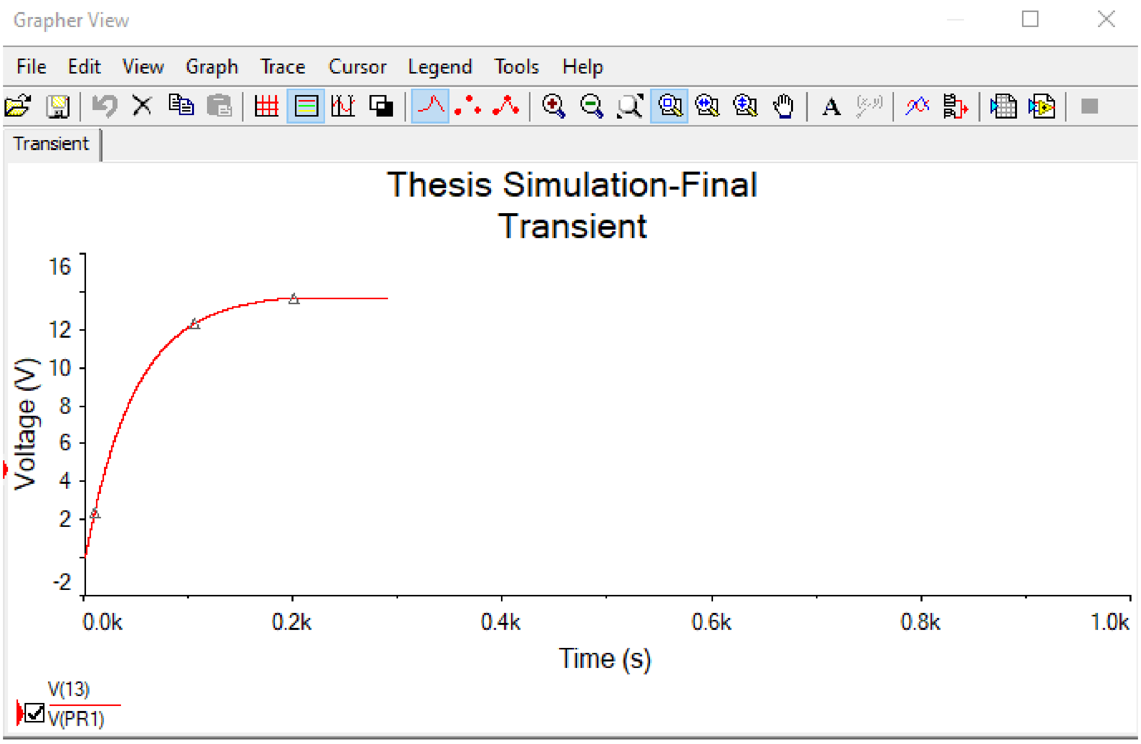


Figure 28. Battery Voltage while charging

The increasing voltage on the battery terminal is shown in figure 28. Initially the battery voltage increases until the voltage on the battery reaches 13.6V, after which the voltage on the battery stays constant.

Figure 29 shows the charging voltage from the LM317 voltage regulator. Initially the LM317 regulator provides a constant output voltage of 14.4V, but after the battery is fully charged to 13.6V, the output of LM317 is cutoff and the voltage reduces to the reference voltage of the LM317 regulator only. The fluctuating voltage for a short period is seen as the battery stabilizes to full capacity of 13.6V

Note: We are using RC circuit to model a battery as a rechargeable battery model is unavailable on the Multisim simulation software.

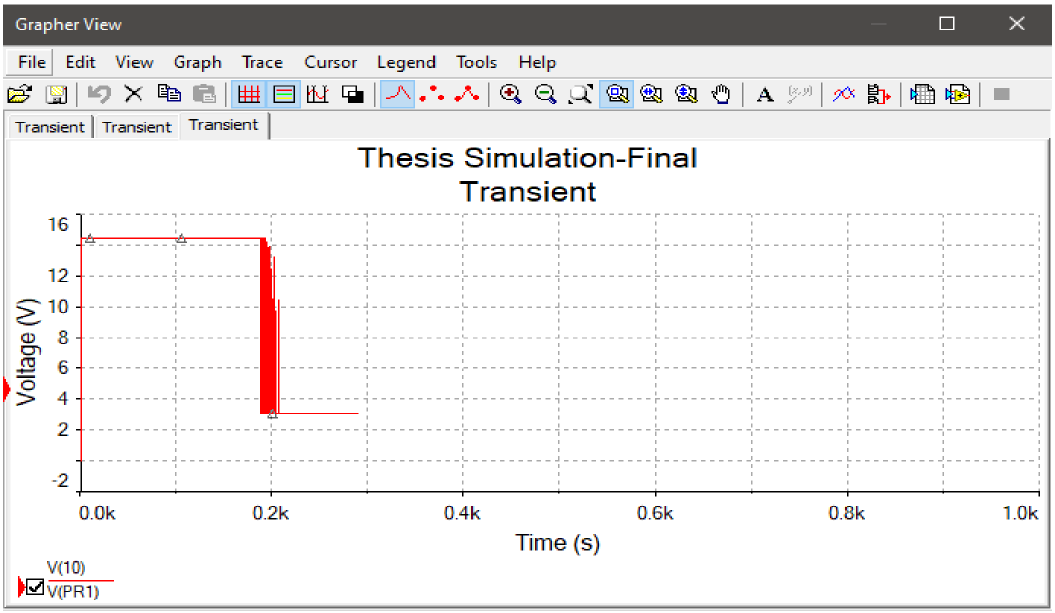


Figure 29. Charging Voltage from the LM317 Voltage Regulator

7 Results and Conclusion

The automatic battery charger was successfully modelled in the Multisim simulator. This battery charger works on the constant voltage method of battery charging. Initially, when a discharged battery is connected to the charger, the charger charges with the battery with constant voltage, until the battery is fully charged. This is displayed by the glowing green LED charging indicator. When the battery is fully charged, the charging voltage ceases, and a red LED indicator is turned on to notify that the battery is fully charged. The charger will maintain the float voltage of the battery when it is connected to the charger to compensate for the self-discharge.

Although this charger is for 12V batteries, we can charge other batteries also such as 6V, 9V etc. by changing the reference voltage. For the safety of the regulator IC, a heatsink to dissipate the excess heat because of voltage drop on the LM317 regulator is required. This model can be further enhanced by using the constant voltage constant current charging method as it is best suitable method for less charging time and also less damage to battery.

We are using linear voltage regulator to step-down the voltage which decreases the voltage by dissipating the difference between input and output voltage as heat, which is highly inefficient. We can use switching regulator instead of using linear so that very little energy is wasted.

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