DESIGN AND CONSTRUCTION OF HIGH VOLTAGE DC POWER SUPPLY AT 150KV OUTPUT USING VOLTAGE MULTIPLIER CIRCUIT FROM 230V AC MAIN SOURCE

BY

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THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL, FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA, NIGERIA IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF THE DEGREE OF MASTER OF ENGINEERING IN ELECTRICAL AND ELECTRONICS ENGINEERING (ELECTRICAL POWER AND MACHINES OPTION).

APRIL, 2012

DECLARATION

I hereby declare that this thesis titled: *Design and Construction of High Voltage Power Supply at 150KV DC Output Using Voltage Multiplier Circuit from 230V AC Main Source* is a collection of my original research work and it has not been presented for any other qualification anywhere. Information from other sources (published or unpublished) has been duly acknowledged.

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CERTIFICATION

The thesis titled: Design and Construction of High Voltage Power Supply at 150KVDC Output Using Voltage Multiplier Circuit from 230VAC Main Source by OLANIRAN, Badiru Babatunde, M.ENG/SEET/2008/1940, meets the regulations governing the award of the degree of Master of Engineering of the Federal University of Technology, Minna and it is approved for its contribution to scientific knowledge and literary presentation.

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DEDICATION

This work is dedicated to my late immediate younger brother, Olaniran Mumini, who died at flower of his age and never be allowed to make his inevitable contribution to human development.

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ABSTRACT

This work describes the details of high voltage DC power supply with an output DC voltage of 150 KV from 230V AC. This device is suitable for field testing of high voltage cables as a prime DC source for very low frequency high voltage test, oscillating wave technique and impulse voltage charging unit due to its light weight and portability. Cockcroft-Walton method of voltage multiplier was adopted due to its less stress on components and cost effectiveness. In this study, a prototype high voltage power supply based on design and implementation of hardware was constructed in laboratory and the result obtained complied with the output of the existing device.

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LIST OF ABBREVIATIONS, GLOSSARIES AND SYMBOLS

M	Permittivity of free space
ρ	Wire resistivity (Ω-cm)
I_{tot}	Total_RMS winding currents (A)
$\mathrm{I}_{m,ma}$	Peak magnetizing current (A)
P_{cm}	Allowed copper loss (W)
A_c	Cross sectional area of wire (cm^2)
$n_{1,}$	Turns (turns, primary)
n_2	Turns (turns, secondary)
K_u	Winding fill factor (unitless)
B_{max}	Core maximum flux density (T)
EC35	*PQ 20/16, 704*, Core type (mm)
K_g	Geometrical constant (cm^5)
K_{gfe}	Geometrical constant (cm^5)
W_A	Window area (cm^2)
MLT	Mean length per turn (cm)
l_m	Magnetic path length (cm)
l, or l_g	Air gap length (cm)
μ	Permittivity (Wb A-1 m-1)
μ_r	Relative Permittivity (unitless)
AWG	American wire gauge
V_P	Primary input voltage (v)
ε	Emissivity
V_o	Secondary output voltage (v)
η	Efficiency

f	Operating frequency(Hz)
P_o	Output power (w)
A_p	Area product
p_t	Power handling capacity (VA)
K_v	Volume coefficient
J	Current density
K_s	Surface area coefficient for UUR core
K_j	Current density coefficient
K	Coefficient indicating square wave input
P_Σ	Total estimated transformer losses
p_{cu}	Copper loss
A_w	Base wire size for primary
N	Number of stage of multiplier
AC	Alternating current
DC	Direct current
CRT	Cathode-ray tubes
T	Transformer
B	Magnetic field
C	Capacitor
R	Resistor
MOSFET	Metal oxide semiconductor field effect transistor
D	Diode
IC	Integrated circuit
PIV	Peak Inverse Voltage
I_L	Load current

V_{Smax}	Peak values of secondary voltage
CW	Cockcroft–Walton
L	Inductor
Hz	Hertz
T	Period
SMPS	Switched mode power supply
HV	High Voltage
EHT	Extra high tension
PCB	Printed circuit board

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the Study

With the widespread development of high voltage direct current (DC) transmission, test equipment for very high voltages has gained particular significance in the past few years. Previously, standard facilities were high-voltage DC test plants with voltages up to 2 million volts (MV) and currents up to 30mA. However, component development for ultra-high voltage DC transmission lines required voltages between 2 MV and 3 MV. The advanced development of high voltage DC power supplies for high voltages and low current was not only prompted by ultra high voltage (UHV) DC transmission projects but also by the growing interest of plasma physicists in high-current injectors for experiments on controlled nuclear fusion (Kuffel, E. and Abdullah, M., 2000).

High voltage DC power supply is widely used in research work (especially in field of applied physics) and in industry level the main application of high voltage DC Power supply is in proof design of high voltage cables with relatively large capacitive load, which draws high current if it is tested with alternating current (AC) high voltage power frequency of sinusoidal waveform instead of DC voltage (Kuffel *et al.*, 2000).

High voltages are primarily produced for insulation testing of high voltage equipment under power frequency AC, DC, switching and lightening impulse voltages. For insulation testing equipment, the voltages are increased up to several million volts but currents are decreased to a few mA or maximum 1 ampere both for AC and DC test sets. (Naidu, M.S. and Kamaraju,V., 2004).

In the fields of electrical engineering and applied physics, high voltage DC are required for several applications such as anode for cathode-ray tubes (CRT) in radar scopes, oscilloscopes, and television picture tubes. They may also be used as primary power supplies in devices that rectify AC inputs to pulsating DC. Although the measured output voltage may be several times greater than the input voltage, connecting a load causes the value of the output voltage to decrease (Naidu, M.S. and Kamaraju, V., 2004). Consequently, voltage multipliers are used mainly in specialized applications where the load remains constant and with high impedance, or when input voltage stability is not critical. The high voltage equipment is required to study the insulation behavior under all conditions, which the apparatus is likely to encounter. Tests are also made with voltages higher than the normal working voltage to determine the factor of the safety over the working conditions and to ensure that the working margin is neither too high nor too low. The conventional forms of high voltage in use can be divided into the following classes:

a) Alternating current voltages

b) Direct current voltages and

c) Transient voltages (Khan N, 2004).

(Joseph, M.B., 2001) presented his paper as the basic operation of multiplier circuit such as half wave voltage doublers and tripler circuit, and discussed guide lines for electronic components selection for diodes and capacitors. (Spencer, F., Aryaeinejad, R. & Reber, E.L., 2011) designed prototype surface mounted Cockcroft-Walton board and tested for use in battery operated, palm sized radiation detection device and it took around output voltage of 1kV and current less than 15mA. When high voltage output is required, the voltage doublers rectifier is able to generate AC line current with lowest current distortion.

In this project, the main emphasis is given to different methods of generating high voltage DC with a critical look at Cockcroft-Walton, Villard, Greinacher methods of voltage multiplier. All their limitations and superiorities are clearly stated in this work. More so, the scope of this project is limited to analysis, design and construction of very high voltage multiplier with low current precisely 1mA with 150KV DC output.

1.2 Significance and Motivation for the Study

With the rapid growth in energy generation supplied by regenerative and decentralized sources the supplying cabling grid is increasing. Therefore, a large demand on high-voltage cable test systems results in the coming years.

In power system, cable insulation test is a major aspect that requires keen attention because it shows the performance of the cable desired to be used for transmitting certain amount of power under load condition. The device to carry out this test is not readily available and where it is available, it costs million of Naira. The Nigerian power system is moving toward generating and transmitting 750KV, equipment for carrying out insulation test should be manufactured and produced locally. As a result of this, this project intends to design and construct an equipment to generate 150KV DC from 230V AC while the solid foundation is being laid for design and construction of extremely high voltage generator in the range of 330KV DC in the future.

1.3 Aim and Objectives

The aim of this project is to design and construct a device to generate very high voltage DC output to be used for insulation test and other scientific research works in the laboratory.

The objectives of the study are therefore, as follows:

1. To design high voltage DC generator that is compact, light weight, reliable, efficient and suitable for laboratory tests.
2. To encourage local production of this device as against foreign importation of highly expensive DC generator.
3. To prove viability of DC-DC converter technique in generating extremely high DC

voltage for cost effectiveness, efficiency and less ripples.

1.4 Project Methodology

To achieve the stated objectives of high voltage power supply, the adopted approach is:

- High frequency switching converter technique

1.5 Project Scope and Limitations

This work shall be limited to the design and implementation of high voltage DC power supply with output of 150KV from 230V AC main source using voltage multiplier circuit technique. Cock-croft multiplier half wave topology is used due to less stress on diodes and capacitors and cost effectiveness.

1.6 Organization of Thesis

This report comprises of five chapters including this introductory one. Chapter two focuses on the literature review as well as the background theory on which this work and others in the existing literature are based. Chapter three discusses materials and methods of voltage multiplier with 150KV DC output. Cockcroft-Walton topology is used for this design. Effects of different loads, input voltage waveforms and frequency of input voltage on output of the voltage multiplier are established. Chapter four presents the result and discussion of result of design and construction of high voltage power supply at 150KV DC output from 230V AC using voltage multiplier circuit technique. Chapter five provides the conclusion and recommendations.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Introduction

This chapter consists of two sections. The first section presents an overview of the technical literature on voltage multiplier. The second section treats various background concepts on high frequency switching direct current to direct current (DC-DC topology.

Generating high dc voltage from low voltage main source using multiplier circuit in cascaded form has a lot of constraints like voltage ripples, voltage regulation, corona and harmonics which result in voltage drop at the output. Better approach to minimize these bottlenecks is to adopt the use of switching converter to limit the number of stages in the design of voltage multiplier circuit. The previous researches show increase in the number of stages has direct correlation with the voltage drop and ripples at the output. One way of reducing the ripples and high voltage drop is to limit the number of stages and use of high capacitance value at the early stage of the multiplier circuit in case of multiplier with large number of stages (Mazen *et al.*, 2000).

2.2 Mode of Operation of High Frequency Switching Converter

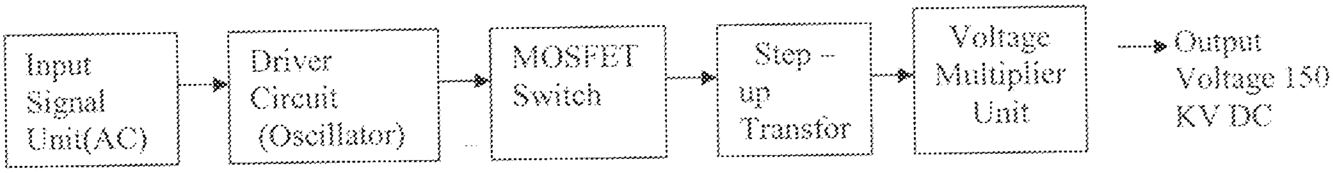


Figure 2.1: A Block Diagram of High Voltage Generator Using Voltage Multiplier Technique

Figure 2.1 shows a block diagram consists of input signal, MOSFET driver, ferrite core step up transformer and voltage multiplier circuit. The input voltage is 230V AC which is rectified to DC voltage and regulated as low as 12 volt which is required to generate smooth and stable voltage output .This is called rectification. The rectifier produces an unregulated DC voltage which is then sent to a large filter capacitor. The current drawn from the mains supply by this rectifier circuit occurs in short pulses around the AC voltage peaks. If an input range switch is used, the rectifier stage is usually configured to operate as a voltage doubler when operating on the low voltage (~120V AC) range and as a straight rectifier when operating on the high voltage (~240V AC) range. If an input range switch is not used, then a full-wave rectifier is usually used and the downstream inverter stage is simply designed to be flexible enough to accept the wide range of DC voltages that will be produced by the rectifier stage. MOSFET switch and ferrite core transformer with (step up transformer) convert DC to AC by running it through a power oscillator comprising of MOSFET switch and step up transformer with many windings at a 20 kilohertz (KHz). The frequency is usually chosen to be above 1 KHz and below 100MHz, if multiplier circuit is to be used to step up DC output to high voltage. The switching is implemented as a multistage (to achieve high gain) MOSFET amplifier. MOSFETs are a type of transistor with a low on-resistance and a high current-handling capacity. If the output is required to be isolated from the input, as is usually the case in mains power supplies, the inverted AC is used to drive the primary winding of a high-frequency transformer. This converts the voltage up to 10KV AC on its secondary winding as in this research work. The output transformer in the block diagram serves this purpose. The voltage multiplier circuit is directly connected to the output of the ferrite core transformer at 10KV AC to generate 150KV DC. The voltage multiplier circuit for this work consists of fifteen stages of coupled two diodes and two capacitors to regulate 10KV AC to approximately 150KV DC.

2.3 Voltage Multiplier

Voltage multipliers are AC-to-DC power conversion devices, comprised of diodes and capacitors that produce a high potential DC voltage from a lower voltage AC source. Multipliers are made up of multiple stages. Each stage is comprised of one diode and one capacitor. The input AC waveform can be sinusoidal (sine wave), rectangular (square wave), or in the form of another shape. Voltage multipliers are usually classified as doublers, triplers, quadruplers, pentuplers. The classification depends on the ratio of the output voltage to the input voltage. For example, devices that increase the peak input voltage by a factor of two are called voltage doublers (VMI Voltage Multiplier Inc.com, 2011)

The most commonly used multiplier circuit is the Half-Wave Series Multiplier. All multiplier circuits can be derived from its operating principles. The following description assumes no losses and represents sequential reversals of polarity of the transformer T_s in Figure 2.2 (in reality several cycles are required to reach full voltage):

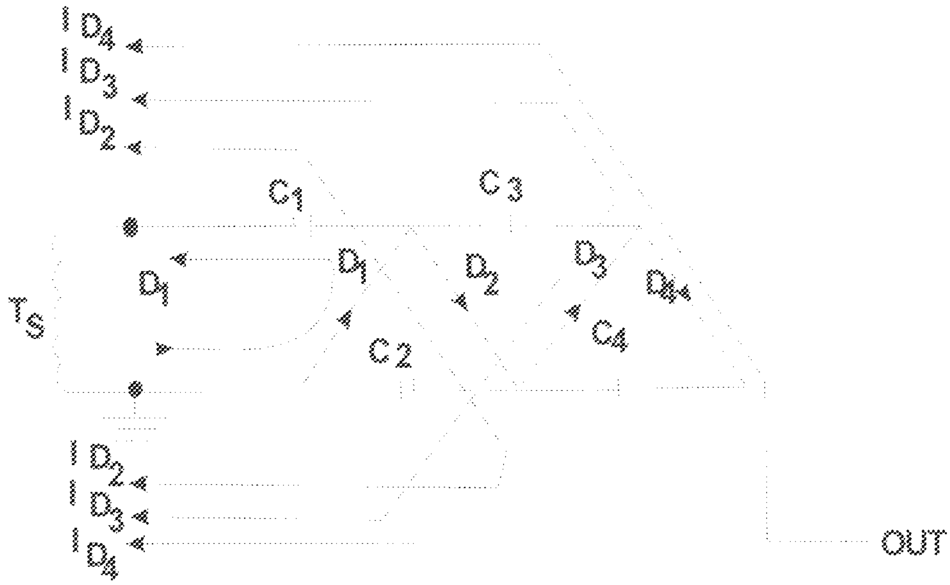


Figure 2.2: Multiplier Circuit

1) T_s=Negative Peak: C_1 charges through D_1 to E_{pk}

2) T_s=Positive Peak: E_{pk} of T_s adds arithmetically to existing potential C_1, so C_2 charges to $2E_{pk}$ thru D_2

All diodes and capacitors must be dimensioned for 2x Up. For sinusoidal input voltage, C1 of the first stage may be reduced to 1x Up.

An n-stage cascade produces 2n x Up output voltage. By choosing an appropriate number of stages, any voltage can be reached. However, this is only valid for negligible current draw. As soon as there is output current, there is also an AC current through the capacitors, resulting in a voltage drop and a lower input voltage for subsequent stages. In fact, numbers much higher than, say, 10 or 20, are not sensible in practice. This means, the voltage drop is the higher, the higher the output current I, the lower the frequency f and the lower the capacity C. The voltage drop also increases with the number of stages cubed, which means for 10 stages it is already 1000x as large as for a single stage (Encyclopaedia , 2011).

2.6.3 Greinacher Voltage Multiplier

The Greinacher voltage doubler is a significant improvement over the Villard circuit for a small cost in increased components. The ripple is much reduced, being nominally zero under open-circuit load conditions, but, when current is being drawn, depends on the resistance of the load and the value of the capacitors used. The circuit works by following a Villard cell stage with what is in essence a peak detector or envelope detector stage. The peak detector cell has the effect of removing most of the ripple while preserving the peak voltage in the output.

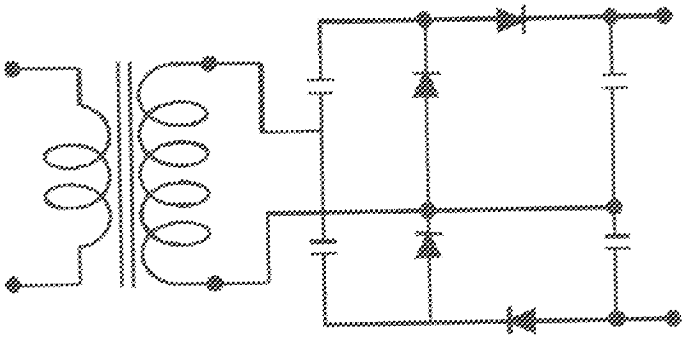


Figure 2.14: Greinacher Quadrupler

This circuit was first invented by Heinrich Greinacher in 1913 in order to provide the 200 – 300 V he needed for his newly invented ionometer, the 110V A.C. supplied by the Zurich power stations of the time being insufficient. He later (1920) extended this idea into a cascade of multipliers. This cascade of Greinacher cells is often inaccurately referred to as a Villard cascade. It is also called a Cockcroft–Walton multiplier after the particle accelerator machine built by John Cockcroft and Ernest Walton, who independently rediscovered the circuit in 1932. The concept in this topology can be extended to a voltage quadrupler circuit by using two Greinacher cells of opposite polarities driven from the same AC source. The output is taken across the two individual outputs. Note that, like a bridge circuit, it is not possible to simultaneously ground both the input and output of this circuit (Encyclopaedia, 2011).

2.6.4 Cockcroft–Walton Multiplier

This Cockcroft–Walton (CW) voltage multiplier was part of one of the early particle accelerators responsible for development of the atomic bomb. Built in 1937 by Philips of Eindhoven it is now in the National Science Museum in London, England (Encyclopedia, 2011).

The Cockcroft–Walton generator, or multiplier, was named after the two men who in 1932 used this circuit design to power their particle accelerator, performing the first artificial nuclear disintegration in history. John Douglas Cockcroft and Ernest Thomas Sinton Walton used this voltage multiplier cascade for most of their research, which in 1951 won them the Nobel Prize in Physics for "Transmutation of atomic nuclei by artificially accelerated atomic particles". Less well known is the fact that the circuit was discovered much earlier, in 1919, by Heinrich Greinacher, a Swiss physicist. For this reason, this doubler cascade is sometimes also referred to as the **Greinacher multiplier**. The CW is a voltage multiplier that converts AC or pulsing DC electrical power from a low voltage level to a higher DC voltage level. It is made up of a voltage multiplier ladder network of capacitors and diodes to generate high voltages. Unlike transformers, this method eliminates the requirement for the heavy core and the bulk of insulation/potting required. Using only capacitors and diodes, these voltage multipliers can step up relatively low voltages to extremely high values, while at the same time being far lighter and cheaper than transformers. The biggest advantage of such circuits is that the voltage across each stage of the cascade is equal to only twice the peak input voltage in a half wave rectifier. In a full wave rectifier it is three times the input voltage. It has the advantage of requiring relatively low cost components and being easy to insulate. One can also tap the output from any stage, like a multitapped transformer (Encyclopaedia, 2011).

Operation of the CW multiplier, or any voltage doubler, is quite simple. Consider the simple two-stage version of Figure 2.15. At the time when the AC input reaches its negative peak potential the left most diode is allowing current to flow from the ground into the first capacitor, filling it up. When the same AC signal reverses polarity, the first diode switches off and the second one, to its right, switches on. Now current flows out of both the AC source and the first capacitor, charging the second capacitor to twice the charge held in the first. With each change in polarity of the input, the capacitors add to the upstream charge and boost the voltage level of the capacitors downstream, towards the output on the right. The increase in voltage, assuming perfect components, is two times the input voltage times the number of stage (Encyclopedia, 2011).

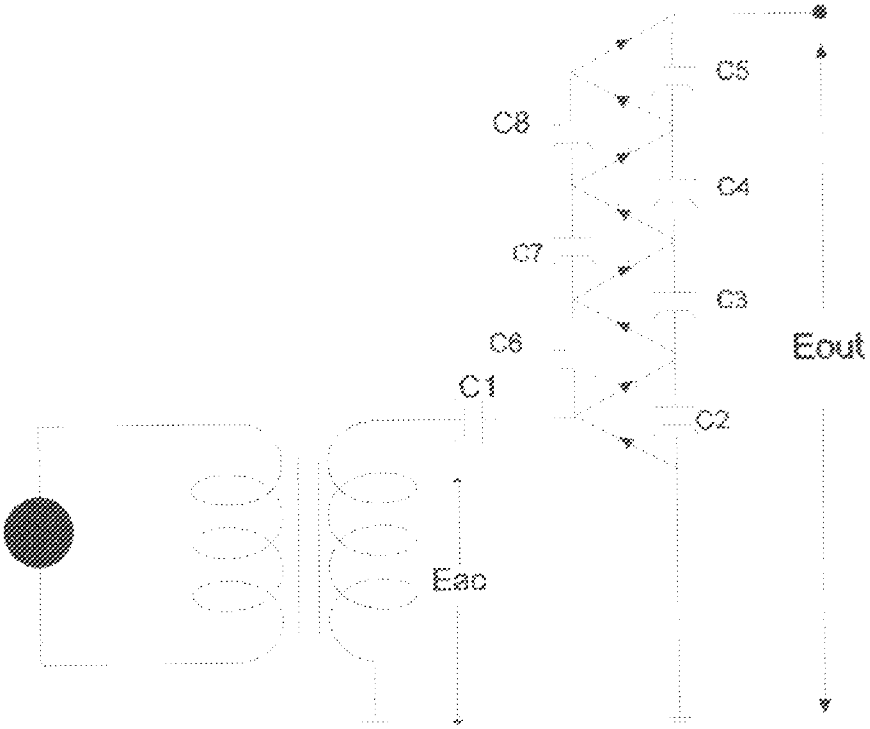


Figure 2.15: Cockcroft–Walton Voltage Multiplier

2.6.5 Operational Characteristics

In practice, the CW has a number of drawbacks. As the number of stages is increased, the voltages of the higher stages begin to 'sag', primarily due to the AC impedance of the capacitors in the lower stages. And, when supplying an output the voltage ripple rapidly increases as the number of stages is increased. For these reasons, CW multipliers with large number of stages are used only where relatively low output current is required. These effects can be partially compensated by increasing the capacitance in the lower stages, by increasing the frequency of the input power and by using an AC power source with a square or triangular shaped waveform. By driving the CW from a high frequency source, such as an inverter, or a combination of an inverter and HV transformer, the overall physical size and weight of the CW power supply can be substantially reduced (Encyclopedia, 2011).

CW multipliers are typically used to develop higher voltages for relatively low current applications such as bias voltages ranging from tens or hundreds of volts to millions of volts for high-energy physics experiments or lightning safety testing. CW multipliers are also found, with a higher number of stages, in laser systems, high-voltage power supplies, X-ray systems, LCD backlighting, traveling wave tube amplifiers, ion pumps, electrostatic systems, air ionisers, particle accelerators, copy machines, scientific instrumentation, oscilloscopes, TV sets and CRTs, bug zappers and many other applications that use high-voltage DC (Encyclopedia, 2011).

2.6.6 Delon Circuit

The Delon circuit uses a bridge topology for voltage doubling. This form of circuit was, at one time, commonly found in cathode ray tube television sets where it was used to provide an extra high tension (e.h.t.) voltage supply. Generating voltages in excess of 5KV with a transformer has safety issues in terms of domestic equipment and in any case is not economic. However, black and white television sets required an e.h.t. of 10KV and colour sets even more. Voltage doublers were used to either double the voltage on an e.h.t winding on the mains transformer or were applied to the waveform on the line flyback coils.

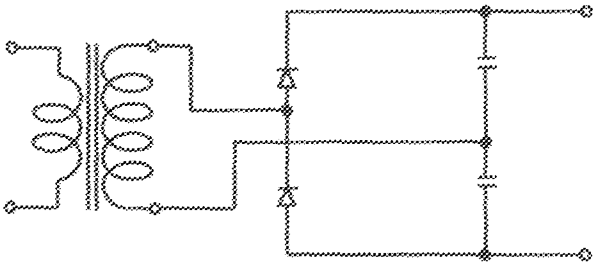


Figure 2.16: Full-Wave voltage Doubler

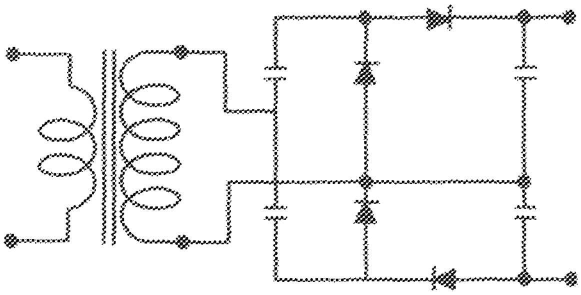


Figure 2.17: Half-Wave Voltage Doubler

The circuit consists of two half-wave peak detectors, functioning in exactly the same way as the peak detector cell in the Greinacher circuit above. Each of the two peak detector cells operates on opposite half-cycles of the incoming waveform. Since their outputs are in series, the output is twice the peak input voltage.

A full-wave version of this circuit has the advantage of lower peak diode currents, improved ripple and better load regulation but requires a centre-tap to the transformer as well as more components.

2.7 Design Consideration of Voltage Multiplier Circuit

In designing multiplier circuit, there are factors to consider in choosing the diodes and capacitors if expected output current will be realized. Proper selection of active components of the multiplier circuit especially at high voltage level determines the efficiency and reliability of the multiplier technique for generation of high DC voltage. If proper attention is not paid to these factors, there may not be output at all from the voltage multiplier.

2.7.1 Capacitor Selection

The size of capacitors used in multiplier circuits is directly proportional to the frequency of the input signal. Capacitors used in off-line, 60Hz applications are usually in the range of 1.0 to 200mF while those used in higher frequency applications, say 10KHz, are typically in the range of .02 to .06mF. In practice, it is usually easier, and less costly, to use the same large capacitance value for all capacitors, both "AC" and "DC" type. The overall capacitive reactance of the circuit must be considered, however, to determine the largest permissible value. The voltage rating of capacitors is determined solely by the type of multiplier circuit. In the half wave doubler circuit of Figure 2.6, C4 must be capable of withstanding a maximum voltage of Vm, while C2 must withstand a voltage of 2Vm. In the full-wave doubler circuit of Figure 2.10, both C1 and C2 must withstand voltages of Vm. The half wave voltage tripler of Figure 2.12 requires C1 to withstand a voltage of Vm, and both C2 and C3 to withstand voltages of 2Vm. A good rule of thumb is to select capacitors whose voltage rating is approximately twice that of the actual peak applied voltage. For example, a capacitor which will see a peak voltage of 2Vm should have a voltage rating of approximately 4Vm (Mazen., *et al* 2000).

2.7.2 Rectifier Diode Selection

Prior to selection of diode basic device parameter must be considered. These parameters determine the suitability of the rectifier for the design of high voltage, high frequency voltage multiplier circuit.

(a) Repetitive Peak Reverse Voltage (VRRM)

Repetitive peak reverse voltage is the maximum allowable instantaneous value of reverse voltage across the rectifier diode. Applied reverse voltages below this maximum value will produce only negligible leakage currents through the device. Voltages in excess of this maximum value, however, can cause circuit malfunction — and even permanent component damage — because significant reverse currents will flow through the device. For example, General Semiconductor's GP02-40 rectifier diode has a peak reverse voltage rating (VRRM) of 4,000 Volts, maximum. Applied reverse voltages of 4kV or less will produce a maximum reverse leakage current, IR, of 5 microamperes through the device when operated at room temperature (25°C). In most cases, this leakage current is considered negligible, and the device is said to be completely blocking (IR = 0). So devices must be selected with reverse voltage (VRRM) ratings of at least 2Vm (Mazen., *et al*, 2000).

(b) Reverse Recovery Times (TRR)

In general terms, reverse recovery time is a measure of the time needed for a rectifier diode to reach a state of complete blocking (IR=0) upon the application of a reverse bias. Ideally, this time should be zero. In reality, however, there is a finite period of time in which a stored charge at the diode junction must be "swept away" before the device can enter its blocking mode. This stored charge is directly related to the amount of forward current flowing through the device just prior to the application of the reverse bias. Fortunately, since operating currents are very low in multiplier circuits, reverse recovery times are kept to a minimum. Nevertheless, TRR plays an important role in multiplier design. When selecting rectifier diodes, the frequency of the input signal to the multiplier network must be considered. For symmetrical signal inputs, the device chosen must be capable of switching at speeds faster than the rise and fall times of the input. If the reverse recovery time of the rectifier is too long, the efficiency and regulation of the circuit will suffer. In the worst case, insufficient recovery speeds will result in excessive device heating, as reverse power losses in the rectifier become significant. Continued operation in this mode usually results in permanent damage to the device. The reverse recover time (TRR) specification is very dependent upon the circuit and the conditions being used to make the measurement. Several industry standard TRR test circuits exist (Figure 2.18 is the test circuit used for the GP02-40). Therefore, it is very important to note which test circuit is being referenced, as the same device may measure differently on different test circuits. Furthermore, the TRR specification should be used for qualitative, not quantitative purposes, since conditions specified for TRR measurement rarely reflect those found in actual "real life" circuit operation. The TRR specification is most valuable when comparing two or more devices that are measured on the same circuit, under the same conditions. Figure 2.18 shows the relationship between forward current and TRR in the GP02-40. As you can see, decreasing current flow in the multiplier circuit makes it possible to use higher input frequencies. An increase in current flow has the opposite effect. Ideally, the multiplier network load should draw no current.

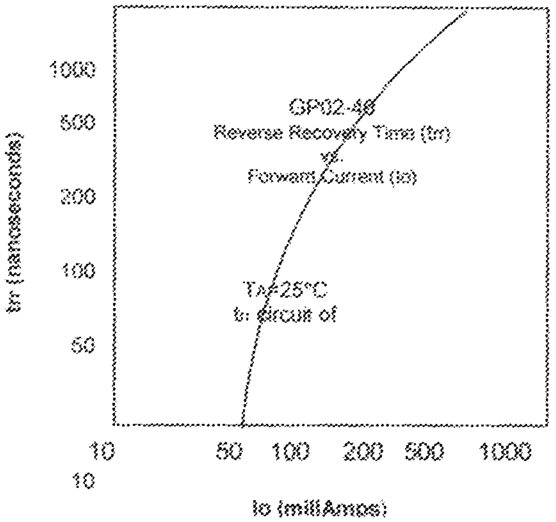


Figure 2.18: TRR as a function of forward

(c) Frequency of Input Signal

While selecting rectifier diode, the frequency of input signal to multiplier circuit must be taken into account. For symmetrical input signals, the device chosen must be capable of switching at speed faster than the rise and fall times of the input. If the reverse recovery time is too long the efficiency and regulation of the device will suffer. In the worst case, insufficient recovery speed will result in accessing heating of device. And in this case permanent damage of device will take place. The reverse recovery time is very dependent upon the circuit and the condition being used to make the measurement. Reverse recovery Time specification should be used for qualitative, not quantitative purposes since condition specified for the measurement rarely reflects those found in actual real life circuit operation. Decreasing current flow in the multiplier circuit makes it possible to use higher input frequency. An increase in current flow has been the opposite effect. Ideally the multiplier network load should draw no current (Mazen, *et al*, 2000).

(d) Peak Forward Surge Current (PFSC)

A peak forward surge current rating is given for most rectifier diodes. Most often, this rating corresponds to the maximum peak value of a single half- sine wave (50 or 60Hz) which, when superimposed upon the devices rated load current, can be conducted, without damage by the rectifier. This rating becomes important when considering the large capacitance associated with multiplier circuitry.

Surge currents can develop in multiplier circuits, due to capacitive loading effects. The large step up turns ratio between primary and secondary of most high voltage transformers causes the first multiplier capacitor (C1, secondary side) to be reflected as a much larger capacitance into the primary. For example, a transformer with a turns ratio of 25 will cause a 1.0mF capacitance to be reflected into the primary circuitry as a capacitance of (1.0)(25)mF, or 625mF. At circuit turn-on, large currents will be developed in the primary side as this effective capacitance begins charging. On the secondary side, significant surge currents can flow through the rectifiers during initial capacitor charging at turn-on. The addition of a series resistance can greatly reduce these current surges, as well as those in the primary circuitry. For example, the GP02-40 has a forward surge rating, I_{FSM}, of 15 amperes. Considering a maximum secondary voltage of 260 V_{RMS}, 60Hz, and the calculation of Rs is as follows:

$$R_S = \frac{V_{peak}}{I_{fsm}} \tag{2.12}$$

$$R_S = \frac{(1.41)(260)}{15}$$

$$R_S = 24.4 \text{ ohm}$$

(e) Forward Current, Io

As stated earlier, in the ideal multiplier configuration the load will draw no current. Ideally, the only significant current flow through the rectifiers occurs during capacitor charging. Therefore, devices with very low current ratings (hundreds of milliamperes) can be used. It must be noted, however, that the forward current and forward surge current ratings are related, since both are a function of silicon die area. Generally speaking, devices with a high surge current rating, I_{FSM}, will also have a high forward current, I_O, rating and vice versa.

(f) Forward Voltage, VF

In practice, the forward voltage drop, V_F, of the rectifiers does not have a significant effect on the multiplier network's overall efficiency. For instance, the GP02-40 has a typical forward drop of 2.0 Volts when measured at a current of 100 milliamperes. A half-wave doubler with an 8kV output will have less than 0.05 percent (2 x 2V/8kV) loss in efficiency due to the forward voltage drops (Mazen, *et al*, 2000)

(g) Stray Capacitance

Stray capacitance becomes an important consideration as input frequency increases. As the following expression indicates, an increase in frequency decreases the capacitive reactance, resulting in increased current flow through the insulating materials (VMI Voltage Multiplier Inc.com, 2011)

$$X_C = \frac{1}{2\pi fC} \tag{2.13}$$

Power losses through insulation, which are negligible at 50Hz, become significant at high frequency.

(h) Corona

Corona is the result of gas ionization (air, oxygen, etc.), due to a high voltage field. This extremely destructive phenomenon usually results in slow degradation of the insulating materials, causing latent failures. Careful design, consistent manufacturing processes, eliminating air entrapment in encapsulation, and a thorough understanding of what causes corona minimize this problem (Voltage Multiplier Inc.com, 2011).

$$K_e = 0.145 f^2 \Delta B^2 (10)^{-4} \tag{2.23}$$

The core geometry, Kg, is given as

$$K_g = \frac{P_{in} D_{\max}}{\alpha K_e} \tag{2.24}$$

The number of primary turns, Np, is expressed as,

$$N_p = \frac{V_{in} D_{\max} 10^{-4}}{f \Delta B A_C} \tag{2.25}$$

The current density, J, using window utilization, Ku

$$J = \frac{P_{in\sqrt{D_{\max}}} \times 10^{-4}}{f \Delta B W_a K_u} \text{ amps/cm}^2 \tag{2.26}$$

The primary rms current, Ip, is expressed as,

$$I_p = \frac{P_{in}}{V_{in\sqrt{D_{\max}}}} \text{ amps} \tag{2.27}$$

The primary bare wire area, $A_{wp}(B)$ is given as :

$$A_{wp}(B) = \frac{I_p}{J} \text{ cm}^2 \tag{2.28}$$

The required number of primary strands, N_{SP}.

$$N_{sp} = \frac{A_{wp}}{gauge} \tag{2.29}$$

The primary resistance, Rp,

$$R_p = MLT \times N_p \quad \text{ohms} \tag{2.30}$$

The primary copper loss, Pp, is given as

$$P_p = R_p I_p^2 \quad \text{watts} \tag{2.31}$$

The secondary turns, Ns.

$$N_S = \frac{N_p V_o}{D_{\max} V_{in}} \text{ turns} \tag{2.32}$$

The secondary rms current, Is,

$$I_S = \frac{I_o}{\sqrt{2}} \text{ amps} \tag{2.33}$$

The secondary winding resistance, Rs, is gotten from mean turn ratio as,

$$R_S = MLT \times N_S \text{ ohms} \tag{2.34}$$

The secondary copper loss, Ps, is

$$P_S = I_S^2 R_S \text{, watts} \tag{2.35}$$

While the total primary and secondary copper loss, Pcu, is:

$$P_{CU} = P_P + P_S \text{, watts} \tag{2.36}$$

The total loss, P_ε, is found to be

$$P_\varepsilon = P_{CU} + P_{fe} \text{ watts} \tag{2.37}$$

2.14 Oscillator/Multivibrator

A form of electronic circuit that employs positive feedback to cross-couple two devices so that two distinct states are possible, for example, one device ON and the other device OFF, and in which the states of the two devices can be interchanged either by use of external pulses or by internal capacitance coupling. When the circuit is switched between states, transition times are normally very short compared to the ON and OFF periods. Hence, the output waveforms are essentially rectangular in form.

Multivibrators may be classified as bistable, monostable, or astable. A bistable multivibrator, often referred to as a flip-flop, has two possible stable states, each with one device ON and the other OFF, and the states of the two devices can be interchanged only by the application of external pulses. A monostable multivibrator, sometimes referred to as a one-shot, also has two possible states, only one of which is stable. If it is forced to the opposite state by an externally applied trigger, it will recover to the stable state in a period of time usually controlled by a resistance-capacitance (*RC*) coupling circuit. An astable multivibrator has two possible states, neither of which is stable, and switches between the two states, usually controlled by two *RC* coupling time constants. The astable circuit is one form of relaxation oscillator, which generates recurrent waveforms at a controllable rate. IC (LM 555 Timer) was used in this project work wired as astable multivibrator.

2.14.1 555 Timer Circuit

The 555 timer IC is an integrated circuit (chip) used in a variety of timer, pulse generation and oscillator applications. The 8-pin 555 is one of the most useful ICs ever made and it is used in many projects. With just a few external components it can be used to build many circuits.

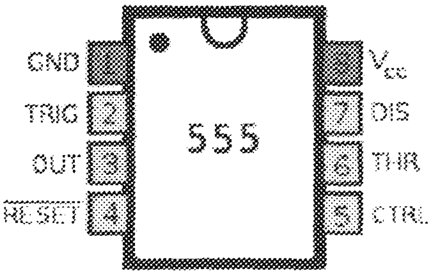


Figure 2.19: 555 Timer IC

1 GND - Ground, low level (0 V)
2 TRIG - OUT rises, and interval starts, when this input falls below 1/3 V_{CC}.
3 OUT - This output is driven to $+V_{CC}$ or GND.
4 RESET A timing interval may be interrupted by driving this input to GND.
5 CTRL- "Control" access to the internal voltage divider (by default, 2/3 V_{CC}).
6 THR - The interval ends when the voltage at THR is greater than at CTRL.
7 DIS - Open collector output; may discharge a capacitor between intervals.
8 $V+$, V_{CC} - Positive supply voltage is usually between 3 and 15 V.

2.14.2 Astable Multivibrator using 555 IC -Design method

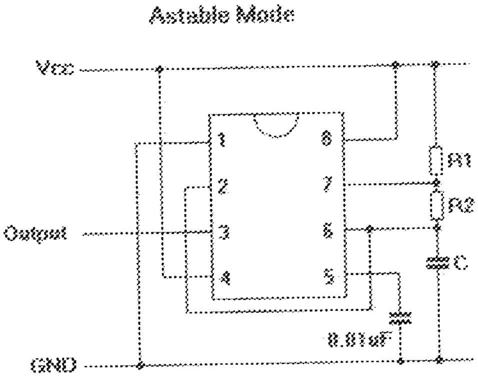


Figure 2.20: Astable Multivibrator

The time during which the capacitor C charges from $\frac{1}{3}V_{CC}$ to $\frac{2}{3}V_{CC}$ is equal to the time the output is high and is given as t_c or $T_{HIGH} = 0.693(R_1 + R_2)C$, which is proved below.

Voltage across the capacitor at any instant during charging period is given as,

$$V_C = V_{CC}^{\left(1-\frac{at}{RC}\right)} \tag{2.35}$$

The time taken by the capacitor to charge from 0 to $+\frac{1}{3}V_{CC}$

$$\frac{1}{3}V_C = V_{CC}^{\left(1-\frac{at}{RC}\right)} \tag{2.36}$$

The time taken by the capacitor to charge from 0 to $+\frac{2}{3}V_{CC}$

$$or\, t_2 = RC\log_e 3 = 1.0986RC \tag{2.37}$$

So the time taken by the capacitor to charge from $+\frac{1}{3}V_{CC}$ to $+\frac{2}{3}V_{CC}$

$$t_C = (t_2 - t_1) = (1.0986 - 0.405)RC = 0.693RC$$

Substituting $R = R_1 + R_2$ in above equation, we have

$$T_{HIGH} = t_C = 0.693(R_1 + R_2)C \tag{2.38}$$

Where R_1 and R_2 are in ohms and C is in farads.

The time during which the capacitor discharges from $+\frac{2}{3}V_{CC}$ to $+\frac{1}{3}V_{CC}$ is equal to

the time, the output is low and is given as:

t_d or $T_{LOW} = 0.693 R_2 C_1$ where R_2 is in ohms and C_1 is in farads The above equation is worked out as follows: Voltage across the capacitor at any instant during discharging period is given as:

$$V_C = \frac{2}{3} V_{CC}^{e-\frac{t_d}{R_2C}} \tag{2.39}$$

Substituting $V_C = \frac{1}{3}V_{CC}$ and $t = t_d$ in above equation we have

$$+\frac{1}{3}V_{CC} = +\frac{2}{3}V_{CC}^{e-\frac{t_d}{R_2C_1}}$$

$$\text{Or } t_d = 0.693 R_2 C \tag{2.40}$$

Overall period of oscillations, $T = T_{HIGH} + T_{LOW} = 0.693(R_1 + 2R_2)C$, The frequency of oscillations being the reciprocal of the overall period of oscillations T is given as:

$$f = \frac{1}{T} = \frac{1.44}{(R_1 + 2R_2)C} \tag{2.41}$$

Equation indicates that the frequency of oscillation is independent of the collector supply voltage $+V_{CC}$.

Often the term duty cycle is used in conjunction with the astable multivibrator.

The duty cycle, the ratio of the time t_c during which the output is high to the total time period T, is given as:

$$\%\ \text{duty cycle},\ D = \frac{t_C}{T}100 = \left(\frac{R_1 + R_2}{(R_1 + 2R_2)100}\right) \tag{2.42}$$

From the above equation it is obvious that square wave (50 % duty cycle) output cannot be obtained unless R_1 is made zero. However, there is a danger in shorting resistance R_1 to zero.

With R_1 = 0 ohm, terminal 7 is directly connected to + V_{CC}. During the discharging of capacitor through R_2 and transistor, an extra current will be supplied to the transistor from V_{CC} through a short between pin 7 and +V_{CC}. It may damage the transistor and hence the timer (Ward, 2010).

2.15 Direct to Direct (DC-DC) Converter

A DC-to-DC converter is a device that accepts a DC input voltage and produces a DC output voltage. Typically the output produced is at a different voltage level than the input. In addition, DC-DC converters are used to provide noise isolation, power bus regulation, etc. This is a summary of some of the popular DC-DC converter topologies: There are many different types of DC-DC converter, each of them tends to be more suitable for some types of application than for others. For convenience they can be classified into various groups, however. For example some converters are only suitable for stepping down the voltage, while others are only suitable for stepping it up; a third group can be used for either. Another important distinction is between converters which offer full dielectric isolation between their input and output circuits, and those which don`t. Needless to say this can be very important for some applications, although it may not be important in many others (Colonel, 2000).

2.16 Type of DC-DC Converter

Basically, there two types of DC-DC converter, namely:

- Non-Isolating DC-DC Converter
- Isolating DC-DC Converter

2.16.1 Non-Isolating DC-DC Converter

The non-isolating type of converter is generally used where the voltage needs to be stepped up or down by a relatively small ratio (say less than 4:1), and there is no problem with the output and input having no dielectric isolation. Examples are 24V/12V voltage reducers, 5V/3V reducer and 1.5V/5V step-up converters.

There are five main types of converter in this non-isolating group, usually called: buck, boost, buck-boost, Cuk and charge-pump converters. The buck converter is used for voltage step down/reduction, while the boost converter is used for voltage step-up. The buck-boost and Cuk converters can be used for either step-down or step-up, but are essentially voltage polarity reverses or inverters as well. (The Cuk converter is named after its originator, Slobodan Cuk of Cal Tech University in California). The charge-pump converter is used for either voltage step-up or voltage inversions, but only in relatively low power applications (Colonel, 2000).

(a) Buck Converter

The Buck converter has a lower voltage, and it has pulsating input current generating high harmonics into the power line. This circuit is not practical for low-line input because it does not draw the input current when input voltage is lower than the output voltage. Schematic diagram of buck converter is as shown in Figure 2.21.

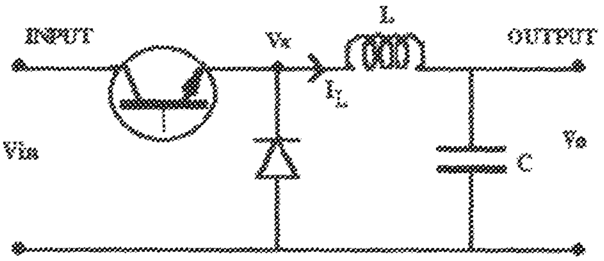


Figure 2.21: Buck Converter

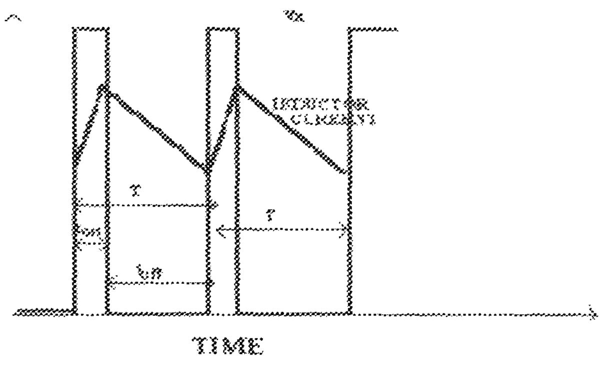


Figure 2.22: Voltage and Current Changes

In this circuit the transistor turning ON will put voltage Vin on one end of the inductor. This voltage will tend to cause the inductor current to rise. When the transistor is OFF, the current will continue flowing through the inductor does not reach zero, thus the voltage at Vx will now be only the voltage across the conducting diode during the full OFF time. The average voltage at Vx will depend on the average ON time of the transistor provided the transistor the inductor current is continuous (Colonel, 2000).

The Buck converter has a lower output voltage than input voltage, and it has pulsating input current generating high harmonics into the power line. This circuit is not practical for low-line input because it does not draw the input current when input voltage is lower than the output voltage. The line current of the converter is discontinuous as in Figure 2.22, therefore, it has relatively low power factor.

(b) Boost Converter

The schematic in Figure 2.23 shows the basic boost converter. This circuit is used when a higher output voltage than input is required.

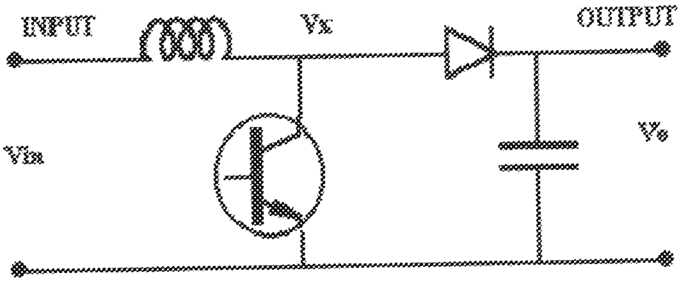


Figure 2.23: Boost Converter Circuit

While the transistor is ON $V_x = V_{in}$, and the OFF state the inductor currents flows through the diode giving $V_x = V_o$. For this analysis it is assume that the inductor current always remains flowing (continuous conduction). The voltage across the inductor is shown in Figure 2.24 and the average must be zero for the average to remain in steady state.

$$V_{in}t_{on} + (V_{in} - V_o)t_{off} = 0 \tag{2.42}$$

This can be rearranged as

$$\frac{V_o}{V_{in}} = \frac{T}{t_{off}} = \frac{1}{(1-D)} \tag{2.43}$$

and for a lossless circuit the power balance ensures

$$\frac{I_o}{I_{in}} = (1 - D) \tag{2.44}$$

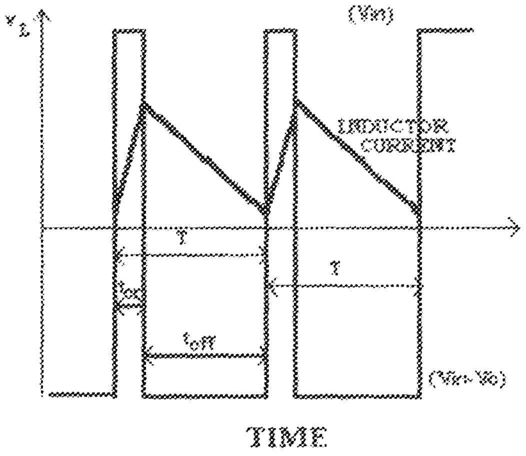


Figure 2.24: Voltage Across Conductor

The Boost converter is shown in Figure 2.23, it has step-up conversion ratio. Therefore the output voltage is always higher than the input voltage. The converter will operate throughout the entire line cycle, so the input current does not have distortions and continuous as shown. It has a smooth input current because an inductor is connected is sourced-grounded; therefore it is easy to drive. This topology is a universal solution for off-line power supplies and SMPS applications.

(c) Buck-Boost Converter

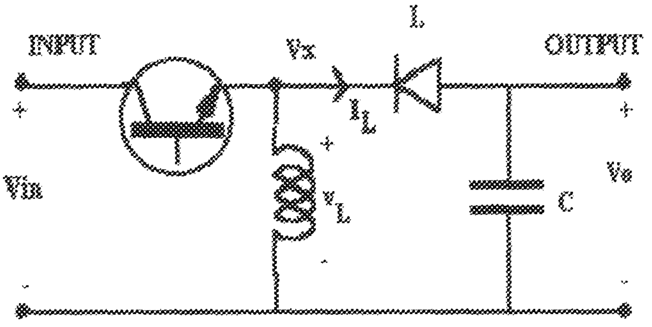


Figure 2.25: Schematic for Buck-Boost Converter

With continuous conduction for the Buck-Boost converter $V_x = V_{in}$ when the transistors is ON and $V_x = V_0$ when the transistor is OFF. For zero net current change over a period the average voltage across the inductor is zero.

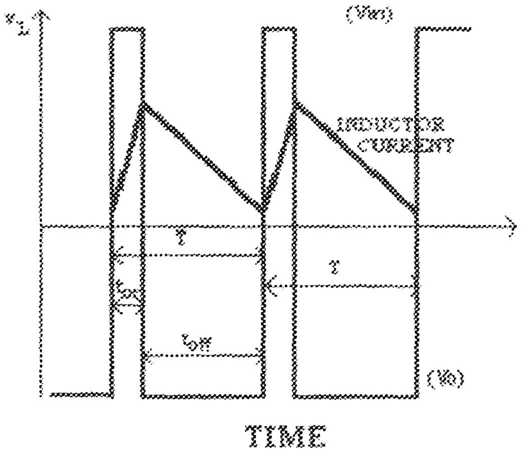


Figure 2.26: Waveforms for Buck-boost Converter

$$V_{in}t_{ON} + V_o t_{OFF} = 0 \tag{2.45}$$

which gives the voltage ratio

$$\frac{V_o}{V_{in}} = \frac{D}{(1-D)} \tag{2.46}$$

and the corresponding current

$$\frac{I_o}{I_{in}} = -\frac{(1-D)}{D} \tag{2.47}$$

Since the duty ratio "D" is between 0 and 1 the output voltage can vary between lower or higher than the input voltage in magnitude. The negative sign indicates a reversal of sense of the output voltage.

The Buck-boost converter is a type of DC-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude .It is a switch mode power supply with a similar circuit topology to the boost converter and the buck converter. The output voltage is adjustable based on the duty circle of the switching transistor. One possible drawback of this converter is that the switch does not have a terminal at ground; this complicates the driving circuitry. Also, the polarity of the output is opposite the input voltage. Neither drawback is of any consequence if the power supply is isolated from the load circuit (if, for example, the supply is a battery) as the supply and diode polarity can simply be reversed. The switch can be on either ground side or supply side.

(d) Cuk Converter

The buck, boost and buck-boost converters all transferred energy between input and output using the inductor, analysis is based on voltage balance across the inductor. The CUK converter uses capacitive energy transfer and analysis is based on current balance of the capacitor. The circuit in Figure 2.27 is derived from DUALITY principle on the buck-boost converter.

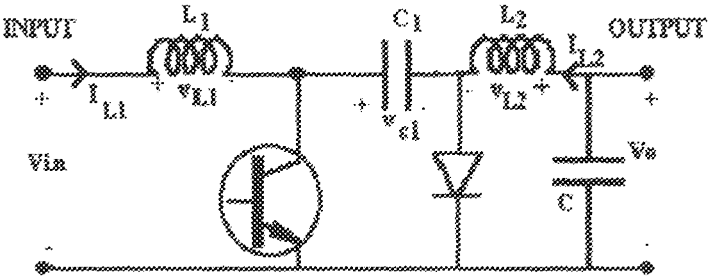


Figure 2.27: CUK Converter

If we assume that the current through the indicators is essentially ripple free we can examine the charge balance for the capacitor CI. For the transistor ON the circuit becomes

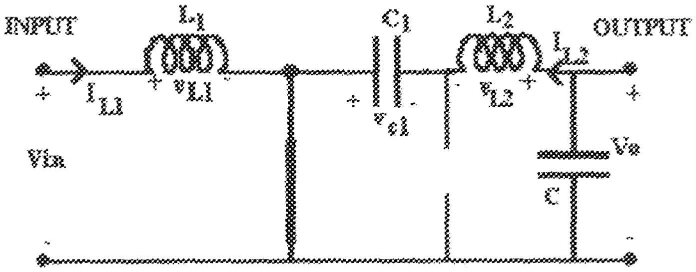


Figure 2.28: CUK "ON-STATE"

and the current CI is I_{L1}. When the transistor is OFF, the diode conductors and the current inn CI becomes I_{l2}.

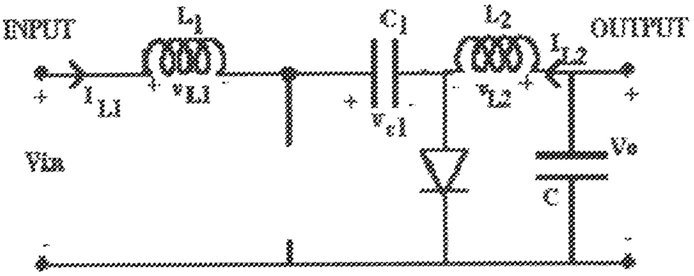


Figure 2.29: CUK "OFF-STATE"

Since the steady state assumes no net capacitor voltage rise, the net current is zero

$$I_{L1}t_{on} + (-I_{L2})t_{OFF} = 0 \tag{2.48}$$

which implies

$$\frac{I_{L2}}{I_{L1}} = \frac{(1-D)}{D} \tag{2.49}$$

The currents match the input and output currents, the using the power conservation rule.

$$\frac{V_o}{V_{in}} = \frac{D}{(1-D)} \tag{2.50}$$

Thus the voltage ratio is the same as the buck-boost converter. The advantage of the CUK converter is that the input and output inductors create a smoothly current at both sides of the converter while the buck, boost and buck-boost have at one side with pulsed current.

2.16.2 Isolating Converters

All of the converters we have looked at so far have virtually no electrical isolation between the input and output circuits; in fact they share a common connection. This is fine for many applications, but it can make these converters quite unsuitable for other applications where the output needs to be completely isolated from the input. Here's where a different type of inverter tends to be used-the isolating type (Colonel, 2000). There are two main types of isolating inverter in common use: the 'flyback' type and forward' type. Like most of the non-isolating converters, both types depend for their operation on energy stored in the magnetic field of an inductor-or in this case, a transformer.

(a) Flyback Converter

The flyback converter can be developed as an extension of the Buck-Boost converter. Figure 2.32 shows the basic converter; Figure 2.33 replaces the inductor by a t works by storing energy in the inductor by a transformer. The buck-boost converter works by storing energy in the inductor during then ON phase and releasing it to the output during OFF phase. With the transformer the energy storage is in magnetization of the transformer core. To increase the stored energy a gapped core is often used.

In Figure 2.34 the isolated output is clarified by removal of the common reference of the input and output circuits (Colonel, 2000).

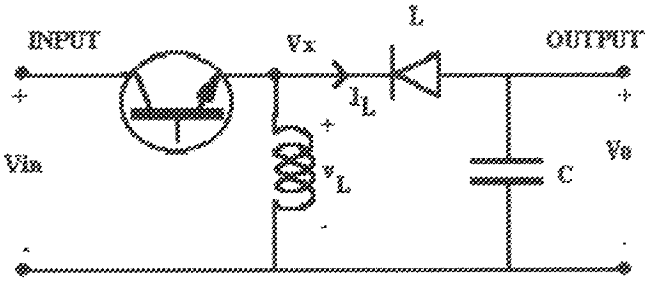


Figure 2.32: Buck-Boost Converter

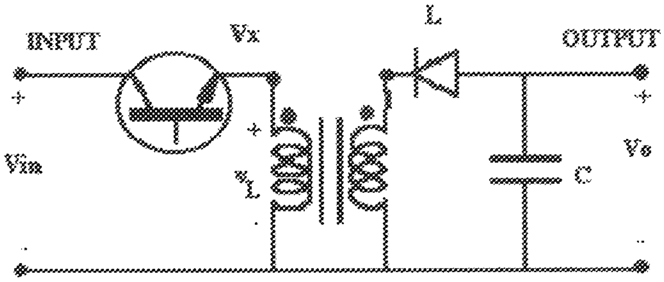


Figure 2.33: Replacing Inductor by Transformer

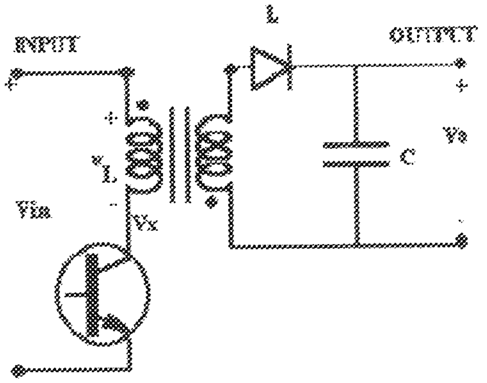


Figure 2.34: Flyback Converter Re-configured

(b) Forward Converter

The concept behind the forward converter is that of the ideal transformer converting the input AC voltage to an isolated secondary output voltage. For the circuit in Figure 2.35, when the transistor is ON, V_{in} appears across the primary and then generates

$$V_X = \frac{N_1}{N_2} V_{in} \tag{2.51}$$

The diode D1 on the secondary ensures that only positive voltages are applied to the output circuit while D2 provides a circulating path for inductor current if the transformer voltage is zero or negative.

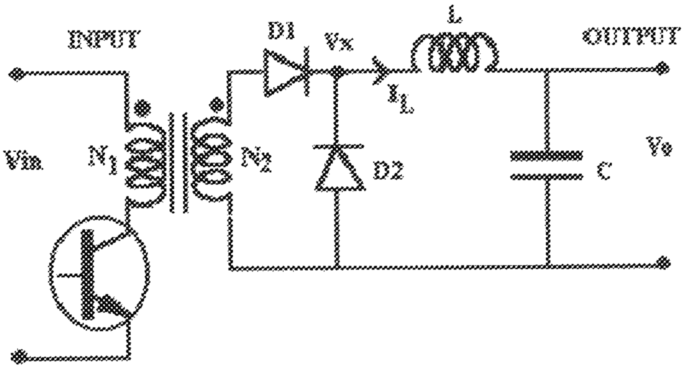


Figure 2.35: Forward Converter

The problem with the operation of the circuit in Figure 2.35 is that only positive voltage is applied across the core, thus flux can only increase with the application of the supply. The flux will increase until the core saturates when the magnetizing current increases significantly and circuit failure occurs. The transformer can only sustain operation when there is no significant DC component to the input voltage. While the switch is ON there is positive voltage across the core and the flux increases. When the switch turns OFF we need to apply negative voltage to reset the core flux. The circuit in Figure 2.36 shows a tertiary winding with a diode connection to permit reverse current. Note that the "dot" convention for the tertiary winding is opposite those of the other windings. When the switch turns OFF current was flowing in a "dot" terminal. The core inductance current in a dotted terminal, thus

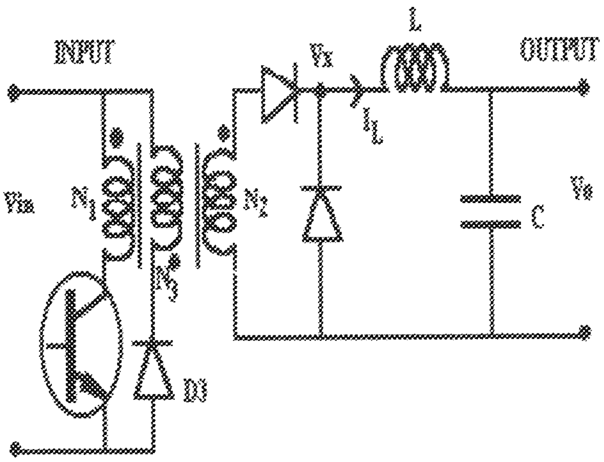


Figure 2.36: Forward Converter withTertiary Winding

CHAPTER THREE

3.0 MATERIALS AND METHOD

In the course of every design it is expected that the mode of operation of the system be given adequate consideration. This is because every system performance depends strongly on the design procedures. In this chapter, the design is explained in stages in order to simplify the operation of the device. These stages are shown in the block diagram in Figure 3.1. Each of the component blocks will be discussed.

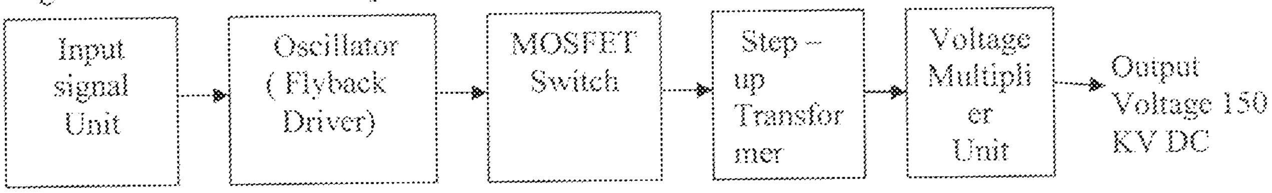


Figure 3.1: Block Diagram of High Voltage Multiplier

3.1 Input Signal Unit

This unit includes the filter, rectification and regulation sections. This unit may be seen as the most sensitive in this project work because it is responsible for the conversion of 230V AC to 12V DC output. The 12V DC used in powering the oscillator gets the supply from this input signal.

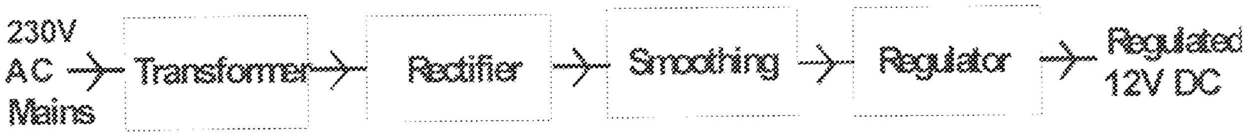
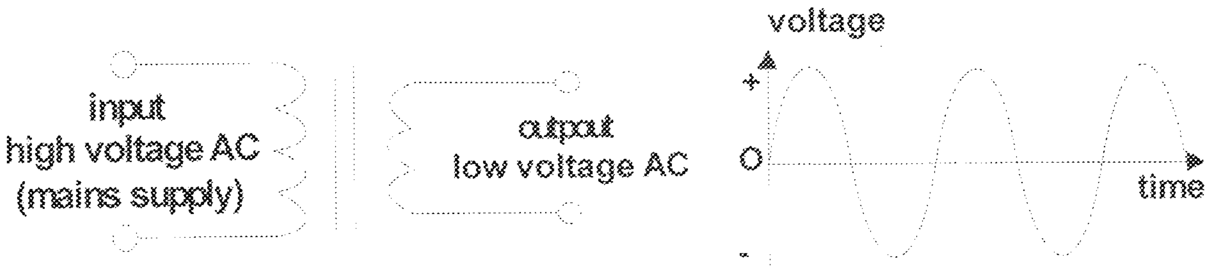


Figure 3.2: Block diagram of a Regulated Power Supply

Each of the blocks is described in more detail below:

- **Transformer**

It steps down high voltage AC mains to low voltage AC. In this project work, the input voltage to the transformer is 230V AC and the output is 12V AC. 230/12V linear transformer with current rating of 4A was chosen.



Transformer

Output: low voltageAC

Figure 3.3: The Transformer Circuit

- **Rectifier**

  Converts AC to DC, but the DC output is varying. Full wave rectifier is used due to its ability to deliver high power and current. The 12V AC from output of the transformer is fed into this circuit.

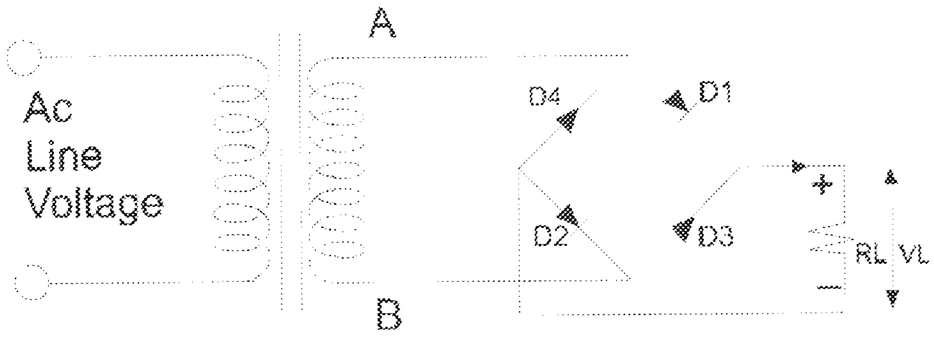


Figure 3.4: Full-Wave Rectifier Circuit

- **Smoothing**

Smoothing does the work of smoothing the DC from varying greatly to a small ripple. Smoothing is performed by a large value electrolytic capacitor connected across the DC supply to act as a reservoir, supplying current to the output when the varying DC voltage from the rectifier is falling. The diagram shows the unsmoothed varying DC (dotted line) and the smoothed DC (solid line). The capacitor charges quickly near the peak of the varying DC, and then discharges as it supplies current to the output.

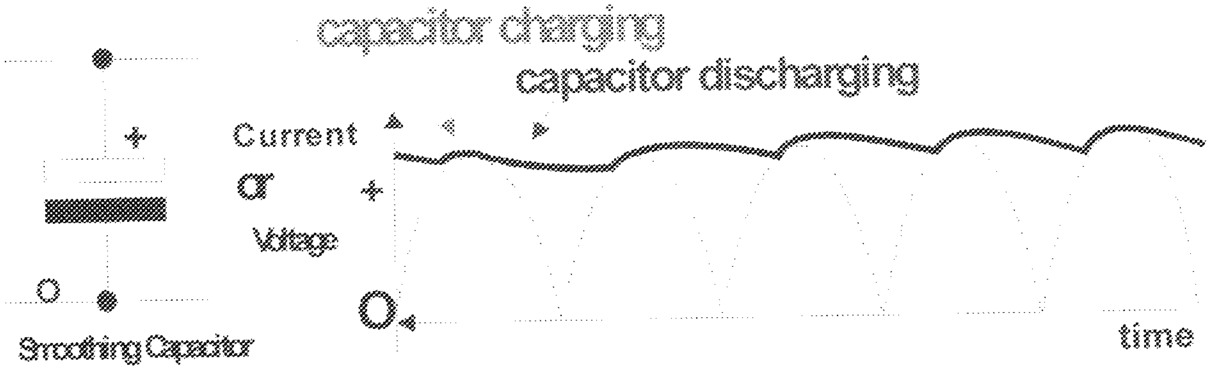


Figure 3.5: Smoothing Capacitor and Output Waveform

A ripple of 10% is allowed in this design, so capacitance value is calculated as

$$C = \frac{5 \times I_o}{V_S \times f} = \frac{5 \times 4}{16.8 \times 50} = 0.024F \qquad (3.1)$$

C = 24000μF, 35V is used.

- **Regulator**

Regulator eliminates ripple by setting DC output to a fixed voltage. Voltage regulator ICs are available with fixed (typically 5, 12 and 15V) or variable output voltages. They are also rated by the maximum current they can pass. Negative voltage regulators are available, mainly for use in dual supplies. Most regulators include some automatic protection from excessive current ('overload protection') and overheating ('thermal protection').

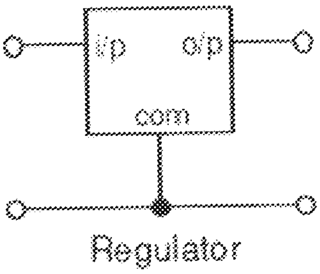


Figure 3.6: Regulator

LM 8712 regulator is used due to its availability. The importance of this component is to ensure the maximum voltage to power oscillator circuit does not go beyond 12V DC.

3.2 Oscillator Circuit/Flyback Driver

Oscillator circuit is required to switch the power MOSFET ON and OFF to drive the high voltage ferrite core transformer to generate thousands of voltage at the output. As shown in the circuit below, input power to the circuit is 12-16 volts, the current draw can reach a few amps and that is why linear transformer of current rating of 4A is used for this design. As mentioned above this driver drives the ferrite core transformer in flyback mode. It means the MOSFET is turned on by the timer, and current starts to flow through the primary winding. After some time the timer will turn off the MOSFET again and the current will be forced to stop. However, this is not possible since the primary has significant inductance. The current then causes the voltage at the MOSFET drain to increase in an attempt at allowing current to flow. The voltage will rise up to the breakdown voltage of the MOSFET, where it stops (since the MOSFET is avalanche rated this does no harm, and only produces heat in the MOSFET). The voltage at the MOSFET drain will potentially be equal to the breakdown voltage of the MOSFET, meaning the primary voltage will be hundred of volts now. Due to the large turns ratio of the flyback the few hundred volts at the primary become several thousand volts on the secondary.

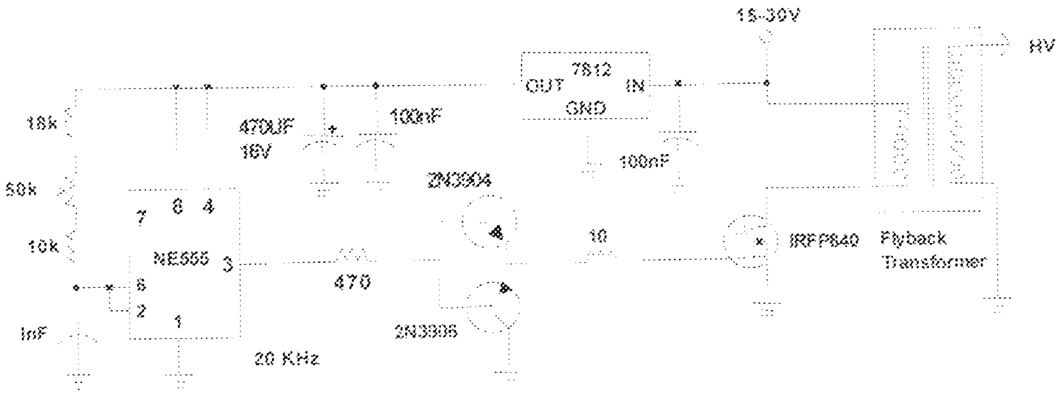


Figure 3.7: Flyback Driver with 555 Timer

The 555 was wired as an astable multivibrator with frequency of 20 KHz. The square wave generated from pin 3 is then fed into a totem pole made up of a 2N3904 and a 2N3906. The totem pole ensures the gate being charged and discharged very fast (approx 50nS). The IRF 840 is a cheap, reliable and powerful power MOSFET; it has current capability of 8A continuous and 32A pulse, 800V drain source voltage, protecting internal zener diode. There is a snubbing network to ensure that voltage spikes are kept low (unless the insulation of the transformer start to leak) protecting both transistors and 555 timer. Following that, the output from the totem pole is used to drive MOSFET, IRF 840 which connected to both side of primary winding of the standard step-up transformer. The MOSFET switches will turn on and turn off. Consequently, it produces the square wave on the primary winding. As a result, the step up transformer produces 10,000V AC at secondary winding.

3.2.1 Design of Astable Multivibrator

The schematic diagram of Astable multivibrator is as shown below. The switching frequency is 20 KHz.

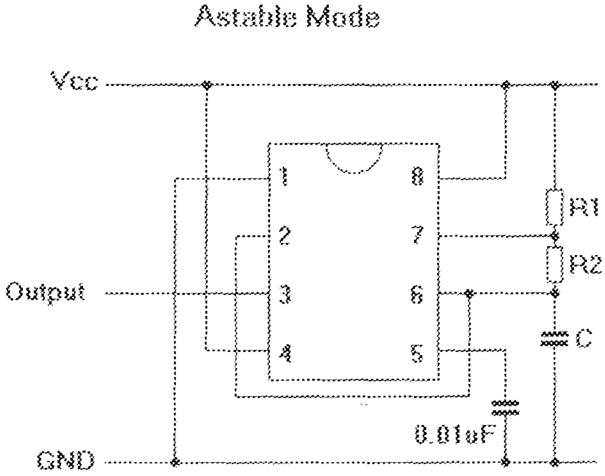


Figure 3.8: Astable Multivibrator Circuit

$$\text{Frequency} = f = \frac{1.44}{(R_1 + 2R_2)C} \qquad (3.2)$$

$$f = \frac{1.44}{(R_1 + 2R_2)C},$$

$$C = \frac{1.44}{(R_1 + 2R_2)f}$$

$f = 20KHz$, let $R_1 = 100\Omega$, $R_2 = 355\Omega$, then

$C = 10nF$

So, to realise switching frequency of 20 KHz:

$R_1 = 100\Omega$

$R_2 = 355\Omega$

$C = 10nF$

The positive output is high for T(h) seconds based on this formular:

Time High (secs) $= 0.693 \times (R_1 + R_2)C = 0.003ms$ (3.3)

The negative output is low for T(l) seconds based on this formular:

Time Low (secs) $= 0.693 \times (R_2)C = 0.003ms$

The duty cycle percentage is the relationship of the high time to the overall cycle time and is derived by the formula:

$$DCP = \frac{T(h)}{(T(h) + T(l))} \times 100 = 50 \qquad (3.4)$$

3.3 MOSFET Switch

Power MOSFETs are voltage controlled. Their gates appear as capacitance (of the order of pico farad/nano farad) and must be charged for on state and discharged for off state. This means the current needs only flow during the short time it takes to charge/discharge the small gate capacitor. This leads to very short switching times, making MOSFETs highly switchable for high frequency applications. Due to their construction, a MOSFET on resistance increases rapidly with the device's blocking rating. MOSFETs also have a positive temperature coefficient.

High switching MOSFET transistor with high voltage capability is used in this project due to high frequency output of the oscillator. Therefore IRF 840 was used. Other fast switching devices can be used but MOSFET proves to be reliable for this operation.

Features of IRF 840

- 8A, 500V
- rDS(ON)= 0.850
- Single Pulse Avalanche Energy Rated
- Nanosecond Switching Speeds
- Linear Transfer Characteristics
- High Input Impedance

3.4 High Voltage Ferrite Core Transformer

The purpose of a power transformer in Switch-Mode Power Supplies is to transfer power efficiently and instantaneously from an external electrical source to an external load. In doing so, the transformer also provides important additional capabilities:

- The primary to secondary turns ratio can be established to efficiently accommodate widely different input/output voltage levels.
- Multiple secondary's outputs with different numbers of turns can be used to achieve multiple outputs at different voltage levels.
- Separate primary and secondary windings facilitate high voltage input/output isolation, especially important for safety in off-line applications.

As explained in chapter two, ferrite core transformer is used in this design to step up input voltage to multiplier circuit. If 230V AC is to be fed into input of voltage multiplier, the design of multiplier circuit will require 653 stages to achieve 150KV DC output. The input to this high frequency switching transformer is 12V DC, inverted by flyback driver and produce 10KV AC at the output.

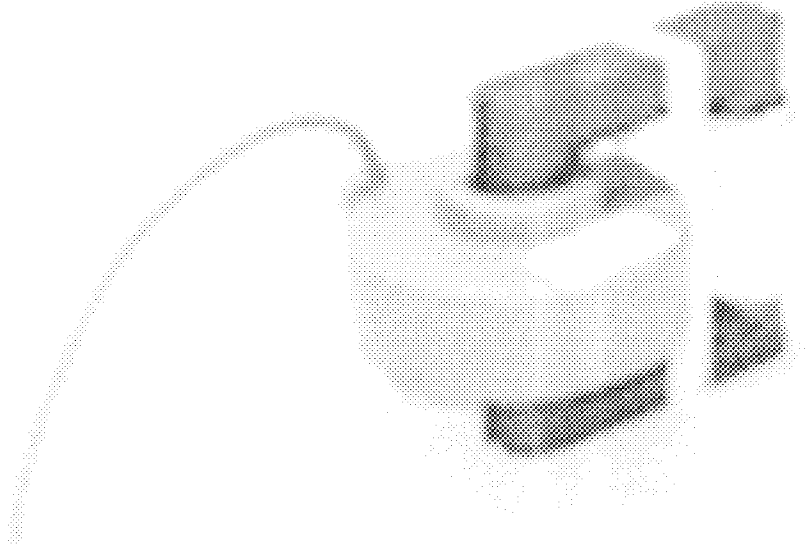


Plate II: High Voltage Ferrite Core Transformer

3.4.1 Design of High Voltage, High Frequency Ferrite Core Transformer

$V_p = 12$	V - primary square wave
$V_o = 10000$	V - secondary voltage
$P_o = 25VA$	VA – output power
$f = 20000$	Hz – operating frequency
$\eta = 0.98$	efficiency – specified
$\Delta T = 30$	degree census – allowable temperature
$B_m = 0.2$	Tesla – maximum core flux density

1. Calculation of power handling capacity, P_t

$P_{in} = P_o$ VA – approximate power input

$P_t = 2 \times P_{in}$ VA – apparent power handling capacity (3.5)

$P_t = 2 \times 25 = 50VA$

2. Calculation of area product, A_p

$K = 4$ (Coefficient indicating square wave input)

$K_u = 0.29$ (window utilization factor)

$Kj = 323$ (current density coefficient)

$$A_p = \left[\frac{\left(P_t \times 10^4\right)}{\left(K \times B_m \times f \times K_u \times K_j\right)}\right]^{-8} \tag{3.6}$$

$$A_p = 0.28$$

3. Evaluation of core geometry

Volume of transformer core

$K_v = 17.9$ (volume coefficient for UUR core (EC35))

$$\text{Volume} = K_v \times A_p^{0.75}, \tag{3.7}$$

$$\text{Volume} = 6.89 \quad \text{cm}^3$$

Transformer core surface area, A_t

$K_s = 39.2$ (surface area coefficient for UUR core)

$$A_t = K_s \times A_p^{0.5}, \tag{3.8}$$

$$A_t = 20.74 \quad \text{cm}^2$$

4. Transformer current density, J

$K_j = 468$ (current density for U core at temperature rise of 50 degree C

$$J = k_j \times A_p^{-0.125}, \tag{3.9}$$

$$J = 548.7\ \text{A/cm}^2$$

5. Total estimated transformer losses, P_e

$$P_e = \left(\frac{P_o}{\eta}\right) - P_o, \tag{3.10}$$

$P_\varepsilon = 0.51 \text{ W}$

6. Maximum efficiency when P_e (core loss) = p_{cu} (copper loss)

Best case efficiency when $p_\varepsilon = p_{cu}$

$$P_{CU} = \frac{P\varepsilon}{2}, P_{CU} = 0.255 \text{ W}, \text{since } P_\varepsilon = P_{CU}, P_e = 0.255 \quad \text{W}$$

7. Calculation of core loss

For Fernk type 100/57/44 (mmg-neosid) at 0.25T and frequency of 20kHz

$P_{Fe25} = 0.2 \text{ W/cm}^2$ at 25 degree C, $P_{Fe100} = 0.3 \text{ W/cm}^2$ at 100 degree c

So at $T = ambient + 50 \deg ree.C$

$$P_{Fe} = P_{Fe25} + \left[\left(\frac{75-25}{100-25}\right)\right] \times \left(P_{Fe100} - P_{Fe25}\right), P_{Fe} = 0.26 \quad \text{W/cm}^3$$

The effective volume of core must be greater than $\frac{P_\varepsilon}{P_{Fe}} = 4.25 \text{ cm}^3$

The worst case efficiency is for $P_e >> P_{cu}$, so we need an effective volume of Core: $\frac{P_\varepsilon}{P_{Fe}} = 8.5 \text{ cm}^3$

8. Calculation of primary turns, N_p

Cross sectional area A_c = 13cm (from core data book due to availability)

$$N_p = \frac{\left(V_p \times 10^4\right)}{4 \times B_m \times A_C \times f} \tag{3.11}$$

$N_p = 1$ turn

9. Primary current, I_p

$$I_o = \frac{P_o}{V_o}, \tag{3.12}$$

$$I_o = \frac{25}{10000} = 0.0025 \text{ A}$$

$$I_p = \left(\frac{V_o \times I_o}{V_p} \right),$$

$$I_p = \left(\frac{10000 \times 0.0025}{12} \right) = 2.08 \text{ A}$$

10. Calculation for base wire size for primary, A_w

$$A_w = \frac{I_p}{J}, \tag{3.13}$$

$$A_w = 3.8 \times 10^{-3} \text{ cm}^2$$

11. Wire Gauge

This is approximately AWG 21.

12. Calculation of primary resistance

Mean length per turn $MLT_p = 3.80$ cm

Resistivity of copper, $\rho = 1.71881 \times 10^{-6}$ Ω.cm

Resistance per cm, $R_p = \dfrac{\rho}{0.21} = 8.1848 \times 10^{-6}$ Ω/cm

Temperature coefficient of resistance at resistance at 75 deg.C, $r = 1.24$

$$R_p = MLT_p \times N_p \times r \times R_p, R_p = 3.80 \times 1 \times 1.24 \times 8.1848 \times 10^{-6} = 38.6 \times 10^{-6}$$

$$R_p \times 1000 = 38.6 \times 10^{-3}\,\Omega$$

13. Primary copper loss

$$I_p^2 \times R_p = 0.00802 \text{ W} \tag{3.14}$$

14. Calculation of secondary turns

$$n_s = \frac{\left(n_p \times V_o\right)}{V_p} = \frac{1 \times 10000}{12} = 833 \tag{3.15}$$

To allow use of a nominal 80% duty cycle on the primary

$$N_s = \frac{n_s}{0.8} = 1042 \text{ , 1,045 was chosen}$$

15. Calculate base wire size for secondary

$$A_w = \frac{I_o}{J} = \frac{0.0025}{548.7} = 4.6 \times 10^{-6} \text{ cm}^2 \tag{3.16}$$

AWG45 was used

16. Calculation of secondary resistance

Mean length per turn: $MLT = 3.80\,\text{cm}$

$MLT = 3.80\Omega/\text{cm}$ from AWG table

$R_s = MLT_s \times n_s$

$R_s = 418.9\Omega$

3.5 Multiplier Circuit

A voltage multiplier is an electrical circuit that converts AC electrical power from a lower voltage to a higher DC voltage by means of capacitors and diodes combined into a network. Voltage multipliers can be used to generate bias voltages of a few volts or tens of volts or millions of volts for purposes such as high-energy physics experiments and lightning safety testing. As stated early, the output of high voltage, high switching transformer serves as an input to the voltage multiplier. The multiplier circuit comprises of fifteen (15) stages with input of voltage of 10KV AC (square wave signal)

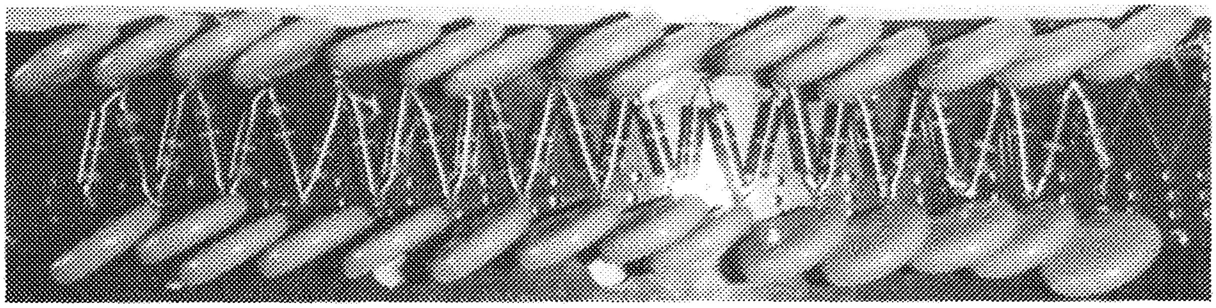


Plate III: Practical High Voltage Multiplier

3.5.1 Design Calculations of Multiplier Circuit

The multiplier specifications are:

Input voltage = 10V

Output voltage = 150KV

Input current = 5mA

Output power = 150W

Output current (Load Current) = 1mA

Operating frequency = 20 KHz

Output power, $P = IV$

Where I = output current without load

V = output voltage

$P = 1 \times 10^{-3} \times 150000$

$P = 150\,\text{W}$

The number of stages is calculated as:

$V_o = (n)(V_m)$,

Where n = number of capacitors, or diodes,

Assuming equal value capacitors, ideal diodes and symmetrical signal input.

$$n = \frac{V_o}{V_m} \tag{3.17}$$

$$n = \frac{150000}{1000} = 15 \text{ Stages}$$

A stage comprises of two diodes and two capacitors i.e. there are thirty (30) diodes and capacitors each.

The output of voltage multiplier is given as:

$$E_{out} = 2n \times V_m - \left(\frac{I_{Load}}{6fC}\right) \times \left(4n^3 + 3n^2 - n\right) \tag{3.18}$$

$$\frac{(150000 - 2(15)(10000))}{(4 \times 15^3 + 3 \times 15^2 - 15)} = \frac{-I_{Load}}{6fC}$$

$$\frac{-150,000}{14,160} = -\frac{I_{Load}}{6fC}$$

$$-10.59 = \frac{-I_{Load}}{6fC}$$

$$C = \frac{I_{Load}}{6f} = \frac{0.001}{6 \times 20,000} = 8.3 \times 10^{-9}$$

$$C = 10nF$$

Though 1nF, 15KV is used in this project due to availability

Total capacitance, $C_{total} = 3 \times 10^{-8}\, pF$

Diode that can switch within the frequency of 20 KHz is chosen, therefore,

$$f = \frac{1}{T}, T = \frac{1}{f} = \frac{1}{20,000} = 5 \times 10^{-5}\, s. \tag{3.19}$$

So, parameter of the diode chosen for this project work is: 12KV, 150ns.

3.5.2 Regulation Voltage

Regulation voltage can be expressed as:

$$V_{REG} = \frac{I\left[\left(N^3\right) + \left(\frac{9N^2}{4}\right) + \left(\frac{N}{2}\right)\right]}{12fC} \tag{3.20}$$

Where: N = number of stages, (2 capacitors and 2 diodes = 1 stage)

f = AC input frequency (Hz)

C = capacitance per stage (F)

I = DC output current (A)

$$V_{REG} = 1\times10^{-3}\left[\frac{\left(15^3\right)+\left(\frac{9\times15^2}{4}\right)+\left(\frac{15}{2}\right)}{12\times20000\times1000\times10^{-12}}\right]$$

$$V_{REG} = 16.203V$$

3.5.3 Ripple Voltage

$$V_{RIP} = I\left(\frac{N^2+\frac{N}{2}}{8fC}\right) \tag{3.21}$$

$$V_{RIP} = 1\times10^{-3}\left(\frac{15^2+\frac{15}{2}}{8\times20000\times1000\times10^{-12}}\right)$$

$$V_{RIP} = 1{,}453V$$

The total voltage loss due to ripples and voltage regulation is **17,656V**. It means the output of the voltage multiplier will fluctuate between **150KV** and **132,344V.**

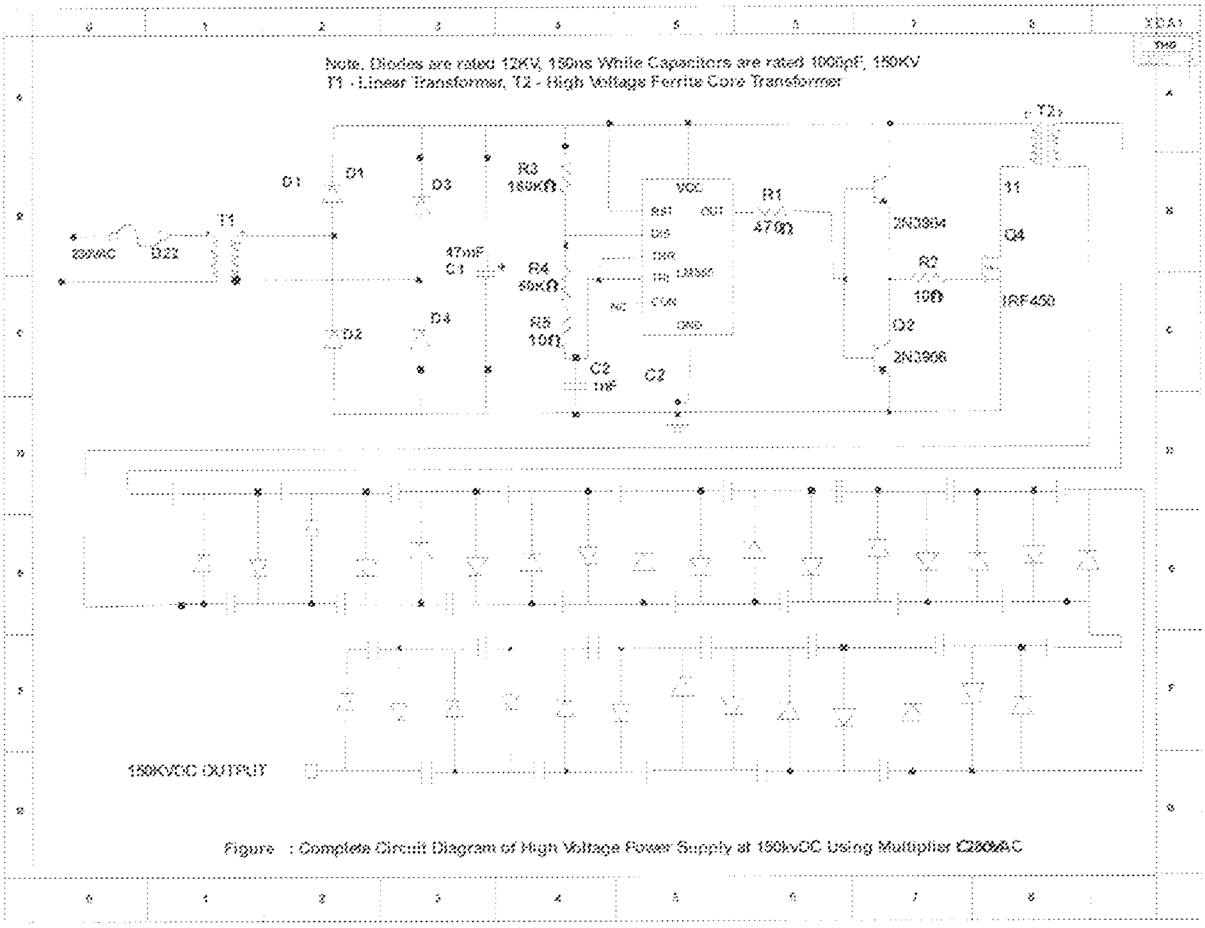


Figure 3.9: Complete Circuit Diagram of High Voltage DC Power Supply at 150KV DC Using Voltage Multiplier Circuit Output from 230V AC Main Supply

3.6 Establishing Limitations of Voltage Multiplier Technique and Corrective Measures

Limitations of voltage multiplier method are established experimentally and corrective measures are proffered. To establish the effects of input signal waveform, frequency of the input signal and nature of load; each constraint is verified by designing ten (10) stages low voltage high and low frequency multiplier circuit. The output voltages were measured under different load conditions, input signal waveforms and input frequencies.

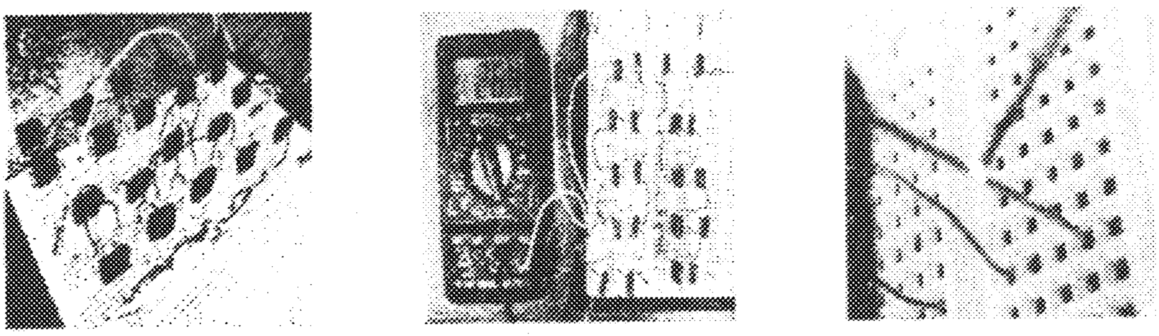


Plate IV: Multiplier Output Voltage

- To establish the effect of input signal wave form, ten stages multiplier circuit is designed with AC input voltage of 11V. Different signal waveforms (sine wave, square wave and triangle wave) were fed into the multiplier circuit and output voltage from each stage was measured.

- Performance of multiplier circuits under different frequencies was verified by varying the frequencies of the input voltage under 30, 50, 70, 100, 120, 150 Hz and corresponding voltages were measured.

- Multiplier circuit with 1 through 10 stages were used with loads of 1M, 100k, 10k and 1k resistors to determine how much voltage drops under load. All data values were taken at very frequency – about 5MHz – to avoid non-ideal behaviour caused by lower frequency.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

The result of design of high voltage power supply at 150KV using voltage multiplier circuit from 230V AC and experimental analysis of limitations of voltage multiplier circuit with tables and figures carried out in chapter three are stated in this chapter. The explanations of each of the table and figure drawn in this chapter are provided in later part of this chapter.

4.1 Result of Design and Construction of High Voltage Power Supply

The input voltage to Cockcroft-Walton Voltage multiplier circuit was set to 10KV AC and its output voltage, obtained from fifteen stages Cockcroft-Walton Voltage multiplier circuit as shown in Figure 3.9 is 150KV.

From hardware experiment in laboratory, the following data have been obtained:-

- Driver stage frequency - **20 KHz**
- Open circuit output voltage – **132,344V**
- Output ripple voltage – **1.453KV**
- Output ripple factor – **0.97%**
- Output voltage on full load – **120KV**
- Voltage drop in multiplier circuit – **17.656KV**

The calculated data are as follows:-

- Output voltage – **150KV DC**
- Minimum stage output power – **15 W**
- CW output power - **15W**

The values of main hardware components are given below:-

- High voltage ferrite core transformer - **12 V/10.0KV, 10mA**
- Capacitors used - **15KV, 1000pF Mica Capacitors**
- Diodes used – **12KV, 150ns, 10mA (Fast Recovery Diodes)**

4.2 Experimental Results of Limitations of Voltage Multiplier

The results of the verification of limitations of voltage multiplier under different input signal waves, frequencies and load conditions are given in figures and tables below.

A. Results of Effect of Input Wave Form Signal on Voltage Multiplier Output

Table 4.1 shows the effect of sine wave input voltage on the output of voltage multiplier.

Table 4.1: Result of Stage Voltage with Input Sine Wave Form Signal Showing the Effect of Signal Wave Form on the Output of Voltage Multiplier.

Stage	Output Voltage
1	19
2	34
3	42
4	31
5	28
10	27

Table 4.2 shows the effect of square wave input voltage on the output of voltage multiplier.

Table 4.2: Result of Stage Voltage with Input Square Wave Form Signal Showing the Effect of Signal Wave Form on the Output of Voltage Multiplier.

Stage	Output Voltage
1	19
2	38
3	52
4	74
5	92
10	168

Table 4.3 shows the effect of triangle wave input voltage on the output of voltage multiplier.

Table 4.3: Result of Stage Voltage with Input Triangle Wave Form Signal Showing the Effect of Signal Wave Form on the Output of Voltage Multiplier.

Stage	Output Voltage
1	19
2	34
3	42
4	31
5	28
10	27

B. Results of Effect of Frequency of Input Signal on Voltage Multiplier Output

Table 4.4 shows the effect of frequency of input voltage on output of voltage multiplier under stage one of ten stage voltage multiplier.

Table 4.4: Result of Effect of Frequency of Input Voltage (Stage One) Showing the Variation in Output Voltage of the Voltage Multiplier Due to Different Input Signal Frequency.

Frequency (Hz)	Output Voltage (V)
30	20
50	20
70	20
100	20
120	20
150	20

Table 4.5 shows the effect of frequency of input voltage on output of voltage multiplier under stage two of ten stage voltage multiplier.

Table 4.5: Result of Effect of Frequency of Input Voltage (Stage Two) Showing the Variation in Output Voltage of the Voltage Multiplier Due to different Input Signal Frequency.

Frequency (Hz)	**Output Voltage (V)**
30	35
50	40
70	40
100	45
120	46
150	50

Table 4.6 shows the effect of frequency of input voltage on output of voltage multiplier under stage three of ten stage voltage multiplier.

Table 4.6: Result of Effect of Frequency of Input Voltage (Stage three) Showing the Variation in Output Voltage of the Voltage Multiplier Due to different Input Signal Frequency.

Frequency (Hz)	**Output Voltage (V)**
30	0
50	0
70	75
100	80
120	80
150	90

Table 4.7 shows the effect of frequency of input voltage on output of voltage multiplier under stage four of ten stage voltage multiplier.

Table 4.7: Result of Effect of Frequency of Input Voltage (Stage Four) Showing the Variation in Output Voltage of the Voltage Multiplier Due to Different Input Signal Frequency.

Frequency (Hz)	Output Voltage (V)
30	0
50	85
70	72
100	97
120	100
150	103

C. Results of Effect of Load Condition on Output of Voltage Multiplier.

Table 4.8 shows the effect of load condition on output of voltage multiplier under 1M Ω load verified with ten stage voltage multiplier.

Table 4.8: Result of Effect of Load Condition on Output Voltage of Voltage Multiplier (1M Load).

Stage	Voltage (V)
1	21
2	42
3	63
4	84
5	105
6	130
7	150
8	170
9	287
10	207

Figure 4.1 shows the graph of output voltage versus stage under 1MΩ load condition based on the results of Table 4.8.

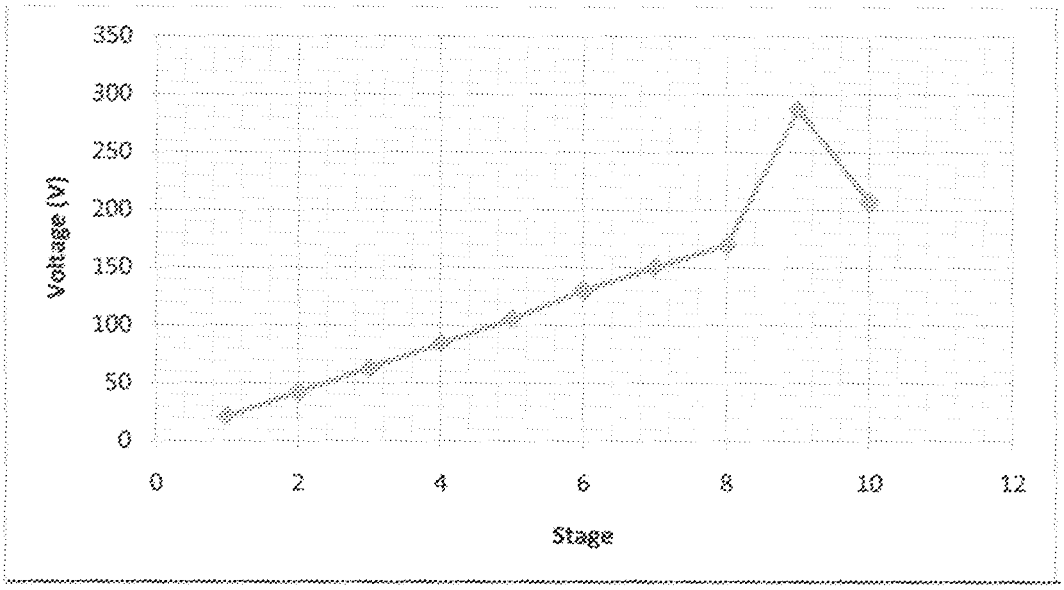


Figure 4.1: Graph of Output Voltage / Stage Showing the Effect of 1M Load on the Output of Voltage Multiplier.

Table 4.9 shows the effect of load condition on output of voltage multiplier under 100K Ω load verified with ten stage voltage multiplier.

Table 4.9: Result of Effect of Load Condition on Output Voltage of Voltage Multiplier (100K Load).

Stage	Voltage (V)
1	21
2	41
3	60
4	72
5	54
6	110
7	123
8	136
9	147
10	156

Figure 4.2 shows the graph of output voltage versus stage under 100KΩ load condition based on the results of Table 4.9.

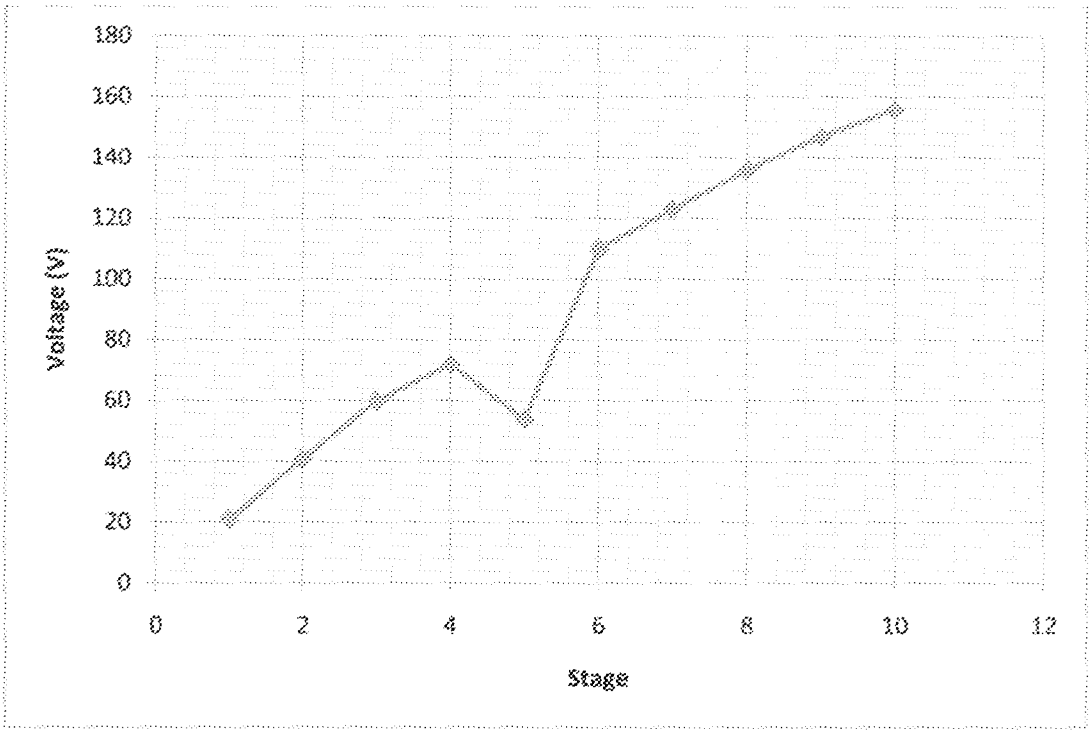


Figure 4.2: Graph of Output Voltage / Stage Showing the Effect of 100K Load on the Output of Voltage Multiplier.

Table 4.10 shows the effect of load condition on output of voltage multiplier under 10K Ω load verified with ten stage voltage multiplier.

Table 4.10: Result of Effect of Load Condition on Output Voltage of Voltage Multiplier (10K Load).

Stage	Voltage (V)
1	19
2	35
3	45
4	52
5	55
6	56
7	55
8	52
9	51
10	49

Figure 4.3 shows the graph of output voltage versus stage under 10KΩ load condition based on the results of Table 4.10.

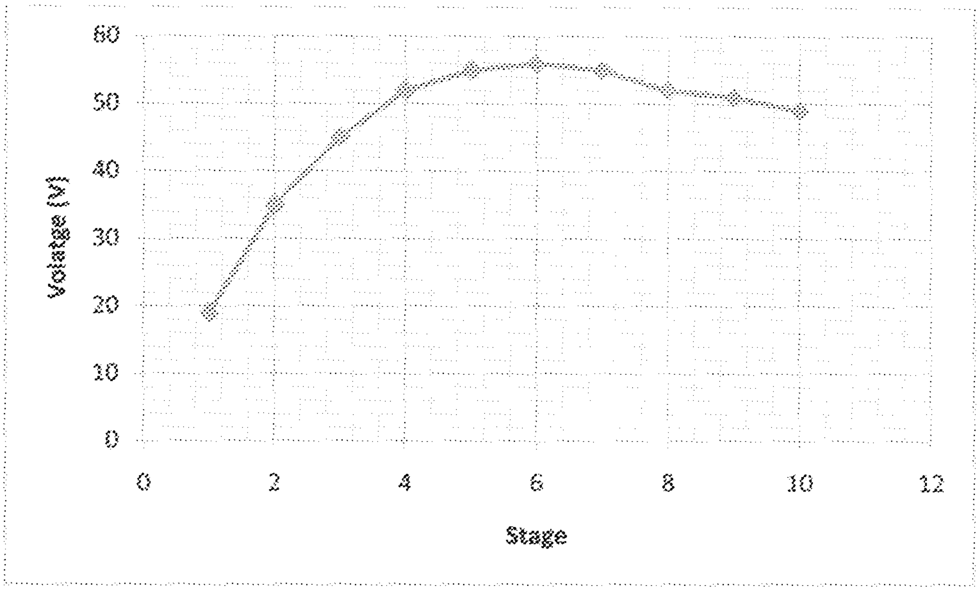


Figure 4.3: Graph of Output Voltage / Stage Showing the Effect of 10K Load on the Output of Voltage Multiplier.

Table 4.11 shows the effect of load condition on output of voltage multiplier under 1K Ω load verified with ten stage voltage multiplier.

Table 4.11: Result of Effect of Load Condition on Output Voltage of Voltage Multiplier (1K Load).

Stage	**Voltage (V)**
1	14
2	17
3	15
4	13
5	10.9
6	10.3
7	10
8	10
9	9
10	9

Figure 4.4 shows the graph of output voltage versus stage under 1KΩ load condition based on the results of Table 4.11.

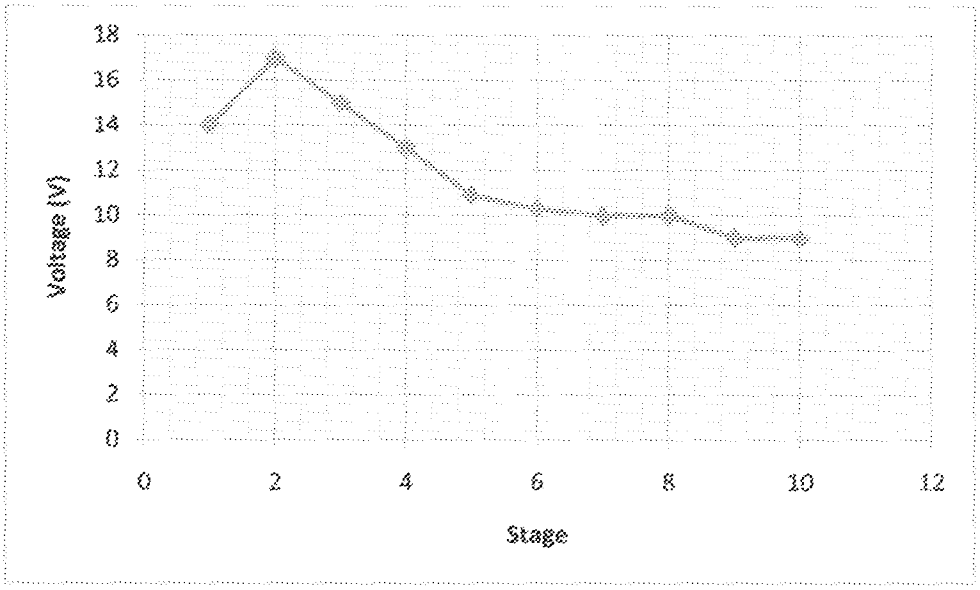


Figure 4.4: Graph of Output Voltage / Stage Showing the Effect of 1K Load on the Output of Voltage Multiplier.

4.3 Discussion of the Results

Voltage multiplier circuit technique had been used to generate extremely high voltage from low voltage source. It has been shown that for high voltage cable insulation test and other applications in need of high DC voltage, high voltage power supply can be designed and constructed by method of high frequency switching converter method to generate high voltage from low source. The output of the multiplier circuit under load condition oscillates due to effects create by ripples voltage, corona and voltage regulation. So, output of the voltage multiplier, generally, as shown in section 4.1, cannot be applied where constant voltage under load is required. Also, input voltage waveform and frequency of the input voltage have great impact on the output voltage of the multiplier circuit as established in Table 4.1 - 4.11. Based on the experimental results in Table 4.1, the output voltage is lowest for triangle wave, and highest for square waves, with sine waves in the middle; for small numbers of stages, these differences were small – particularly between the sine and triangle wave – but could result in high differences in output between the square and sine wave inputs for higher stages. So, voltage multiplier favours square waves over sine waves – and sine waves over triangle - because the AC signal spending more time at the highest voltages allow the capacitor to charge faster.

The disparity in measured voltage of the device and the calculated value is due to the effects of stray capacitance and corona effect. The output current is measured to be 1mA. The output current can affect the voltage stresses on a multiplier's diodes and capacitors. Since regulation is directly proportional to output current, and as input voltage is usually increased to compensate for regulation, the diodes and capacitors near the input side of the multiplier will be subjected to higher voltage stress at higher output currents by. As a result of this, a load above 15W cannot be powered by this device. If higher power capability is required, full wave series multiplier circuit should be adopted for design and construction of high voltage multiplier circuit.

4.4 Construction

This project involves extremely high voltage although with very low current, so extra care was taken during construction. High voltage step up transformer which is part of sensitive and hazardous components of this project is placed in a strategic position and well insulated to avoid current leakage. Special board was created for this project because it involves dangerous voltage which can cause voltage sparks and short circuit the whole system. The use of Vero Board is completely eliminated in this project to avoid short circuiting. The output of voltage multiplier is equally insulated to avoid electric shock due to leakage current. Design of voltage multiplier at a very high voltage requires a lot cautions to avoid short circuiting the entire components due to high voltage discharge from the capacitors. 100 ohm resistors were connected in series with diodes to avoid short circuiting the diodes due to capacitor discharge. All the stages involved in this project are placed on the special board separately and clearly labeled for ease troubleshooting in case of malfunctioning of the system. The output of ferrite core transformer is 10KV, immediately the multiplier circuit was connected, there were arcing and dangerous voltage spikes. To overcome these effects, entire multiplier circuit is immersed inside transformer oil, this eventually solved this problem.

4.5 Testing

High voltage DC meter was used to measure the output voltage of this designed work. The output conforms to design specification. In measuring the output of this project, attention was given to safety due to dangerous voltage involved.

4.6 Packaging

The finished work was housed into a wooden casing considering the fact that this type of device contains dangerous over voltage which can kill or cause injuries. The case used was cut out of a plain wooden sheet and measured 35cmx10cmx3cm. Holes were drilled by the sides of the casing to provide ventilation while a hole is provided at the back for protruding cables. The front panel was drilled with holes at the bottom to accept the switches, with others holes drilled to allow for the mounting of the fuses and AC meter to measure the input and output voltages. The entire multiplier circuit is immersed under transformer oil to reduce voltage arcing and corona effect due to very high voltage involved.

4.7 Safety

Power supplies that can deliver energy in excess of 10 J at more than 50 V are considered potentially hazardous. An appropriate warning sign shall identify electrical hazards in areas or equipment accessible to unqualified personnel. Internal component failure of power supplies can result in excessive voltages across components that may not be appropriately sized. An internal component short in a capacitor bank may result in excessive fault current, extremely high temperatures, over-pressurization of components, fires, and explosions. Overloading or improper cooling of power supplies can cause excessive temperatures and fires. Output circuits and components may remain energized after input power is secured.

Power supplies with output currents less than 5 mA pose virtually no electrical shock hazard. In hazardous locations, however, such equipment may spark and cause an explosion. Voltage surges in excess of normal ratings may result from faults or lightning. Over current protective devices (fuses or circuit breakers) for conventional applications may not be adequate for highly inductive direct-current systems. Stored energy in capacitors/long cable runs may cause additional hazards.

In the course of design of this project, safety measures were put into consideration to avoid any unnecessary injuries from operation of this device. Below is the safety rules adopted in designing this device:

- Wooden casing is used to house this device to avoid current leakages from the internal circuit and insulation break down.
- To avoid unskilled person operating this equipment, caution sign (DANGEROUS VOLTAGE GENERATOR) is boldly written on top of this device.
- High voltage multiplier section is separated from the rest of the circuit and enclosed inside a plastic housing to avoid voltage fluctuation due to corona effect.
- Though very difficult to source for, high voltage DC meter was connected to the output of this device to determine the exact output voltage and to indicate voltage level.
- Variable transformer is supplied with this device to achieve variable and controllable output. This enables this device to generate voltage from 10KV – 150KV.
- In case of electric shock or other hazards, operating **switch** is mounted on the panel of the equipment to isolate the equipment from the main supply.

Above measures were considered during the design and implementation of this device, with a view to ensuring this device does not fail or cause unnecessary hazard to operators. Yet, operator needs to carefully pay attention to under listed guidelines because this device itself is marked 'dangerous'.

- Don't work alone - in the event of an emergency another person's presence may be essential.
- De-energize the equipment at least twice prior to beginning work. Make sure that the controls applied will prevent operation of the equipment and that all hazardous energy, including residual or stored energy, is blocked, discharged, or relieved prior to starting work.
- After you have discharged everything, only touch the circuit with the back of your hand first. This allows you to let go if you need to.
- Never enter alone into an area containing exposed electrical energy sources.
- Use only the test instruments, and insulated tools rated for the voltage and current specified.
- Always keep one hand in your pocket when anywhere around a powered line-connected or high voltage system.
- Wear rubber bottom shoes or sneakers.
- Don't wear any jewelry or other articles that could accidentally contact circuitry and conduct current, or get caught in moving parts.
- Set up your work area away from possible grounds that you may accidentally contact.
- If you need to probe, solder, or otherwise touch circuits with power off, discharge (across) large power supply filter capacitors (at least 2 times). Monitor while discharging and/or verify that there is no residual charge with a suitable voltmeter.
- If you must probe live, put electrical tape over all but the last 1/16" of the test probes to avoid the possibility of an accidental short, which could cause damage to various

components. Clip the reference end if the meter or scopes to the appropriate ground return so that you need to only probe with one hand.

4.8 Reliability

Reliability is defined as probability that a device will perform a required function without failure under stated conditions for a stated period of time. For this device to perform optimally, at a design stage of this device , following reliability measures were considered:

- Use successful topology with proven components was used to design this device.
- Design process was structured, with design reviews for reliability, manufacturability, and testability.
- Transient protection at input. Standard fuse was at the input of the device to protect the device from high input voltage and inrush current.
- Zero-crossing circuitry was used to minimize switching losses.
- Printed circuited board (PCB) & packaging was designed for best thermal transfer, along with optimal layouts for minimizing circuit noise, and best EMC performance.
- PCB heat flow was directed towards chassis mount or heat dissipating surface, with path as short as possible to provide low thermal resistance. Accurate heat sink was attached with MOSFET switch for proper heat dissipation.
- 100Ω was connected to each diode of multiplier circuit in series to prevent the diodes from being damaged by high voltage discharge by high voltage capacitor.
- Diodes and capacitors used for voltage multiplier circuit were a bit higher than the calculated values to ensure the components perform well in air and under oil.

- Capacities of this device are specified to avoid overloading. The output power of this device is 15KW with maximum output current of 1mA.
- Temperature reduction technique was used to design transformers using low loss core material and Litz wire / foil for reduced coil heating.

The above measures were adopted to enhance the reliability of the device coupled with the reliability indices specified by the components manufacturers.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The design and construction of high voltage power supply at 150KV from 230V AC main source using high frequency switching converter method had been carried out. The result obtained was in conformity with expected results. Major constraints of voltage multiplier as a means of generating high voltage were established with few corrective measures suggested.

5.2 Recommendations

After developing the DC power supply at 150KV output and handling of experimental results and overall situation, it is noted that the developed DC power supply based on C-W voltage multiplier circuit, is a unique designed and developed for a special application. Developed power supply, it is unique because voltage multiplier circuits are diode and capacitor circuits and they have the advantages of being simple solid state circuits with fairly low parts and being able to produce output voltages much higher than the input voltage according to project demand. It is less expensive compare with conventional way of generating high voltage, less insulation is required.

The fabricated DC power supply, it is a single pulse voltage multiplier since it has only one rectified wave per cycle. Hence its ripple content is high. In order to reduce the ripple as well as regulation and to improve the efficiency and power, it is recommended to use capacitor with high capacitance value at the beginning of the stage, full wave assemblage and square wave signal at the input of the multiplier. Finally, this project work involves dangerous voltage which must be carried out inside well equipped power laboratory with high voltage equipment. These equipment are not available in most Nigerian Universities, therefore, there is a need for availability of these equipment for precision, accuracy and proper measurement at every stages of this work. If higher voltage beyond this work is desired for future work, these pieces of equipment must be in place to facilitate the construction of this work. Also, this work involves high voltage; it must be a group project for safety, security and cost implication. Finally, this project provides a good line of course from which more complexes and elaborate study could be continued.

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APPENDIX

Appendix A: Bill of Engineering Measurement and Evaluation for Design and Construction of High Voltage DC Power Supply at 150KVDC Using Voltage Multiplier Circuit From 230V AC Main Source.

S/N	DESCRIPTION OF MATERIALS	UNIT	QUANTITY	RATE (N)	AMOUNT (N)
1	230/12V, 4A Linear Transformer	No	1	5,000.00	5,000.00
2	Bridge Rectifier	No	1	200.00	200.00
3	Electrolytic Capacitor (3500µF, 35V)	No	1	120.00	120.00
4	12V Regulator IC	No	1	50.00	50.00
5	Resistors	No	5	20.00	100.00
6	555 Timer IC	No	1	50.00	50.00
7	Transistor(Bipolar)	No	2	20.00	40.00
8	Transistor(Metal Oxide Semi-conductor Field Effect Transistor)	No	1	350.00	350.00
9	High Voltage Ferrite Core Transformer, 12/10KV, 10mA.	No	1	40,000.00	40,000.00
10	High Voltage Capacitor (1000pF, 15KV, Mica)	F	30	450.00	13,500.00
11	High Voltage Diode (12KV, 150ns,)	No	30	500.00	15,000.00
12	Variac Transformer (0-280V, 1.5A)	No	1	15,000.00	15,000.00
13	High Voltage DC Meter	No	1	25,000.00	25,000.00
14	High Voltage Ammeter	No	1	15,000.00	15,000.00

15	Switch	No	1	50.00	50.00
16	Fuse	No	1	50.00	50.00
17	Special Circuit Board	No	3	150.00	450.00
18	Other Materials	No	-	1000.00	1000.00
19	Transportation	Lot	Lot	10,000.00	10,000.00
	TOTAL				**140,9600.00**