High Voltage Pulse Generator Using Semiconductor Devices

Major Project Report

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING

(**Power Electronics, Machines & Drives**)

By

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13MEEP17

DEPARTMENT OF ELECTRICAL ENGINEERING

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May-2015

CERTIFICATE

This is to certify that the Major Project Report entitled **"High Voltage Pulse Generator Using Semiconductor Devices"** submitted by **Ms. SWATI GEHLOT (13MEEP17)**, towards the partial fulfillment of the requirements for the Degree of **Master of Technology (Electrical Engineering)** in the field of **Power Electronics, Machines & Drives** of Nirma University is the record of work carried out by her under our supervision and guidance. The work submitted has reached a level required for being accepted for examination. The results embodied in this major project to the best of my knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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Undertaking of Originality of the Work

I, **Swati Gehlot, Roll.No.13MEEP17** , give undertaking that the Major Project entitled **"High Voltage Pulse Generator Using Semiconductor Devices"** submitted by me, towards the partial fulfillment of the requirements for the degree of Master of Technology in Power Electronics, Machines and Drives of Nirma University, Ahmedabad, is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere; it will result in severe disciplinary action.

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Success of any work depends upon the dedication, sincerity and hard work. It also requires some ingredients such as motivation, guidance, encouragement and time.

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Abstract

As a scheme of delivering accumulated energy in short period of time to gain high instant power, pulsed power technology is widely used to generate high power transient electric pulses. In recent years low energy nanosecond range pulse width application has gained a lot of attention. The improvement of solid state switches make it possible to build a full solid state pulse power unit to generate nanosecond pulses. Pulse generators are capable of producing high voltage pulses with fast leading edge rise time. HV pulse generator can be differentiated mainly in two parts where rise and fall time are not critical and in applications where rise time should not exceed 5ns. In the latter application mentioned above would require power semiconductor devices using series/ parallel combinations. The main aim of this project is to design an energizer using flyback topology combined with step up transformer to generate pulse with a rise time of 5ns with peak output voltage of 4kV at 500 Ω load. The system will be simulated using Psim/Pspice and Gecko Circuits software and when satisfied output will be obtained, the hardware of the same will be implemented.

List of Figures

Nomenclature

V_o .... phase voltage .... [Volts]
I_o .... phase current .... [amp]
V_{cc} .... D-axis component of phase volatge .... [Volts]
V_{ccmax} .... Q-axis component of phase volatge .... [Volts]
V_{ccmin} .... Q-axis component of phase volatge .... [Volts]
f_s .... Q-axis component of phase volatge .... [Volts]
n .... Q-axis component of phase volatge .... [Volts]
D_{max} .... Q-axis component of phase volatge .... [Volts]
D_{min} .... Q-axis component of phase volatge .... [Volts]
α .... Q-axis component of phase volatge .... [Volts]
ΔI_n .... Q-axis component of phase volatge .... [Volts]
ΔB_n .... Q-axis component of phase volatge .... [Volts]
B_m .... Q-axis component of phase volatge .... [Volts]
V_d .... Q-axis component of phase volatge .... [Volts]
N_1 .... Q-axis component of phase volatge .... [Volts]

Abbreviations

DCM .... Discontinuous Conduction Mode
CCM .... Continuous Conduction Mode
IGC .... Impulse Generator Circuit
HVPPS .... High Voltage Pulse Power Supply

Chapter 1

INTRODUCTION

Pulsed power is defined as an energy storage system where energy is released in the form of an intense pulse or pulses, also known as an energizer. Pulsed power technology is characterized by the concentration of energy, to pulses of high intensity. The energizer are capable of producing a succession of very short time duration of pulses with fast, leading edges. It is a device by which energy is stored over a long period of time is delivered to a load in a much shorter scale. High peak to average power ratio or high instantaneous power is the fundamental characteristic of pulse power generators. Those applications which are not possible with any other method, by the unique characteristic of pulse power generators these applications work successfully. The application will perform better if been pulsed. Pulse generators are available commercially and are of many types. According to the load requirement these pulse generators are chosen. The performance parameter of pulse power generators are as follows

- Voltage Output
- Rise time
- Pulse width
- Fall time
- Repetition Rate

- Peak and Average Power

To convert a low power, long time input into a high power, short time output is the fundamental purpose of all pulsed power generators. The example of above statement is shown in figure below(Fig. 1.1 and Fig. 1.2) The 1 kW, 1s input pulse is compressed into a 1GW, 1 μs output. The input and output energies are equal, in the ideal case of lossless system.

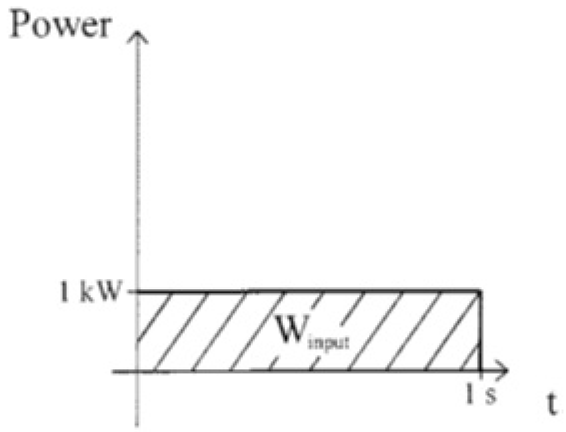

Figure 1.1: Input Pulse

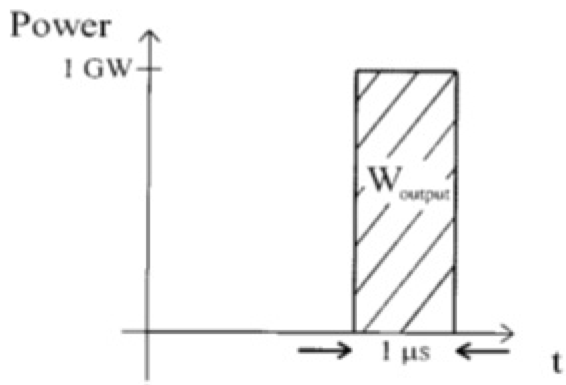

Figure 1.2: Output pulse

1.1 History and Use of Pulse Power Generators or energizer

John Chiristopher (Charlie) Martin and his colleagues at the Atomic Weapon Establishment in 1960s, was the developer of first modern pulsed power system.Where the transient high power is needed these systems play a very useful and efficient role. After pulse power generator's invention, pulsed power science and technology rapidly disseminated to United States, former Soviet Union and the present day Russia, Europe, and Asia. At the early age, pulsed power was mainly used in the gigantic system like accelerator, fusion research, laser system and electromagnetic weapon research. Nowadays, pulsed power is widely spread into civil low energy compact systems like the ignition system in automobile and biological researches. Since World War II, the of pulsed power has mainly been driven by military requirements, both for the advancement of pulsed-power based weapons and for the evolution of new simulation and diagnostic tools. Considerable effort has been undertaken to develop pulsed-power based weapon systems such as electromagnetic mass launchers and beam weapons. But many systems have been built for military research and development programmers to study the effects of nuclear weapons, to determine the properties of materials under extreme shock wave loading, and to create strong pulses of hard X-rays to image fast explosives. Recent progress in the development of reliable and affordable components for pulsed power systems such as long lived high voltage capacitors and new types of high-power semiconductor switches has created new interest in utilizing pulsed power techniques for commercial and industrial purposes. In contract to some military applications, economic considerations have the strongest impact on commercialization.

1.2 Literature Survey

Literature survey plays an important role in proper understanding and to gain better knowledge about the entire project. It consist of all literature and idea of the paper which are referred i.e. IEEE, Science direct, Reference Books etc.. which are as listed below:

[1]**"A Novel Electric Fence Energizer: Design and Analysis"** By Duleepa J. Thrimawithana Department of Electrical and Computer Engineering ,The University of Auckland ,New Zealand ,June 2008

This thesis presents multilevel topology for the implementation of pulsed power generator.

[2] **"Design and Implementation of Full Solid State Voltage Nanosecond Pulse Generators"** by Tao Tang

In this dissertation, solid state pulsed power systems will be discussed in system, device and topology levels and several application specific nanosecond high voltage pulse generators are presented.

[3]**"A Compact High Voltage Nanosecond Pulse Generator"** Drew Campbell, Jason Harper, Vinodhkumar Natham, Funian Xiao, and Raji Sundararajan

A compact High Voltage MOSFET-based nanosecond pulser was designed, tested successfully which met all the design specifications.

[4] **"Nanosecond switching using power MOSFETs"** R. J. Baker E. G.

This paper presents that Fast rise time (nanosecond) high-voltage (hundreds of volts) electrical pulses and many applications in instrumentation for fast transient measurements. Some typical applications are laser diode drive circuits, sweep circuits for CRT streak cameras, the gating of micro channel plates and pockels cells, and the triggering of scopes and transient recorders.

[5] **"Design For a FET Based 1 MHz, 10 kV Pulse Generator"** M.J. Barnes

In this paper Extensive PSpice simulations have been carried out to evaluate various design options.

[6]**"MHz Pulse Power Generator Using MOSFET"** Weihua Jiang, Takuya Matsuda, and Kiyoshi Yatsui Extreme Energy Density Research Institute Nagaoka University of Technolam, Nagaoka,Akira Tokuchi Nichicon Corporation,Yagura, Kusatsu

A stacked MOSFET switch has been developed and tested. Commercially available MOSFETs are used to form the stack of 8 in series and 6 in parallel. Each FET is triggered by an optically couple signal so that all units are controlled simultaneously by a common trigger circuit.

[7] **"Nanosecond Pulse Generator Using a Fast Recovery Diode"** M. Gundersed , A. Kutbi, P. Gabrielsson and M. Behrendand
Design and operation of a fast recovery diode based pulse generator is presented. Diode switched pulse generators have been described in the literature using mostly custom fabricated snap recovery diodes.

[8] **"Marx Generator Using Power MOSFETs"** W. Jiang, W. Diao, and X. Wang Tsinghua University, Beijing, China
A compact Marx generator has been developed by using power MOSFETs as the switches. The objective is to develop repetitive, compact, efficient, short-pulse, high voltage generator for industrial applications.

[9]**"A Review of Short Pulse Generator Technology"** John Mankowski, Member, IEEE, and Magne Kristiansen, Life Fellow, IEEE
A review of generator implementation methods is presented that includes a detailed discussion of the various circuit designs and a list of commercially available high voltage pulse generators. All of these generators are capable of rise times less than a few ns and voltages greater than several hundred volts. Finally, a brief description of the three primary switch types, reed, spark gap, and solid state is presented.

[10] **"Compact Solid-State Switched Pulsed Power and Its Applications"** Weihua Jiang, Member, IEEE, Kiyoshi Yatsui, Member, IEEE, Ken Takayama, Mitsuo Akemoto, Eiji Nakamura, Naohiro Shimizu, Akira Tokuchi, Sergei Rukin, Victor Tarasenko, and Alexei Panchenko
This paper represents that power semiconductor devices, such as insulated gate bipolar transistors, metal oxide semiconductor field effect transistors, and static induction thyristors , are used in different kinds of pulsed power generators developed for different applications. In addition, the semiconductor opening switch is found to have very effective applications in pulsed power generation by inductive energy storage. Semiconductor switches have greatly extended the scales of pulsed power parameters, especially in repetition rate and lifetime. They have also enabled new areas of pulsed power applications, such as accelerators, gas treatment, and gas lasers.

[11] **"Very Fast Rise Time Short-Pulse High Voltage Generator"** Laurent Pcastaing, Jean Paillol, Thierry Reess, Alain Gibert, and Pierre Domens

This paper relates to the development of an ultrafast compact system readily applicable to the field of ultra wide band microwave applications such as transient radar or laser drivers. The design, production, and experimental results of a short pulse generation system are presented in this paper.

[12] "Simple MOSFET Based High Voltage Nanosecond Pulse Circuit"
Alton Chaney and Raji Sundararajan
A novel but simple and economical nanosecond pulse generator based on Schmitt trigger and Integrated circuit driver and a single MOSFET buffer was designed, built, and tested successfully.

Chapter 2

Introduction to Energizer

The energizer is a device which converts the electrical energy into an electric impulse with limited energy. The PVs, batteries and electric utility are the sources of electric energy. To generate high voltage pulses, modern energizer employes a pulsed power supply together with an appropriate high voltage charging scheme.

2.1 General Block Diagram

The general pulsed power system diagram, refer to as a pulsed power train as shown in figure 2.1. The description of this pulsed power train is given below.

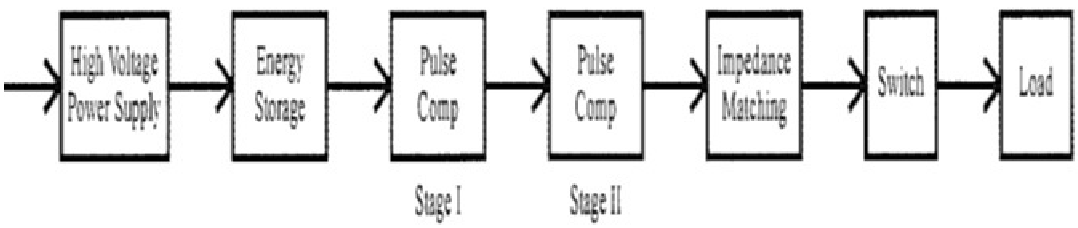

Figure 2.1: General Block Diagram of Pulsed Power Train

- The high voltage power supply is the power source to the system and usually plugs directly into the wall (prime power).

- The charging time of the energy storage section is most often determined by the specifications of the high voltage power source and can range from less than microseconds to minutes. The energy storage section stores the pulse energy for an indeterminate amount of time, dependent upon output requirements.

- Pulse compression starts when the energy in the energy storage section is switched into the first pulse compression stage. The pulse compression stages perform the primary operation of compressing the pulse to an output similar to that of figure 1.2. The number of pulse compression stages can vary from one to many, dependent upon the application.

- Each of these stages usually requires a switch. The impedance match section, e.g., a transformer, is necessary to transfer maximum power to the load and to minimize reflections.

- The final section before the load, the primary switch, delivers the pulse to the load.

2.2 Principle of Pulsed Power Generator

These generators also differ in circuit design and switch type. It consists of 3 blocks as shown in figure 2.2:

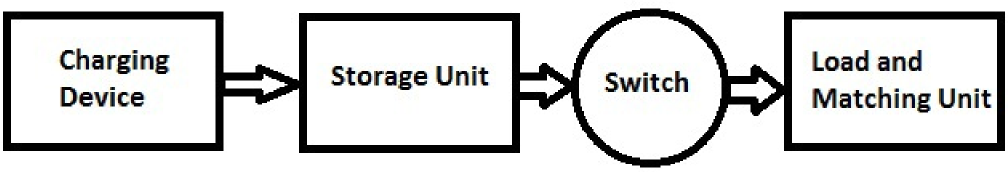

Figure 2.2: Block Diagram of Pulsed Power Generator

- Storage Unit

- Switching Unit

- Load and Matching Unit

2.2.1 Storage Unit

This unit accumulate energy and store it. It accumulate energy over a period of time and store in various forms like:

- Electrical energy
- Magnetic energy
- Kinetic energy
- Chemical energy

There are two fundamental characteristics of a storage unit:

- Maximum energy density that determines the size of subunit
- Maximum energy release speed that determines the maximum peak average power ratio which is directly related to rise or fall time of the generated pulse.

As energy density is higher, the subunit will be small.

2.2.2 Switching Unit

After energy being stored, the switching unit will initiate energy releasing. It also act as "pulse forming" unit. With the large difference in impedance there are two states of switching:

a. On state (Low impedance state)

b. Off state (High impedance state)

In the on state, the switch will have low voltage difference across the terminals and current can flow through the switch. On other hand when switch is in off state, it will have large voltage difference across its two terminals and current flow is forbidden. The hold off voltage and switching speed are the two key characteristics of a switching element. The maximum voltage across the switch before spontaneous conduction is known as hold off voltage. It is directly related to the maximum charging voltage and/or output voltage. The time interval between the states changing is known as the switching speed. It will determine the rise/fall time of the pulses. The switch will start the formation of pulses by connecting with other components.

2.2.3 Load and Matching unit

By the load and matching unit, the shaped pulses will be delivered to the load. This is a major unit. There is difference between a load under pulsed power condition and load under normal condition. The high electric field causes nonlinear effect of the load and makes the impedance of the load vary during a pulse. And the high frequency components introduced by the short pulse width will make parasitic capacitive/inductive components an important role in the load. To maximize the energy or electrical field delivered to the load, an impedance matching scheme is needed. The electric circuit of energizer is divided into two parts:

- Supply Circuit
- Impulse Generator Circuit

The block diagram with above two circuits, is shown below:

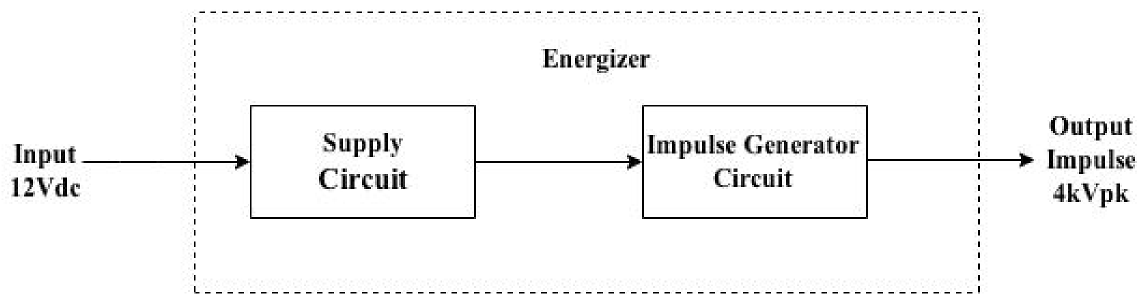

Figure 2.3: Energizer Block Diagram

2.2.4 Supply Circuit

The supply circuit provides a DC link to charge the storage capacitor. Two usual supply circuits are shown below:

- Conventional power supply, 127/220 V_{ac}, 50/60 Hz, grid connected (Fig 2.4)
- A 12V battery associated with a flyback converter (Fig. 2.5)

Both circuits are used in commercial equipments to raise the input voltage around 300 to 600V.

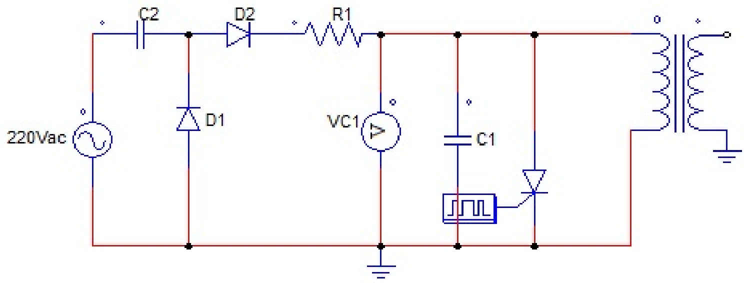

Figure 2.4: Supply circuit using conventional power supply

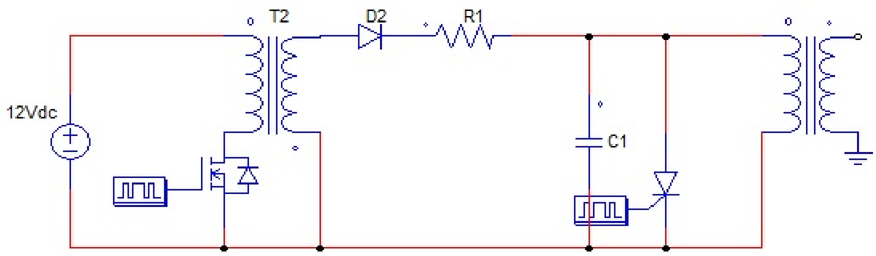

Figure 2.5: Supply circuit using flyback converter

2.2.5 Impulse Generator Circuit

The IGC consists a discharging impulse magnetizer circuit. The operation of this circuit is discussed in this section.

- C1 = The capacitor C1 is the energy storage element. To charge this capacitor, circuit has around 1s.

- s = The switch 's' is implemented by a thyristor that provides the discharge path to the capacitor.
- R1 = The resistance R1 limits the current of the supply in the charging of C1 and in the discharging of C1.
- T = The transformer T has two main functions:
  a. To provide electric isolation
  b. Boost the input voltage

The transformer in commercial circuits, normally present with turn ratio around 1:10. It will depend on the charge voltage of the capacitor and the desired peak voltage of the electric impulse produce in the load. There are two cases of the IGC, as shown in figure below:

a. When switch s is open. As shown in fig 2.6

b. When switch s is close. As shown in fig 2.7

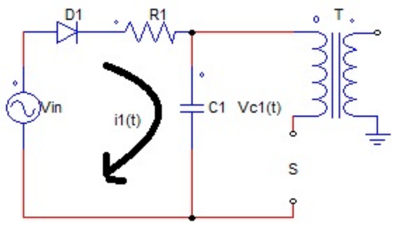

Figure 2.6: Charging of the capacitor

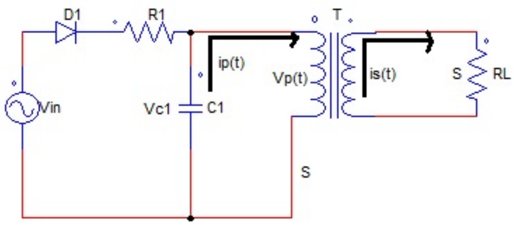

Figure 2.7: Discharge of the capacitor

2.3 Types of pulse power generators

In the literature, four pulsed power supply technologies can be found that utilize capacitors for energy compression. By the design to generate high voltage pulse,the technology varies. Some technologies are on semiconductor based solutions,while others utilize magnetic elements for the purpose of generating high voltage pulses. These technologies are as follows:

a. Direct discharge type pulse generator

b. Pulse transformer type pulse generator

c. Marx generator type pulse generator

d. Vector inversion type pulse generator

Brief idea of technologies are as follows:

2.3.1 Direct discharge type pulse generator

This topology is the straight forward implementation of high voltage pulse power generators. Pulse generating components, such as switches and diodes, are required for the implementation. These components are able to withstand the high voltages and currents that are being generated by the converter.Thus these components require fast switching capabilities, very high blocking voltage and high surge current ratings.Common semiconductor devices that are commercially available,can not withstand such high voltages. Therefore these types of converters are designed with components that are connected in series to achieve the required voltage rating. The block diagram of direct discharge type pulse generator is shown in fig. 2.8:

- Output RFI filter used to reduce the conducted RFI caused by the output pulses.

- Charger used to charge the storage capacitance (C) to a very high voltage, which is approximately equal to the required peak output voltage.

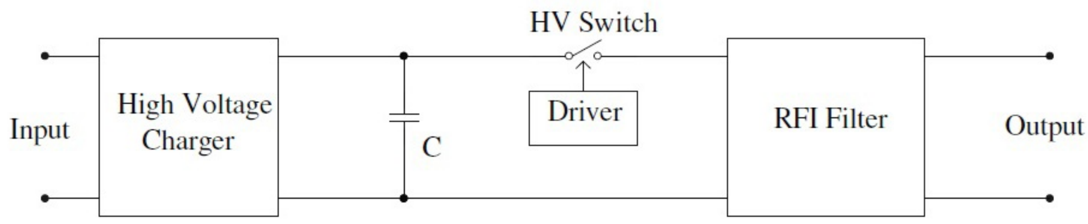

Figure 2.8: Direct discharge type pulse generator

2.3.2 Pulse transformer type pulse generator

This topology has become popular among manufacturers due to the simplicity. The output pulse transformer reduces the voltage stress on the components. This topology design is simple and robust that can be manufactured with common industrial grade devices. Hence such a system can be built at a very competitive cost. This topology operates similar to the direct discharge type generator topology. The use of a step up output transformer in the pulse transformer type topology make it different from direct discharge type topology. A block diagram of an energizer design based on the pulse transformer topology is shown in fig. 2.9:

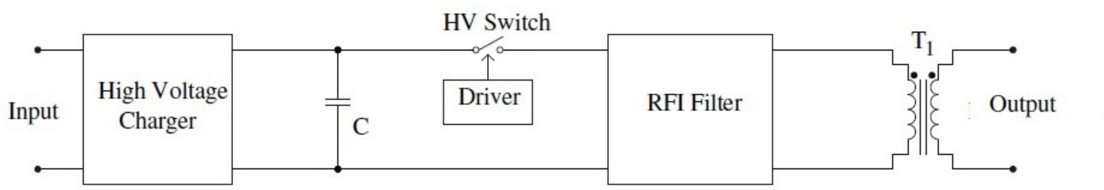

Figure 2.9: Pulse transformer type pulse generator

2.3.3 Marx generator type pulse generator

In 1924, E. Marx proposed a pulsed power generator topology which named as marx generator type pulse generator. This topology utilizes a switching matrix to amplify the voltage to generate high voltage pulses from a low voltage supply without the aid of magnetic elements. The Marx topology can be implemented through semiconductor devices which are readily available.By increasing the number of stages, voltage stress on the components can be reduced. Marx generator does not require HV storage capacity, it makes the design safe and reliable. The marx generator type pulse generator is shown in fig 2.10:

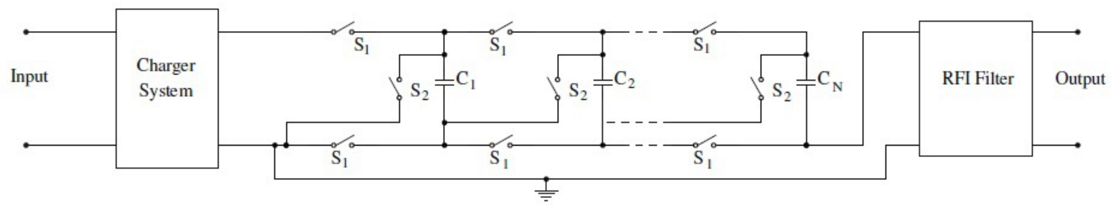

Figure 2.10: Marx generator type pulse generator

It is realized by implementing the switching matrix. In this topology the storage capacitors are charged in a parallel configuration and discharged in a series configuration. By closing switches S_1 while switches S_2 are left open, the storage capacitors C_1- C_N are charged. When the voltage across the capacitors reaches the desired value, charging is terminated by opening the switches S_1. Switches S_2 are closed while switches S_1 are left open, to form a high voltage pulse at the output. During this time, the capacitors are arranged in a series configuration causing the peak output voltage to be N-times greater than the initially charged voltage of the individual capacitors. Without the expense of high voltage stresses on the components, high voltage pulses can be generated at output.

2.3.4 Inversion type pulse generator

The concept of this topology is quite similar to marx generator topology. These generators utilizes closely coupled transformers instead of switches.The transformers are used to connect the storage capacitors in a series configuration to generate a high voltage pulse at the output as shown in fig.2.11: Through the transformer magnetizing inductance, the storage capacitors are charged in a parallel configuration. The charge stored in odd numbered capacitors is of opposite polarity to the charge stored in even numbered capacitors. The net voltage across the load during charging phase is zero.

Switch S_2 is pulse forming switch. When the switch S_2 is turned on, it causes the voltage across the odd numbered capacitors to invert.It bcause the result of resonance between the storage capacitance and the leakage inductance of the transformers. This topology produces a high voltage pulse at the output of the generator, which could be as high as 2N times the initially charged voltage of a capacitor.

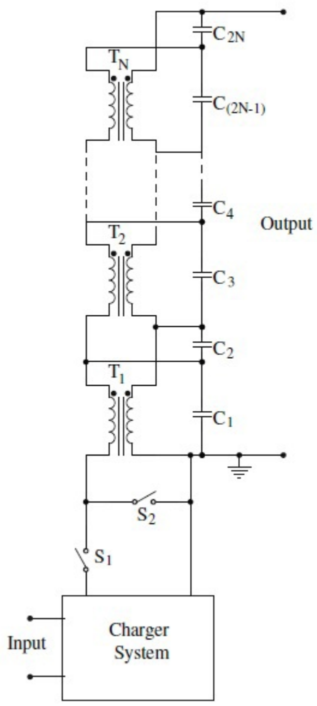

Figure 2.11: Vector inverse type pulse generator

The comparision between these technologies are shown below in the tabular form:

Table 2.1: Comparision of Various Topologies

Property	**Direct Discharge**	**Pulse Transformer**	**Marx Generator**	**Vector Inversion**
Output Pulse Width	Controllable	Filter dependent	Controllable	Load dependent
Output Voltage	Restricted Control	Restricted Control	Controllable	Load dependent
Efficiency	High	Low	High	Lower
Reliability	Low	High	Medium	High
Design Complexity	Medium	Low	High	Low
Safety	Low	High	Medium	Lower
Voltage Stress on Components	High	Low	Low	Low
Current Stress on Components	Low	High	Low	High
Output Filter Design	Complex	Simple	Complex	Simple
Cost	Medium	Low	High	Medium
Size	Compact	Bulky	Compact	Bulky

Chapter 3

Flyback Converter

For the power isolated converters with output power below 100 W, flyback converter has been the designer's choice. The flyback converter requires only one magnetic component and one output rectifier. The multiple outputs are easily implemented by flyback converters. From the buck boost topology flyback converter can derive. The peculiarity of the flyback and buck boost topology is, the energy is only stores from the source during the ON time of the switching MOSFET. And during the OFF time, the energy from the primary winding is delivered from the inductor to the output. The circuit of flyback converter is shown below in fig 3.1 In ideal case, transformer doesn't store energy. All the energy in primary transferred instantaneously from primary to the secondary. Rather than a typical transformer, a flyback transformer is more like multiple inductors on the same core. In the flyback transformer primary current and secondary current never flow at the same time, only a small position of the magnetizing energy is actually stored in the transformer.

3.1 Principle of Operation

The principle of operation of flyback converter is devided into 3 modes. These modes are decribe below:

Mode 1(When the switch is ON): Primary winding of the transformer gets connected to the input supply with its dotted end connected to the positive side. The diode connected to the secondary side of the transformer gets reverse biased in this mode. This operation is described by the figure (3.2 and 3.3)

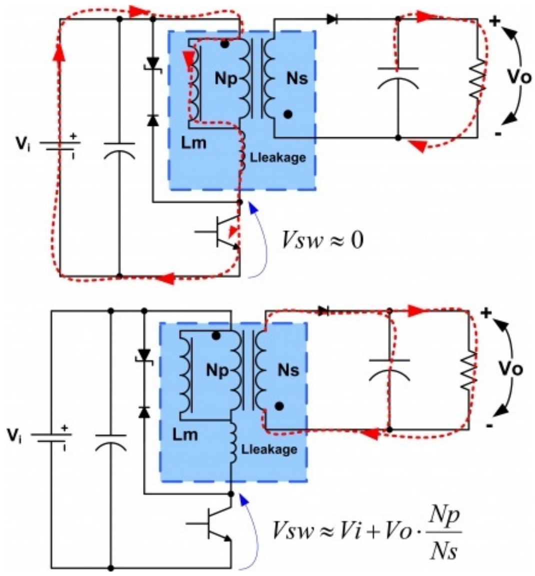

Figure 3.1: Flyback Converter

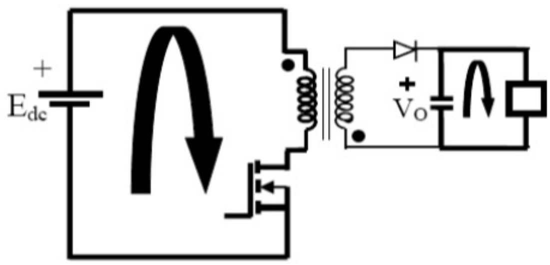

Figure 3.2: Flyback operation when switch is ON

Mode 2(When switch is OFF): In this mode, the current in the primary suddenly drops and the voltage across the primary reverses. The diode of secondary becomes forward biased. The secondary winding starts transferring energy from the magnetic field of the flyback transformer to the output, while charging the output capacitor. The energy transferred in the form of electrical energy. The magnetic field energy is completely transferred to the output capacitor and load if the off period of switch kept large. Also the secondary current gets sfficient time to decay to zero. In this mode flux linked by the windings remain zero until the next turn ON of the switch. The circuit is under DCM of operation. In the case when off period of the switch is small, the next turn on will take place before the secondary current decays to zero. At this time, the circuit is then under CCM of operation. The circuit operation in this mode is shown in fig(3.4 and 3.5)

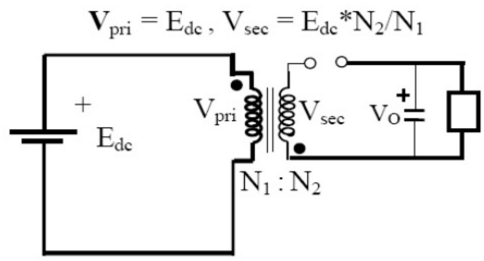

Figure 3.3: Equivalent circuit in ON condition

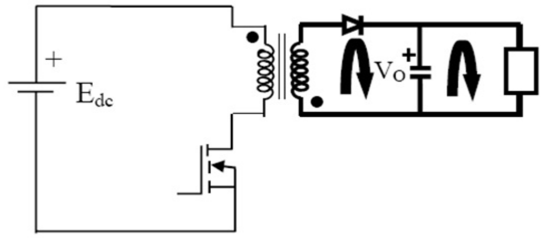

Figure 3.4: Flyback operation when switch is OFF

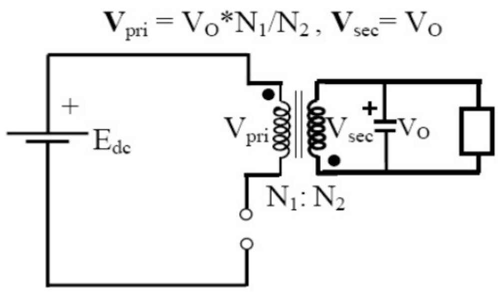

Figure 3.5: Flyback operation when switch is OFF

Mode 3: In this mode of operation the transfer of the magnetic field to the output is completed. The secondary winding emf fall to zero as well as current also. The diode connected in series of the winding stops conducting. The output capacitor however continues to supply uninterrupted voltage to the load. This part of operation is shown in fig (3.6.and 3.7).

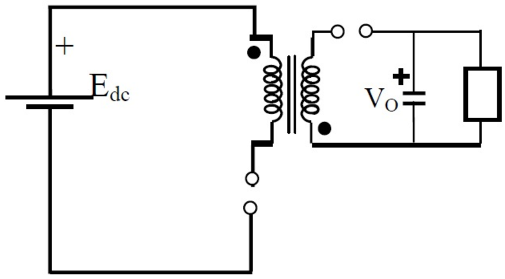

Figure 3.6: Flyback operation Mode 3(DCM)

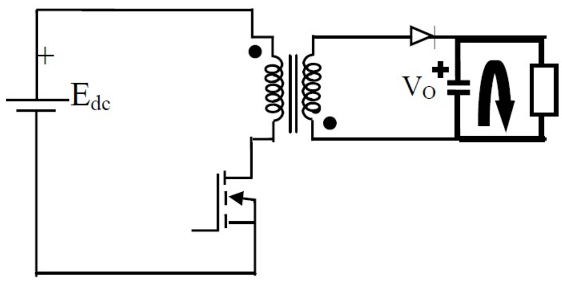

Figure 3.7: Equivalent circuit in Mode 3

3.2 Advantages

- Simplicity
- Low cost
- Protect users from potentially lethal voltages and currents
- Preserve instrument accuracy by interrupting ground loops
- Easily provide positive regulated voltages from a negative power bus without compromising the benifit of that bus.

3.3 Disadvantages

- High value output capacitor needed
- There is high current stress in power switch and in output diode

- In the air gap area, high current losses
- Large transformer core
- Potential EMI problem

3.4 Comparision between CCM and DCM

The flyback converter has two different modes of operation: DCM and CCM

- If output current is increased beyond certain value, the circuit will move into CCM that has beed designed for DCM.
- In DCM, all the energy stored during on period in the primary completely delivered to the secondary. Before the next cycle it delivered to the load. There is a dead time between the instant of secondary current reaches to zero and the start of the next cycle. In CCM, at the beginning of the next cycle there is still some energy left in the secondary. Flyback converter can be operate in both modes but with different characteristics.
- During the turn off, DCM has higher peak currents and therefore higher output voltage spikes. It has faster load transient response, lower primary inductance so the transformer can be of small size. As the forward current is zero, the reverse recovery time of the diode is not critical. Conducted EMI noise is reduced in DCM because transistor turn on occurs with zero collector current.
- CCM has lower peak current, therefore lower output voltage spikes.
- In DCM smaller transformer can be used. It has some advantages like smaller transformer, lower RFI and better stability.

The output of flyback converter in CCM and DCM mode is shown in fig(3.8 and 3.9).

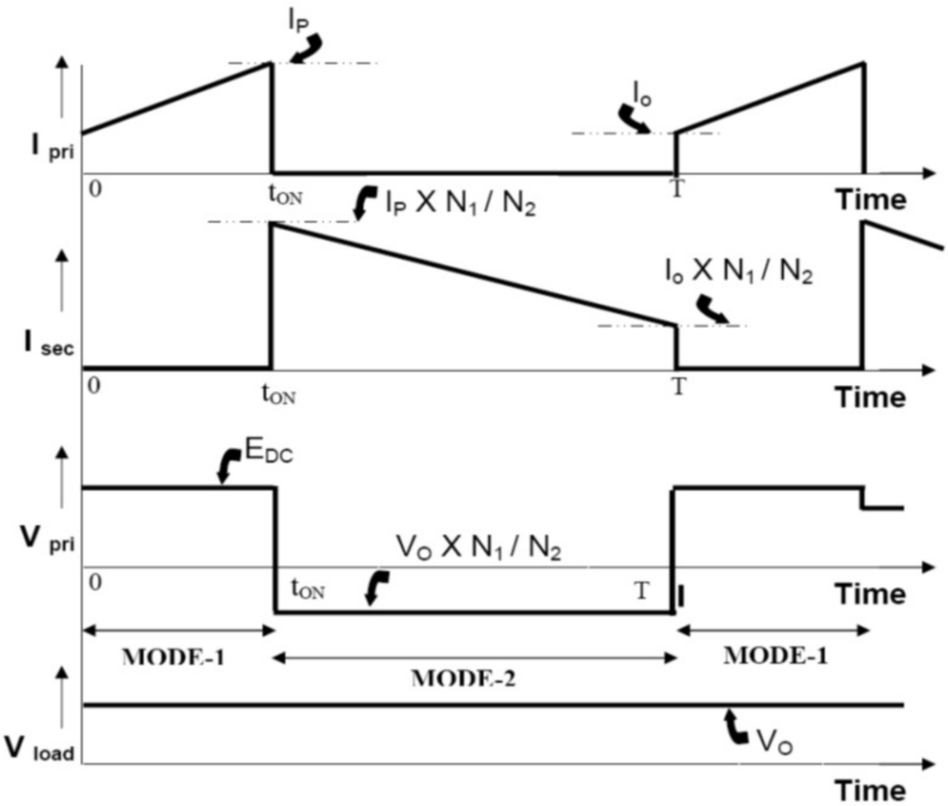

Figure 3.8: CCM

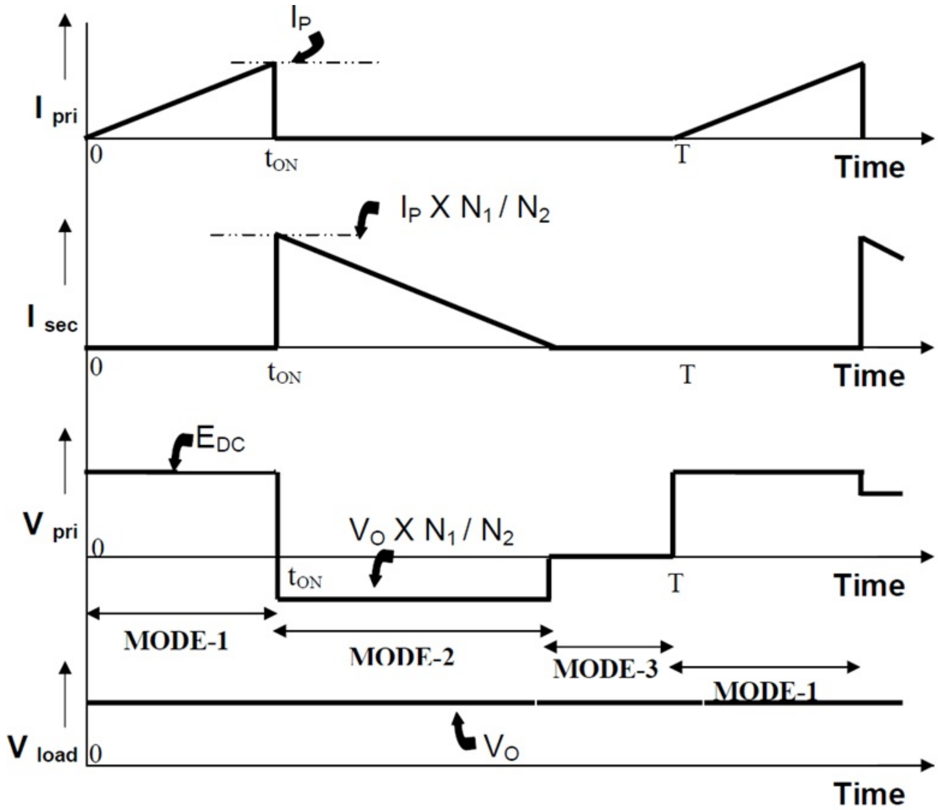

Figure 3.9: DCM

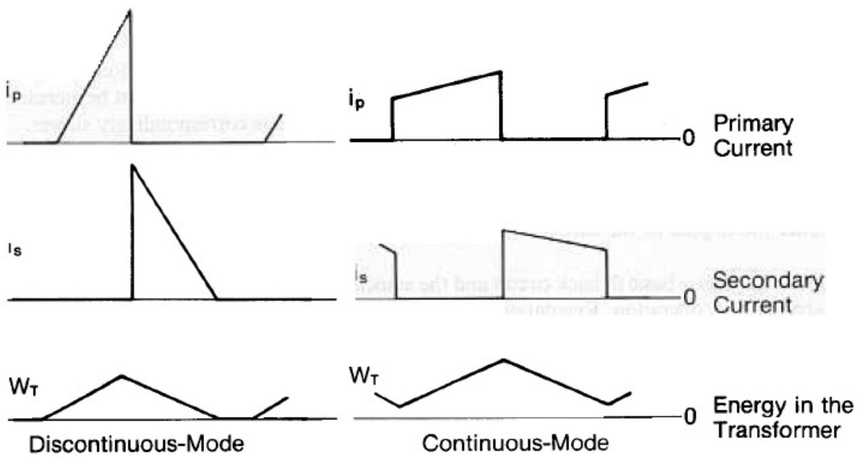

Figure 3.10: Comparison between CCM and DCM

Chapter 4

High Frequency Transformer Design

In inverter and converter applications, the high frequency transformers are used. SMPS requires high frequency transformers. For low frequency applications, steel laminations are best suited and for high frequency applications, ferrite cores are best suited. Each best suited for different applicayions. Specification of ferrite material:

- Dense
- Homogeneous ceramic structure (made by mixing iron oxide with oxides or carbonates of one or more metals.)

The laminated cores can not be used in high frequency (in the range of kHz), only core made of ferrite material can be used. The frequency range within 50 to 70 Hz, ordinary laminated core made of steel laminations can be employed. The majority ferrite materials used in SMPS relevance. At high frequencies eddy current losses will occur, because they have a tendency to vary with frequency square. In order to remove these losses the ferrite core is prepared with laminated metal alloy and power metal cores are used. The Common core used for the transformer is E42 type. The number of turns in the primary and secondary side of the transformer is determined by the standard wire gauge of the conductor to be used. The core is specifically designed for frequency capability. Ferrite is the best choice in high frequency transformer. The most frequently used configurations are the forward converter and its derivatives and the flyback configuration. They are as follows:

- Forward converter
- Half bridge converter
- Full bridge converter
- Push pull converter
- Flyback converter

Listed below are the assumptions for the design of high frequency transformers:

a. The converter diodes in the secondary of the transformer will show a significant drop as they are carrying high currents. The diode drops may be as high as 1.5V for fast recovery diodes. It is safe to design for the worst case of 1.5V.

b. Drops due to the winding resistance of the inductor and transformer. It has been found that V_{rl}= 10 percent of V_o is a safe choice generally.

c. At high frequencies, usually the core material choice is ferrite. It has a saturating flux density of 0.3 Tesla, so the maximum allowable flux density in the core should be 0.2 Tesla or less.

d. Another design parameter is the current density J. If the current density is choosen very low, then for a given current, a very large conductor cross section is required, demanding a large window area, which means that the resistance presented to the current flow will be low. A current density between 2 and 5 $\frac{A}{mm^2}$ is found to be good compromise between conductor resistance and window area. So current density is taken as $3\frac{A}{mm^2}$.

e. The maximum duty cycle in isolated converters should not exceed 50 percent to avoid core saturation. So we shall design for 45 percent .

f. The window utilisation factor K=0.4 and the efficiency of transformer is taken to be 0.8.

4.1 Flyback Transformer Calculation

- The governing equation for the flyback configuration is given by

$$V_o + V_D = \frac{N2}{N1} * V_{ccmin} * \frac{D_{max}}{1 - D_{max}} \tag{4.1}$$

- Area Product For Flyback Converter Transformer

The power handling capacity of a transformer is related to area product. In the flyback converter configuration, the transformer acts as an inductor in addition to its normal function of energy transfer. The area product for flyback converter transformer in complete energy transfer mode is given below:

$$A_p = \frac{P_{o2\left(\frac{1}{\eta}\sqrt{\frac{4D\alpha}{3}}+\sqrt{\frac{4(1-D)}{3}}\right)}}{K_w J \Delta B f_s} \tag{4.2}$$

- Turns ratio calculation

$$n = \frac{N2}{N1} = \left(\frac{V_0 + V_D}{V_{ccmin}}\right)\left(\frac{1 - D_{max}}{D_{max}}\right) \tag{4.3}$$

- Minimum Duty ratio calculation

$$D_{min} = \frac{D_{max}}{D_{max} + (1 - D_{max}\frac{V_{ccmax}}{V_{ccmin}})} \tag{4.4}$$

- Calculation of number of turns

primary number of turns As E42 is the proper choice for the core of transformer. Choose Ac according to this.

$$N_1 = \frac{V_{ccmax} D_{min}}{A_c B_m f_s} \tag{4.5}$$

secondary number of turns

$$N_2 = nN_1 \tag{4.6}$$

- Wire Gauge Selection

  The rms value of currents are given by

$$I_2 = \sqrt{\left(\frac{(1-D_{max})}{3}\right)[\Delta I_2^2 + \frac{3}{4}\left(\left(\frac{2I_o}{1-D_{max}}\right)^2 - \Delta I_2^2\right)]} \quad (4.7)$$

$$I_1 = \sqrt{\left(\frac{(D_{max})}{3}\right)[\Delta I_1^2 + \frac{3}{4}\left(\left(\frac{2I_{1avg}}{D_{max}}\right)^2 - \Delta I_1^2\right)]} \quad (4.8)$$

- The cross section areas can be calculated by

$$a_1 = \frac{I_1}{J} \quad (4.9)$$

$$a_2 = \frac{I_2}{J} \quad (4.10)$$

- The inductance see at the primary is given by

$$L_1 = \frac{V_{ccmin} D_{max}}{\Delta I_1 f_s} \quad (4.11)$$

- Calculation of Air gap Length

$$l_g = \frac{\mu_o N_1^2 A_c}{L_1} \quad (4.12)$$

The core volume in complete energy transfer mode is less than in incomplete energy transfer mode. Also the area product required is very less in the complete energy transfer mode.

Chapter 5

Design of flyback converter and high frequency transformer using MATLAB

By using the formulas given in privious chapter we can write a step by step program of high frequency transformer design.

5.1 Power Calculation

- First step is to calculate the power rating of flyback converter and the rating of storage capacitor. The MATLAB program of this calculation and its results are shown below:

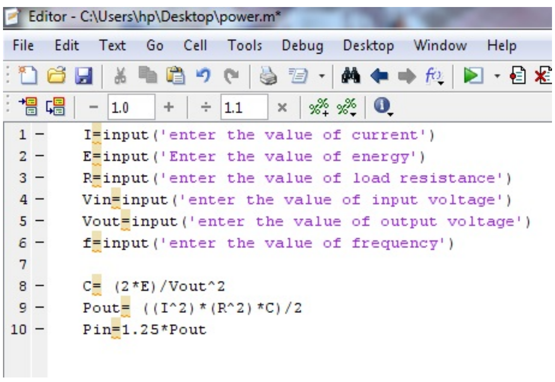

Figure 5.1: Power calculation

5.2 Design of flyback transformer

The MATLAB programming and result parameters for flyback transformer design is given below in table form: The steps are as follows:

a. Calculation of area product

b. Calculation of turns ratio

c. Calculation of minimum duty ratio

d. Calculation of number of primary and secondary turns

e. Choose transformer core cross section area

f. Wire guage selection

g. Calculation of primary inductance of transformer

h. Calculation of air gap length

```
Vo=input ('enter the value of output voltage')
Io=input ('enter the value of output current')
fs=input('enter the value of switching frequency')
Vcc=input('enter the value of supply voltage')
Dmax=input('enter the value of max. duty cycle')
Ac=input('enter the value of core cross section area')
Vd=1.5
delIn=1
delB=0.2
eff=0.8
Kw=0.4
Bm=0.2
j=3
ripple=(Vo*1)/100
Vccmax=Vcc+((Vcc*10)/100)
Vccmin=Vcc-((Vcc*10)/100)
Dmin=Dmax/(Dmax+((1-Dmax)*(Vccmax/Vccmin)))
n=((Vo+Vd)/Vccmin)*((1-Dmax)/Dmax)
I1plus=((2*n*Io)/Dmin)/(2-delIn)
delI1=I1plus*delIn
delI2=delI1/n
Po2=((Vo+Vd)*Io)*((1-Dmin)/Dmin)
A= ((4*Dmax)/3)^(1/2);
B=((4*(1-Dmax))/3)^(1/2);
Ap=(Po2*(((1/eff)*A)+B))/(Kw*j*Bm*fs)
N1=((Vccmax*Dmin)/(Ac*Bm*fs))*10000
N2=n*N1
L1=(Vccmin*Dmax)/(delI1*fs)
```

Figure 5.2: Transformer calculation

Table 5.1: Transformer Parameters

	Parameters	**Specification of Parameters**	**Value**	**Unit**
1	E	Output Energy	5	Joule
2	R	Load resistance	500	Ohms
3	V_{out}	Output voltage	300	Volt
4	f_s	Switching frequency	30	Khz
5	C	Storage capacity	0.625	uf
6	P_{out}	Output power	5	Watts
7	P_{in}	Input power	6.25	Watts
8	I_o	Output current	0.025	Amp
9	V_{CC}	Supply voltage	12	Volts
10	D_{max}	Maximium duty ratio	0.45	-
11	A_c	Core cross section area	1.07	Volts
12	V_{ccmax}	Maximum supply voltage	13.2	Volts
13	V_{ccmin}	Minimum supply voltage	10.8	Volts
14	D_{min}	Minimum duty ratio	0.40	-
15		Effeciency	0.8	-
16	n	Turns ratio	22.8053	-
17	A_P	Area product of transformer	0.0019	$mm2$
18	N_1	Priomary number of turns	8	-
19	N_2	Secondary number of turns	188	-
20	L_p	Primary inductance of transformer	56.97	uH

Chapter 6

Multilevel Topology of High Voltage Pulse Generator

6.1 Introduction

This is the new energizer technology. This technology based on the marx concept, it facilitates transformerless implementation of reliable, efficient, and high power energizer. The proposed technique has the unique ability of generating output pulses with flexible voltage levels and pulse widths.It also facilitates an economical and reliable implementation of a low power energizer due to the lower circuit complexity and its inherent ability to share voltage stresses equally among the components. The operation of the proposed converter is analyzed mathematically and through simulations to verify the validity of the proposed concept.

6.2 Proposed Technology

The proposed high voltage pulse generation scheme, shown in Fig. 7.1, is derived from a multi-level converter topology and, hence, called a multi-level HVPPS. This technique appears to be similar to the direct discharge type, it has the unique ability of generating pulses with flexible amplitudes and durations similar to that of the Marx type. The complexity of circuit is less in this topoplogy. In addition, the special arrangement of switches and diodes reduce both voltage and current stresses on the switches, thereby facilitating a simple and reliable implementation.

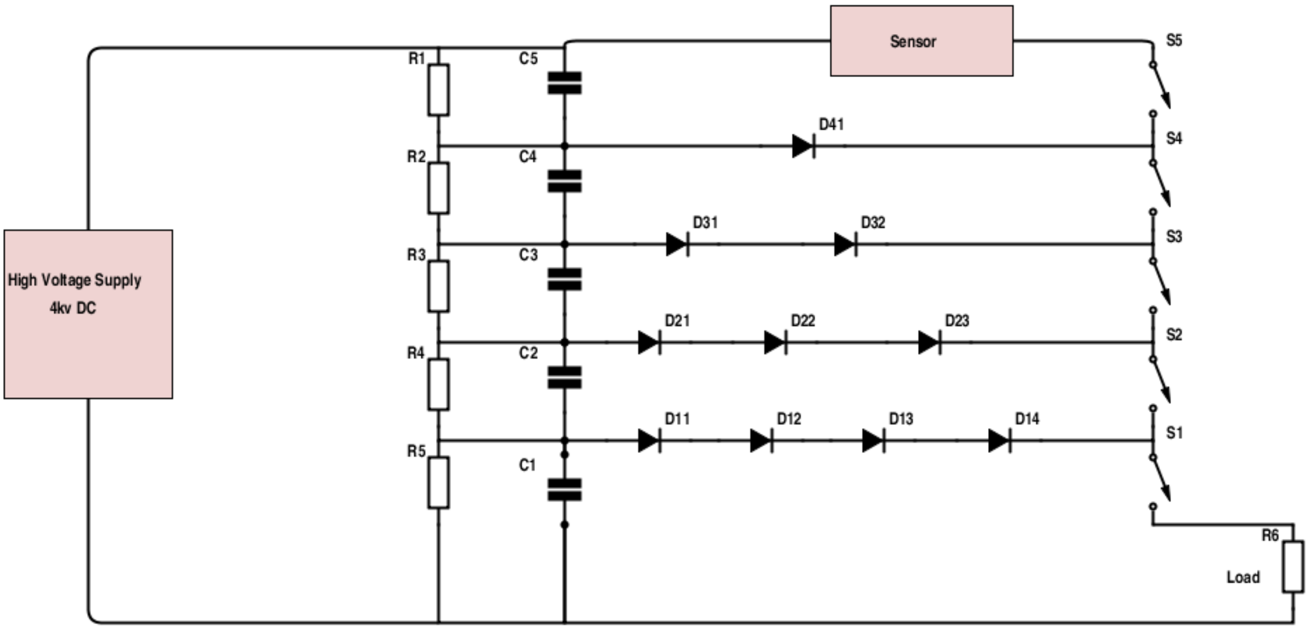

Figure 6.1: A 5 Level Type HVPPS

6.2.1 Operation of Circuit

The operation of the multi-level HVPPS is initiated by charging a series connected storage capacitor bank (C1-CN) to the desired voltage while the switches (S1-SN) are turned-off. Although a charging circuit with a single high voltage output can be used for this purpose, it is preferable to use a multi-output charger to charge the stages separately. This will improve the efficiency of the design with better charge balancing between the capacitors. Alternatively, an active charge balancing circuit can be employed to charge all the capacitors to an equal voltage through a charger that has a single output. The maximum voltage, to which a single stage is charged, is limited by the breakdown voltage rating of the capacitor and the switch. Therefore, if these devices have a voltage rating of V_c, then the required number of stages (N) to generate a peak output voltage of V_o is given by

$$N = V_o/V_c = 5 \tag{6.1}$$

Where

V_c=800V

V_o=4000V

When all capacitors are charged to the specified voltage level, the switches S1 to S5 are turned-on sequentially to initiate an output pulse. During this state, the storage capacitors of the stages that are turned-on are in series with the load. They discharge through the load as the pulse current flows through the switches and the diode chain of the top-most stage that is turned-on. The pulse can be terminated by turning-off the switches sequentially from S5 to S1. Similar to a Marx generator, a delay between the switching of subsequent stages could be introduced easily to generate an output pulse with a variable amplitude and pulse width. During such an operation the diode links between the energy storage capacitors and corresponding switches ensure proper voltage sharing across the switches, eliminating the requirement for complicated snubber and driver circuitry.

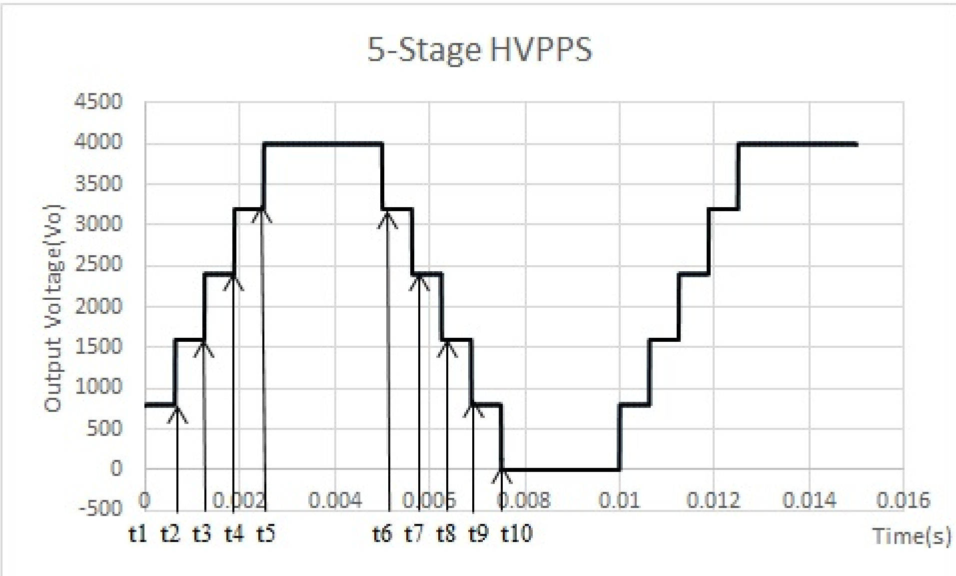

Figure 6.2: An output pulse generated by a 5-stage multi-level HVPPS

This is an example of an output pulse shape that can be generated across a resistive load.

- During the time period t1-t2, only the first switch (S1) is turned-on connecting C1 in a series arrangement with the load.

- The diode chain D11-D14 conducts the pulse current that flows from C1 to the load, therefore discharging C1 through the load and generating an output pulse with a peak amplitude of V_c.
- The maximum voltage stress experienced by the switches S2-S5 remains unchanged at V_c since the diode chain D11-D14 clamps the emitter of S2 to C2.
- At t2, switch S2 is also turned-on, which commutates D11-D14 to off-state and D21-D23 to on-state.
- As a result the output voltage is increased to $(2 * V_c)$ since the capacitors C1-C2 are now connected across the load.
- The 3rd stage is turned-on at t3 increasing the output voltage further to $(3 * V_c)$, this will carried out till $(5 * V_c)$.
- After that since all five capacitors (C1-C5) are now connected in series with the load.
- Under this condition D41 is forward-biased whereas D11-D14 , D21-D23 and D31-D32 are reverse-biased.
- Therefore, the pulse current flows from the capacitors through D41 and S1-S5 to the load.
- The output voltage can be increased further by turning-on the subsequent stages.
- However in this particular example the pulse is terminated by turning-off the switches S5, S4, S3, S2 and S1 at t6, t7, t8, t9 and t10 respectively.

As evident from the above illustration, during all states of circuit operation the diode chains restrict the maximum voltage stress across each switch and capacitor to V_c, thus facilitating a reliable implementation without complex snubber and supervisory circuitry. However, the reverse voltage exerted across a particular diode chain can be much larger than V_c. The reverse voltage applied across a diode chain is determined by the location of the diode chain and the number of switches that are turned-on. Furthermore, the diode chains experience maximum voltage stress when all the stages are turned-on, and the voltage stress on the nth diode chain under this condition is given by equation below. Hence, if the voltage rating of diodes are the same as for the switches, multiple diodes are required in each stage to meet the voltage rating given by below equations. The converter illustrated in Fig. 7.1 thus utilizes diode chains that contain multiple diodes with individual voltage ratings of V_c.

$$V_{D(n)} = V_c \times (N - n) \tag{6.2}$$

According to the equation, we can calculate diode chain voltage rating.

$$V_{D(1))} = 800 \times (5 - 1) = 3200V \tag{6.3}$$

$$V_{D(2))} = 800 \times (5 - 2) = 2400V \tag{6.4}$$

$$V_{D(3))} = 800 \times (5 - 3) = 1600V \tag{6.5}$$

$$V_{D(4))} = 800 \times (5 - 4) = 800V \tag{6.6}$$

Based on the analysis presented above, it is evident that the proposed HVPPS technology has many advantages in comparison to the pulse generation technologies that were discussed in previous chapters. Mainly, it allows an implementation of a reliable solid-state HVPPS by utilizing the multi-level concept with a simple switching scheme as the component voltage and current stresses are low. Moreover, this topology also eliminates the need for expensive snubbing circuits, balancing circuits and driver circuits. The converter could also generate waveforms with variable amplitude and duration similar to the Marx generator, but with lower circuit complexity and cost. Owing to its superior performance, the technique has applications in many pulsed power disciplines that require reliable, compact and efficient solid-state HVPPS.

6.2.2 Theoretical Analysis

Prior knowledge of power requirements, voltage and current stresses on devices and output characteristics of a multi-level converter is essential to realize an optimized design. This can be achieved through a mathematical model that adequately represents the behavior of the converter. This section presents such a mathematical model that facilitates theoretical analysis related to output voltage, component stresses and power throughput on an N-stage converter. It is assumed that the multi-level converter is supplying an output voltage of Vo to a resistive load RL at a pulse repetition rate of frp and a pulse width of T_p. The proposed converter stores energy in the storage capacitors C1-CN. Therefore, assuming that each stage of the converter has a capacitance of C, which is charged V_c , the total amount of energy stored in the converter is given by,

$$E_s = \frac{1}{2} N C V_c^2 \tag{6.7}$$

Where

Es= Stored Energy=5 Joules

N= Number of stages=5

C=Capacitance of series connected capacitors

Vc= Voltage across each capacitor=800 v

By the above equation we can calculate the capacitance C

So, C=3.125 μf

Through the capacitance basic equation we can calculate the each capacitor value connected in series. As all the capacitors have equal voltage charge so all have same capacitance value.

$$\frac{1}{C} = \frac{1}{C1} + \frac{1}{C2} + \frac{1}{C3} + \frac{1}{C4} + \frac{1}{C5} = 15.625 \mu f \tag{6.8}$$

The minimum power throughput of the charger that is required to charge the storage capacitors within one pulse period is a function of the stored energy as given by,

$$P_{charger} = \frac{E_s f_{rp}}{1 - T_p f_{rp}} = 5W \tag{6.9}$$

All capacitors in this proposed design are charged together in a series arrangement through a single-output HV charger. Since this is a low power unit, passive balancing is used to balance voltages across the capacitors in order to minimize circuit complexity. A low power fly-back converter is used as the charger due to its ability of generating high voltages while utilizing a high frequency transformer with a lower turns-ratio. Each IGBT switch in the converter is supplied with its own driver circuit. These driver circuits are controlled by a microcontroller that is powered with reference to the emitter of S1 through opto-isolators. The opto-isolators minimize the parasitic coupling between stages that could cause false triggering of switches.

6.3 Simulation and Results

The design parameters for the simulation are give below

Table 6.1: Design Parameters

Property	**Value**	**Unit**	**Specification**
C	3.125	uf	Capacitance
Vc	800	V	Capacitor Voltage
frp	1	s	Pulse Repetition Rate
Tp	10	ms	Pulse Width
Rload	500	ohms	Resistive Load

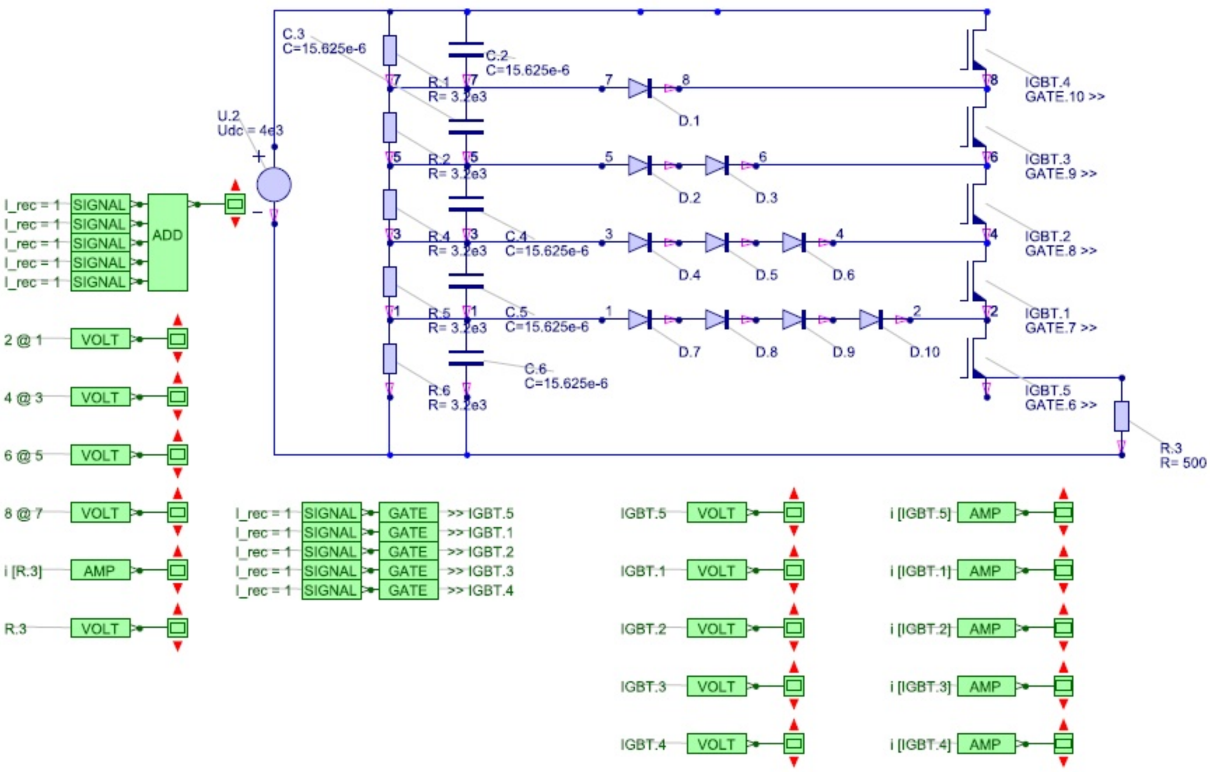

Figure 6.3: Gecko Simulation Circuit of 5 Level HVPPS

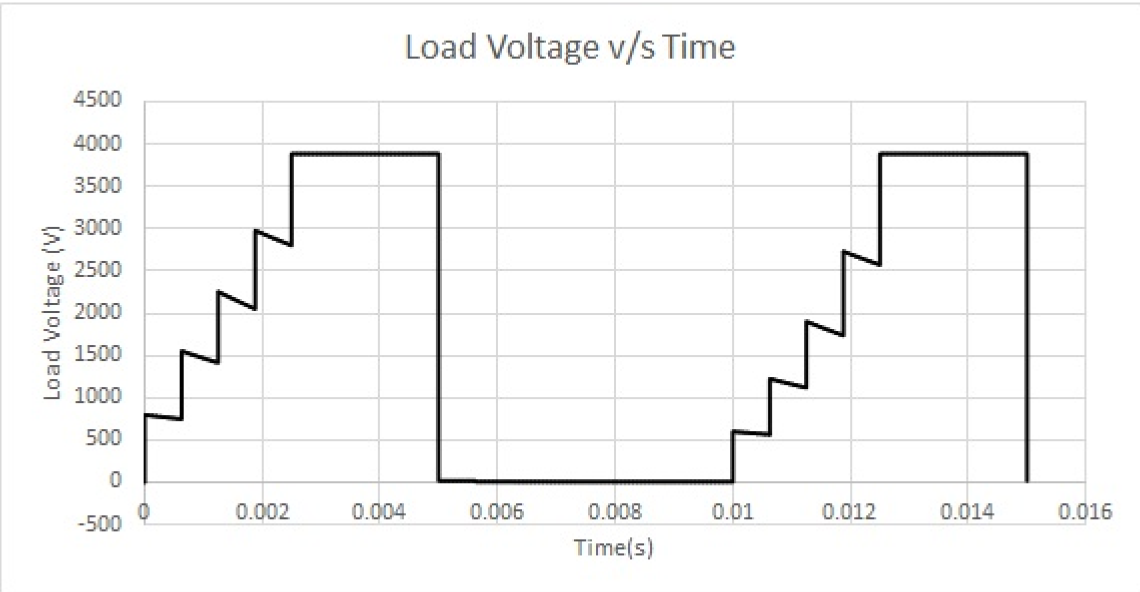

Figure 6.4: Load Voltage

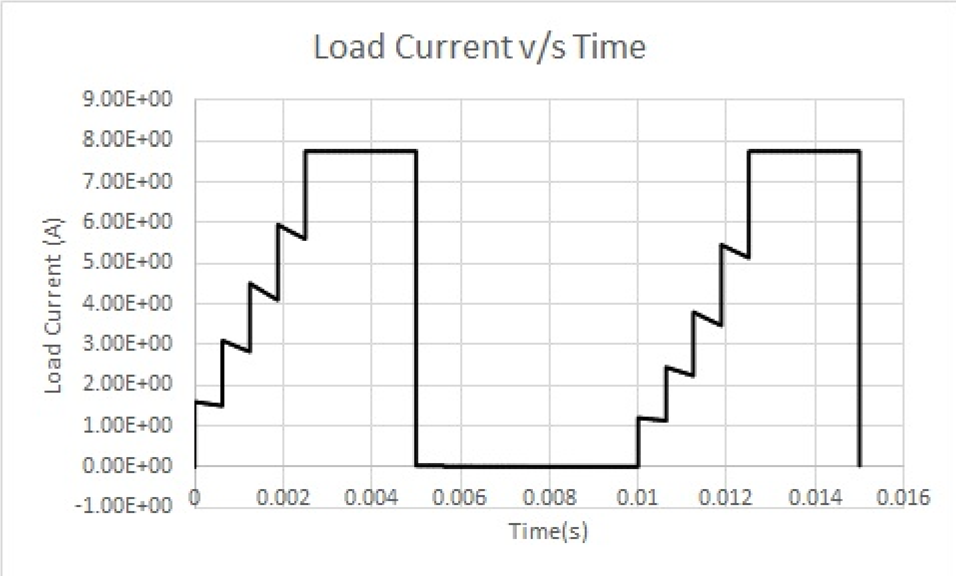

Figure 6.5: Load Current

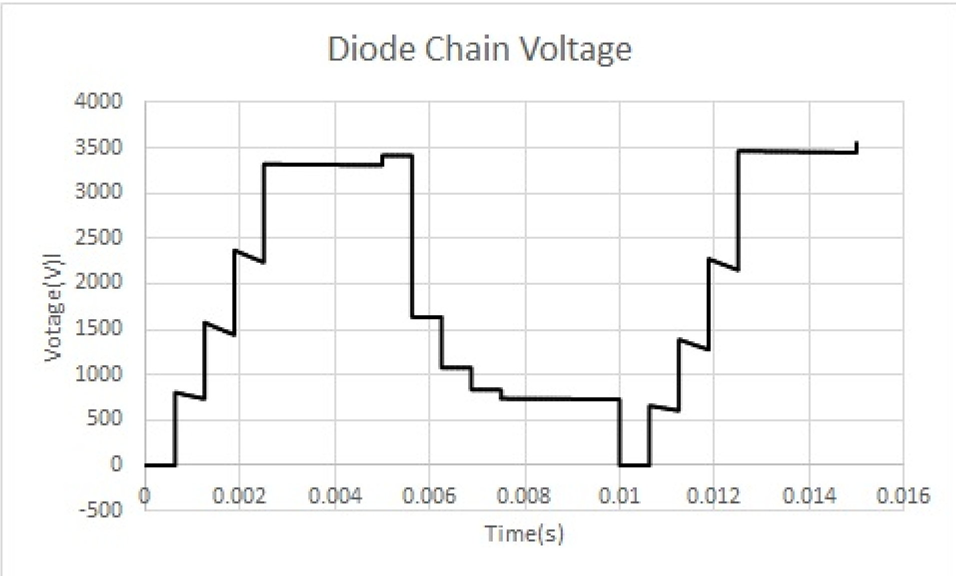

Figure 6.6: Voltage Across Diode Chain

Chapter 7

Hardware Implementation of Multilevel HVPPS

The multilevel HVPPS consists of 2 section as listed below

a. High Voltage Charger Section

b. Energizer Section (Multilevel converter Topology)

The block diagram of entire hardware implementation shown below:

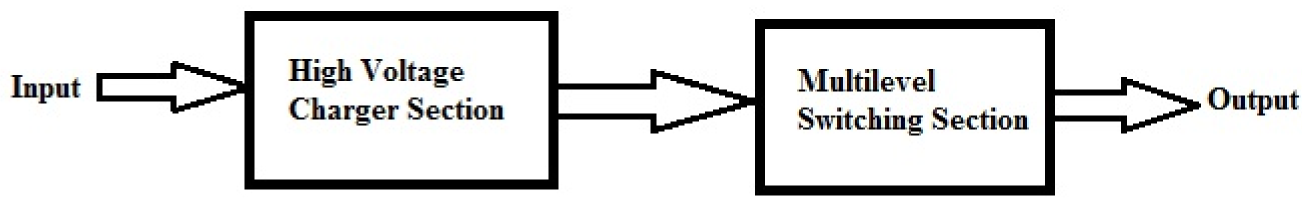

Figure 7.1: Block Diagram for Hardware Implementation

Also the block diagram of energizer using multilevel topology shown below:

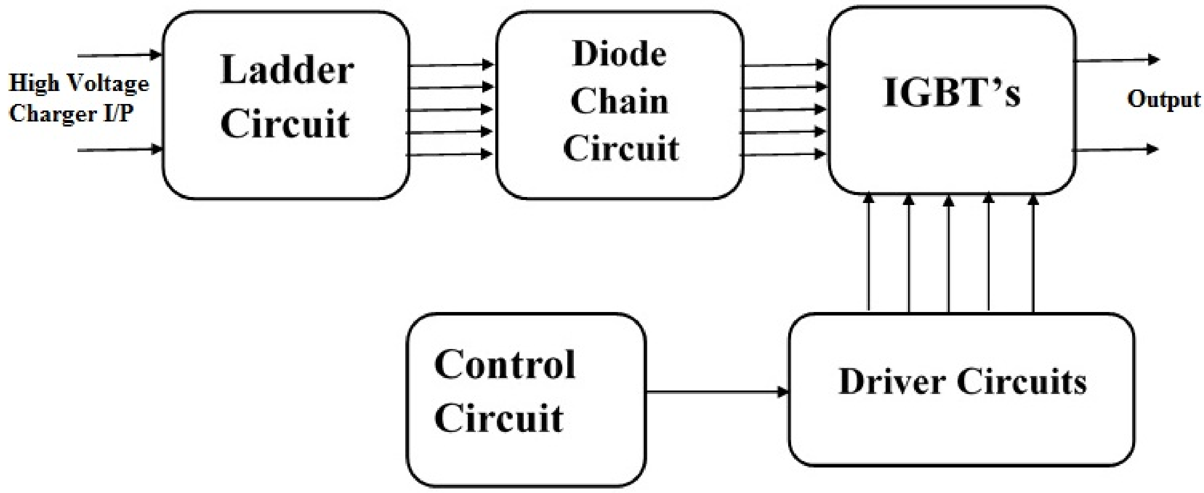

Figure 7.2: Multilevel Topology Hardware Arrangement

7.1 High Voltage Charger

The circuit diagram to generate high voltage as per desire is shown below:

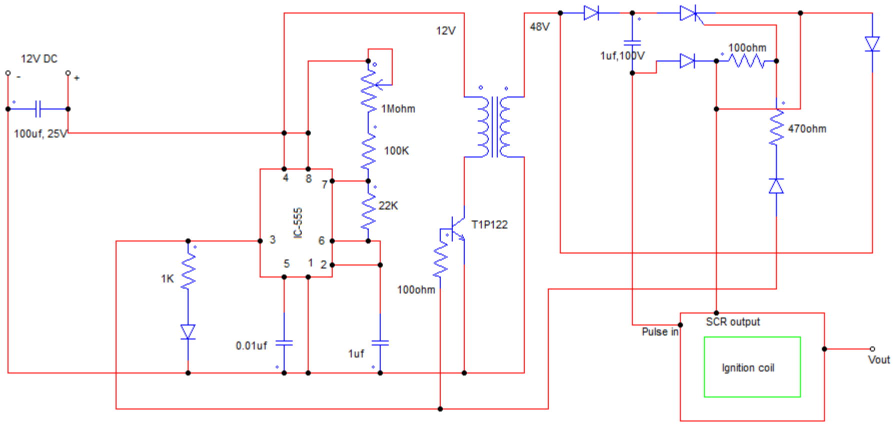

Figure 7.3: High Voltage Charger Circuit Using 555 Timer

The PCB design of the circuit:

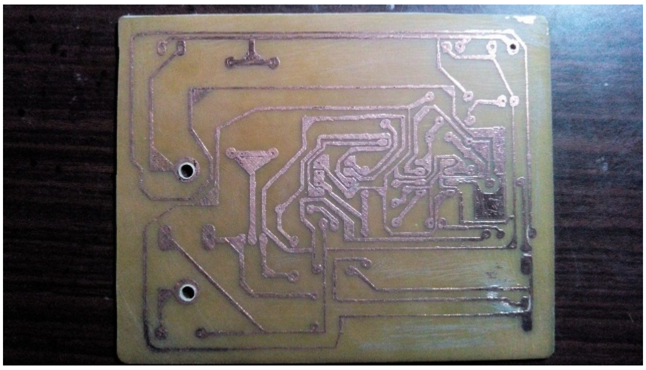

Figure 7.4: PCB Design

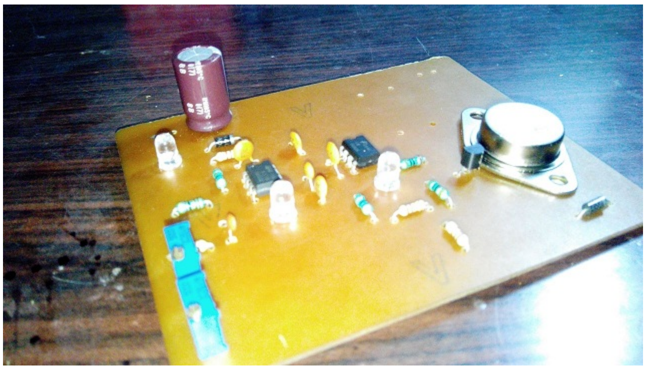

Figure 7.5: Assembled PCB

7.2 Driver Circuit Design Using TLP250

TLP250 is suitable for gate driving circuit of IGBT as well as for MOSFET The main specifications of TLP250 are shown below:

- Input threshold current:5mA(max.)
- Supply current : 11mA(max.)
- Supply voltage : 10 to 35V
- Output current : 1.5A (max.)

- Switching time : 1.5s(max.)
- Isolation voltage: 2500Vrms(min.)

7.2.1 Driver Circuit

The circuit diagram of driver circuit using tlp250 are shown below

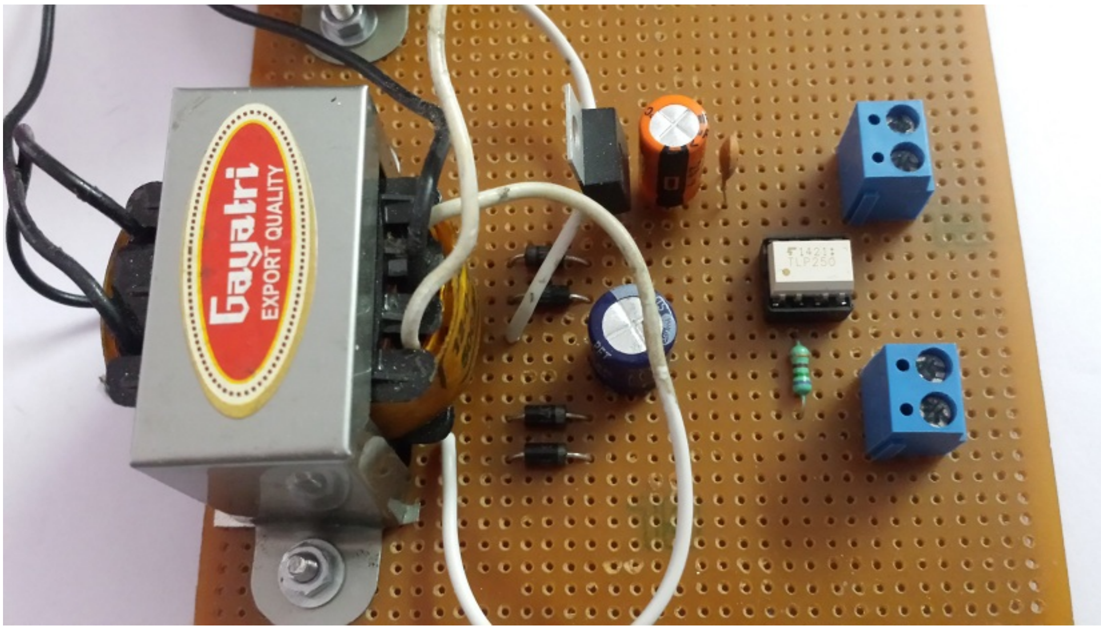

Figure 7.6: Driver Circuit

Chapter 8

Conclusion and Future Scope

8.1 Conclusion

The design of the proposed concept to generate output pulses with flexible amplitudes and durations has been demonstrated through Gecko Circuit simulations and theoretical analysis performed on a 5-stage converter. noindent Also possible hardware implementation carried out of proposed concept.

8.2 Future Scope

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