UNIVERSITI TEKNOLOGI MALAYSIA

DECLARATION OF THESIS / ~~UNDERGRADUATE~~ PROJECT PAPER AND COPYRIGHT

Author's full name : **NORSHAHFARIZ BIN BISNI**

Date of birth : **30TH AUGUST 1983**

Title : **DESIGN AND CONSTRUCTION OF A SMALL SCALE TESLA COIL (2 kV)**

Academic Session : **20102011/1**

I declare that this thesis is classified as :

☐	**CONFIDENTIAL**	(Contains confidential information under the Official SecretAct 1972)*
☐	**RESTRICTED**	(Contains restricted information as specified by the organization where research was done)*
√	**OPEN ACCESS**	I agree that my thesis to be published as online open access (full text)

I acknowledged that Universiti Teknologi Malaysia reserves the right as follows:

1. The thesis is the property of Universiti Teknologi Malaysia.
2. The Library of Universiti Teknologi Malaysia has the right to make copies for the purpose of research only.
3. The Library has the right to make copies of the thesis for academic exchange.

Certified by :

SIGNATURE

SIGNATURE OF SUPERVISOR

830830 – 01 – 5811
(NEW IC NO. /PASSPORT NO.)

ASSOC. PROF. DR. ZULKURNAIN ABD. MALEK
NAME OF SUPERVISOR

Date : 29/4/2010

Date : 29/4/2010

NOTES : * If the thesis is CONFIDENTAL or RESTRICTED, please attach with the letter from the organization with period and reasons for confidentiality or restriction.

"I hereby declare that I have read this project report and in my opinion this project report is sufficient in terms of scope and quality for the award of the degree of Master of Engineering (Electrical-Power)"

Signature : ....

Name of Supervisor : Assoc. Prof. Dr. Zulkurnain Abdul Malek

Date : 29 April 2010

DESIGN AND CONSTRUCTION OF A SMALL SCALE TESLA COIL (2 *kV*)

NORSHAHFARIZ BIN BISNI

A project report submitted in partial fulfilment of the
requirements for the award of the degree of
Master of Engineering (Electrical-Power)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

APRIL 2010

I declare that this project report entitled " *Design and Construction of a Small Scale Tesla Coil (2 kV)* " is the result of my own research except as cited in the references. The project report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : Norshahfariz Bin Bisni

Date : 29 April 2010

Special dedicated to my beloved wife Suraya Hani Sharon, my son Uwais Iqram, all my beloved family and others who encouraged me throughout my journey of education.

A warm thanks to all.

ACKNOWLEDGEMENT

With God's grace, I have completed my final year master project. I would like to take this opportunity to thank all those who are involved in helping me to complete this project.

I would like to thank to Assoc. Prof. Dr. Zulkurnain Bin Abdul Malek for being the source of inspiration and for the advices and guidance that helped me in completing this project. A special thanks for the willingness to share the expertise throughout this project.

I am also would like to delivered my most grateful to my beloved wife, son, parents and siblings for always providing me with moral and supports.

Last but not least, for my friends who was involved directly or indirectly in this project, which have been extremely supporting me all the time and not to forget for my colleagues, MEP's student for their help, support and collegiality over the years. Thank you all.

ABSTRACT

A Tesla coil is a type of resonant transformer circuit invented by Nikola Tesla around 1891. It is used to produce high voltage, low current and high frequency. The purpose of this project is to design and construct a small scale Tesla coil that produce 2 kV output voltage. The TeslaMap Version 1.11 program was used to design the parameters. By using this program, it will reduce the time to calculate all the parameters of this Tesla coil. There are five basic components of Tesla coil such as the power supply, primary capacitor, primary coil, secondary coil and toroid. In addition, spark gap is used as a switch in Tesla coil. The switch allows the primary capacitor circuit capacitance to charge and discharge. There are five basic fundamental design parameters that need to be determined, which is output characteristic of high voltage transformer, size and dimension of primary coil, secondary coil, toroid and size of primary capacitor. By using the theoretical calculations, the voltage at secondary coil is approximately 2.82 kV. The results show that the spark gap successfully performed the switching function as designed. However, the expected high voltage sparks from the high voltage toroid could not be observed. The corrective action could not be done because of the time constraint. For better performance of the Tesla coil, a protection filter and RF chokes can be added into the circuit for safety. In addition, recommendation for future research is to study how to measure the secondary voltage to attain more accurate voltage at the top terminal of the secondary coil.

ABSTRAK

Tesla coil adalah sejenis litar pengubah bertalun yang dicipta oleh Nikola Tesla sekitar 1891. Ia digunakan untuk menghasilkan voltan tinggi, arus rendah dan frekuensi tinggi. Tujuan projek ini dijalankan adalah untuk merekabentuk dan membina *Tesla coil* berskala kecil yang menghasilkan voltan keluaran sebanyak 2 kV. Program TeslaMap Versi 1.11 telah digunakan untuk merekabentuk parameter. Dengan menggunakan program tersebut, ia dapat mengurangkan masa untuk mengira parameter *Tesla coil* ini. *Tesla coil* mempunyai lima komponen asas iaitu bekalan kuasa, kapasitor utama, belitan utama dan sekunder serta toroid. Selain itu, sela bunga api digunakan sebagai suis untuk *Tesla coil*. Suis ini membolehkan kapasitans pada kapasitor utama untuk cas dan nyahcas. Terdapat lima asas parameter rekabentuk yang perlu ditentukan iaitu ciri-ciri pengubah piawai voltan tinggi, saiz dan dimensi bagi belitan utama dan sekunder, toroid serta saiz kapasitor utama. Dengan menggunakan kiraan secara teori, voltan keluaran yang terhasil dibahagian sekunder adalah anggaran sebanyak 2.82 kV. Keputusan ujikaji menunjukkan sela bunga api telah berfungsi sebagai suis. Walaubagaimanapun, bunga api yang dijangka terhasil pada toroid tidak kelihatan. Tindakan pembetulan tidak dapat dijalankan disebabkan oleh kekangan masa. Bagi hasil *Tesla coil* yang lebih baik, penapis perlindungan dan RF choke boleh ditambah ke dalam litar untuk keselamatan. Selain itu, cadangan untuk penyelidikan akan datang adalah untuk mengkaji bagaimana untuk mengukur voltan sekunder pada beban atas di belitan sekunder bagi memperolehi bacaan yang lebih tepat.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

NST	-	Neon Sign Transformer
MMC	-	Multi Miniature Capacitor
M	-	Mega (10^6)
k	-	Kilo (10^3)
c	-	Centi (10^1)
m	-	Mili (10^{-3})
μ	-	Mikro (10^{-6})
n	-	Nano (10^{-9})
Hz	-	Unit of Frequency
V	-	Voltage
CAD	-	Computer Aided Design
AC	-	Alternating Current
DC	-	Direct Current
HV	-	High Voltage
L	-	Inductor
C	-	Capacitor
R	-	Resistor
N	-	No. Of turns
λ	-	Wavelength
π	-	Phi / 3.142
UV	-	Ultra Violet
A	-	Ampere
GFI	-	Ground Fault Interrupter
RMS	-	Root Mean Square

F	-	Farad
W	-	Watt
σ	-	Electrical Conductivity
δ	-	Skin Depth
μ	-	Relative Permeability
H	-	Henry
PVC	-	Polyvinyl Chloride
mm	-	milimeter
RF	-	Radio Frequency

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Project Background

A Tesla coil is a type of resonant transformer circuit invented by Nikola Tesla around 1891. It is used to produce high voltage, low current, and high frequency alternating current electricity. Tesla experimented with a number of different configurations and they consist of two, or sometimes three, coupled resonant electric circuits. Tesla used these coils to conduct innovative experiments in electrical lighting, phosphorescence, x-ray generation, high frequency alternating current phenomena, electrotherapy, and the transmission of electrical energy without wires.

The early Tesla coil transformer design employs a medium to high voltage power source, one or more high voltage capacitor(s), and a spark gap to excite a multiple layer primary inductor with periodic bursts of high frequency current. The multiple layer Tesla coil transformer secondary is excited by resonant inductive coupling, the primary and secondary circuits both being tuned so they resonate at the same frequency (typically, between 25 *kHz* and 2 *MHz*). The later and higher power coil design has a single layer primary and secondary. These Tesla coils are often used by hobbyists and at venues such as science museums to produce long sparks.

Tesla coil circuits were used commercially in spark gap radio transmitters for wireless telegraphy until the 1920s, and in electrotherapy and medical devices such as violet ray. Today their main use is entertainment and educational displays. Tesla coils are built by many high-voltage enthusiasts, research institutions, science museums and independent experimenters. Modified Tesla coils are widely used as igniters for high power gas discharge lamps, common examples being the mercury vapour and sodium types used for street lighting.

In this project, a small scale Tesla coil will be designing and constructing to determine the electrical discharge that occurs. The TeslaMap Version 1.11 program was used to design the parameters of the Tesla coil. By using this program, it will reduce the time to calculate all the parameters of this Tesla coil.

1.2 Problem Statement

It is difficult to find the Tesla coil at Malaysia although it has been around since 1891. It is highly desirable that a moderately rated Tesla coil is built for specific purposes such as to demonstrate the concept of resonance and electrical discharges. Such a coil can also be utilised for a study to demonstrate the concept of energy capture and storage from a renewable source such as lightning.

1.3 Project Objectives

The objectives of the project are firstly, to study the behaviour of Tesla coil itself. Then it is to design suitable parameters of Tesla coil's components that will generate a electric discharge at the top of the secondary of the Tesla coil. After that, it is to construct the Tesla coil and lastly to test the Tesla coil to see the electrical discharge which occurs from toroid to the surrounding air.

1.4 Scope of Project

The scope of this project is to design and construction a small scale Tesla coil that produce 2 *kV* output voltage with 240 *V* source voltage. The parameters of the Tesla coil are determined by using TeslaMap Version 1.11 program. In order to complete the project, the scope of the project is determined so that the process of the work will be running smoothly without any problem. Besides that, the scopes precisely show the overall purpose of the project so that the project objective will be achieved successfully.

1.5 Outline of Thesis

This thesis has five chapters with a series of appendices at the end. The thesis contains the required information to understand the design and construction processes of a Tesla coil. Chapter one consists of general overview of the whole thesis. The introduction, problem statement, objectives and the scope of project are also included.

Chapter two explains about the theoretical background related to Tesla coil. Among other things, the operation of a Tesla coil, the air discharge phenomena, the components of a Tesla coil, and the resonant matching of the primary and secondary circuits are discussed in this chapter.

Chapter three discusses the process of designing and constructing the Tesla coil. In particular, the TeslaMap Version 1.11 program is described in the design process.

Chapter four is about the results and discussion for the constructed and tested of Tesla coil, observation and discussion of test result and determination of secondary voltage.

Lastly, chapter five contains the conclusions and recommendations for the future improvement for this project.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter explains the theories related to Tesla coil. The understanding of theoretical aspects is important before the design and construction processes. This chapter describes the operation of a Tesla coil, its basic components, the air discharge phenomena, and resonant matching of the primary and secondary circuits.

2.2 Overview of Nikola Tesla

Nikola Tesla was born in Croatia on July 9, 1856, and died January 7, 1943. He was the electrical engineer who invented the AC (alternating current) induction motor, which made the universal transmission and distribution of electricity possible. Tesla began his studies in physics and mathematics at Graz Polytechnic, and then took philosophy at the University of Prague. He worked as an electrical engineer in Budapest, Hungary, and subsequently in France and Germany. In 1888 his discovery that a magnetic field could be made to rotate if two coils at right angles are supplied with AC current 90° out of phase made possible the invention of the AC induction motor. The major advantage of this motor being its brushless operation, which many at the time believed impossible.

Tesla moved to the United States in 1884, where he worked for Thomas Edison who quickly became a rival – Edison being an advocate of the inferior DC power transmission system. During this time, Tesla was commissioned with the design of the AC generators installed at Niagara Falls. George Westinghouse purchased the patents to his induction motor, and made it the basis of the Westinghouse power system which still underlies the modern electrical power industry today. He also did notable research on high-voltage electricity and wireless communication; at one point creating an earthquake which shook the ground for several miles around his New York laboratory. He also devised a system which anticipated world-wide wireless communications, fax machines, radar, radio-guided missiles and aircraft.

2.3 Principle of Operation of a Tesla Coil

The basic components of a Tesla coil are shown in Figure 2.1. The primary circuit or oscillator consists of a flat spiral inductor with a few turns, a capacitor, and an AC voltage source which is used to charge the capacitor. A switch in the form of a spark gap is used to create a series connection between the charged capacitor and the inductor (and hence trigger a series resonance). The secondary circuit or oscillator contains a large, tightly wound inductor with many turns, and an effective capacitor, form by the earth on one end, and the output terminal, usually a sphere or a toroid, on the other.

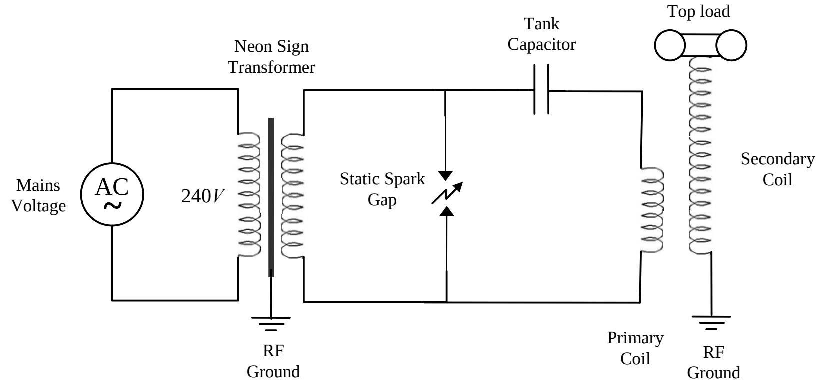


Figure 2.1 Schematic Diagram of Tesla Coil

The switch or the spark gap initially appears as an open circuit as shown in Figure 2.2. The HV power supply will charge the primary tank capacitor to a high voltage. The voltage across the capacitor increases gradually with time as more charge is being stored across its dielectric.

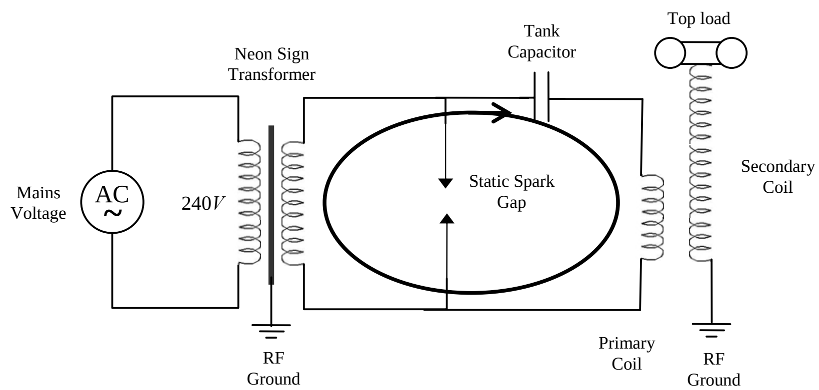


Figure 2.2 High Voltage Charging of the Capacitor

Eventually the capacitor voltage becomes so high that the air in the spark gap is incapable to hold off the high electric field and breakdown occurs. The spark gap becomes a good conductor as the resistance of the air in the spark gap drops dramatically.

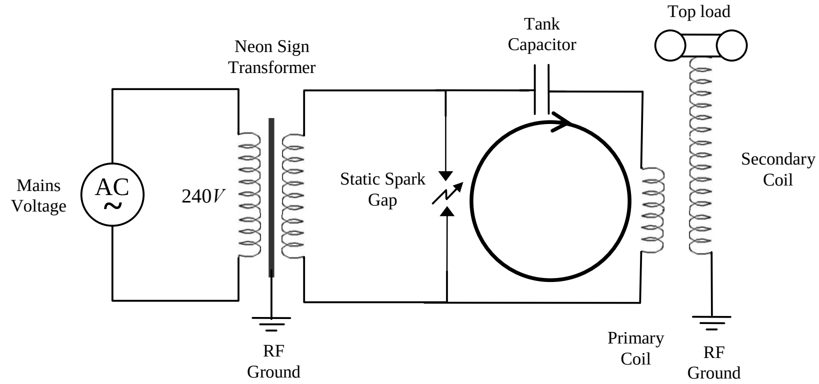


Figure 2.3 Capacitor Discharge to Form LC Circuit

The tank capacitor is now connected across primary winding through the spark gap as shown in Figure 2.3. When a charged capacitor shorted or connected to the inductor, an electric current will flow from the capacitor through the inductor creating a magnetic field in the inductor. The magnetic field will tend to collapse as the electric field in the capacitor is worn out and hence it results in the current to stop flowing.

As the magnetic field collapses, in induces a current to flow in the inductor in the opposite direction to the original current. This new current then charges the capacitor, creating a new electric field, equal but opposite to the original field. As long as the inductor and capacitor are connected, the energy in the system will oscillate between the magnetic field and the electric field as the current constantly reverses.

The oscillation frequency of the given system can is given by $\frac{1}{2}\pi\sqrt{LC}$.

During this damped primary oscillation, energy passes back and forth between the primary capacitor and the primary inductor. The energy is stored interchangeable in the form of voltage across the capacitor, or current through the inductor. Some of the energy from the capacitor also produces substantial heat and light in the spark gap. The energy dissipated in the spark gap is the energy lost from the primary tank circuit. This will finally cause the primary oscillation to decay relatively quickly with time.

The self capacitance of the secondary winding and the capacitance formed between the toroid and ground result in another parallel resonant circuit being made with the secondary inductance. Its natural resonant frequency is established by the values of the secondary inductance and its stray capacitance. The resonant frequency of the primary circuit is intentionally chosen to be the same as the resonant frequency of the secondary circuit so that the s secondary is excited by the oscillating magnetic field of the primary.

In a Tesla coil, the two inductors share the same axis and are located close to one another. In this case the magnetic field produced by one inductor can generate a current in the another. The resulting magnetic field induces a corresponding current in the secondary. A very high electric field is established in the secondary capacitor as its secondary contains many more turns than the primary. The output of a Tesla coil is maximized when two conditions are satisfied. First, both the primary and secondary must oscillate at the same frequency [3]. And secondly, the total length of conductor in the secondary must be equal to one quarter of the oscillator's wave length [3]. Wave length, λ is equal to the speed of light divided by the frequency of the oscillator [3].

As energy is transferred from the primary to secondary, it results in the decreasing amplitude of the primary known as 'primary ring down'. Eventually the energy is totally transferred to the secondary side and none is left in the primary circuit. This point is recognized as the 'first primary notch' because the amplitude of the primary oscillation has fallen to zero. Energy then begins to transfer from the secondary circuit back into the primary circuit, if the spark gap continues to conduct after the first primary notch. The secondary oscillation decays to zero and the primary amplitude increases again.

This energy transfer process can continue for several hundred microseconds. When the energy is transferred to the secondary coil it results in an extremely high voltage at the top of the secondary. The air surrounding toroid is partially breaking down and producing visible sparks (known as electrical discharges) as illustrates in Figure 2.4.

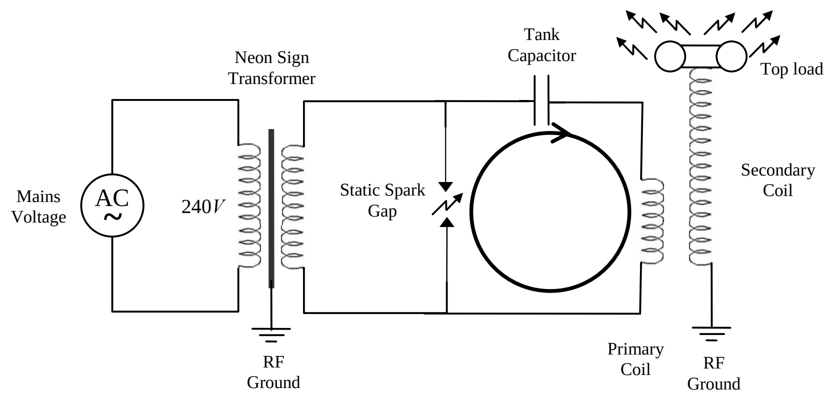


Figure 2.4 Visible Sparks Surrounding the Secondary Side Toroid (due to electrical discharges)

After several transfer of energy between the primary and secondary, the energy in the primary will become sufficiently low that the spark gap extinguishes. It will now then stop conducting at primary notch when the current is minimal. At this point any remaining energy is trapped in the secondary system, because the primary resonant circuit is effectively ‘broken’ by the spark gap going open circuit [4].

2.4 Air Discharge Phenomenon

Electrical energy from the secondary and toroid id transferred to its surrounding in the form of electrical charge, heat, light, and sound when air discharges occur in the Tesla coil. The electric currents that flow through these discharges are actually due to the rapid changing of quantities of charge from the secondary terminal to the surrounding air. The process of charging or discharging a capacitor is mostly being the same with that phenomenon. The current developed from shifting charges within a capacitor is called a displacement current. Tesla coil discharges occur as a result of displacement currents in the form of pulses of electrical charge. The surrounding air is known as space charge regions, which play a meaningful role in the appearance and location of Tesla coil discharges.

Most of the energy which is originally in the primary side is transferred into the secondary side. This energy transfer occurs over a number of cycles. As the secondary energy and hence the output voltage continues to increase, larger pulses of displacement current will further ionize and heat the air at the point of initial breakdown. Consequently a very conductive “root” of hot plasma known as a leader is formed. The leader projects outward from the toroid. The plasma within the leader is considerably hotter than a corona discharge, and is noticeably more conductive and has properties similar to electric arc.

In a spark gapped Tesla coil, the primary to secondary energy transfer process happens repetitively at typical pulsing rates of 50-500 times per second. In this case, previously formed leader channels do not have the ability to fully cool down in between pulses. So, on successive pulses, newer discharges can build upon the hot pathway left by their precursor. This causes incremental growth of the leader from one pulse to the next, broadening the entire discharge on each successive pulse. Repetitive pulsing causes the discharges to grow until the average energy that is available from the Tesla coil during each pulse balances the average energy that is available from the Tesla coil during each pulse balances the average energy being lost in the electrical discharges, which mostly in the form of heat.

At this point, a dynamic equilibrium is reached and the discharges have attained their maximum length for the given Tesla coil’s output power level. The unique combination of a rising high voltage radio frequency envelope and the repetitive pulsing seems to be ideally matched to create long, branching discharges that are significantly longer than would otherwise be expected by output voltage concerns alone.

2.4.1 Corona

Corona discharge is a luminous partial discharge from conductors and insulators which occurs due to ionization of the air as the electrical field exceeds a critical value. This process is associated with excitation of nitrogen molecules, leading to emission of UV radiation. As the dielectric strength of the material surrounding the conductor determines the maximum strength of the electric field the surrounding material can tolerate before becoming conductive, conductors that consists of sharp points, or balls with small radius are more prone to causing dielectric breakdown. Besides, corona can results in corrosive materials such as ozone, and nitrogen oxides which in presence of water vapour will yield nitric acid.

2.5 Components of a Tesla Coil

There are five basic components of Tesla coil. There are the power supply, tank capacitor, primary coil, secondary coil and toroid. In addition, spark gap is used as a switch in Tesla coil. The switch allows the tank primary circuit capacitance to charge and discharge.

2.5.1 Power Supply

There are a number of alternative power supplies that can be used for Tesla coils. The power supply is a step up transformer used to charge the primary capacitor. The transformer should be chosen such that it has at least 5 kV output voltage, otherwise problems with the spark gap may rise. The most common power supply used is a Neon Sign Transformer (NST). These are used to power neon gas tubes for commercial sign purposes. Their voltage output can vary from about 2 *kV* to 15 *kV* and can have a current output from about 10 *mA* to 120 *mA*. There are two different types of NST the older iron cored and the newer switch mode NST. For Tesla coil use the older type is ideal as they have their own built in current limiting magnetic shunt, are secondary midpoint grounded, have no GFI ground fault protection, they can survive high radio frequency current and can run indefinitely in short circuit and no load conditions. The newer switch mode NST's are not ideal for Tesla coil use as they have built in GFI ground fault protection, short circuit protection and their components cannot withstand high frequency radio currents and they will simply be fried if they work at all under Tesla coil conditions.

Other high voltage power supplies that can be utilised for Tesla coil use are ignition coils from cars, oil burner igniters, fly back transformers, microwave oven transformers, medical x-ray transformers and power distribution transformers, also known as pole pig transformers.

2.5.2 Primary Capacitor

The tank capacitor consists of a high voltage capacitor rated at about two or three times the RMS voltage rating of the high voltage transformer, so if NST rated at 10 *kV AC* is used, its RMS voltage would be around 14 *kV AC*, so the tank capacitor must be able to withstand about 40 *kV*. This is because the primary circuit can have many very high voltage peaks present when in operation which can damage a too lower rated capacitor. The tank capacitance usually varies between about 1 *nF* to about 50 *nF* depending on the resonant properties of the primary circuit design.

There are a number of alternative methods for obtaining high voltage capacitors. A very common method of producing such a capacitor is to create an array of smaller rated capacitors, known as an MMC (Multi Miniature Capacitor).

The individual capacitors are set in parallel and series combinations to get the desired voltage and capacitance rating. The following two equations are used for calculating the combined total capacitance parallel and series arrays:

$$C_{parallel} = C_1 + C_2 + C_3 + ... \tag{2.1}$$

$$C_{series} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + ...} \tag{2.2}$$

Adding capacitors in series effectively doubles their voltage rating, whilst adding capacitors in parallel has no effect on the voltage rating. High voltage (~1 *kV*) polypropylene capacitors are usually used for MMC types of tank capacitor. This method can be quite expensive due to the number of capacitors needed, depending on the design some can have over 100 individual capacitors.

Another method is to buy a few higher voltage rated (~10 *kV*) ceramic capacitors (~1 *nF*) and set these up in parallel and series combinations to obtain the required ratings. This is another type of MMC but can be cheaper due to the smaller number of capacitors needed. Another method is to roll or build high voltage capacitor using aluminium foil and sheets of polypropylene, however this method can be hard to obtain an accurate capacitance and produce an efficient capacitor.

2.5.3 Spark Gap

The static spark gap is a simple high voltage switch that is very easy to make and operate. As the tank capacitor charges from the high voltage power supply, the potential across the static spark gap electrodes increases until the air between the spark gap ionises allowing a low resistance path for the current to flow through; the ‘switch’ is closed. Once the capacitor has discharged, the potential across the spark gap is no longer sufficient to maintain ionised air between the electrodes and the ‘switch’ is open. This happens hundreds of times a second producing high frequency (radio frequency) AC current through the primary coil.

A high voltage spark gap becomes very hot during operation and the ionised air surrounding the spark gap will keep the switch closed for longer than desired. It is therefore common for a static spark gap to make up of many smaller spark gaps aligned in series this will reduce the heat produced and dissipate the heat created more effectively. It is also common practice to integrate a fan to quench the spark gap which will blow away the ionised air quickly and help to keep the electrodes cool. Quenching the spark gaps allow the ‘switch’ to be open and closed quicker which will allow the primary circuit to produce higher firing frequency pulses.

A more advanced spark gap is the rotary spark gap where multiple electrodes on a rotating disc pass two fixed electrodes. The rotating disc is powered by a synchronous motor to allow an easy method of varying the spark gap firings. This also helps to keep each electrode cool as there are many electrodes where only two on the rotating disc are firing at one time. An ideal material to use for the spark gap electrodes is tungsten rods as they resist ware and tarnishing due to prolonged use in spark gaps.

2.5.4 Primary Coil

There are three main types of primary coil, which is spiral, helical and inverse conical as shown in Figure 2.6. Helical coils are wound into a helix of equal diameter. Spiral coils (or pancake coils) are wound into a flat spiral. Helical coils are wound into a vertical helical spiral. Inverse conical coils are wound into a conical spiral with an inclined angle of 30° to 45°.

The primary and secondary coils need to be loosely coupled inductively (normal mains transformers have high coupling between separate coils to get better performance and efficiency) to allow the secondary to undergo resonant climbing to very high voltages.

The helical coil is generally not recommended over the other designs as it is not as efficient due to a too larger inductive coupling between the secondary coils, preventing efficient resonant climbing. It is also higher, increasing the chances of top load discharge to its upper windings which can damage the components of the primary circuit especially the tank capacitor. The inverse conical coil and spiral coil are far more common and both can be used in small and medium power Tesla coils. For larger high power (1000 *W* and over) Tesla coils the spiral primary coil design is best. I personally prefer the spiral coil design for all power ranges of Tesla coil due to its simplicity and no obvious difference in efficiency from that of the inverse conical coil design.

The coil is made from hollow copper tubing (micro bore) with a diameter of about 6-8 *mm*. A frame is constructed to support and fix the copper coil in place. The frame is usually made from sheets of a good insulator like polypropylene (plastic chopping boards are a good source for this).

There is a reason for using hollow tubing known as the skin effect. The current density within a conductor depends of the frequency of the current. Alternating current within a conductor tends to have a higher current density at its surface than at its centre. As the frequency of the current increases so does the density of the current towards the surface of the conductor. Figure 2.5 below try to illustrate the effective current density within the cross section of a rod like conductor.

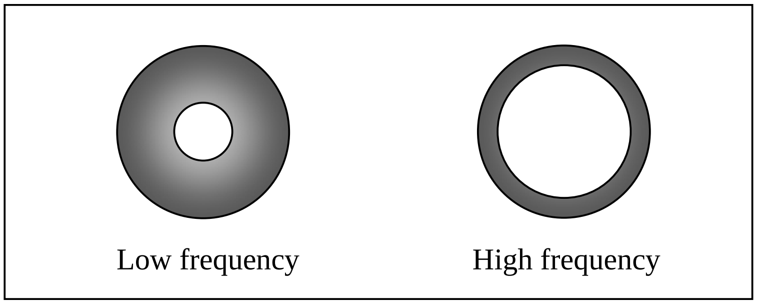


Figure 2.5 Effective Current Density Within the different Cross Section

So for higher frequencies, the centre of the conductor is not used or available for the current to pass through. Using a solid conductor is just wasteful not required, so for high frequency applications tubing is ideal for use as a conductor.

The skin depth can be calculated using the following equation (SI units):

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{2.3}$$

Where f is the frequency of the current in the conductor, μ is the relative permeability of the conductor material and σ is the electrical conductivity of the conductor material.

The reason for using a relatively large conductor for the primary coil is to minimise the impedance and resistance for the high frequency. Also, not only would a solid copper tube be very expensive but it would also be extremely hard to form into a spiral shape.

The skin effect also causes the effective resistance of the conductor to increase with the frequency of the current. The skin effect is basically due to eddy currents induced in the conductor by the AC current.

The equations for each coil design are shown below for calculating the approximate theoretical inductance.

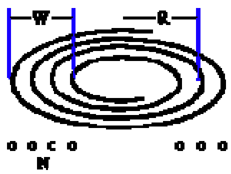
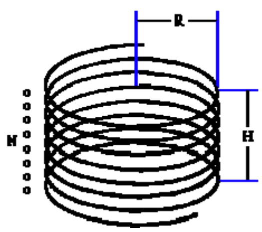
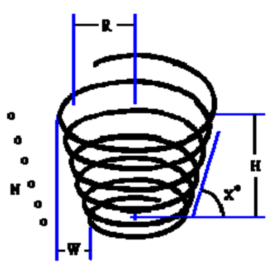
Spiral / Pancake coil 	$$L = \frac{(NR)^2}{8R + 11H} \qquad (2.4)$$ L = inductance of coil in micro-Henry's (μH) R = average radius of the coil in inches, measured from the centre of the coil to the mid point between the inner winding and outer winding. N = number of turns. W = width of the windings in inches, measured from the inner winding to the outer winding.
Helical coil 	$$L = \frac{(NR)^2}{9R + 10H} \qquad (2.5)$$ L = inductance of coil in micro-Henry's (μH). N = number of turns. R = radius of coil in inches, measured from the centre of the coil to the middle of the outer wire/s. H = height of coil in inches.
Inverse conical coil 	$$L_1 = \frac{(NR)^2}{9R + 10H} \qquad L_2 = \frac{(NR)^2}{8R + 11H}$$ $$L = \sqrt{L_1^2 \sin^2(x) + L_2^2 \cos^2(x)} \qquad (2.6)$$ L = inductance of coil in micro-Henry's (μH). L1 = helical inductance factor. L2 = spiral inductance factor. N = number of turns. R = average radius of coil in inches, measured from the centre of the coil to the mid point between the inner/lower winding and the outer/upper winding. H = vertical height of the coil in inches. W = width of windings in inches, measured from the inner/lower winding to the outer/upper winding. x = inclination angle of the coil in degrees.

Figure 2.6 Types of Primary Coil

The primary coil is located underneath the secondary coil and top load which leaves it susceptible to discharge strikes when in operation which can easily damage the components of the primary circuit. These discharges can easy break the tank capacitor and filter components that are not designed to withstand such high frequencies and high voltage. To protect the primary coil and circuit a strike rail is placed above the primary coil. This strike rail is located usually about 2 inches above the highest winding of the primary coil and directly above the outer winding of the primary coil to intercept any discharges that could be drawn to the primary coil. The strike rail is directly connected to RF ground via a low inductance, low impedance thick wire or more commonly a thick metallic strip. The strike rail is made from a length of copper tubing similar to the primary coil material. The strike rail should not be a completed loop (i.e. it must be an open loop), and should have a gap of about 2 or 3 inches. This is to stop the strike rail from experiencing any inductive effects from the primary and secondary coils which would effectively draw out energy from your circuit and ground it.

2.5.5 Secondary Coil

The secondary coil is a large single layered coil often made with magnet wire. The form of the coil is usually a PVC drainage pipe. This pipe needs to be completely free from moisture and needs to be smooth. Leaving the pipe out in the sun for a few hours will remove most of the moisture. It must then be coated inside and out with polyurethane varnish to seal it from moisture. Each end of the pipe must also be sealed off either with commercial PVC pipe end caps or home made PVC end caps. Magnet wire is usually used for the windings and need to wound very tightly with no kinks or gaps. This process can take a very long time by hand and the process must be done with care. Once the coil is wound each end of the windings can be temporarily clamped and the whole coil needs to be coated with a few coats of polyurethane varnish until a smooth finish is obtained.

The approximate dimensions for the secondary coil are the height of the coil should be about 5 to 7 times the diameter of the pipe used and the number of turns on this pipe should be about 1000. A good starting diameter for a Tesla coil is around 60 *mm* to 80 *mm*. I believe it is easier to design and make the secondary coil and top load first and build the other components of the Tesla coil around these components as the other components can be adjusted more easily whereas the secondary coil and top load are fixed once built.

The top secondary winding is directly connected to a top load discharge terminal usually in the form of a toroid or sometimes a sphere. The bottom secondary winding is directly connected to an excellent RF ground connection.

2.5.6 Top Load

The top load is acts as a capacitor in the secondary circuit. The donut or torus (also called a toroid) is the preferred shape. As the coil operates a charge will build up around the surface of the top load. A sphere will have evenly distributed field strength over its entire surface. By flattening the sphere into a toroid, the field strength will increase around the radius of the toroid. The arcs will break out where the field strength is greatest. The benefit of concentrating the field around the radius is to help direct the arcs outward. Using a sphere top load will result in evenly distributed smaller arcs.

The most common method of toroid construction is to wrap aluminium dryer duct around an aluminium pie pan. You can also use a spun aluminium toroid. A top load can be made of practically anything with a smooth shape covered in aluminium foil. Avoid using "metal" paint. Usually there is not enough metal in the paint to create a conductive surface, and even if there is sufficient metal, it's usually quickly burned off.

The size of the top load and the amount of power applied will dictate the size and number of arcs that the Tesla coil produces. If the top load is small, then it will produce numerous simultaneous, shorter arcs. As the size of the top load is increased the number of arcs will be reduced and the arc length will increase. If the toroid is too large the field strength will not be strong enough to allow arcs to breakout. Placing a sharp pointed object like a thumb tack (called a break out point) on the toroid will create a disruption in the field and allow the arc to break out from the break out point.

Generally the diameter of the toroid ring should be about the same as the secondary coil, meaning a secondary coil wound on 4 inch PVC pipe should use 4 inch diameter dryer duct. The overall diameter of the toroid should be about 4 times the ring diameter, so 4 inch diameter dryer duct should be wrapped around an 8 inch pie pan for a total overall diameter of 16 inches.

It is important to physically attach the toroid to the top of the secondary coil. You can get by with sitting the toroid on there, but eventually it's going to fall or get bumped off. At best you'll dent up the toroid or your primary coil, at worst there could be a short that blows out your primary caps or something else. A good way to connect the toroid to the secondary is to get a PVC end cap, drill a hole in the middle and insert a nylon bolt sticking up. Drill a hole in the centre of the pie pan and slide it onto the nylon bolt. You'll have to use nylon or some other non conductive bolt. A metal bolt will shoot an arc straight up. A wooden mount can be used, but wood should be avoided. Wood always has a bit of moisture and is slightly conductive. It can also swell, shrink, warp and crack.

It's important to have the toroid at the correct height above the secondary windings. If the toroid is too high, you'll see a corona develop near the top of the secondary windings. You may also see some little arcs from the top of the secondary coil. The corona and arcs can degrade the secondary winding insulation. If this is a problem try moving the toroid down. If the toroid is too low you may have frequent arcs striking the primary coil. In this case try to move the toroid up. If you can't find a suitable placement for the toroid you can try adding a smaller toroid just under the main toroid. This can help to prevent corona on the secondary windings and strikes to the primary coil.

2.6 Resonant Matching of the Primary and Secondary Circuits

The primary circuit of the Tesla coil consists of the high voltage tank capacitor, the spark gap switch and the primary coil. The secondary circuit consists of the secondary coil, the top load and RF ground.

Both circuits have the form of a series *LCR* circuit which resonates at a particular resonant frequency governed by the component part values. There will be a capacitance (*C*), an inductance (*L*) and a resistance (*R*). The capacitance in the secondary circuit comes from the self-capacitance of the top load and the capacitance of the top load with RF ground. The resistance in both circuits come from the resistance of the parts used in the circuits. The circuit will resonate at its resonant frequency when the sum of the capacitance and inductance impedances equal zero. The resonant frequency of an LCR circuit is given by the equation:

$$\omega_0 = 2\pi f_0 = \frac{1}{\sqrt{LC}} \tag{2.7}$$

Where ω_0 is the resonant frequency in radians per second and f_0 is the resonant frequency in Hertz.

The resistance of the circuit acts as a damping factor to the resonance of the circuit and in most circumstances can be neglected for use in Tesla coil circuit design. The primary and secondary circuits of the Tesla coil must have the same resonant frequency to enable high frequency resonant charging between the primary and secondary circuits which results in the extremely high induced voltage in the secondary circuit.

CHAPTER 3

METHODOLOGY

3.1 Designing of Tesla Coil

TeslaMap Version 1.11 program was used to design the parameters of the Tesla coil. There are several programs that available for Tesla coil design such as WinTesla, Tesla Coil CAD and others. The first thing that needs to be known is that the conventional Tesla coil comprise of five basic fundamental components. There are:-

1) High voltage transformer
2) Primary capacitor
3) Primary coil
4) Secondary coil
5) Toroid

There are five basic fundamental design parameters that need to be determined:

1) Output characteristic of high voltage transformer
2) Size and dimension of primary coil
3) Size of primary capacitor
4) Size and dimensions of secondary coil
5) Size and dimensions of toroid

3.1.1 Selecting of a High Voltage Transformer

The important part in designing the Tesla coil was the selection of high voltage transformer as the output characteristics of the high voltage transformer will affect the design of the primary coil. Neon Sign Transformer fulfilled the requirements and was selected to be used as the HV Transformer for this project because it has a built in current limiter and ideal for direct connection to the Tesla coil system. In this design, the output voltage chosen for the NST was 6 *kV* and the output current was 30 *mA* as shown in Figure 3.1. The output parameters were determined by these formulas:

$$NST_{VA} = NST_{Current} \times NST_{Voltage} \tag{3.1}$$

$$NST_{\mathrm{Im}\,pedance} = \frac{NST_{Voltage}}{NST_{Current}} \tag{3.2}$$

$$NST_{Watts} = \left[\left(\frac{0.6}{\sqrt{NST_{VA}}} \right) + 1 \right] \times NST_{VA} \tag{3.3}$$

$$PFC_{Capacitance} = \left[\frac{NST_{VA}}{\left(2 * \pi * NST_{Frequency} * \left(NST_{Voltage}\right)^2\right)} \right] \times 1000000 \qquad (3.4)$$

$$Primary\ Resonate_{Capacitance} = \left[\frac{1}{\left(2 * \pi * NST_{Impedance} * NST_{Frequency}\right)} \right] \times 1000 \qquad (3.5)$$

$$Primary\ LTR\ Static_{Capacitance} = Primary\ Resonate_{Capacitance} * 1.5 \qquad (3.6)$$

$$Primary\ LTR\ Sync_{Capacitance} = 0.83 * \left[\frac{NST_{Current}}{2 * NST_{Frequency} * NST_{Voltage}} \right] * 1000 \qquad (3.7)$$

Figure 3.1 Neon Sign Transformer

The input and output parameters for NST is as shown in Figure 3.8 and 3.11.

3.1.2 Determining Primary Capacitor Size

The next step was to choose the primary capacitor. The value of the primary capacitor was selected so that for each peak cycle of the output waveform of the NST, the primary capacitor is charged up to the rated output voltage. The value of the primary capacitor can be determined by the aid of Tesla coil calculation, Tesla CAD and others. By using this program, the output characteristics of NST can be simply enter and the program will automatically calculate the required capacitor size as shown in Figure 3.8, 3.10 and 3.11.

3.1.3 Designing Secondary Coil

In the designing process, secondary coil should be designed first before designing the primary coil as it is easier to tune both secondary and primary coil with the same resonant frequency. The output parameters were determined by these formulas:

$$\textit{Secondary Coil Turns} = \left[\frac{1}{\textit{Magnet Wire Diameter} + 0.000001}\right] \times \textit{Secondary Wire Winding Height} * 0.97 \tag{3.8}$$

$$\textit{Secondary Capacitance} = \left(0.29 * \textit{Secondary Wire Winding Height}\right) + 0.41 * \left(\frac{\textit{Secondary Form Diameter}}{2}\right) + \left(1.94 * \sqrt{\left(\frac{\textit{Secondary Form Diameter}}{2}\right)^3 / \textit{Secondary Wire Winding Height}}\right) \tag{3.9}$$

$$Secondary\ Height\ Width\ Ratio = \frac{Secondary\ Wire\ Winding\ Height}{Secondary\ Form\ Diameter}$$

(3.10)

$$Secondary\ Coil\ Wire\ Length = \frac{Secondary\ Coil\ Turns * Secondary\ Form\ Diameter * \pi}{12}$$ (3.11)

$$Secondary\ Coil\ Wire\ Weight = \pi * \left(\frac{Secondary\ Bare\ Wire\ Diameter}{2}\right)^2 * Secondary\ Coil\ Wire\ Length * 3.86$$

(3.12)

$$Secondary\ Inductance = \frac{(Secondary\ Coil\ Turns)^2 * \left(\frac{Secondary\ Form\ Diameter}{2}\right)^2}{\left(\left(9 * \left(\frac{Secondary\ Form\ Diameter}{2}\right)\right) + (10 * Secondary\ Wire\ Winding\ Height)\right) * 0.001 * Secondary\ Inductance\ Adjust}$$

(3.13)

$$Total\ Secondary\ Capacitance = Secondary\ Capacitance + Top\ Load\ Capacitance$$

(3.14)

$$Secondary\ Resonate\ Frequency = \frac{1}{\left(2 * \pi * \sqrt{(Secondary\ Inductance * 0.001) * (Total\ Secondary\ Capacitance * 0.000001)}\right)}$$

(3.15)

The input and output parameters for secondary coil is as shown in Figure 3.9 and 3.11.

3.1.4 Designing Primary Coil

Basically, there only a few rules that should be followed in designing a Tesla coil:-

1) Primary coil should have at least 3 to 5 turns on either side of the calculated tap location to accommodate final tuning. This is important as the actual built secondary coil, capacitor and toroid will have a slightly different value than what any CAD program or equation will tell. Thus, be able to tune out any discrepancies or variances.

2) Around 1.5’’ to 3.0’’ spacing between the inside turn of primary and secondary should be used to prevent arcing between the primary and secondary coil.

The output parameters were determined by these formulas:

$$\textit{Needed Primary Inductance} = \frac{1}{2 * \pi * (\textit{Secondary Resonate Frequency} * 1000)^2 * (\textit{Primary Capacitance} * 1 \times 10^{-13})} \quad (3.16)$$

$$\textit{Primary Coil Hypotenuse} = (\textit{Primary Coil Wire Diameter} + \textit{Primary Coil Wire spacing}) * \textit{Turns} \quad (3.17)$$

Primary Coil Adjacent Side

= Primary Coil Hypotenuse(to Radians (Primary Coil Incline Angle))* (3.18)

Primary Coil Diameter

*= (Primary Coil Adjacent Side * 2) + Primary Coil Hole Diameter* (3.19)

Primary Coil Height

*= Primary Coil Wire Diameter + Primary Coil Adjacent * tan (to Radians(Primary Coil Incline Angle))*

(3.20)

$$Primary\ Coil\ Wire\ Length = Primary\ Coil\ Diameter * \frac{\pi}{12} \quad (3.21)$$

Primary Coil Average Winding Radius

$$= \left(\frac{\Pr imary\ Coil\ Hole\ Diameter}{2}\right) + \left(\frac{\Pr imary\ Coil\ Hypotenuse}{2}\right) \quad (3.22)$$

Primary Coil Inductance Flat

$$= \frac{\left(Turns^2 * \Pr imary\ Coil\ Average\ Winding\ Radius^2\right)}{\left(8 * \Pr imary\ Coil\ Average\ Winding\ Radius\right) + \left(11 * \Pr imary\ Coil\ Hypotenuse\right)}$$

(3.23)

Primary Coil Winding Radius

$$= \left(\frac{\Pr imary\ Coil\ Hole\ Diameter}{2}\right) + \left(\frac{\Pr imary\ Coil\ Wire\ Diameter}{2}\right) \quad (3.24)$$

Primary Coil Inductance Helix

$$= \frac{\left(Turns * \Pr imary\ Coil\ Winding\ Radius\right)^2}{\left(9 * \Pr imary\ Coil\ Winding\ Radius\right) + \left(10 * \Pr imary\ Coil\ Height\right)} \tag{3.25}$$

Angle Percent = 0.01(Primary Coil Incline Angle*1.11111111111)* (3.26)

*Angle Percent Inverted = (100 – (Angle Percent*100))*0.01* (3.27)

Primary Coil Inductance
*= (Primary Coil Inductance Helix * Angle Percent) + (Primary Coil Inductance Flat * Angle Percent Inverted)*
(3.28)

The input and output parameters for primary coil is as shown in Figure 3.8 and 3.11.

3.1.5 Determination of Top Load Capacitance

In this design, an alternative way to reduce cost and to make the design become easier, a corona discharger has been used as a top load and it was obtained form the High Voltage Laboratory. Since its capacitance was not clearly stated, it was determined with the help of the Tesla Map. The ring diameter and overall diameter of the top load was entered into the program and the value of its capacitance was as shown in Figure 3.9 and the output as shown in Figure 3.11 . The output parameters were determined by these formulas:

For large or small toroids, Ring Diameter < 3" or Ring Diameter > 20"
Use the average of three toroid capacitance calculations.

$$\text{Toroid Capacitance 1} = ((1 + (0.2781 - \text{Ring Diameter} / (\text{Overall Diameter}))) * 2.8 * \text{sqrt}((\text{pi} * (\text{Overall Diameter} * \text{Ring Diameter})) / 4)) \tag{3.29}$$

$$\text{Toroid Capacitance 2} = (1.28 - \text{Ring Diameter} / \text{Overall Diameter}) * \text{sqrt}(2 * \text{pi} * \text{Ring Diameter} * (\text{Overall Diameter} - \text{Ring Diameter})) \tag{3.30}$$

$$\text{Toroid Capacitance 3} = 4.43927641749 * ((0.5 * (\text{Ring Diameter} * (\text{Overall Diameter} - \text{Ring Diameter}))) \hat{}0.5) \tag{3.31}$$

$$\text{Toroid Capacitance} = ((\text{Toroid Capacitance 1} + \text{Toroid Capacitance 2} + \text{Toroid Capacitance 3}) / 3) \tag{3.32}$$

Ring Diameter is between 3" and 6"

$$\text{Toroid Capacitance Lower} = 1.6079 * \text{Overall Diameter} \hat{}\ 0.8419 \tag{3.33}$$

$$\text{Toroid Capacitance Upper} = 2.0233 * \text{Overall Diameter} \hat{}\ 0.8085 \tag{3.34}$$

$$\text{Toroid Capacitance} = (((\text{Ring Diameter} - 3) / 3) * (\text{Toroid Capacitance Upper} - \text{Toroid Capacitance Lower})) + \text{Toroid Capacitance Lower} \tag{3.35}$$

Ring Diameter is between 6" and 12"

*Toroid Capacitance Lower = 2.0233 * Overall Diameter ^ 0.8085* (3.36)

*Toroid Capacitance Upper = 2.0586 * Overall Diameter ^ 0.8365* (3.37)

*Toroid Capacitance = (((Ring Diameter - 6) / 6) * (Toroid Capacitance Upper - Toroid Capacitance Lower)) + Toroid Capacitance Lower*

(3.38)

Ring Diameter is between 12" and 20"

*Toroid Capacitance Lower = 2.0586 * Overall Diameter ^ 0.8365* (3.39)

*Toroid Capacitance Upper = 2.2628 * Overall Diameter ^ 0.8339* (3.40)

*Toroid Capacitance = (((Ring Diameter - 12) / 12) * (Toroid Capacitance Upper - Toroid Capacitance Lower)) + Toroid Capacitance Lower*

(3.41)

*Top Load Capacitance = (Toroid Capacitance + Sphere Capacitance) * Top Load Adjust*

(3.42)

3.2 Construction of Tesla Coil's Components

3.2.1 Constructing the Primary Coil

The base of the primary coil for this project was made from plywood. It can be made out of any material as long as it is a nonconductive material. Copper tubing with diameter 0.25 inches was used to create the primary turn and 11 turns were built in order to allow tuning. The spacing between the turns was 6.4 *mm* to allow tapping and to avoid arching between the turns. In this design, primary coil is constructed in a pancake shape as shown in Figure 3.2. Strike ring was built and it is an incomplete ring situated at the most outer turn of the primary coil that was connected to the RF ground to prevent arching towards the primary coil.

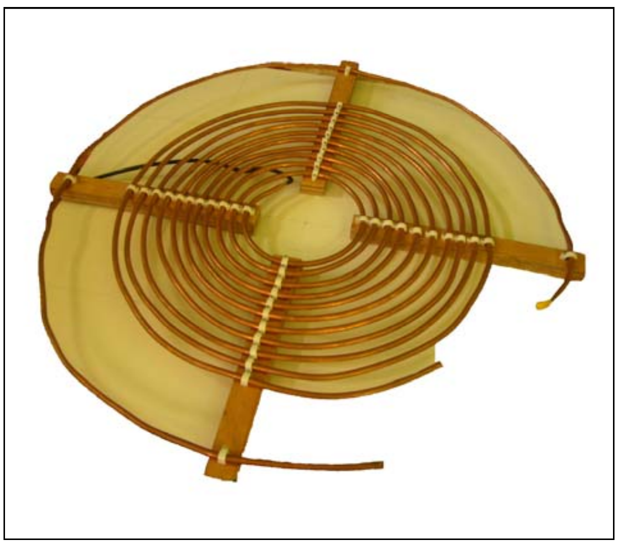


Figure 3.2 Primary Coil

3.2.2 Constructing the Secondary Coil

PVC pipe and 0.7 *mm* (in diameter) 22 *SWG* enamelled copper wire were used to form the secondary coil. The height and diameter of the secondary coil were 60 *cm* and 8.79 *cm* respectively. Secondary coil in this design consists of around 883 turns. The constructed secondary coil is shown in Figure 3.3. Here are the correct methods that need to be followed while winding the coils:-

1) The PV pipe was ensured to be in a clean and dry condition before the winding procedures was done.
2) The end of the magnet wire must first be tapped a few inches from the end of the PV pipe.
3) Some tape was used to easily hold the wire for rest breaks or untagling.
4) No space between the windings must be ensured before proceeding to the next step.
5) The wires were stressed out a little while winding the coils.
6) The end of the magnet wires were tapped down when finished and a couple feet of extra wires was left behind.
7) The winding of the secondary coil should finish somewhat below the bottom of the top load. Thus it is better to make the top insert extra long. The wires were to be winded up five to six extra widely-spaced turns before connecting to the top load. This is to reduce the voltage stress and corona at the top turns.

Figure 3.3 Secondary Coil

3.2.3 Constructing the Multi-Mini Capacitor (MMC)

The MMC was built up from individual capacitors connected in series and parallel to achieve the voltage rating required for the Tesla coil use.

To create the MMC, ten units of polypropylene capacitors 10 *nF*, 1500 *Vdc*, 450 *Vac* and metal glazed high voltage resistor 10 *M*Ω, 0.5 *W*, 2500 *Vac*, 3500 *Vdc* were used.

The capacitors were connected in two parallel strings where each string consists of five capacitors connecting in series creating a 4 *nF*, 7.5 *kV* MMC. The value of primary capacitance was calculated in equation 3.43 and 3.44. The rated voltage was then calculated in equation 3.45.

The value of the series wired capacitors is,

$$\frac{1}{C}=\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}+\frac{1}{C_4}+\frac{1}{C_5}$$

$$\frac{1}{C}=\frac{1}{10\,nF}+\frac{1}{10\,nF}+\frac{1}{10\,nF}+\frac{1}{10\,nF}+\frac{1}{10\,nF}$$

$$C = 2\,nF \qquad (3.43)$$

The value of the parallel wired capacitors is,

$$C = C1 + C2$$

$$C = 2\,nF + 2\,nF$$

$$C = 4\,nF \qquad (3.44)$$

The rated voltage across the MMC is = $1.5\,kV \times 5 = 7.5\,kV$ (3.45)

DC voltage rating is used to work out the number required for the capacitors as Tesla coil builders found that the DC voltage rating can be used as the peak AC voltage rating. When designing, the manufacturer's AC rating for the capacitors was ignored while the DC rating was used instead. No problems occurred and most builders of MMC done this often.

Metal glazed voltage resistor 10 $M\Omega$ also known as bleed resistor was connected in parallel to every capacitor as shown in Figure 3.4. Bleed resistors were employed so as the each capacitor will be safely discharged. The constructed MMC is shown in Figure 3.5.

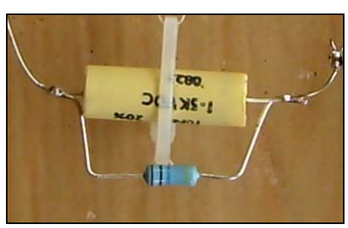


Figure 3.4 Bleed Resistor Connected in Parallel to Each Capacitor

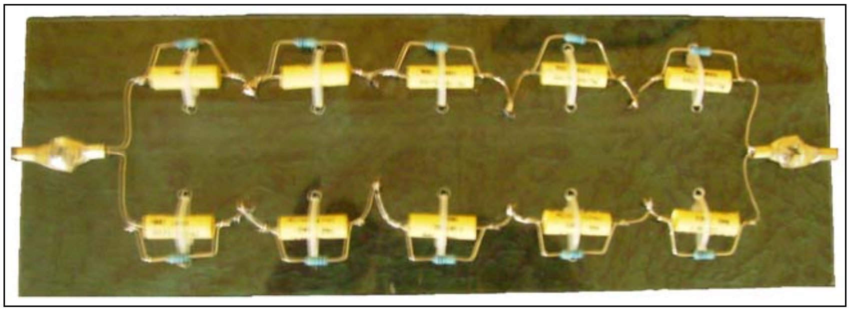


Figure 3.5 Constructed Series-parallel Capacitor

3.2.4 Constructing the Switching Circuit

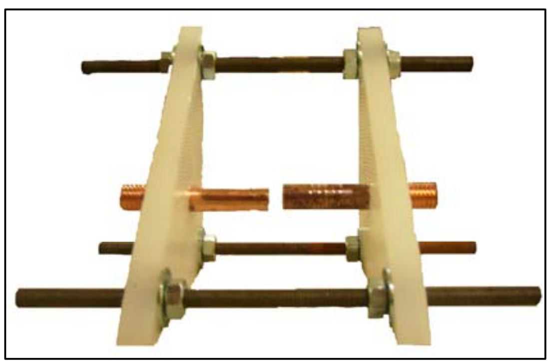


Figure 3.6 Switching Circuit

Figure 3.6 shows the switching circuit for the Tesla coil. Two copper rods were used to design the gap to short. The spark gap is used as a switch to momentarily connect the primary capacitor to the primary coil. When the gap is shorted the cap is allowed to discharge into the coil. Figure 3.7 shows the gap properties, which is the gap of each copper rod is about 0.7143 inch.

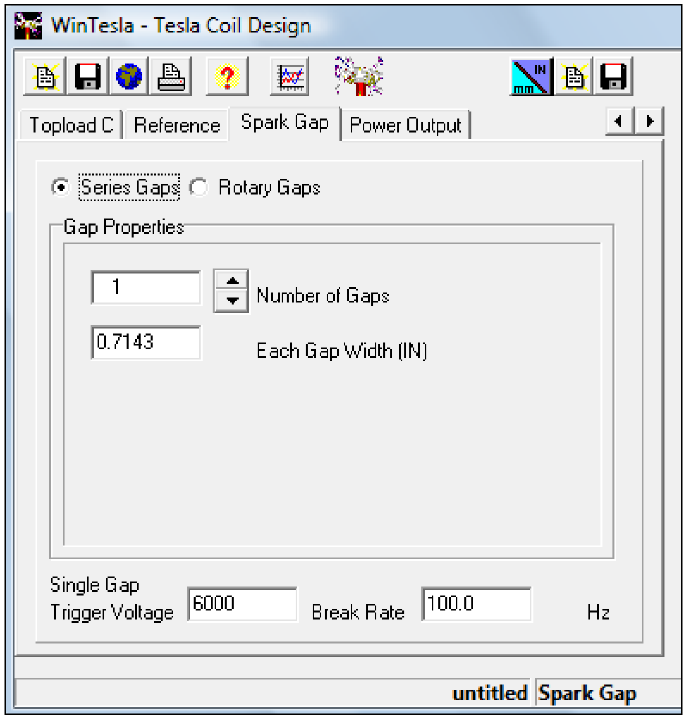


Figure 3.7 Static Spark Gap Properties

3.1 Summary of Cash Flow for Construction of Tesla Coil

The summary of cash flow for construction of Tesla coil as shown in Table 3.1.

Table 3.1 : Cash Flow for Construction of Tesla Coil

NO	ITEM	DESCRIPTION	COMPANY	CASH BILL NO.	QTY	UNIT PRICE (RM)	AMMOUNT (RM)
1.	Power Supply	$6kV$~$30mA$ Neon Transformer DAEHAN (Korea)	TIME Luminaries Sdn. Bhd.	0823	1 no	350.00	350.00
2.	PVC Pipe	3 Inch PVC Class B Pipe	Loh Siam Bu Plumber & Contractor	73701	1 meter	5.90	5.90
3.	Enamel Copper Wire	*SWG* 22 (0.7*mm*)	Asia Marine Electrical Engineering	5102	1700 gram	0.04	59.50
4.	HV Capacitor	$10nF$, $1500Vdc$	Farnell Components (M) Sdn. Bhd.	1507196	10 pcs	3.05	30.50
5.	HV Resistor	$10M\Omega$, $0.5W$	Farnell Components (M) Sdn. Bhd.	1507196	10 pcs	1.76	17.60
6.	Copper Tube	Soft Annealed Copper Tube 1/4" x 0.51*mm* x 15*m* coil	Binson Electric Trading & Service	27822	1 hon	48.00	48.00
7.	Copper Rod		Binson Electric Trading & Service	27822	1 rod	7.80	7.80
8.	Test Pen		Binson Electric Trading & Service	27822	1 pc	2.00	2.00
9.	Crocodile Clip		Binson Electric Trading & Service	27822	4 pcs	0.80	3.20
10.	Bolt		Binson Electric Trading & Service	27822	4 pcs	0.20	0.80
11.	Nut & Washer		Binson Electric Trading & Service	27822	12 pcs	0.15	1.80
12.	Cable	6*mm*	Binson Electric Trading & Service	28112	10 meter	1.20	12.00
11.	Cable Lux		Binson Electric Trading & Service	28112	30 pcs	0.20	6.00
12.	Perspex	3*mm* x 14" x 5"	Acrylic Signs Material Sdn. Bhd.	124495	1 pc	4.00	4.00
					Grand Total		**RM 549.10**

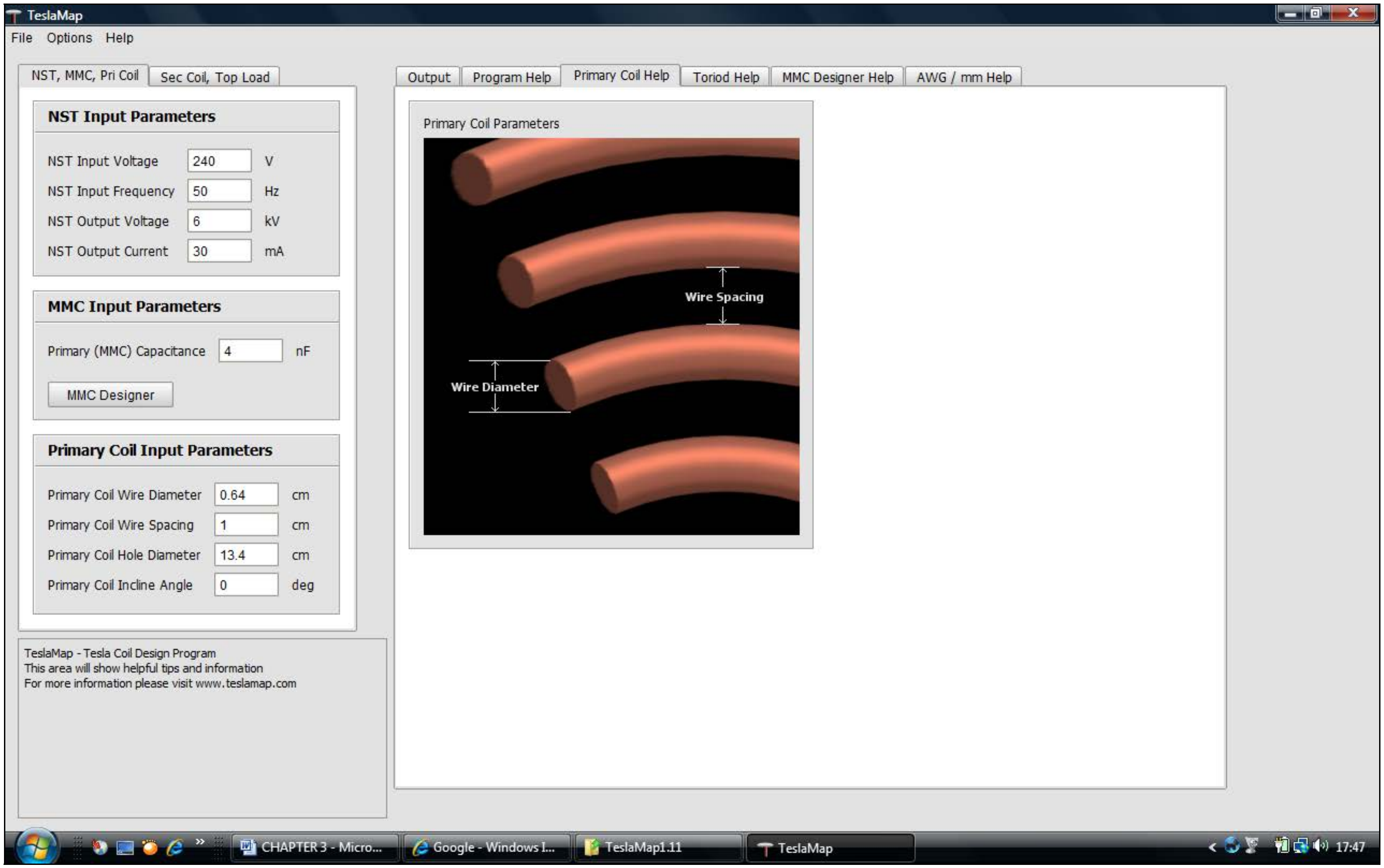


Figure 3.8 Input Parameters of NST, MMC and Primary Coil

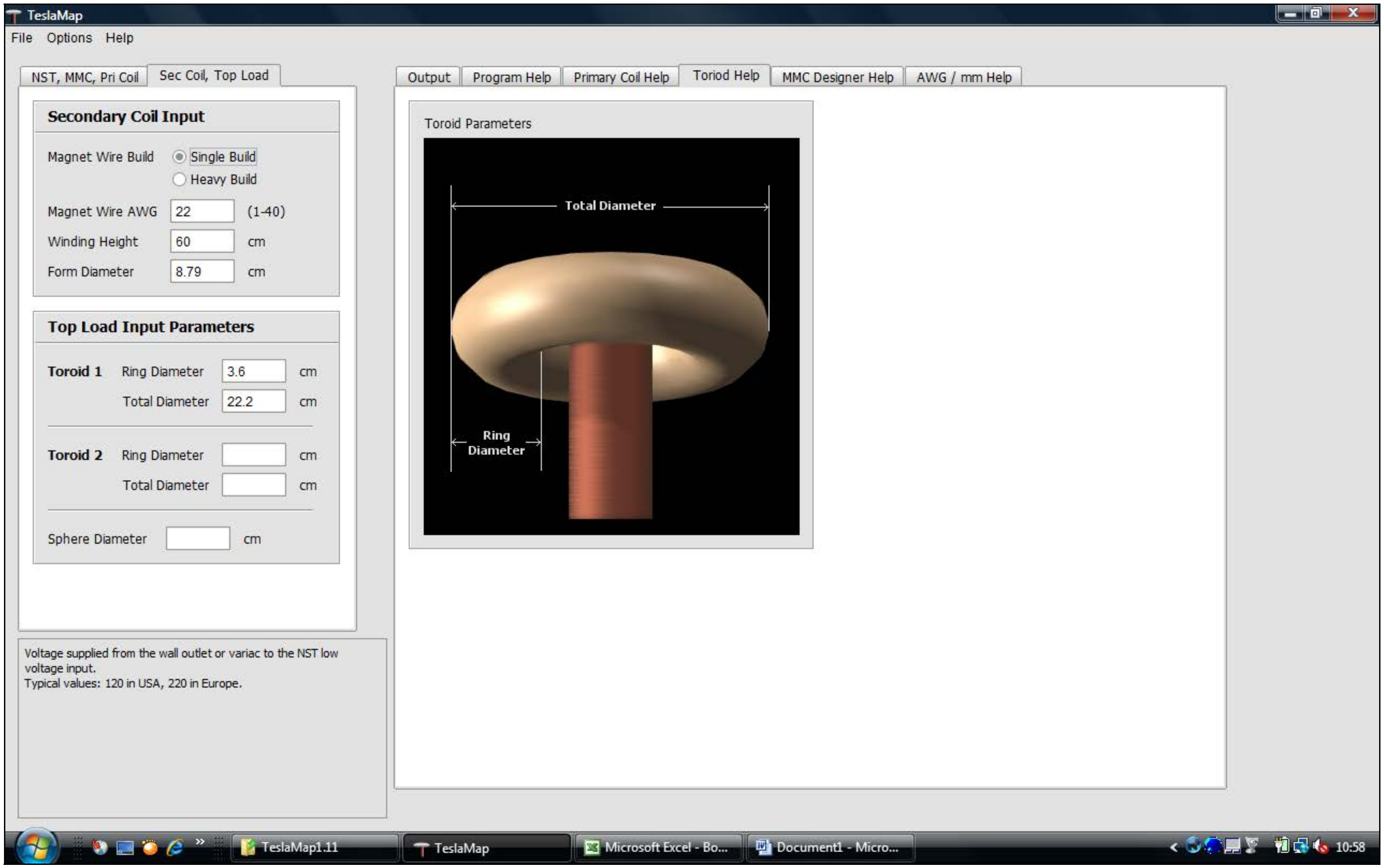


Figure 3.9 Input Parameters of Secondary Coil and Top Load

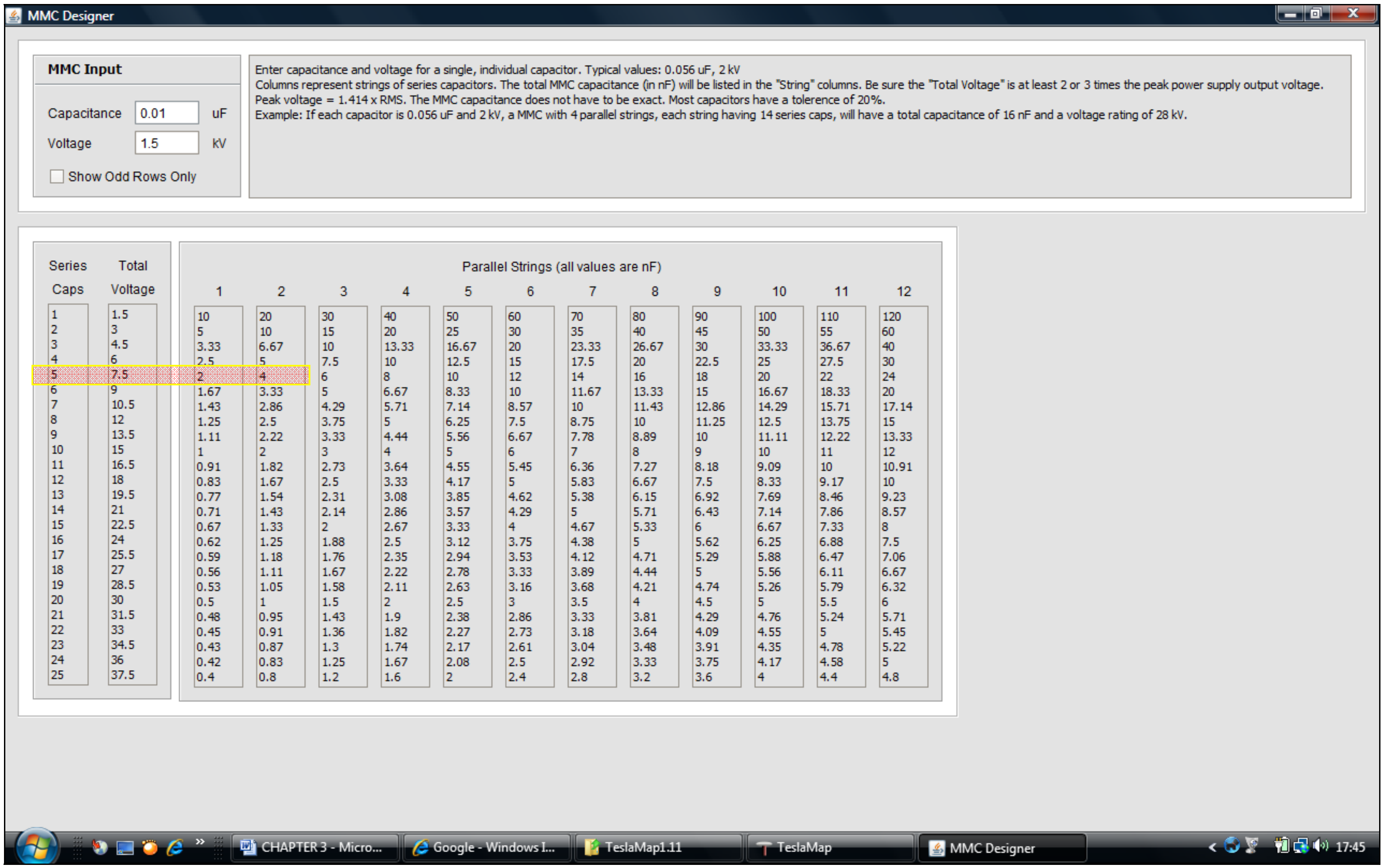


Figure 3.10 MMC Designed

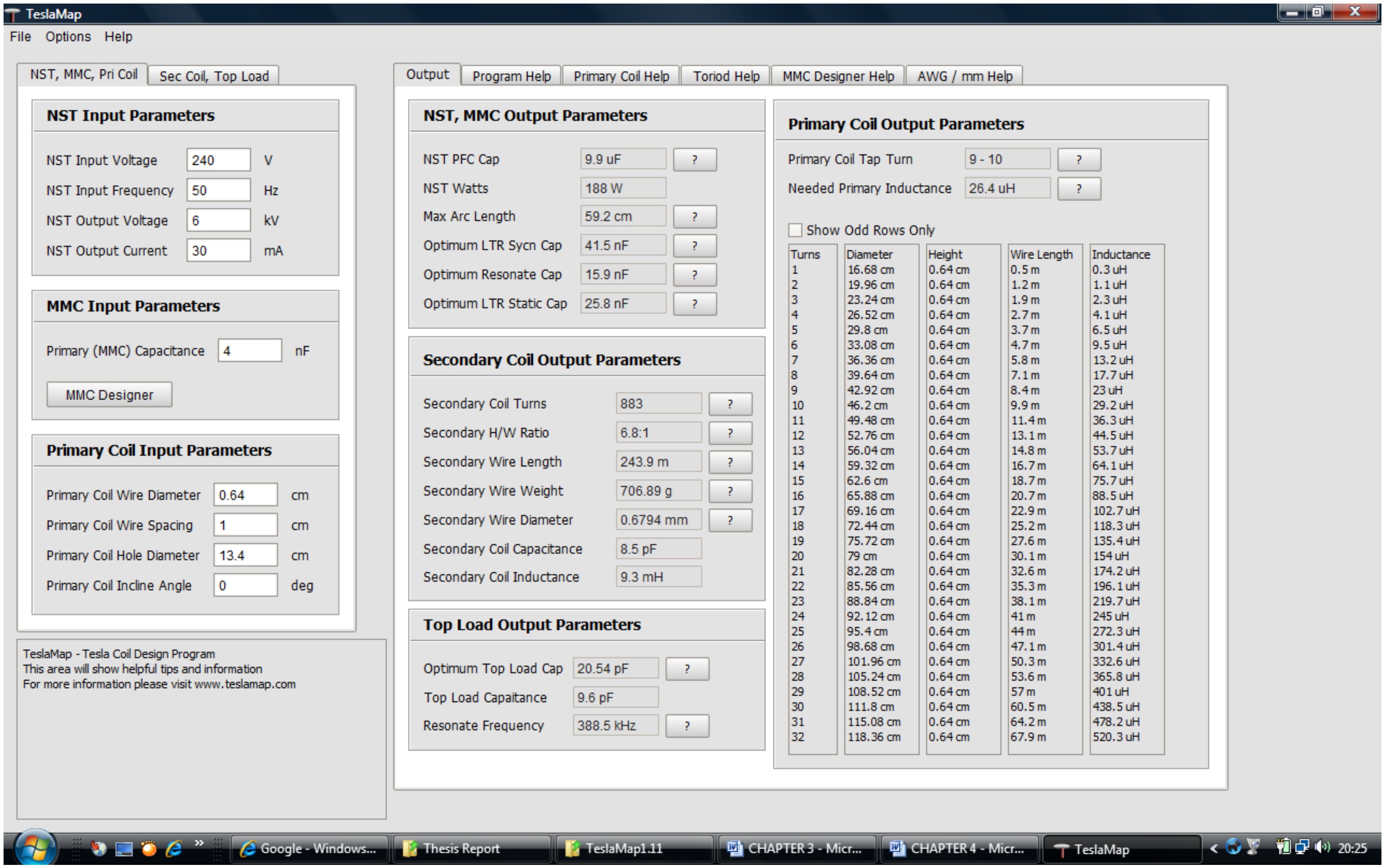


Figure 3.11 Output Parameters for Tesla Coil Designed

CHAPTER 4

RESULTS AND DISCUSSION

4.1 The Finalized Design of Tesla Coil

Table 4.1 below shows the whole specifications of the designed Tesla coil. The Tesla coil will be constructed according to these parameters.

Table 4.1 : Specifications of Designed Tesla Coil

No.	Parameters	Value
1.	Neon Sign Transformer output voltage	6 *kV*
2.	Neon Sign Transformer output voltage	30 *mA*
3.	AC line voltage	240 *V*
4.	Transformer power	188 *W*
5.	Spark gap width	0.7143 Inch
6.	Suggested Primary Capacitor	40 *nF*
7.	Suggested Secondary diameter	8.79 *cm*
8.	Suggested Secondary aspect ratio	6.8:1
9.	Winding height of secondary coil	60 *cm*
10.	Wire diameter of secondary coil	0.7 *mm* (*22 SWG*)
11.	Spacing between windings	0.0 *mm*
12.	Secondary turn	883 turns
13.	Secondary wire length	243.9 *m*
14.	Secondary Inductance	9.3 *mH*
15.	Approximate Resonant Frequency	388.5 *kHz*
16.	Secondary self capacitance	8.5 *pF*
17.	Toroid capacitance required to form quarter wavelength coil	20.54 *pF*
18.	Wire diameter of primary coil	6.4 *mm*
19.	Spacing between turns of primary coil	6.4*mm*
20.	Spacing between the secondary and the inside turn of the primary	50.8*mm*
21.	Primary need to be tapped to form a resonant circuit	Between turn 9 and 10

4.2 Connecting the Components of Tesla Coil

After the construction process was finished, the components were ready to connect to each other to form the designed Tesla coil as shown in Figure 4.1 and Figure 4.2.

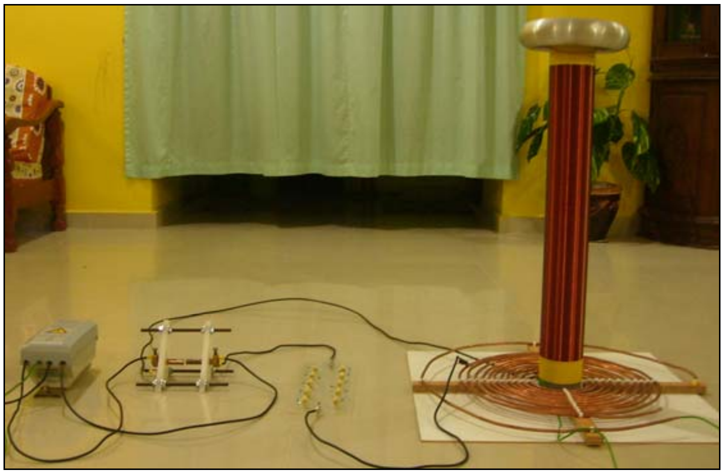


Figure 4.1 Designed Tesla Coil

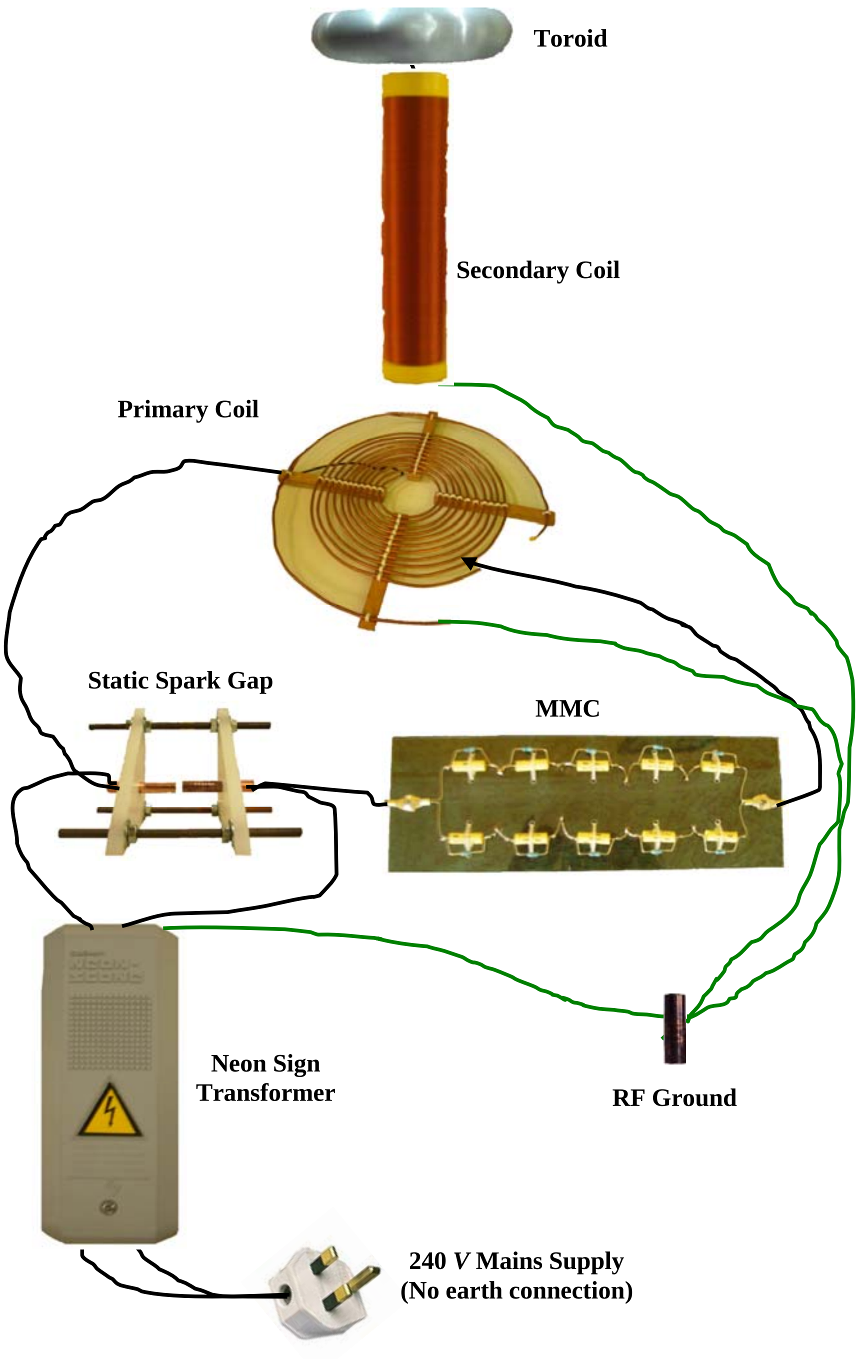


Figure 4.2 Tesla Coil Circuit

4.3 Testing

The testing involves the designed Tesla coil to be tested in determining the output of the electric discharge.

4.3.1 Observation

During the testing, the spark gap successfully performed the switching function as designed as shown in Figure 4.3. However, the expected high voltage sparks from the high voltage toroid could not be observed.

Figure 4.3 Observation of Spark Gap

4.3.2 Discussion

The corrective action cannot be done because of the time constraint, but there are some suggested corrective action to solve the problems as shown in Table 4.2.

Table 4.2 : Suggested Corrective Action

Trouble Symptom	Probable Cause	Test Procedure	Corrective Action
No spark issues from secondary. Visible static spark gap ionization (spark)	Primary oscillation are out of tune with resonant frequency of the secondary.	Connect primary tap one turn above or below the calculated number of turns required to tune the primary. Continue moving up or down one turn at a time if necessary	Discharge MMC before handling. Review calculations for accuracy. If correct, try a different primary turn and run test. If no spark issues after retuning continue to next step.
	Terminal capacitance too large for spark breakout.	Place a pointed director on terminal and rerun. If no spark issues move another grounded director within a few inches of the terminal and retune primary using different tap.	Tuning point is generally different with and without terminal capacitance. The grounded director checks for secondary output > 30kV (10kV/in). If no spark issues continue to next step.
	Secondary winding not continuous or interwinding short.	Visually inspect winding for insulation anomalies or cross windings. Perform continuity (resistance) check on secondary winding ensuring it is close to calculated DC resistance. Measure inductance ensuring it is close to calculated value.	If winding passes visual inspection, continuity and inductance tests continue to next step. If not, repair discontinuity, crossed winding or insulation, or rewind secondary (also use a new form).
	Primary to secondary coupling too tight.	Review calculations. Ensure accuracy and k value is below the critical coupling threshold for the number of turns used. If visible corona or secondary to primary breakdown is observed the coupling is too tight.	If calculation are correct try loosening the coupling by raising the base of the secondary a few inches at a time and run test.

4.4 Determination of Secondary Voltage

Secondary voltage can be measured through several calculation methods. Firstly, the secondary voltage can be calculated by using an oscilloscope. Secondly, based on the non-uniform breakdown theory to obtain the secondary voltage and lastly, by using theoretical calculations.

Because of the high voltage sparks from the high voltage toroid could not be observed, the secondary voltage will calculated by using theoretical calculations.

4.4.1 Theoretical Calculation

Theoretically, the energy stored in the secondary terminal can be calculated by assuming that there were no losses during the transferring of energy from primary to secondary due to the theory of conservation of energy. The energy stored in primary coil can be calculated as shown in equation 4.1. the theoretical secondary voltage obtained using the equation 4.2.

Energy stored in primary coil, $E_p = 0.5C_pV_p^{\ 2}$

$$
\begin{aligned}
&= 0.5 \times 4nF \times (6kV)^2 \\
&= 0.072\,J \qquad (4.1)
\end{aligned}
$$

Theoretical secondary voltage, V_s;

$$
\begin{aligned}
0.5C_pV_p^{\ 2} &= 0.5C_sV_s^{\ 2} \\
0.072 &= 0.5(C_{self} + C_{top})V_s^{\ 2} \\
0.072 &= 0.5(8.5\,p + 9.6\,p)V_s^{\ 2} \\
V_s &= 2.82\,kV \qquad (4.2)
\end{aligned}
$$

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The behaviour of Tesla coil was studied before the design works. The components of Tesla coil are power supply, tank capacitor, primary coil, secondary coil and toroid. In addition, the static spark gap was used as a switch in the Tesla coil. The components of Tesla coil were designed by using the TeslaMap Version 1.11 program. Five basic fundamental design parameters that were determined are output characteristic of high voltage transformer, size and dimension of primary coil, size of primary capacitor, size and dimensions of secondary coil, also size and dimensions of toroid. After that, the Tesla coil was constructed based on that parameters. The overall total cost for this project is RM 549.10. By using the theoretical calculations, the voltage at secondary coil is approximately 2.82 kV. Lastly, the constructed Tesla coil was tested to see the electrical discharge which occurs from the toroid to the surrounding air.

Testing was performed after the construction process was completed. The results show that the spark gap successfully performed the switching function as designed. However, the expected high voltage sparks from the high voltage toroid could not be observed. The corrective action could not be done because of the time constraint. However, the corrective action was suggested for the future improvement of this project.

5.2 Recommendation for Future Improvement

The corrective action need to be done to the Tesla coil because the expected high voltage sparks from the high voltage toroid could not be observed. The corrective actions for the future improvement are:

1. Review calculations for accuracy. If correct, try a different primary turn and run test. If no spark issues after retuning continue to next step.
2. Tuning point is generally different with and without terminal capacitance. The grounded director checks for secondary output > 30 *kV* (10 *kV*/*in*). If no spark issues continue to next step.
3. If winding passes visual inspection, continuity and inductance tests continue to next step. If not, repair discontinuity, crossed winding or insulation, or rewind secondary (also use a new form).
4. If calculation are correct try loosening the coupling by raising the base of the secondary a few inches at a time and run test.

Other than that, for better performance of the Tesla coil, a protection filter can be added into the circuit in which it is connected to the HV transformer output before being feed back to the tank capacitor. The purpose of this filter is to avoid distortion of voltage due to radiated noises. RF chokes is also included into the protection filter to prevent damage to the power supply (NST).

In addition, In addition, recommendation for future research is to study how to measure the secondary voltage to attain more accurate voltage at the top terminal of the secondary coil. This Tesla coil also can be a research purposes equipment for lightning renewable energy studies, electrical discharges, resonance and others.

REFERENCES

[1] Mitch Tilbury (2008). *The Ultimate Tesla Coil Design and Construction Guide*. New York: McGraw-Hill Companies.

[2] Naidu M.S., Kamaraju V.. (2004). High Voltage Engineering. New York: McGraw-Hill Companies.

[3] James E. Brittain (2005). Scanning Our Past. *Electrical Engineering Hall of Fame : Nikola Tesla*. 93(5), 1057-1059.

[4] Gary L. Johnson (1990). Building The World's Largest Tesla Coil. *History and Theory*. 343(4), 128-135.

[5] Tesla Coil Design, Construction and Operation Guide, http://www.teslacoildesign.com/

[6] Tesla Coils, Induction Coils, http://www.educypedia.be/electronics/electricitytesla.htm

[7] DeepFriedNeon – Tesla Coil, http://deepfriedneon.com/tesla_frame0.html

[8] Richie's Tesla Coil Web Page, http://www.richieburnett.co.uk/tesla.shtml

[9] Extreme Electronis – Tesla Coils – How They Work, http://www.extremeelectronics.co.uk/calcs/

[10] Classic Tesla Coil Design, http://www.classictesla.com/

[11] Tesla Coil, http://en.wikipedia.org/wiki/Tesla_coil

[12] Tesla Coil Construction Guide, http://www.teslamap.com/guide.html

[13] Tesla Coil Theory, http://www.GardenBallistics.co.nr

APPENDIX A

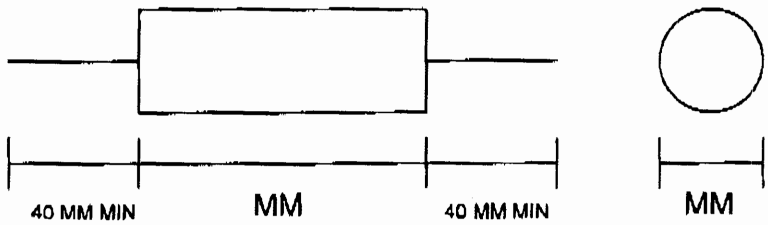
Specification of HV Capacitor

LCR CAPACITORS

LOW LOSS
POLYPROPYLENE
CAPACITORS
TYPE : PC / HV / S / WF

THESE LOW LOSS SERIES WOUND POLYPROPYLENE CAPACITORS ARE PARTICULARY SUITABLE FOR HIGH FREQUENCY APPLICATIONS.

THEY MAY BE OPERATED AT HIGH A.C. VOLTAGES AND WILL WITHSTAND EXCEPTIONALLY HIGH VOLTAGE RISE TIMES.



CHARACTERISTICS

CAPACITANCE	: 0.001 - 0.47 uF
CAPACITANCE TOLERANCE	: +/- 20%
RATED VOLTAGE	: 1000V, 1500V
TEMPERATURE RANGE	: -55°c TO +100°c
PULSE RATING	: 2000 V / us on 1500V
POWER FACTOR	: 0.0005 @ 1 K Hz
INSULATION RESISTANCE	: > 100,000 M

Working Voltage DC	Capacity (mfd)	Length (L - MM)	Diameter (D - MM)
1000V (350V.A.C) 50Hz	0.001	20.5	9
	0.0022	20.5	9
	0.0047	20.5	9
	0.01	20.5	9
	0.022	28	9.5
	0.047	28	12
	0.1	33	14.5
	0.22	33	20
	0.47	48	24
1500V (450V.A.C.) 50Hz	0.001	21	10
	0.0022	21	10
	0.0047	21	10
	0.01	28	10
	0.022	28	13
	0.047	33	16
	0.1	33	22
	0.47	48	33

*Derating above 70°C, details on application

Higher discharge rates possible with small capacity values, details on applications.

LCR ACPACITORS
UNIT 18 , RASSAU INDUSTRIAL ESTATE , EBBW VALE , GWENT , NP23 5SD
TEL. 01495 307070 FAX . 01495 306965

APPENDIX B

Specification of HV Resistor

HIGH VOLTAGE RESISTOR – HVR

FEATURES

- Metal film technology
- High pulse loading capability
- Small size
- Meeting safety requirements of:
  “UL1676” (HVR37 and HVR68, range 510 KΩ ~ 11 MΩ) - pending
  “IEC 60065
  “EN 60065”
  “VDE 0860”
  “BS 60065”

QUICK REFERENCE DATA

DESCRIPTION	HVR25		HVR37		HVR68	
Resistance range	100 kΩ - 22 MΩ	100 kΩ - 10 MΩ	100 kΩ - 33 MΩ	100 kΩ - 10 MΩ	100 kΩ - 10 MΩ	100 kΩ - 10 MΩ
Tolerance and series	±5%, E24	±1%, E24/E96	±5%, E24	±1%, E24/E96	±5%, E24	±1%, E24/E96
Maximum dissipation at T_{amb} = 70 °C	0.25 W		0.50 W		1 W	
Limiting voltage DC RMS	 1600 V 1150 V		 3500 V 2500 V		 10000 V 7000 V	 10000 V 7000 V
Temperature coefficient	±200 ppm/°C					
Basic specification	IEC60115-1 and 60115-2					
Climatic category (IEC 60068)	55/155/56					
Stability $\Delta R/R_{max}$ after:						
Load (1000 h)	±5% +0.1Ω	±1.5% +0.1Ω	±5% +0.1Ω	±1.5% +0.1Ω	±5% +0.1Ω	±1,5% +0.1Ω
Climatic tests	±1.5% +0.1Ω	±1.5% +0.1Ω	±1.5% +0.1Ω	±1.5% +0.1Ω	±1.5% +0.1Ω	±1.5% +0.1Ω
Resistance to soldering heat	±1% +0.1Ω	±1% +0.1Ω	±1% +0.1Ω	±1% +0.1Ω	±1% +0.1Ω	±1% +0.1Ω

TECHNOLOGY

A multi layer metal film is deposited on a high-grade ceramic body. After a helical groove has been cut in the resistive layer, tinned electrolytic copper wires are welded to the end-caps. The resistors are coated with a blue lacquer, which provides electrical, mechanical and climatic protection. The coating is resistant to all cleaning solvents in accordance with "MIL-STD 202, method 215" and "IEC 60068-2-45".

MECHANICAL DATA

AXIAL STYLE

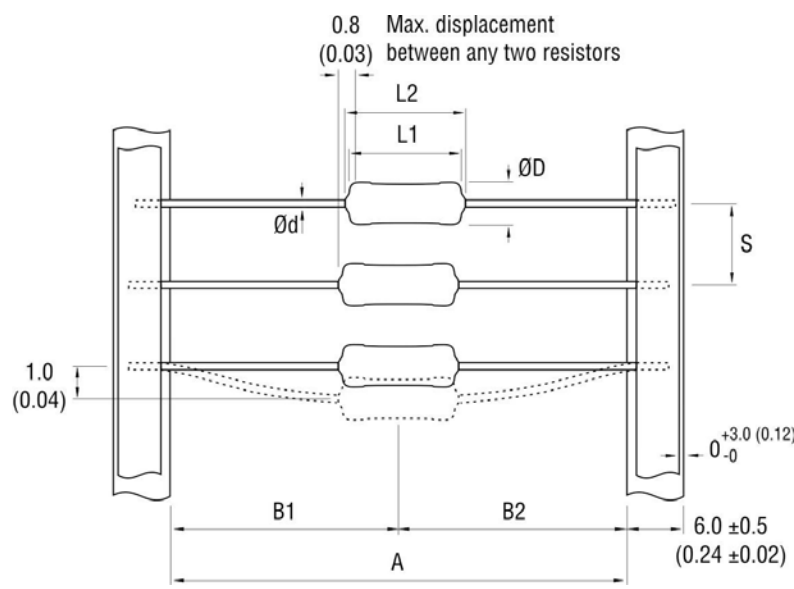


Table 1. Mechanical data.

PRODUCT	L1 max.	L2 max.	ØD max.	Ød	A	|B1 - B2| max.	S	WEIGHT gr/100 pcs
HVR25	6.5 (0.26)	7.5 (0.30)	2.5 (0.10)	0.58 ±0.05 (0.023 ±0.002)	52.5 ±1.5 (2.07 ±0.06)	1.2 (0.05)	5.0 ±0.1 (0.20 ±0.01)	22.0
HVR37	10.0 (0.40)	12.0 (0.47)	4.0 (0.16)	0.80 ±0.03 (0.031 ±0.001)	52.5 ±1.5 (2.07 ±0.06)			50.0
HVR68	16.7 (0.66)	19.5 (0.77)	5.2 (0.21)	0.80 ±0.03 (0.031 ±0.001)	63.0 ±1.5 (2.48 ±0.06)		10.0 ±0.1 (0.40 ±0.01)	110.0

Dimension unless specified in mm (inches)

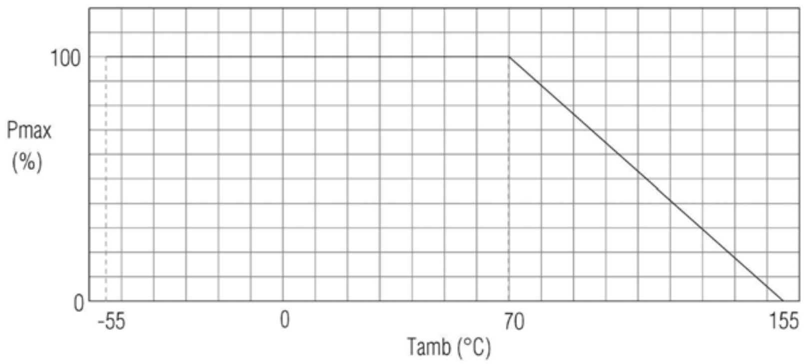
MOUNTING

The resistors are suitable for processing on automatic insertion equipment, cutting and bending machines.

ELECTRICAL CHARACTERISTICS

DERATING

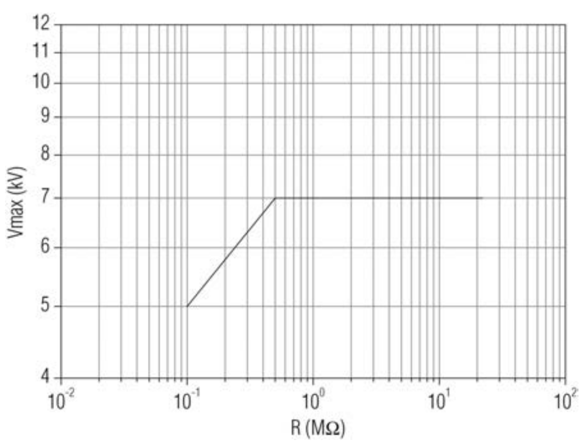
The power that the resistor can dissipate depends on the operating temperature.



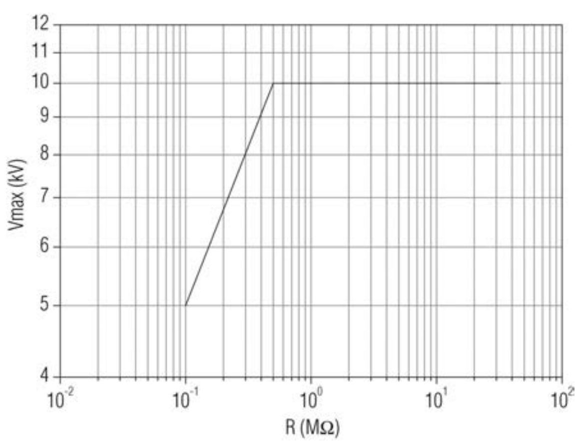
Maximum dissipation (P_{max}) in percentage of rated power as a function of ambient temperature (T_{amb})

PULSE LOADING CAPABILITY

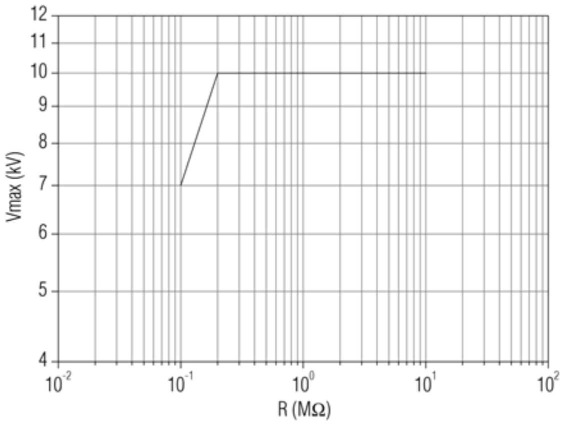
Maximum allowed peak pulse voltage in accordance with "IEC 60065 chapter 14.1"; 50 discharges from a 1 nF capacitor charged to V_{max}; 12 discharges/minute.



HVR25
$\Delta R/R_{max}$ ± 4.0% +0.1Ω



HVR37
For 5% tolerance ➔ $\Delta R/R_{max}$ ± 4.0% +0.1Ω
For 1% tolerance ➔ $\Delta R/R_{max}$ ± 2.0% +0.1Ω



HVR68
$\Delta R/R_{max}$ ± 2.0% +0.1Ω

MARKING

The nominal resistance and tolerance are marked on the resistor using four or five colored bands in accordance with IEC publication 60062 "Color code for fixed resistors". Standard values of nominal resistance are taken from the E24/E96 series for resistors with a tolerance of ±5% or ±1%. The values of the E24/E96 series are in accordance with IEC publication 60063.

ORDERING INFORMATION

Table 2. Ordering code.

PRODUCT	TOLERANCE	ORDERING CODE	TAPING	LEAD ∅	PACKAGING	QUANTITY (pcs)
HVR25	±5%	2306 241 13xxx	52.5 (2.07)	0.58 Cu (0.023)	AMMOPACK	1000
		2306 241 53xxx			AMMOPACK	5000
		2306 241 23xxx			REEL	5000
	±1%	2306 241 8xxxx	52.5 (2.07)		AMMOPACK	1000
		2306 241 7xxxx			AMMOPACK	5000
		2306 241 6xxxx			REEL	5000
HVR37	±5%	2306 242 13xxx	52.5 (2.07)	0.80 Cu (0.031)	AMMOPACK	1000
		2306 242 23xxx			REEL	5000
	±1%	2306 242 8xxxx	52.5 (2.07)		AMMOPACK	1000
		2306 242 6xxxx			REEL	5000
HVR68	±5%	2306 244 13xxx	63.0 (2.48)	0.80 Cu (0.031)	AMMOPACK	500
	±1%	2306 244 8xxxx				

Dimensions unless specified in mm (inches)

Table 3. Last digit of ordering code

RESISTANCE DECADE (5%)	RESISTANCE DECADE (1%)	LAST DIGIT
100 - 910 kΩ	100 - 976 kΩ	4
1 MΩ	1 MΩ	5
≥ 10 MΩ	≥ 10 MΩ	6

Example:

HVR25, 150 kΩ, ±5%, ammopack 1000 pcs is
2306 241 13154

The resistors have a 12 digit ordering code starting with 2306.
The next 4 or 5 digits indicate the resistor type and packaging see table 2.
For 5% tolerance the last 3 digits indicate the resistance value:
- The first 2 digits indicate the resistance value;
- The last digit indicates the resistance decade in accordance with table 3.

For 1% tolerance the last 4 digits indicate the resistance value:
- The first 3 digits indicate the resistance value;
- The last digit indicates the resistance decade in accordance with table 3.

NAFTA ORDERING INFORMATION

Table 4. NAFTA ordering code.

PRODUCT	TOLERANCE	NAFTA ORDERING CODE	TAPING	LEAD ∅	PACKAGING	QUANTITY (pcs)
HVR25	±5%	5043HVxxxxxJ08AFX	52.5 (2.07)	0.58 Cu (0.023)	AMMOPACK	1000
		5043HVxxxxxJ18AFX			AMMOPACK	5000
		5043HVxxxxxJ12AFX			REEL	5000
	±1%	5043HVxxxxxF08AF5	52.5 (2.07)		AMMOPACK	1000
		5043HVxxxxxF18AFX			AMMOPACK	5000
		5043HVxxxxxF12AFX			REEL	5000
HVR37	±5%	5053HVxxxxxJ08AFX	52.5 (2.07)	0.80 Cu (0.031)	AMMOPACK	1000
		5053HVxxxxxJ12AFX			REEL	5000
	±1%	5053HVxxxxxF08AF5	52.5 (2.07)		AMMOPACK	1000
		5053HVxxxxxF12AFX			REEL	5000
HVR68	±5%	5073HVxxxxxJ08AFX	63.0 (2.48)	0.80 Cu (0.031)	AMMOPACK	500
	±1%	5073HVxxxxxF08AFX				

Dimensions unless specified in mm (inches)

Table 5. Examples of the ohmic value.

VALUE	5 DIGITS
1 Ω	1R000
10 Ω	10R00
100 Ω	100R0
1 kΩ	1K000
10 kΩ	10K00
100 kΩ	100K0
1 MΩ	1M000

The ohmic value in the NAFTA ordering code (see table 4) is represented by the "xxxxx" in the middle of the above ordering code. Table 5 gives some examples on how to use these 5 digits.

Example:
HVR25, 150kΩ, ±5%, ammopack 5000pcs is
5043HV150K0J18AFX

TAPE IN AMMOPACK

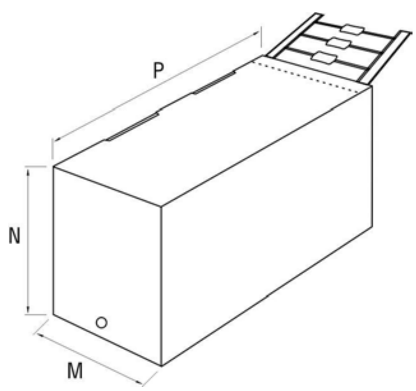


Table 6. Ammopack.

PRODUCT	TAPING	M	N	P	QUANTITY (pcs)
HVR25	52.5 ±1.5 (2.07 ±0.06)	82 (3.3)	28 (1.2)	262 (10.4)	1000
	52.5 ±1.5 (2.07 ±0.06)	78 (3.1)	100 (4.0)	260 (10.3)	5000
HVR35	52.5 ±1.5 (2.07 ±0.06)	78 (3.1)	60 (2.4)	262 (10.4)	1000
HVR68	63.0 ±1.5 (2.48 ±0.06)	86 (3.4)	66 (2.6)	260 (10.3)	500

Dimensions unless specified in mm (inches)

TAPE ON REEL

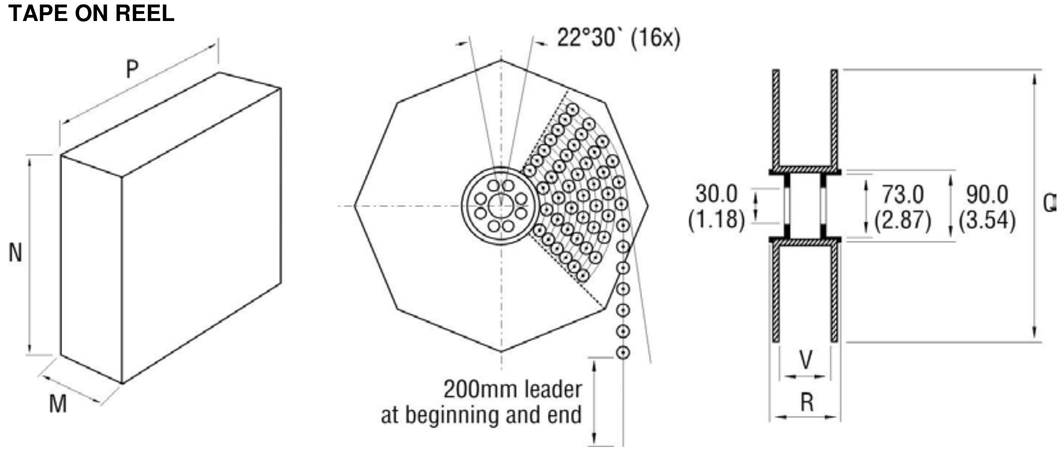


Table 7. Reel.

PRODUCT	TAPING	M	N	P	Q	V	R	QUANTITY (pcs)
HVR25	52.5 ±1.5 (2.07 ±0.06)	92 (3.7)	311 (12.3)	311 (12.3)	305 (12.1)	75 (3.0)	86 (3.4)	5000
HVR37	52.5 ±1.5 (2.07 ±0.06)	92 (3.6)	361 (14.3)	361 (14.3)	355 (14.0)	75 (2.9)	86 (3.4)	5000

Dimensions unless specified in mm (inches)

TESTS AND REQUIREMENTS

Essentially all tests are carried out in accordance with the schedule of IEC publications 60115-1, category 55/155/56 (rated temperature range -55℃ to +155℃; damp heat, long term, 56 days and along the lines of IEC publications 60068-2); Recommended basic climatic and mechanical robustness testing procedure for electronic components and under standard atmosphere conditions according to IEC 60068-1 subclause 5.3, unless otherwise specified.
In some instances deviations from the IEC recommendations were necessary for our specified method.

Table 8. Test and requirements.

IEC 60115-1 CLAUSE	IEC 60068-2 TEST METHOD	TEST	PROCEDURE	REQUIREMENTS		
				HVR25	HVR37	HVR68
4.6.1.1	-	Insulation resistance	500 V (DC) during 1 minute; V-block method.	$R_{ins\ min}$ 10^4 MΩ		
4.7	-	Voltage proof on insulation	700 V (RMS) during 1 minute, V-block method.	No breakdown or flashover		
4.8	-	Temperature coefficient	Between -55 ℃ and +155 ℃	±200 ppm/℃		
4.12	-	Noise	"IEC publication 60195"	Max. 5 µV/V	Max. 2.5 µV/V	
4.13	-	Short time overload	Room temperature; dissipation 6.25 x Pn (voltage not more than 2 x limiting voltage, 10000 V_{max}); 10 cycles; 5 s ON and 45 s OFF	For 5% tolerance ➔ $\Delta R/R_{max}$ ±2.0% +0.1Ω For 1% tolerance ➔ $\Delta R/R_{max}$ ±1.0% +0.1Ω		

IEC 60115-1 CLAUSE	IEC 60068-2 TEST METHOD	TEST	PROCEDURE	REQUIREMENTS		
				HVR25	HVR37	HVR68
4.16	21 (U)	Robustness of terminations:				
4.16.2	21 (Ua1)	Tensile all samples	Load 10 N, 10 s	No damage $\Delta R/R_{max}$ ±1.0% +0.1Ω		
4.16.3	21 (Ub)	Bending half number of samples	Load 5 N, 4 X 90°			
4.16.4	21 (Uc)	Torsion other half of samples	3 x 360° in opposite directions			
4.17	20 (Ta)	Solderability (after ageing)	16 h at 155 °C; immersed in flux 600, leads immersed 2 mm for 2 ±0.5 s in a solder bath at 235 ±5 °C	Good tinning (≥ 95% covered) No damage		
4.18	20 (Tb)	Resistance to soldering heat	Thermal shock: 3 s; 350 ±10 °C; 6 mm from body	$\Delta R/R_{max}$ ±1.0% +0.1Ω		
4.19	14 (Na)	Rapid change of temperature	30 minutes at - 55 °C and 30 minutes at + 155 °C; 5 cycles	No visual damage $\Delta R/R_{max}$ ±1.0% +0.1Ω		
4.22	6 (Fc)	Vibration	Frequency 10 to 500 Hz, displacement 1.5 mm or acceleration 10 g; three directions; total 6 h (3x2 h)	No damage $\Delta R/R_{max}$ ±1.0% +0.1Ω		
4.23		Climatic sequence:		$R_{ins\ min}$ 10^3 MΩ $\Delta R/R_{max}$ ±1.5% +0.1Ω		
4.23.2	2 (Ba)	Dry heat	16 h; 155 °C			
4.23.3	30 (Db)	Damp heat (accelerated) 1st cycle	24 h; 25 °C to 55 °C; 90 to 100% RH			
4.23.4	1 (Aa)	Cold	2 h; - 55 °C			
4.23.6	30 (Db)	Damp heat (accelerated) remaining cycles	5 days; 25 °C to 55 °C; 90 to 100% R.H.			
4.24	3 (Ca)	Damp heat (steady state)	56 days; 40 °C; 90 to 95% R.H. loaded with 0.01Pn	$R_{ins\ min}$ 10^3 MΩ For 5% tolerance → $\Delta R/R_{max}$ ±5.0% +0.1Ω For 1% tolerance → $\Delta R/R_{max}$ ±1.5% +0.1Ω		
4.25.1	-	Endurance (at 70 °C)	1000 h loaded with Pn or V_{max}; 1.5 h ON and 0.5 h OFF	For 5% tolerance → $\Delta R/R_{max}$ ±5.0% +0.1Ω For 1% tolerance → $\Delta R/R_{max}$ ±1.5% +0.1Ω		
4.29	45 (Xa)	Component solvent resistance	Isopropyl alcohol followed by brushing in accordance with MIL STD 202	No visible damage		