DEVELOPMENT OF A SURGE PROTECTOR SUITABLE FOR EQUATORIAL BELT COUNTRIES

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Degree of Master of Science in Industrial Automation

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Dissertation submitted in partial fulfilment of the requirements for the Degree Master of Science in Industrial Automation

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DECLARATION OF THE CANDIDATE & SUPERVISOR

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Prof. J.R. Lucas

Signature of the supervisor: …………………. Date :
Dr. D.P. Chandima

DEDICATION

I dedicate this thesis to Mr. Buddhika Ranatunga, my husband for his endless encouragement and patience and to Mr. Nissanka & Mrs.Ramyalatha, my parents for earning an honest living for us and for supporting and encouraging me, to believe in myself and for nursing me with affections and love and their dedicated partnership for success in my life.

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Lastly, I should thank many individuals, friends and colleagues who have not been mentioned here personally in making this educational process a success. I could not have made it without your support.

ABSTRACT

In most tropical countries like Sri Lanka, lightning activity is high and can cause severe damage to equipment within buildings. Thus lightning surges should be prevented from entering sensitive equipment by installing high quality surge protection devices. Traditionally, surge protection circuits use non-linear devices to clamp the overvoltage. However, typical non-linear devices have low relatively short duration energy absorption ratings and cause the life of the surge protection device to decrease.

As it is known that supercapacitors have large continuous energy storage capabilities, a supercapacitor based surge energy absorption technique has been developed by combining a multi-winding magnetic component with a typical non-linear device in a novel configuration. This research presents an overview of new supercapacitor technique and the basis for selecting the magnetic core required so that the supercapacitor sub-circuit works effectively.

Selection of the magnetic core is critical for the success of the technique, since the combination of the leakage and magnetizing components of the multi-winding magnetic core plays a dominant role. Experimental results generated using a lightning surge simulator with surge capability up to 6 kV/3 kA are used to validate the results. Overall performance of this technique with optimized magnetics is compared with a typical commercially available surge protector, which is practically used to safeguard electronic systems against transient over-voltage related power quality issues.

This technique utilizes a multi-winding transformer, common surge protector devices such as metal oxide varistors combined with a supercapacitor sub-circuit to absorb part of the surge energy usually expected to dissipate within the metal oxide varistor and improve the life of the surge protective device. Also the output clamping voltage is controlled to a lower value to give better protection for the equipment.

Test results clearly indicate, the supercapacitor assisted surge protective device has a much higher energy absorption capacity than tested commercial products and can be used in commercial surge protectors with better performance than traditional surge protectors with higher component counts.

Keywords: Lightning Protection, Supercapacitor, Metal Oxide Varistor, Non Linear Device

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LIST OF ABBREVIATIONS

Abbreviation	Description
BBD	Bidirectional Break-Over Diode
HV	High Voltage
MOV	Metal Oxide Varistor
NLD	Nonlinear Device
SC	Supercapacitor

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1 INTRODUCTION

1.1 Background

Lightning is a huge discharge originating in cumulonimbus clouds. As is seen in figure 1, they can occur within a cloud, between clouds, down to earth or just expend their charge in air. Fortunately in the tropics, only about 10 % of the discharges terminate on the earth or earth bound object. However, even this 10% can cause a disaster, and these disasters have occurred in a cyclical pattern in the world.

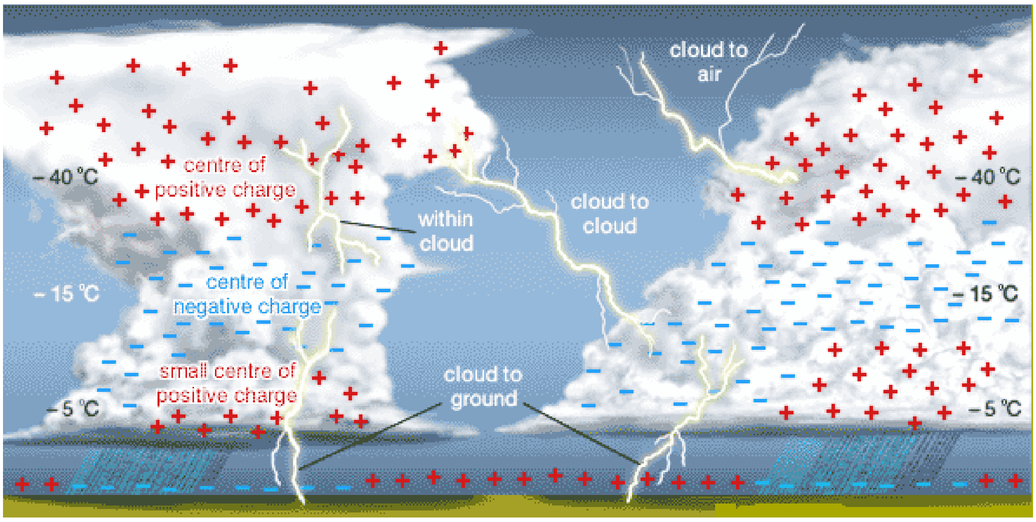


Figure 1.1: Propagation of lightning channel

Lightning causes damage to buildings, electronic and other equipment as well as causing injury and even death to people and livestock. This may be compared to typical temperate climates where the thunder days may be low, around 25 or 30 per year. Since the majority of high technology specialized military, communications, navigational and switching equipment is designed and generally manufactured in these temperate countries, scant regard is often paid to the need to protect this equipment from the devastating effects of lightning strikes whether they be direct or indirect. For this reason lighting protection against both direct and indirect lighting strikes at critical communications and navigational aid sites in tropical regions of the world should perhaps be mandatory.

In most tropical countries, lighting and storm activity is high, compared to the more temperate regions of the world. For example in the equatorial belt, ten degrees north and south of the equator, thunder day statistics may vary from 150 to 200 days per year.

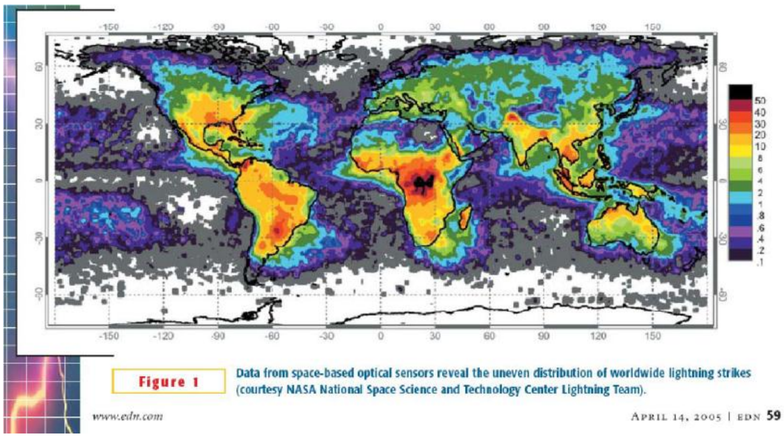


Figure 1.2: Lightning distribution in the world
Source : EDN Magazine, Aprl14, 2005

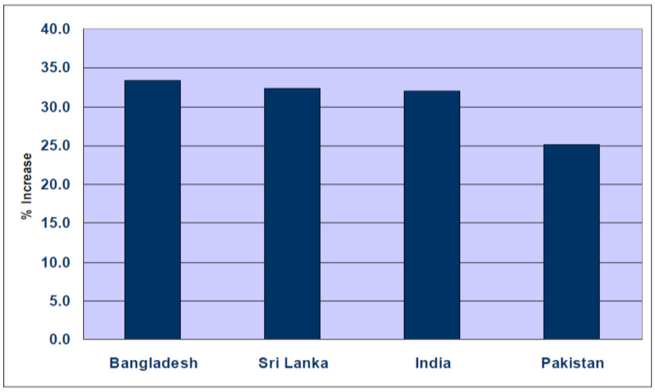


Figure 1.3: Percentage increase in storm surge zone, SAR Region
Source : Sea-Level Rise and Storm Surges: A Comparative Analysis Of Impacts in Developing Countries

When lightning strikes, a human being may be killed, badly injured or spared with some skin burns. When lightning strikes a building, it may explode, catch fire or left with few cracks on the walls. However, most often when a building is lightning struck, many of the electrical and electronic appliances housed in the building will be destroyed. Equipment may also be damaged by large current pulses that may come through service lines such as electricity and telephone.

In order to protect buildings against lightning, a structural protection system should be installed at the building. These do not protect domestic appliances which can usually be protected from lightning currents by unplugging them from service lines during thunderstorm periods. However, such an act is not realistic in most of the industrial and service sectors as even a short period of out-of-operation could cost the company a few million rupees. Therefore in such cases, lightning surges should be prevented from entering the building, or in particular sensitive equipment.

This is done by installing surge protection devices (SPDs) to the power and communication lines. In the case of surge protection, both the quality of the product and the engineering of installation are equally important. It should be remembered that the provision of lighting protection both against direct strikes and indirect effects will only improve lighting immunity.

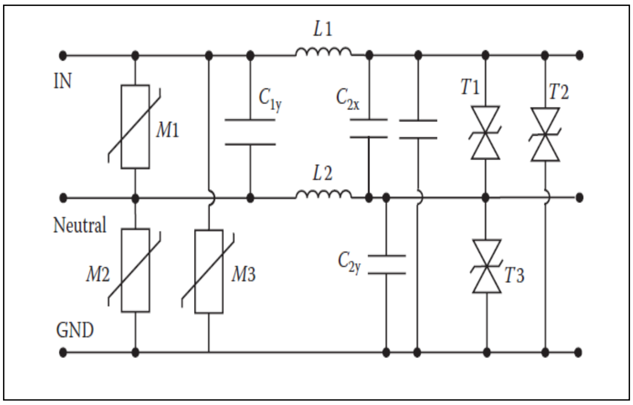
It is unlikely that 100% protection can ever be achieved even by proper design at an early stage before equipment installation. It can both reduce later costs and substantially improve protection in the longer term. Most common surge protectors consist of non-linear devices in the market do not work well during monsoon lightning times in equatorial belt countries like Sri Lanka and many other parts of the world due to their failure of components, such as capacitors. The use of high value capacitors (supercapacitors) could probably overcome some of these problems as they reduce the spikes.

A supercapacitor (SC) is a high-capacity electrochemical capacitor, with capacitance values much higher than other capacitors, but in lower voltage limits. It has the ability to absorb high-voltage (HV) transient surges with a short-duration occurrence. Early researchers[3] have shown that a supercapacitor is not destroyed by the repeated application of HV transients and the gradual voltage rise across terminals after each hit is in the order of millivolt This also indicates that the device still retains its capacitive behaviour and not adversely affected by the transient HV at the terminals. Therefore a supercapacitor can be used to absorb part of the surge energy in the SPD during a transient traveling through the incoming mains or the telecom/data circuits.

1.2 Problem Statement

1.2.1 Typical Surge protector circuit

Figure 1.4 shows a typical surge protector circuit with nonlinear devices (NLDs) such as metal oxide varistors (MOVs) and bidirectional break-over diodes (BBDs), coupled with LC-type filter stages. Depending on the level of protection required, different sizes of NLDs are used in varied versions of this general configuration.



(a)

(b)

Figure 1.4: Typical Surge Protective Device

Figure 1.4 (a) is a circuit which is designed to protect against both common and differential mode transients. M1 to M3 are MOVs that will enter their firing or conduction mode when the transient exceeds the threshold voltage limit. Inductors L1 and L2 acts high impedances for the transient signal. Similarly, the capacitors Cnx and Cny act as low impedance paths to the transient signal. The overall effect of these circuitry is to minimize the transfer of the transient voltage toward the critical load side. Figure 1.4 (b) represents its PCB arrangement and the component arrangement of the typical surge protective device.

1.2.2 Associated Problems

Power surges can cause failure, permanent degradation, or temporary malfunction of electronic devices and systems. The development of an effective surge protective device is of paramount importance to manufacturers and users of industrial electronic equipment.

When a HV surge such as a lightning gets induced on the wire pairs (differential form on the live-neutral pair, common mode on neutral-earth or live-earth pairs), if the peak voltage of the induced voltage exceeds the firing voltage of the corresponding MOV. It fires and starts conducting a high instantaneous current. A maximum voltage termed as clamping voltage develops across the terminals of the MOV and the MOV starts absorbing the surge energy based on the voltage current product over the period of the surge. Table 1 shows the comparison of common TVS (Transient Voltage Suppression) devices.

Suppression Element	**Features**	**Expected Life**
GDT (Gas Discharge Tube)	Very high current handling capability Low capacitance High insulation resistance Slow response time	Limited
MOV (Metal Oxide Varistor)	High current handling capability Broad current & voltage spectrum High clamping voltage Gradual degradation	Degrades
TVS diodes	Low clamping voltage Extremely fast response Does not degrade Limited surge current rating	Long limited
Spark Gaps	Slow to conduct Require high initiating voltage to form the arc	Degrades
Fuse	Less reliability Suffer aging from mechanical shock	Age over a period of a few years

Table 1.1 : Comparison of TVS devices

1.2.3 Problem statement

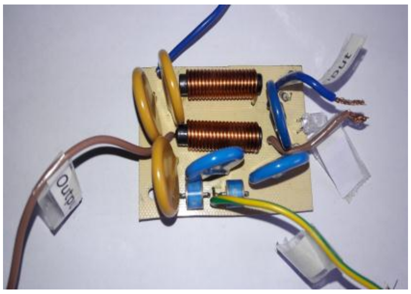
Overall, a surge protector that absorbs the energy of the HV transient is designed on the basis of transient energy absorption capability of the NLDs used. In general, these NLDs are characterized by their transient energy absorption rating given for a short duration such as few milliseconds, which is typically related to transients lasting less than about 100–200 microseconds. During this time, the NLD heats up due to the absorbed transient energy, while maintaining the clamping voltage across the device. However, if repeated high-energy transients keep firing the NLD, device's transient energy absorption rating (Joule rating) will be exceeded and device ends up in a failure.

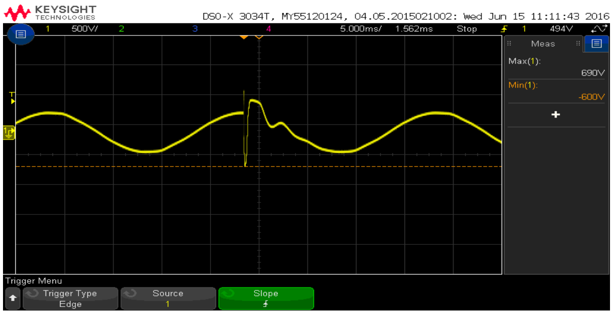
In most general cases of MOVs, every time a transient is absorbed by the device, it deteriorates gradually, and after a limited period of time, its surge absorption capability could be totally lost.

1.3 Typical designs of SPDs

Some typical designs of SPDs are shown in figure 1.5.

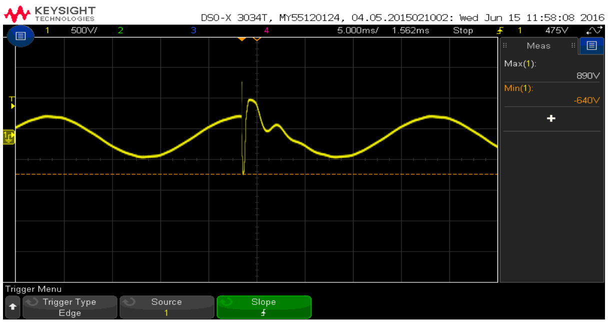
MOV+GDT





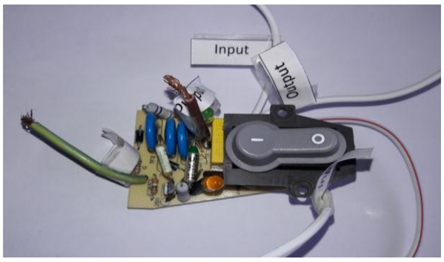
Output clamping voltage = 690 V

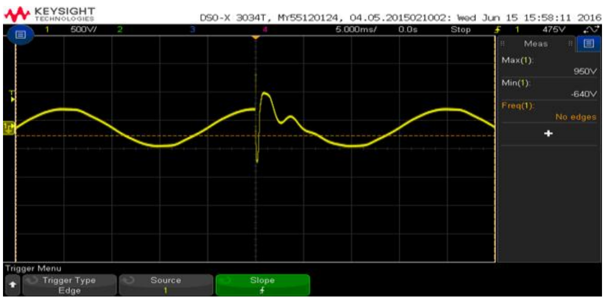
MOV + Spark Gaps



Output clamping voltage = 890 V

MOV + 15A Fuse





Output clamping voltage = 950 V

Figure 1.5: Typical designs of SPDs

In those typical designs, there is no other way to absorb part of the surge energy apart from the available non-linear devices such as MOV, GDT and spark gaps. Therefore, their life time is much more less than the proposed design of this research.

In this thesis, a supercapacitor-based SPD includes NLDs is proposed for the class III type protection level which overcomes the identified problem.

1.4 Objectives

The main objective of this research is to develop and implement a super-capacitor assisted surge absorber to improve the performance of a surge protective device by diverting the surge energy from the non-linear device in the SPD to improve its life time and to minimize the clamping voltage across the critical load to be protected.

2 LITERATURE REVIEW

Surge voltages occurring in low-voltage ac power circuits have two origins; external surges, produced by power system switching operation or by lightning, and internal surges produced by switching of loads within the local system. Typical voltage levels of these surges are sufficient to cause the failure of sensitive electronic appliances or devices, and high surges can cause the failure of rugged electromechanical devices such as clocks, motors, and heaters. However, lightning and other external sourced power disturbances rank high on the list of uncontrollable events that have shut down facilities in recent years.

Equipment damage cause by lightning strike was been a hot topic for a quite long ago especially in tropical region. Due to certain component sensitivity level was decreased, so that components easily failed.

The research paper[1] based on **"Satellite Communication Equipments Reliability And Lightning Surge Measurement Results"**, provides that the system facing a wear out zone where the hazard rate is increasing by using satellite equipments reliability calculation. So the appropriate protection level for these equipments to survive during lightning strike would be a challenge. However in this tropical country the study on statistical data for lightning occurrence probability and standardization is fewer even though they experiences on high lightning coupling methods promoting more than activities of 200-240 thunderstorm days / year.

Annual equipment's damage statistical is recorded and illustrated in Fig 2.1 for the year 2003. This damages was been quantified as the damaging due to lightning strike. The damages counted on higher number for May and August. The damaging equipment can be correlated with the raining monsoon lightning activities which is the evening raining season would be a good reason for the damaging.

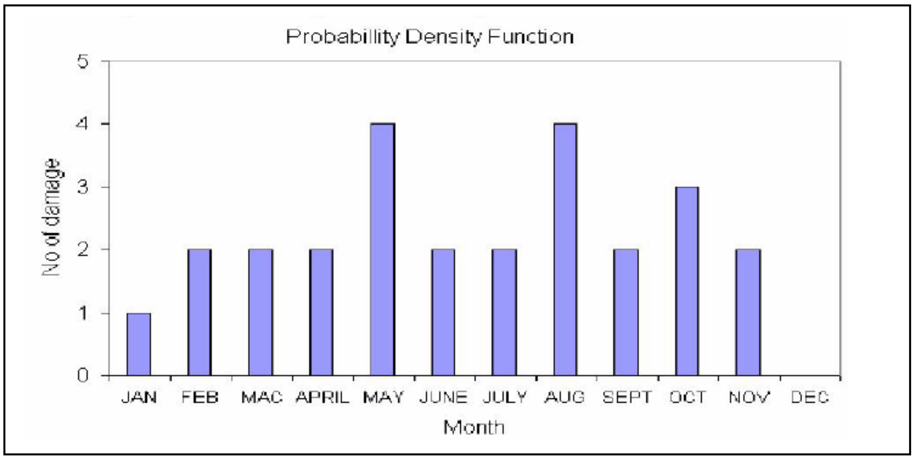


Figure 2.1: Histograms of Annual Damage by lightning strike for a year 2003

There are several SPDs available, utilizing different overvoltage-protection technologies and topologies. The commercially available SPDs significantly differ in terms of their surge handling capabilities and the level of protection they provide. Field experience has revealed serious safety issues related to the SPD operation, particularly during its end of life situation.

The research paper[5] based on **"A Tutorial On The Selection And Installation Of Surge Protection Devices In A TT Wiring System ",** provides an easy-to-understand guidance for the selection and installation of transient protection devices & several fringe issues with respect to surge protection. The information presented can be used as educational material that guides electrical engineers in addressing lightning protection issues of Low Voltage power systems.

The low voltage power line SPDs are most often connected in shunt. In a TT wiring system shown in figure 2.2 which is the most practiced in the South Asian region, SPDs are recommended to be connected in one of the two arrangements as shown in Figure 2.3. Out of the two arrangements, the connection type two has a wider usage among many engineers in the region.

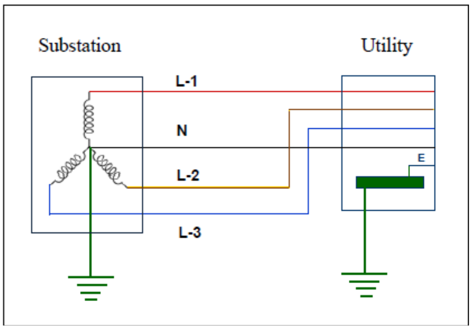


Figure 2.2: TT wiring system

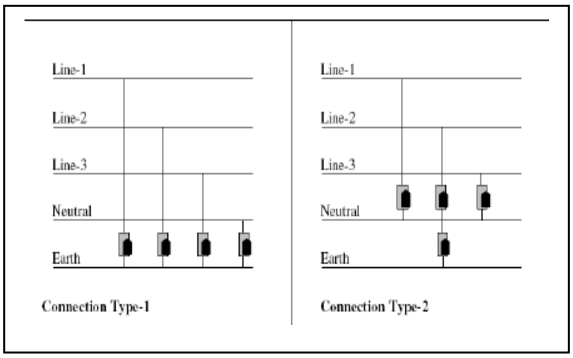


Figure 2.3 : Two types of SPD connections in a TT wiring system

Due to several reasons, SPDs are needed to be connected to the LV system at several stages in a given building. This scenario of connecting SPDs in several stages is known as the “Zonal Concept” as shown in figure 2.4.

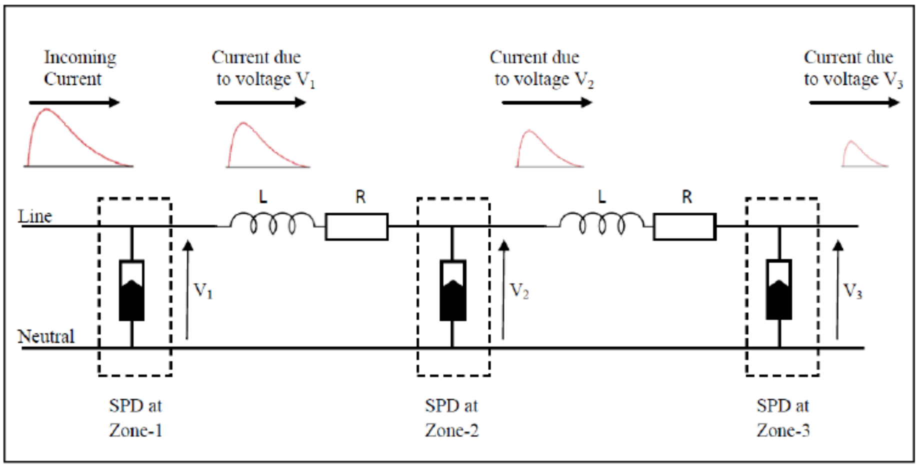


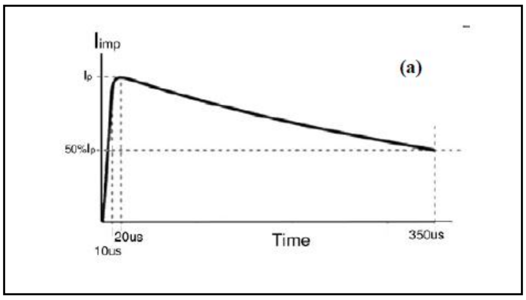
Figure 2.4: Concept of zonal protection

The most exposed zone, closer to the power entry point (usually the main power panel) and power outreaching points is termed Zone-1. The Zone-2 is usually the sub panels to which only partial lightning currents or reduced voltage impulses reach and Zone-3 is the power socket level which experiences even lower lightning energy.

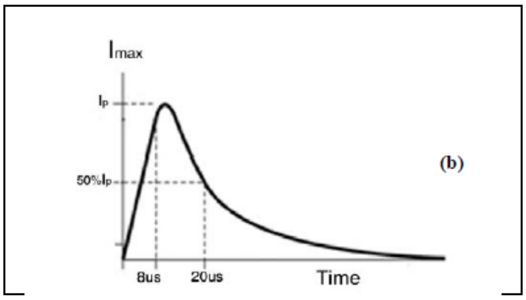
The surge protective devices are usually referred by their impulse current handling capacity. The more logical way is to refer them by the zone at which they should be connected. The IEC 62305 (2006) Standards specify two current impulse waveforms (figure 2.5) for the testing of surge protective devices (Table 2.1).

Zone / Class	Current waveform
Zone-1 / Class I	tested for 10 / 350 µs current impulse
Zone-2 / Class II	tested for the 8 / 20 µs current impulse
Zone-3 / Class III	

Table 2.1: Impulse current waveforms



(a) 10 / 350 µs impulse



(b) 8 / 20 µs impulse

Figure 2.5 : Two current test waveforms

With over 10 years' experience in the South Asian region in recommending SPDs for various types of buildings, they have developed the following table of specifications for the current handling capacity of SPDs which provides reasonably good outcome (Table 2.2). The specifications have been refined by taking into account the performance of SPDs over 200 installations in the region.

Location	**High lightning density areas (Current in kA/Phase)**	**Low lightning density areas (Current in kA/Phase)**
Main panel * (Zone-1)	40 (Low risk) 60 (High risk)	30 (Low risk) 40 (High risk)
Sub-panels ** (Zone-1)	30 (Low risk) 40 (High risk)	15 (Low risk) 20 (High risk)
power feeder level ** (Zone-3)	07 (Low risk) 15 (High risk)	03 (Low risk) 07 (High risk)

Table 2.2: The current handling capacity of SPDs.

Low Risk: domestic, offices, factories, non-essential service providers etc.

High Risk: hospitals, power generation and distribution, communication, broadcasting and other essential service providers

High lightning density areas: Areas where isokeraunic (lightning activity in an area based upon the audible detection of thunder) level is greater than 80 thunder days/year

Low lightning density areas: Areas where isokeraunic level is less than 80 thunder days/year

* For 10 / 350 µs current impulse   ** For 8 / 20 µs current impulse

Another important factor that should be considered in selecting SPDs is the "Voltage Protection Level" or simply the "Protection Level". This is the maximum let-through voltage that will appear across the line and neutral (differential mode voltage) and that between the neutral/line and the earth (common mode voltage). Any given electronic equipment has a certain impulse withstanding voltage beyond which the equipment will undergo permanent damage or temporary malfunctioning. This tolerable level should significantly be higher than the voltage protection level of the SPDs that one selects to protect the equipment. Therefore, SPDs with lower value of voltage protection level is better than that with a higher value.

The manufacturer should specify the voltage protection level of an SPD at Zone-1 and Zone-2 (Class I and class II SPDs) by applying the maximum current waveform (8 µs / 20 µs) that it is rated for. The SPDs at Zone-3 (class III) should be tested by applying the so called combinational waveform which produces 8 / 20 µs short circuit current waveform and 1.2 / 50 µs open circuit voltage waveform from an impulse generator.

The class III SPD should be subjected to such a waveform with peak values 3 kA and 6 kV respectively and the output should be less than 0.6 kV as per the IEC 62305-4 (2006). As in Figure 2.4, it is the output voltage of the Class III SPD (at Zone-3), that will appear across the equipment to be protected. Hence in a properly coordinated surge protection network, the voltage protection level of Class III SPD plays the most vital role in safeguarding the protected equipment.

Lightning impulses may have rise times that are in the order of sub-microseconds. Therefore the SPD should have appreciable speed in switching from high impedance to low impedance mode. The response time of a SPD depends basically on its constituent components. SPDs are primarily made by one or more of the following components

- Spark gaps or gas discharge tubes (GDT)
- Metal Oxide Varistors (MOV)
- Zener Diodes or Silicon Avalanche Diodes (SAD)

In addition some other linear and non-linear devices such as, capacitors, inductors and positive temperature coefficient resistors (PTCR) etc are also included in the circuits to improve the performance.

The three basic components have their own advantages and drawbacks. The current handling capacity and the response time increase in the order of SAD, MOV and GDT. The increment of the former characteristic is an advantage while that of the latter is a disadvantage. Hence, in most of the products the components are combined to improve the overall performance. Thus, the end-product response time may be different from the response time of any of the individual components.

Under no-impulse conditions, the SPD remains almost open circuited. However, if the operating voltage (e.g. 230 V rms) is increased to a higher value for few cycles (due to some fault) there is a chance that the SPD may switch into low impedance mode. The SPD goes through this transition at few kilovolts under impulse conditions but at much lower voltage at 50 Hz. If such transition takes place, a large current under nearly operating voltage will flow through the SPD which is not made to withstand such high energy. As a result the SPD may be totally damaged.

The maximum of such operating voltage, only under which the SPD is safe, is termed the maximum continuous operating voltage (MCOV). As per the standards IEC 62305-4 (2006), the MCOV should be above 110% of the operating voltage. In most of the European countries an MCOV of 270 V is recommended for MOV based SPDs. However, in countries where the power quality is not very reliable (significantly fluctuating voltage) a value of 300 V or 320 V is more appropriate. It can be shown that the larger the value of MCOV, the greater the let-through voltage of the SPD. Therefore, it is always advisable to select an SPD with the least MCOV that can withstand a power quality of a given region.

The research paper[2] based on, "**Electrical Surge-Protection Devices for Industrial Facilities**", provides an overview of the critical issue of overvoltage protection for industrial electronic applications and the commercially available surge-protection technologies designed for industrial applications.

It is a common practice in the surge protection industry to install protection devices in parallel to achieve a higher rating than just one device. A typical example of a parallel MOV technology is shown in figure 2.6. It is also commonly assumed that the surge performance of a number of devices is a simple multiplication of the performance of an individual device.

Figure 2.6 : Multiple MOV based SPD

Differences in mechanical design can lead to one individual MOV always having to handle more current than its neighbours. As a Lorentz forces rule, an electrical transient takes the shortest most conductive path, and when it goes around the corners, it exerts forces on the current carrying conductors. The net result is that for large transient currents ad SPDs often explode as a result of these forces as shown in figure 2.7 .

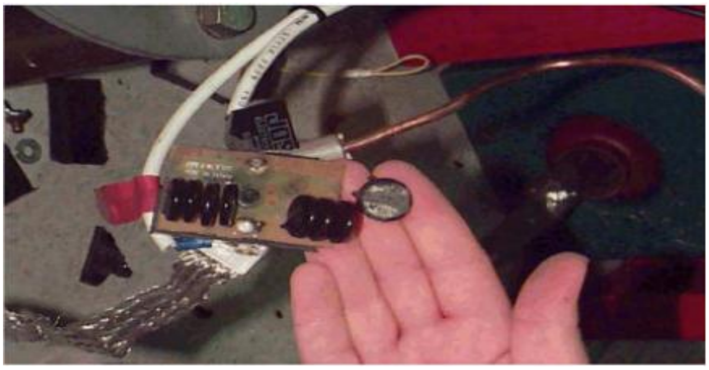


Figure 2.7 : Exploded multiple MOV based SPD module

Also, the thermal fuses used in SPDs are known to have reliability issues and age over a period of few years usually accentuated by thermal cycling. Conventional and thermal fuses also suffer aging from mechanical shock which can be delivered during operation of the SPD by the transients. Fuses are progressively weakened by transient currents. Obviously, when a fuse opens, the protector is rendered totally ineffective, leaving the equipment unprotected to subsequent surges. Figure 2.8 shows the internal fire due to its failure in fuses.

Figure 2.8 : SPD internal fire

The research paper[3] based on, **"Surge Capability Testing of Supercapacitor Families Using a Lightning Surge Simulator"** provides some valuable insight in estimating the capabilities of supercapacitor families to withstand surges and transients.

The supercapacitor, also known as ultracapacitor or double-layer capacitor, differs from a regular capacitor in that it has very high capacitance,but lower voltage limits (Ex; 1F 2.5V). A capacitor stores energy by means of a static charge as opposed to an electrochemical reaction. Applying a voltage differential on the positive and negative plates charges the capacitor. Supercapacitors typically store 10 to 100 times more energy per unit volume or mass than electrolytic capacitors. They can accept and deliver charge much faster than batteries, and tolerate many more charge and discharge cycles than rechargeable batteries.

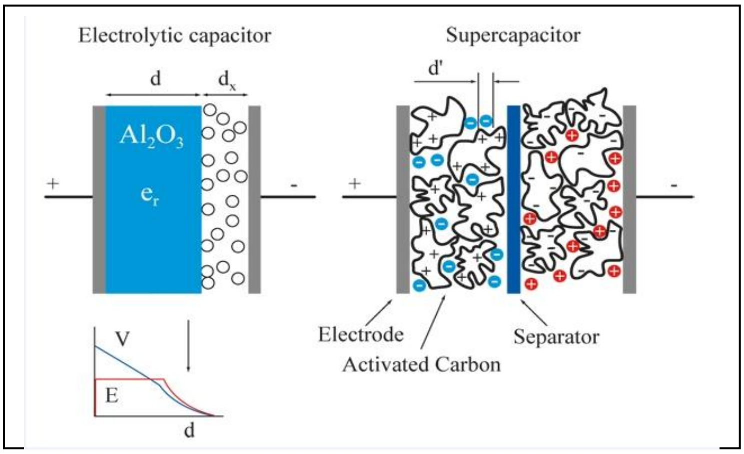


Figure 2.9 : Structural comparison of capacitors

All the tests conducted by the authors are using a Lighting Surge Simulator (LSS) with voltage variation capability of 6.6 kV, and with a maximum short circuit current capability of 3.3kA.

In a simple preliminary test conducted by the authors where several supercapacitors were subjected to a single-shot high voltage surge as well as multiple surges of identical shape from a lightning surge simulator. The waveforms used were as prescribed in standards such as IEEE C62-41 and IEC 61400-4-5.The terminal voltage develop across the supercapacitors are in order of millivolts and do not develop adequate DC terminal voltage even after 20 pulses that would exceed the rated DC voltage.

The results demonstrate the fact that a limited number of high voltage transients, up to100 microsecond duration, do not destroy most commercial supercapacitor families. This useful observation, confirms that a limited number of repeated high voltage surges can be safely tolerated by the current commercial supercapacitors and, it leads us to consider more statistical type tests to develop more detailed surge endurance test data for these devices.

These information provides that the supercapacitor topology could be used as a base technique to develop full-scale common and differential mode surge protective devices with better performance than traditional surge protectors available in the market.

The research paper[6] based on**, "An Electrical Circuit Model for Magnetic Cores. "** Unitrode Seminar Manual SEMIOOO, 1995, provides the magnetic basics and the process of magnetization in ferromagnetic materials. The fundamental purpose of any magnetic core is to provide an easy path for flux in order to facilitate flux linkage, or coupling, between two or more magnetic elements.

In an inductor, the core provides the flux linkage path between the circuit winding and a non-magnetic gap, physically in series with the core. Virtually all of the energy is stored in the gap. High permeability ferrites, or magnetic metal alloys such as Permalloy are incapable of storing significant energy. These cores approach the ideal magnetic material characteristic – square loop with extremely high permeability (60,000), high saturation flux density (0.9 Tesla = 9000 Gauss) and insignificant energy storage. Unfortunately, resistivity of these metal alloys is quite low. To minimize losses due to induced eddy currents, these cores are built up with very thin tape wound laminations.

Tape-wound cores are used primarily at 50, 60, and 400 Hz line frequencies. They are generally unsuitable for transformer applications in Switch Mode Power Supplies. Tape-wound cores using the newer, lower loss amorphous metal alloys are used in SMPS applications up to l00
-200kHz, especially as magnetic amplifiers.

Ferrites are the most popular core materials used in SMPS applications. Ferrites are ceramic materials made by sintering a mixture of iron oxide with oxides or carbonates of either manganese and zinc or nickel and zinc. MnZn ferrites are used in applications up to 1 or 2 MHz and include the power ferrite materials used in switching power supplies. The permeability of power ferrite materials is in the range of 1500 to 3000 (relative). As shown in the low frequency characteristic of Fig. 2.10, a ferrite core will store a small amount of energy, as shown by the areas between the hysteresis loop and the vertical axis. This undesired magnetizing energy must be subsequently dealt with in a snubber or clamp. Sometimes it can be put to good use in Zero Voltage Transition circuitry. The permeability is high enough to keep the magnetizing current at a generally acceptable level in transformer applications.

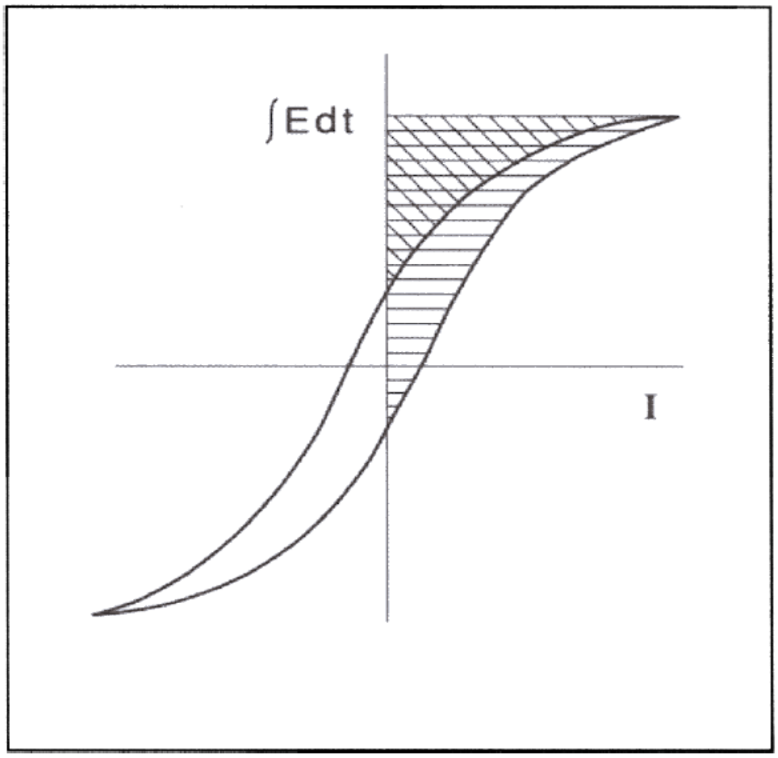


Figure 2.10 : Ferrite Core Characteristic

Composite powdered-metal cores, such as powdered iron, Kool Mμ, and Permalloy powder cores do store considerable energy, and are therefore used in inductor and flyback transformer applications. However, energy is not stored in the very high permeability magnetic metal portions of the composite, but in the non-magnetic regions between the magnetic particles in the binder that holds the cores together.

Essentially, these composite cores store their energy in a non-magnetic gap that is distributed throughout the entire core. These cores are manufactured and categorized by their effective permeability. Different effective permeabilities in the range of 15 to 200 (relative) are achieved by varying particle size and the amount of magnetically inert material in the composite mix. Composite powdered metal cores are not normally used in true transformer applications because their relatively low permeability results in high magnetizing current and energy storage undesired in a transformer.

The much greater saturation flux density BSAT of the powdered metal cores compared to ferrite (0.8T vs. 0.3T) would permit a much smaller inductor as a gapped ferrite for the same application. But at 100 kHz and above, this promise is seldom fulfilled because of the restrictions imposed by losses and rounding.

3 METHODOLOGY

3.1 Background

Researchers have shown [3] that supercapacitors could have continuous energy storage capabilities in the range of energy carried in a transient surge into an electrical circuit. They are comparable with the transient energy absorption capabilities of non linear devices used in typical surge protectors such as metal oxide varistors (MOVs) and bidirectional break-over diodes (BBDs) , coupled with LC-type filter stages.

However, at present commercially available supercapacitors have very low DC voltage ratings, such as less than 4 V for single-cell devices. (Ex: 2.5V 1 F, 2.7V 5F). This voltage is far below the instantaneous voltages occurring on the AC mains. Given this problem, a surge protector cannot just substitute a supercapacitor for a MOV or any other non linear devices. Thus the necessity of testing is very important with the instantaneous voltage developed across the supercapacitor sub circuit for the entire design.

3.2 Design Approach

Tests were carried out as per the IEC 61643-11 with the 1.2/50 voltage - 8/20 current combination wave generator (EM TEST/UCS 500-M) which has a maximum transient voltage up to 6 kV and the maximum current up to 3 kA. Testing flow chart of the voltage protection level of the class III type SPDs is shown in figure 3.1.

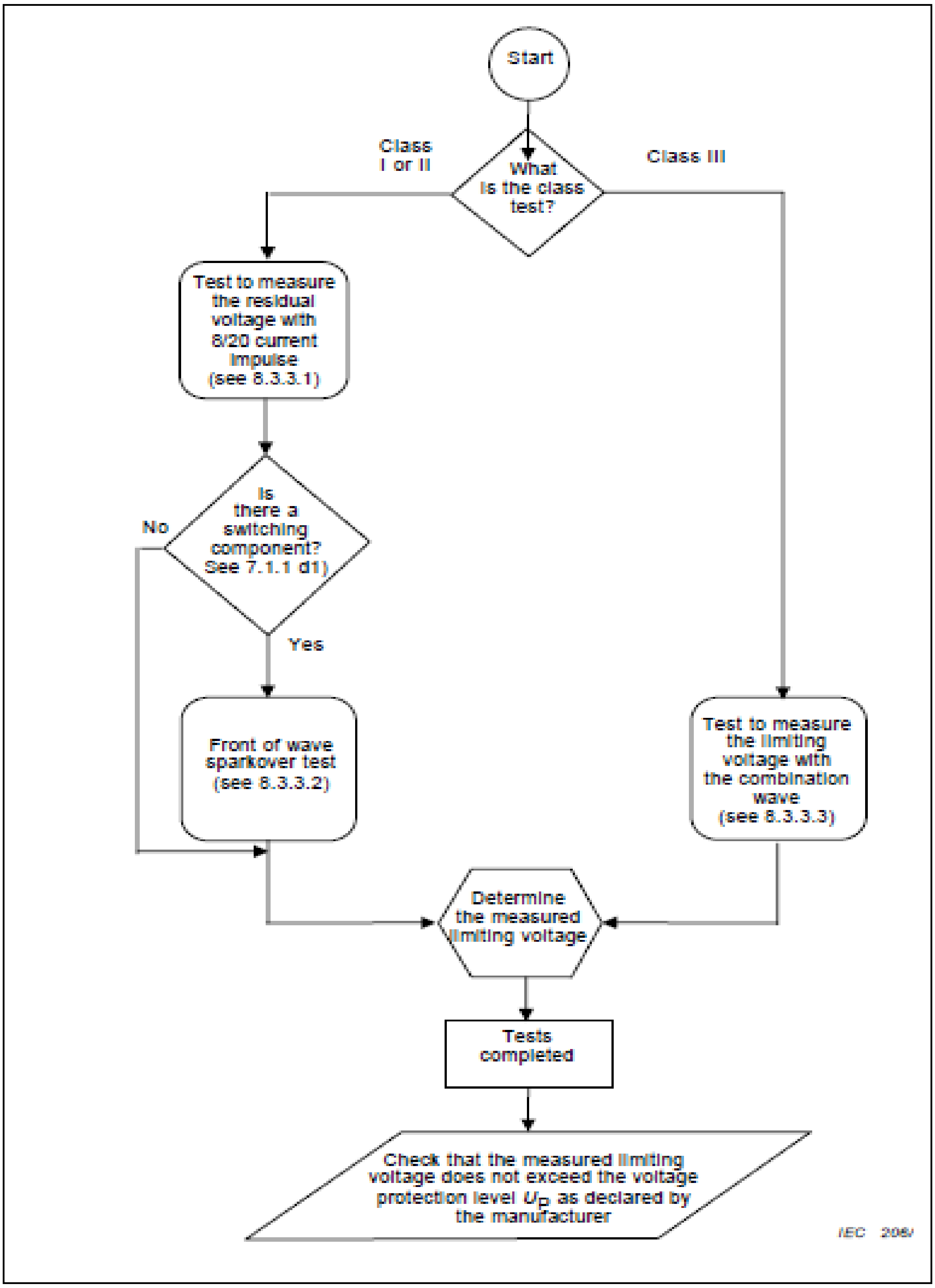


Figure 3.1 : Flow chart of testing of the voltage protection level
Source : IEC 61643-11 – Low voltage surge protective devices

3.3 Selection of components

3.3.1 Characteristics of MOVs

Two types of MOVs which has following characteristics were tested using the lighting surge simulator (UCS 500-M). As per the IEC 61643-11, class III type SPDs have the output clamping voltage of 600V. Therefore two MOVs which has the voltage rating of 230 V and the clamping voltage about 595 V, were selected for this design. Details description of these two components are shown in Appendix B.

Parameter	**Type of MOV**	
	Epcos – S20	**B722 PANASONIC**
Voltage Rating V AC	230 V	230 V
Voltage Rating V DC	300V	300V
Clamping Voltage Vc	595V	595V
Peak Surge Current @ 8/20µs	8kA	10kA
Operating Temperature Min	-40°C	-40°C
Operating Temperature Max	85°C	85°C
Peak Energy (10/1000uS)	130J 	255J 

Table 3.1 : Comparison of two types of MOVs

3.3.2 Voltage build up across MOVs

By applying 1 kV to 6 kV surges from the lighting surge simulator, different clamping output voltages could be observed.

Applied Surge Voltage (V)	**Output Clamping Voltage (V)**	
	Epcos – S20	**B722 PANASONIC**
1000	510	570
4000	630	710
6000	690	760

Table 3.2 : Comparison of clamping voltage

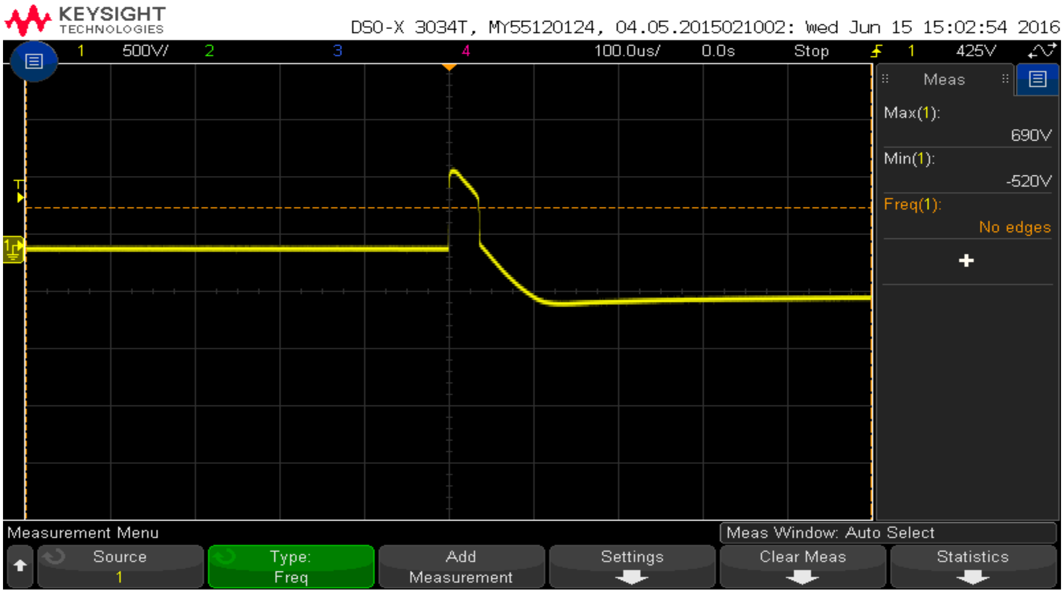


Figure 3.2 : MOV - Epcos – S20 characteristic for 6 kV

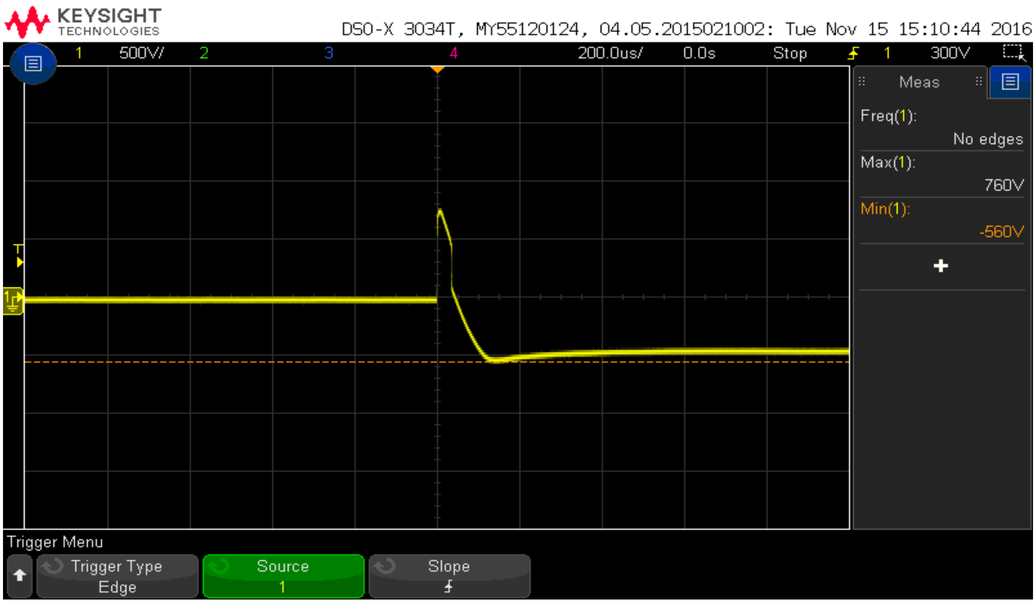


Figure 3.3 : MOV - B722 PANASONIC characteristic for 6 kV

Therefore, Epcos – S20 MOV which has the clamping voltage nearly 600 V, was selected for this design topology.

3.3.3 Voltage buildup across super capacitors

Four types of supercapacitors were tested by applying different levels of transient voltages. Terminal voltage developed across supecapacitor after several strikes were measured using a multimeter. The test data set provides some valuable insight in estimating the capabilities of these new supercapacitors to withstand surges and transients, which in turn could lead to non-traditional applications. Details description of these supercapacitors are shown in Appendix C.

(a) 1F – 2.5V SC (B Series)– Initial voltage 0.20mV

No. of strikes	mV (for 1.5 kV)	mV (for 4.5 kV)	mV (for 6.0 kV)
5	22.5	58.3	76.43
10	43.7	78.2	145.3
15	64.1	90.6	209.3
20	83.5	110.2	269.2

Table 3.3: Voltage build up across 1F-2.5 V SC

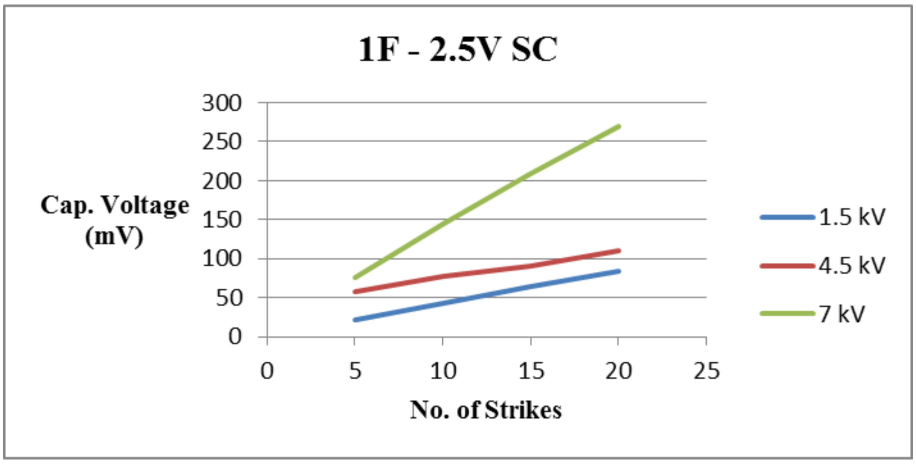


Figure 3.4 : Terminal voltage development versus number of surges

(b) 5F - 2.7V SC (Maxwell)– SC – Initial voltage 0.26 mV

No. of strikes	mV (for 1.5 kV)	mV (for 4.5 kV)	mV (for 6.0 kV)
5	3.7	10	22.8
10	4.1	15	44.9
15	4.3	20	66
20	4.5	24	88

Table 3.4 : Voltage build up across 5F-2.7 V SC

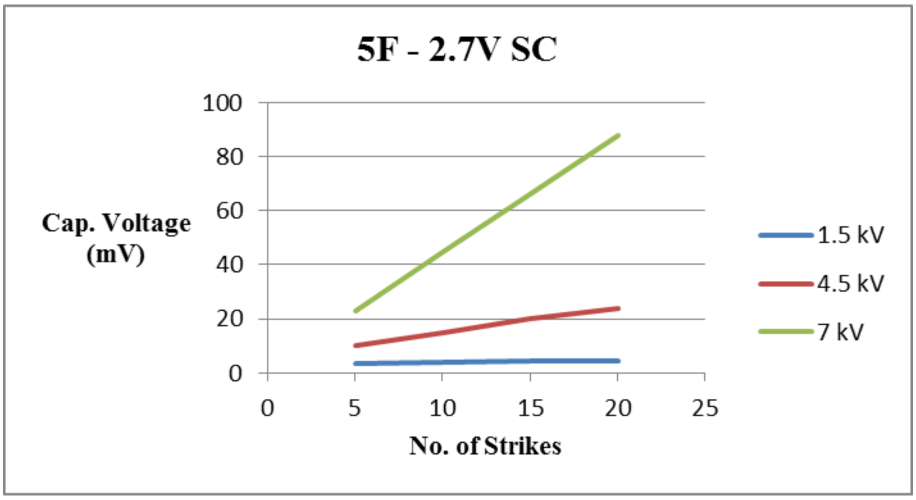


Figure 3.5 : Terminal voltage development versus number of surges

(c) 5F – 2.7 V (DCN) – Initial voltage 16.6 mV

No. of strikes	mV (for 1.5 kV)	mV (for 4.5 kV)	mV (for 6.0 kV)
5	16.6	35.9	121
10	21.2	53.68	154
15	25.1	71.82	185
20	29.1	89.6	215

Table 3.5 : Voltage build up across 5F-2.7 V SC

Figure 3.6 : Terminal voltage development versus number of surges

(d) 150F - 2.7V SC (Maxwell) – Initial voltage 17 mV

No. of strikes	mV (for 1.5 kV)	mV (for 4.5 kV)	mV (for 6.0 kV)
5	42	56	72
10	45	60	77
15	48	64	80
20	50	67	83

Table 3.6 : Voltage build up across 150F-2.7 V SC

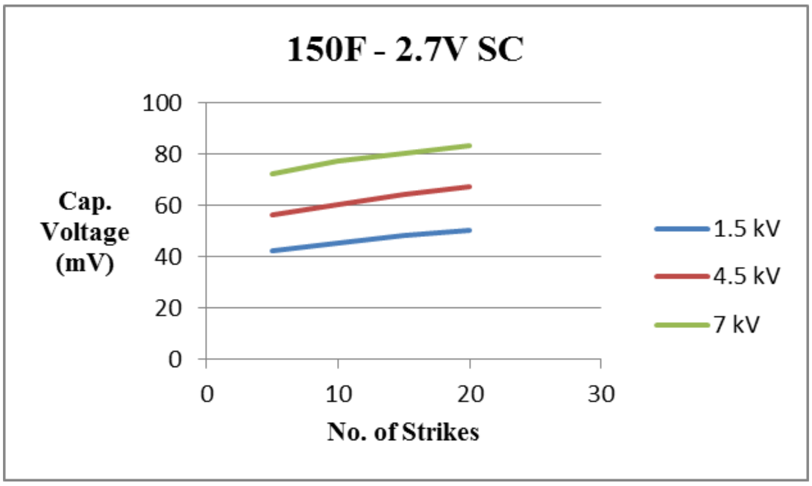


Figure 3.7 : Terminal voltage development versus number of surges

These results indicated that the supercapacitor is not destroyed by the repeated application of HV transients and the gradual voltage rise after each hit is in the order of millivolt. Also they still retain its capacitive behaviour and not adversely affected by the transient HV at the terminals. Therefore , 1F-2.5 V supercapacitor which has the highest voltage rise with 1 ohm resistor was selected as a supercapacitor sub circuit for this design.

4 SYSTEM DEVELOPMENT

4.1 Design Overview

The implemented supercapacitor assisted surge absorber device was developed by using 2.5V/1F SC, 1Ω resistor, transformer and a non-linear device(MOV). SC's continuous surge energy absorption capability given by 1⁄2 CV^2 could be effectively used with several other components such as MOVs, LC filters and a multi-winding magnetic components. This magnetic part works as a transformer when a surge travels through the power line and fires a nonlinear device such as a MOV or a semiconductor device such as bidirectional break-over device .

4.2 Complete Design Circuit & Its Operation

Designed circuit of the surge protective device for the differential mode based on the supercapacitor concept is shown in Figure 4.1.

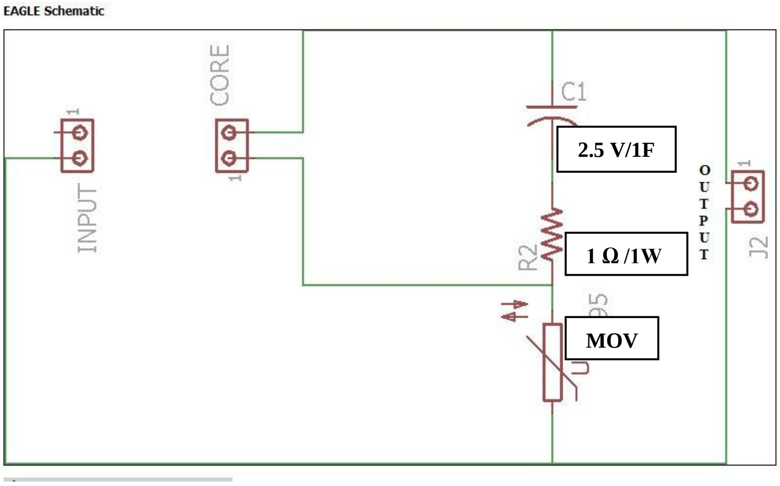


Figure 4.1: Circuit Diagram – Differential Mode

In this circuit, typical NLDs such as a MOV is combined with a magnetic component and an SC-based sub circuit. However, compared to a typical surge arrestor without supercapacitors, where NLDs are placed directly across the pairs of wires such as the neutral and the live (differential mode) or neutral or live and earth(common mode) as shown in figure 4.2

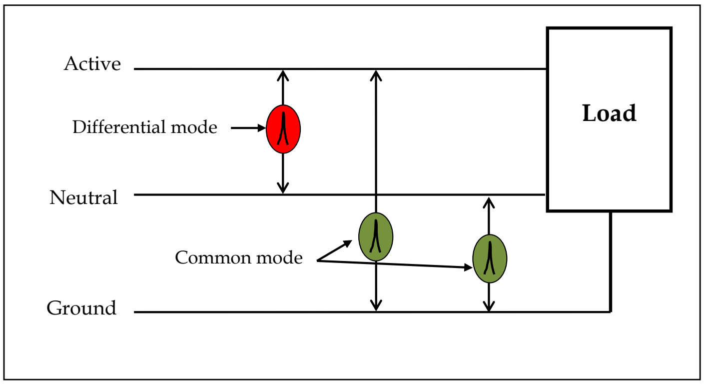


Figure 4.2: Differential and common mode surges

The NLD is placed in between the load side end of a primary coil of a transformer and the return wire as in Figure 4.1. Given this configuration, when a surge occurs at the AC input, and when the instantaneous voltage due to surge exceeds the firing voltage of the NLD, high instantaneous current flows through the primary coil, developing a voltage across the primary turns. This in turn develops an induced voltage across the secondary coil, and by winding the secondary coil in the opposite direction, secondary induced voltage can be generated to oppose the surge voltage. Result is to create a voltage across the critical load to be protected, which could be less than the instantaneous surge voltage. By adjusting the turns ratio, we can adjust secondary voltage in such a way that the instantaneous voltage across the supercapacitor-based sub circuit can be varied.

Mathematical relationship for this design can be shown as follows.

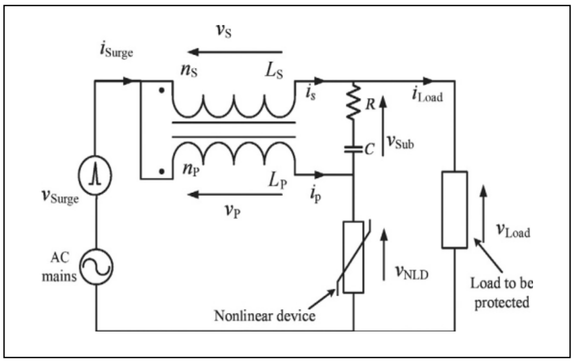


Figure 4.3: Mathematical relationship

$V_{surge} = V_p + V_{NLD}$

$V_p = L_p\, di_p/dt + M\, di_s/dt$

$V_s = L_s\, di_s/dt + M\, di_p/dt$

$I_{sub} = (Vs - Vp)/Z_{sub}$

$V_{load} = V_{NLD} - i_{sub} * Z_{sub}$

$V_{load} = V_{surge} - V_s$

Once a superimposed HV transient travels along the mains input, NLD fires and enters into conduction stage, developing a transient voltage across the connected winding (Vp). When the HV transient exceeds the firing voltage of the NLD, it conducts heavily creating a surge current through the primary coil. Due to induction, secondary coil also develops a voltage (Vs) and the two windings are configured to create this induced secondary voltage higher than that of the primary winding and to oppose the transient so that the critical load end sees the difference between these two voltages.

4.3 Impact of The Supercapacitor Subcircuit and The Magnetic Component

As indicated in Figure 4.4, a supercapacitor-based subcircuit configuration could have a few possible variations as shown in figure 4.4.

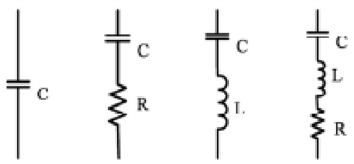


Figure 4.4: Possible Sub Circuits

SC-based sub circuit receives the voltage difference between the two coils to create a circulating current through the sub circuit, absorbing part of the surge energy into the supercapacitor. With the ability of the supercapacitor to absorb part of the surge energy, which will be dissipated in the closed loops formed, transient surge energy burden on the NLD is significantly reduced. In addition, supercapacitor sub circuit will perform a useful filter function to reduce the ringing waveform created by the surge.

In the SCASA technique, overall performance is mainly governed by the capability of the magnetic component, where its leakage inductance combined with the transformer action assists creating a lower effective clamping voltage across the critical load. Depending on the permeability of the selected core material, overall performance varies, since the secondary winding voltage due to the superimposed surge depends on the core's saturation behavior. Therefore, powdered core transformer with primary to secondary turns ratio (np/ns) of 6:30 with relative permeability (μr) of 60 is used for this design. Detailed description of the powdered core is attached under Appendix D.

The most practiced power distribution in the South Asian region is the TT wiring system as shown in figure 4.5. The low voltage power line SPDs are most often connected in shunt. Therefore it is essential to have SPDs which are designed for the common mode as well.

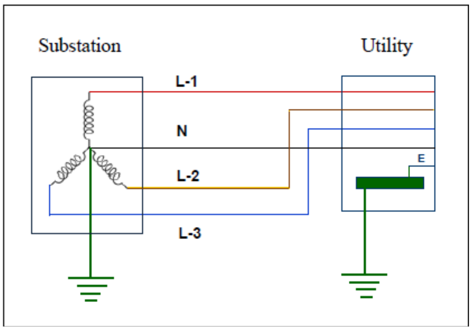


Figure 4.5: TT wiring system

Figure 4.6 shows the conceptual design for the common mode as well.

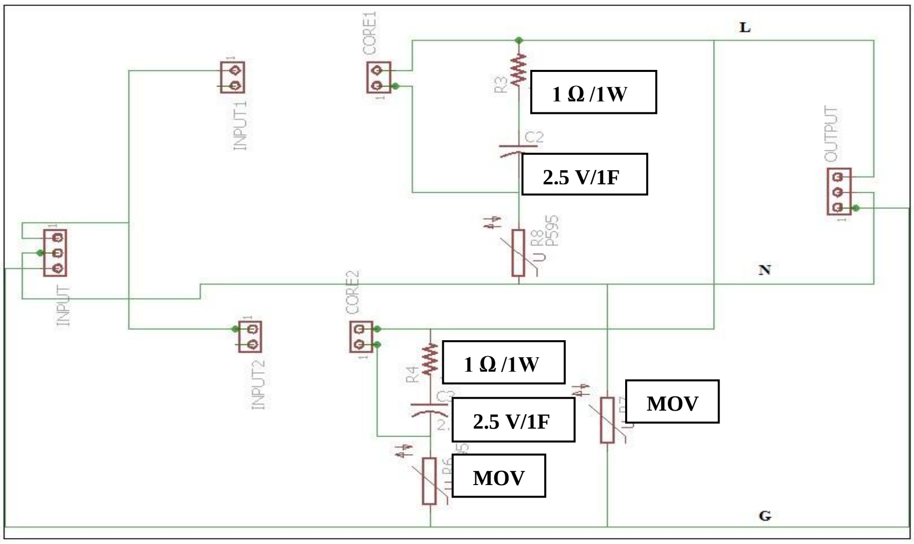


Figure 4.6: Design Circuit – Common Mode

5 RESULTS AND ANALYSIS

In general practical circuit developments for low voltage surge protector for equipment are based on designing the protective circuit as an add-on block to the input wiring of the equipment. This block is used to attenuate the incoming transient using passive series impedances or bypassing the surge currents and absorbing the transient energy which is done using non-linear devices such as GDTs, MOVs, TVS, spark gaps, fuses, etc.

In the usual surge protector devices, the high transient energy can cause these non-linear devices to deteriorate and eventually fail. If this energy can be taken out from the non-linear devices their life time will be greatly enhanced.

This chapter presents the results of the use of supercapacitor based together with non-linear devices to not only absorb the transient energy, but also to control the output clamping voltage to a lower value to give better protection for the equipment. In particular a math lab simulation has been carried out to determine the best sub-circuit combinations as describe in chapter 4 (4.3).

The implementation of the supercapacitor concept in the final prototype was analysed with different input voltages to determine the clamping voltage at the load end.

Since the protection circuit is for class III SPD, the equipment should be subjected to a 6 kV. Thus testing has been carried out at both 4 kV and 6 kV in the comparison.

5.1 General Math lab simulation results

If we consider a supercapacitor as an ideal device, the device will have an energy storage capacity of $1/2CVc^2$, where C is the device capacitance and Vc is the rated DC voltage of the device. Now if this capacitor is used in a simple circuit where an ideal DC voltage source of value Vs and a resistor of value R are used, the overall RC circuit will have a time constant of Ʈ=RC. The capacitor voltage is given by the following equation.

$$V_{c\,max} = V_{max} \left(1 - e^{-T/RsC}\right)$$

Based on the general validity of above equation, if we can control the duration of occurrence of a HV source to a “short-enough” period, final voltage across the terminals of the capacitor will be kept within the limit of Vc. This discussion indicates us that a very large value capacitor, such as a supercapacitor in a circuit loop of finite series resistance, can be used to safely absorb energy from a HV (transient) source with a short-duration occurrence. The charging curve for the supercapacitor and the normal electrolytic capacitor is shown in figure 5.1.

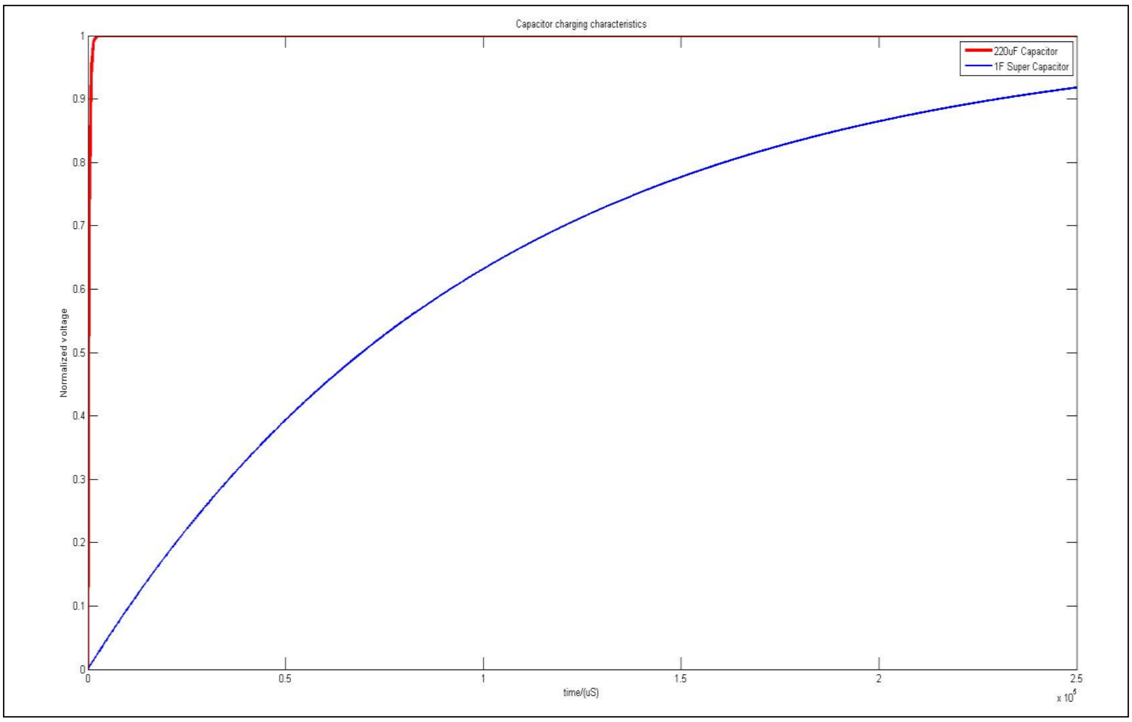


Figure 5.1 : Capacitor charging curves

Open circuit surge voltage waveform which we have used (1.2/50us) can be mathematically represented as,

$$V_{SG}(t) = \frac{\propto \beta}{\alpha - \beta}\left(e^{-\alpha t} - e^{-\beta t}\right)$$

By suitable mathematical manipulations and approximations we can get the following relationship to approximate the normalized open circuit voltage waveform and the short circuit current as a function of time in microseconds.

$$V_{SG,nor\ (t)} = 1.02032\ (e^{-0.0139t} - e^{-4.16t})$$

$$I_{SG,nor\ (t)} = 4\ (e^{-0.0866t} - e^{-0.1732t})$$

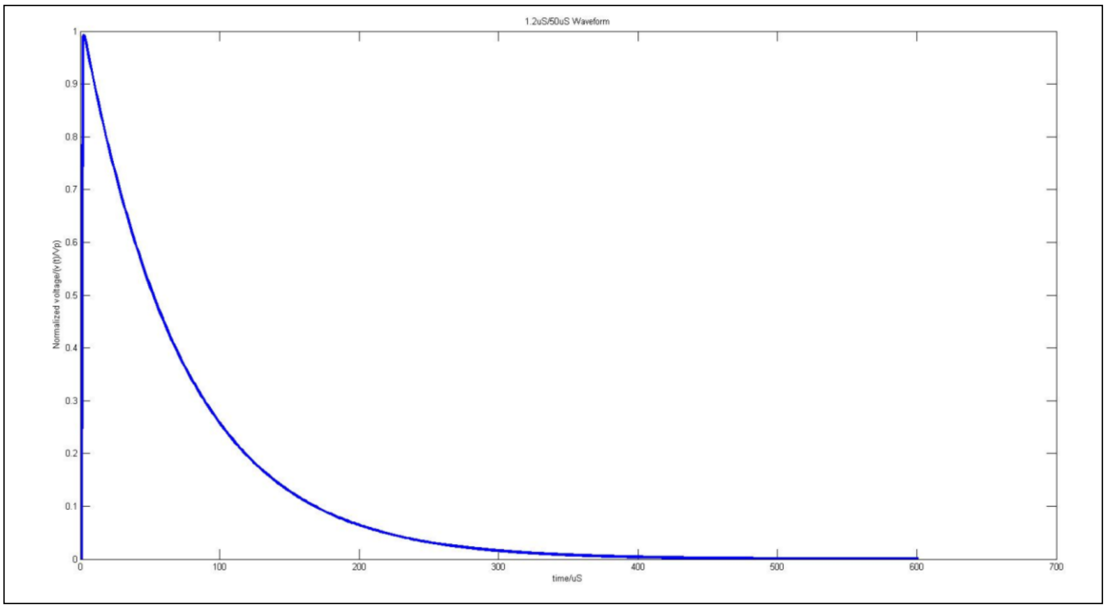


Figure 5.2 : 1.2/50us - Normalized open circuit voltage

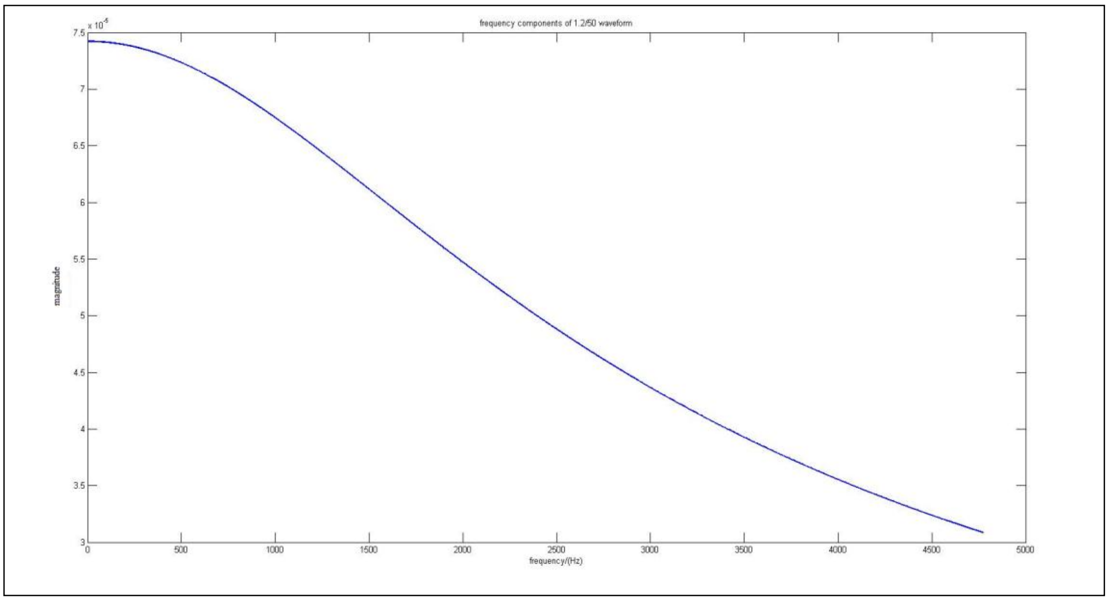


Figure 5.3 : 1.2/50us – Fourier transform of open circuit voltage

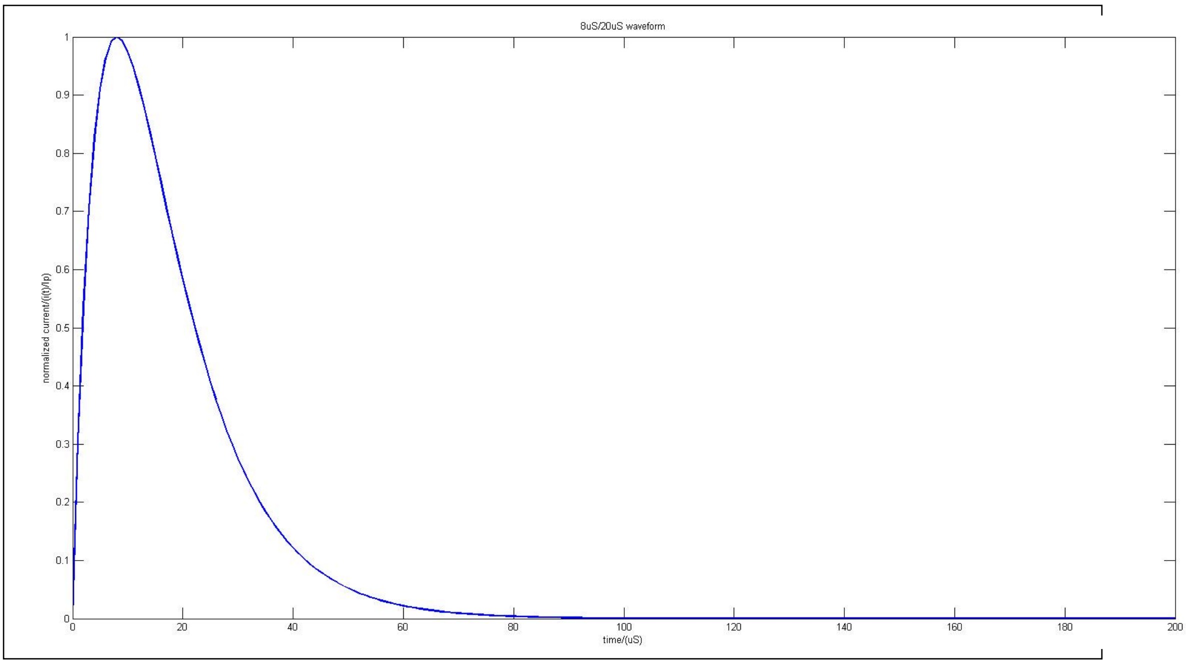


Figure 5.4 : 8/20us - Normalized short circuit current

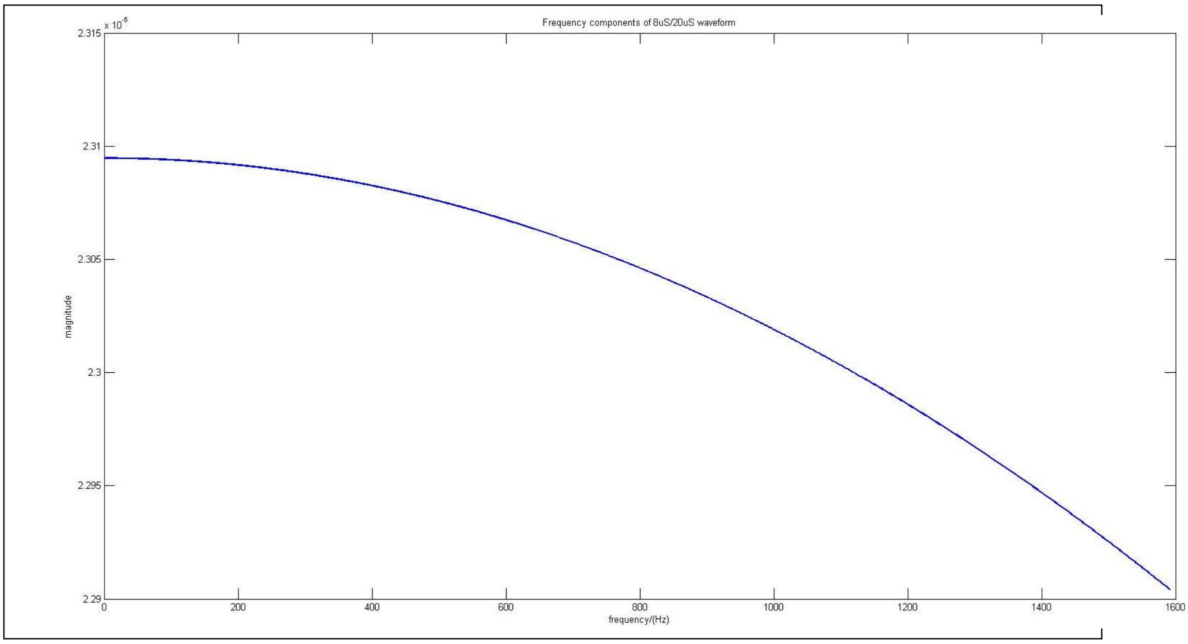


Figure 5.5 : 8/20us – Fourier transform of short circuit current

Figure 5.6 indicates the MATLAB generated waveform, which closely matches the shape of the normalized open circuit voltage waveform together with its impact on an RC circuit comprising of 220μF and 1F capacitors in series with a 1 Ω resistor.

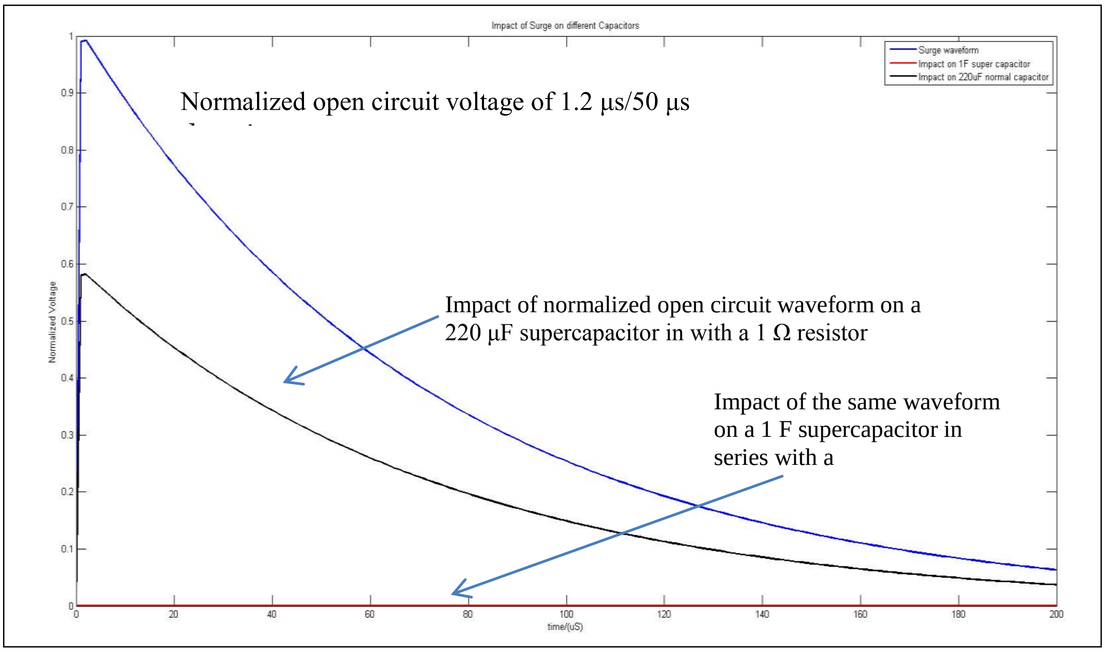


Figure 5.6 : Impact on an RC circuit

Figure 5.6 clearly indicates that due to very large time constants in supercapacitors, such a high voltage waveform which has a total duration of about 200μs will not develop an adequate voltage across the capacitor. For example, if the peak of the surge waveform is 6 kV, a 220 μF capacitor in series with a 1Ω resistor could develop an approximate peak voltage of 600V, while a 1F capacitor will develop only an extremely minimal voltage.

Non-linear equation for the metal oxide varistor is,

$$V = K.I^h$$

The observation values for the voltage and current of the MOV is shown in figure 5.7.

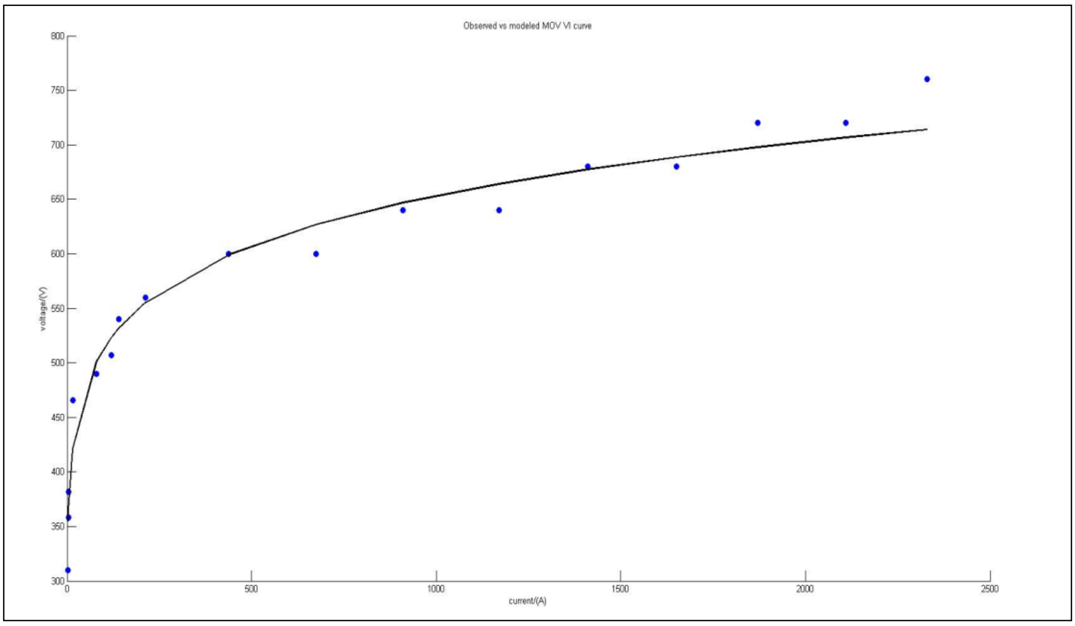


Figure 5.7 : MOV V-I observation curve

By plotting ln(V) vs ln(I), we can calculate the coefficients of K and n.

$$lnV = lnK + n\ lnI$$

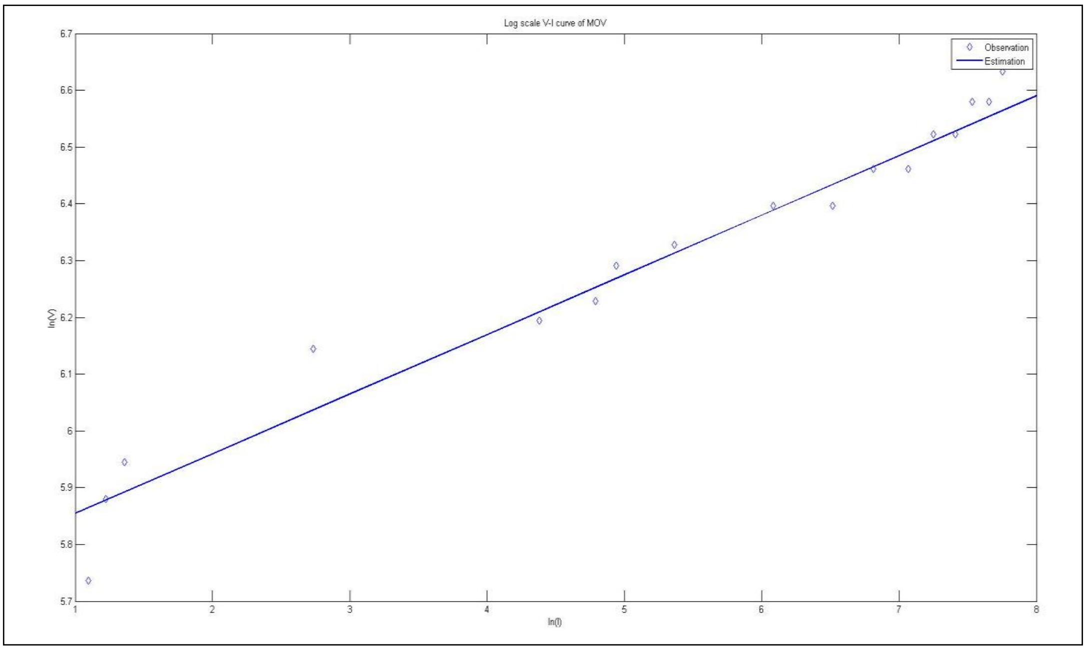


Figure 5.8 : MOV Log scale V-I curve

K= 330.3 n = 0.105

Therefore the characteristics equation for the MOV is,

$$V = 330.3\, I^{(0.105)}$$

Current and voltage variation of MOV is shown in figure 5.9.

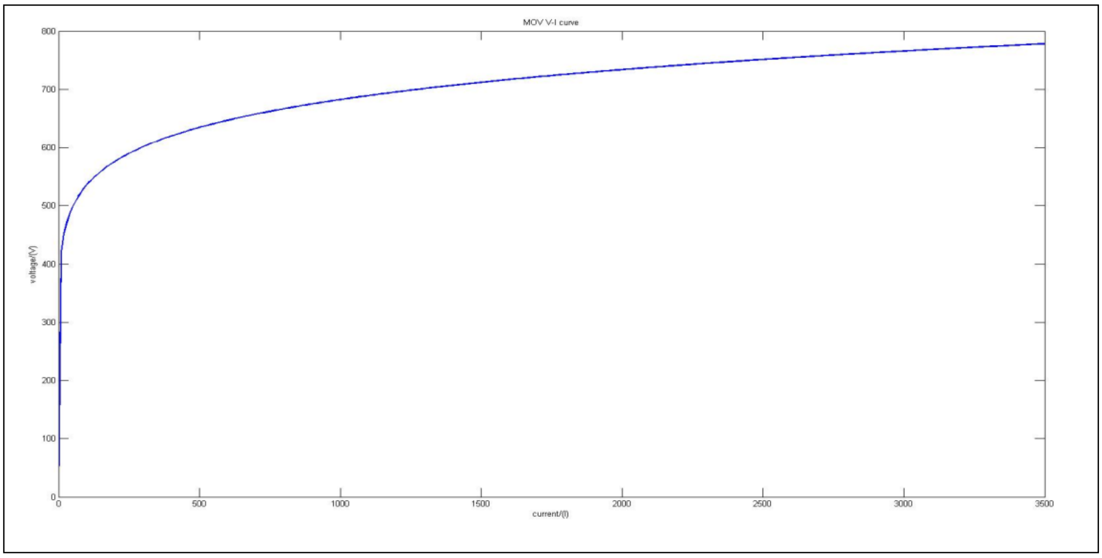


Figure 5.9 : V-I curve of MOV

Power and Energy absorption capability of supercapacitors

$P_{0.1F} > P_{1F} > P_{5F}$

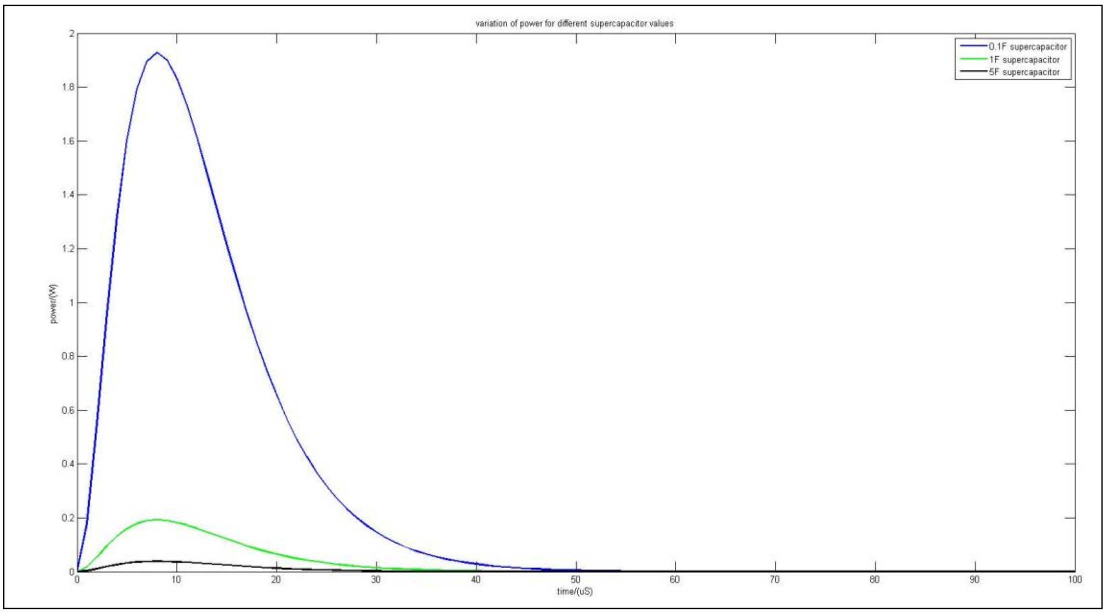


Figure 5.10 : Power variation for different supercapacitors

$E_{0.1F} > E_{1F} > E_{5F}$

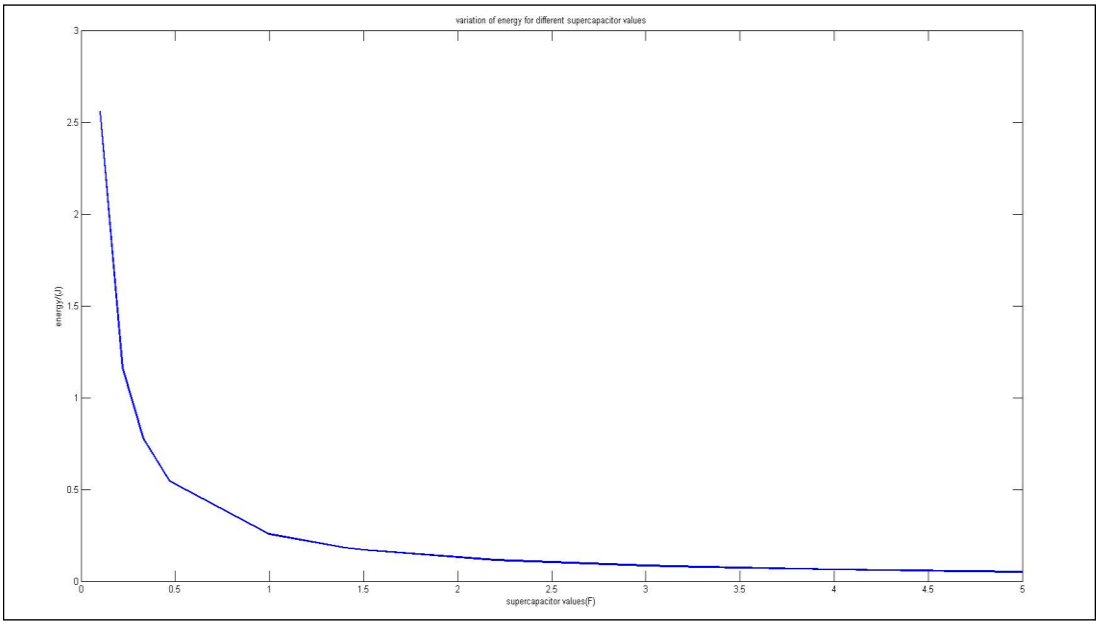
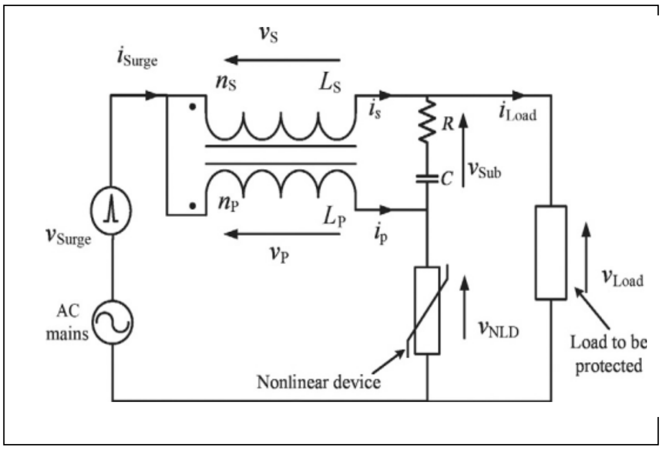
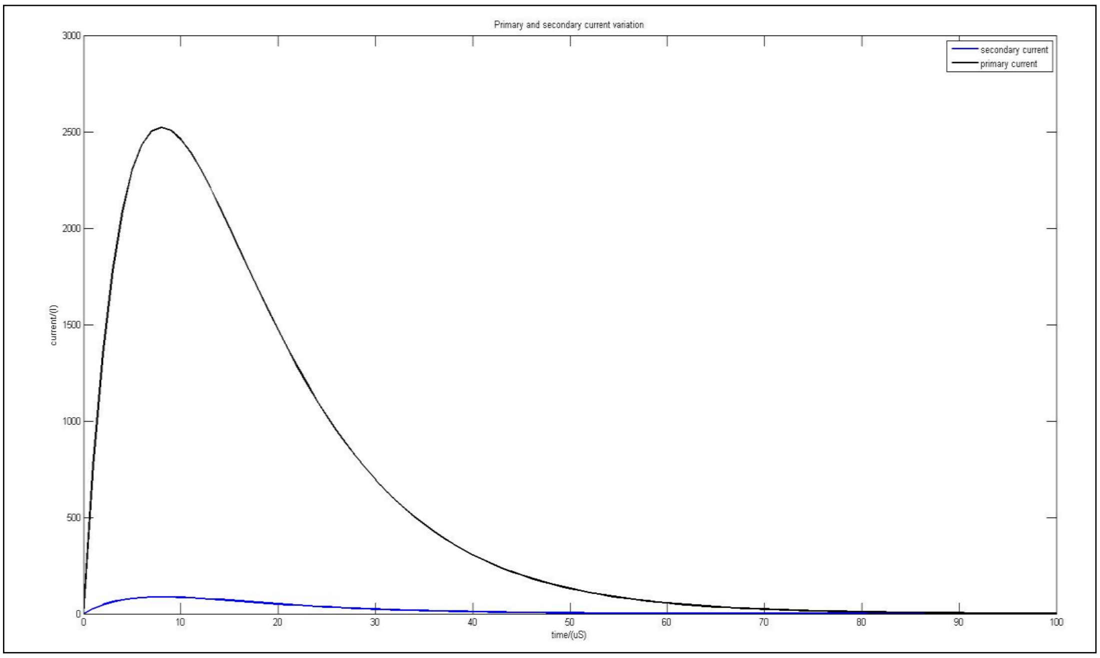


Figure 5.11 : Energy variation for different supercapacitors

5.2 MATLAB simulation results for the complete circuit



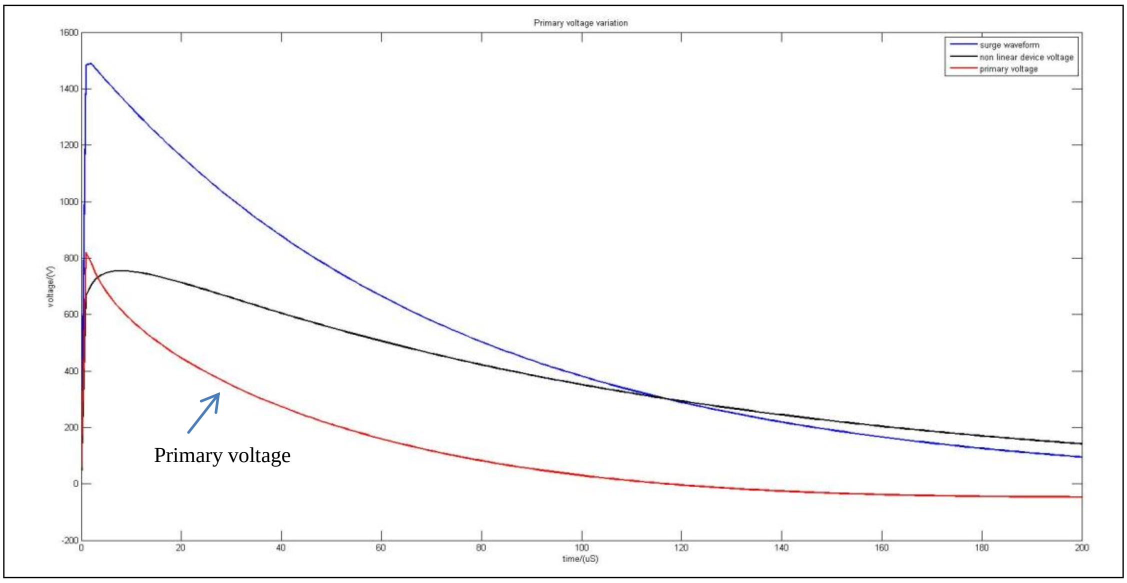
By applying surge input of 6 kV, the primary and secondary current variation of the magnetic core is shown as in figure 5.12.



$I_p(max) = 2523$ A $\qquad$ $I_s(max) = 87$A

Figure 5.12 : Primary and secondary winding current variation

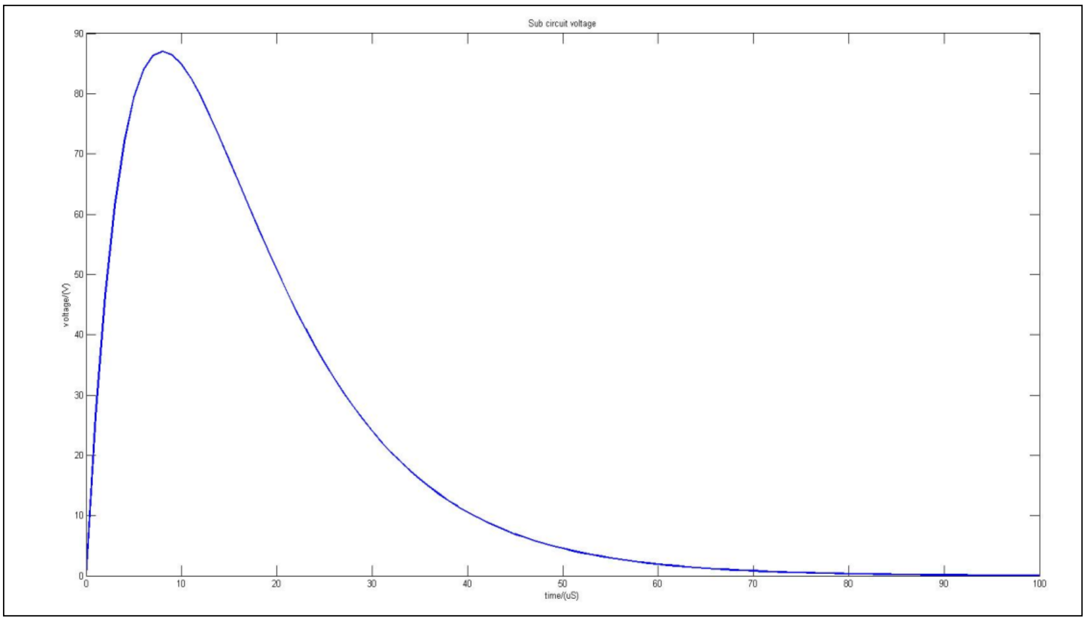
$Vp = V_{surge} - V_{NLD}$



$Vp(max) = 734$ V

Figure 5.13 : Primary voltage variation

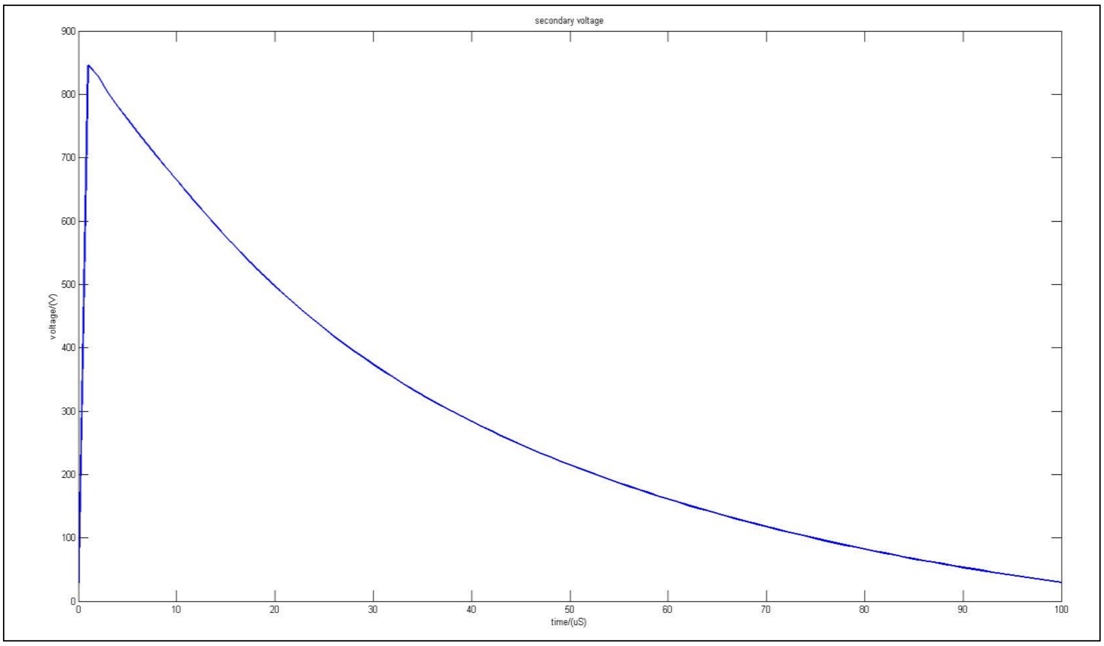
Vsub = Isub*Zsub



Vsub(max) = 87 V

Figure 5.14 : Sub-circuit voltage variation

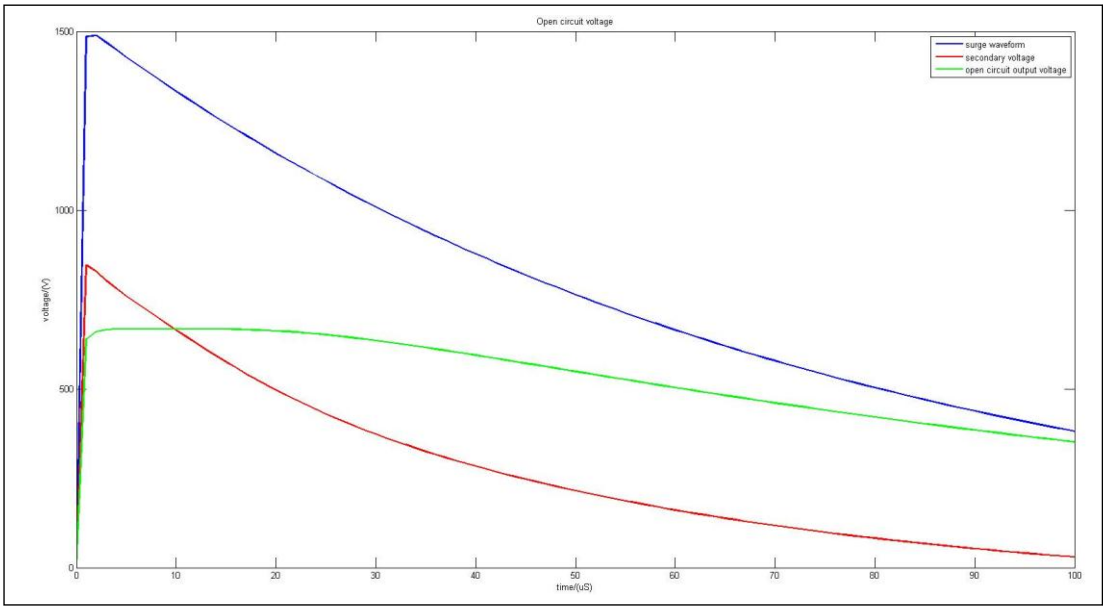
Vs = Vp+Vsub



Vs(max) = 821

Figure 5.15 : Secondary voltage variation

Voc = Vsurge-Vs



Voc(max) = 667 V

Figure 5.16 : Open circuit voltage (No-load)

Sub-circuit voltage variation for different capacitors

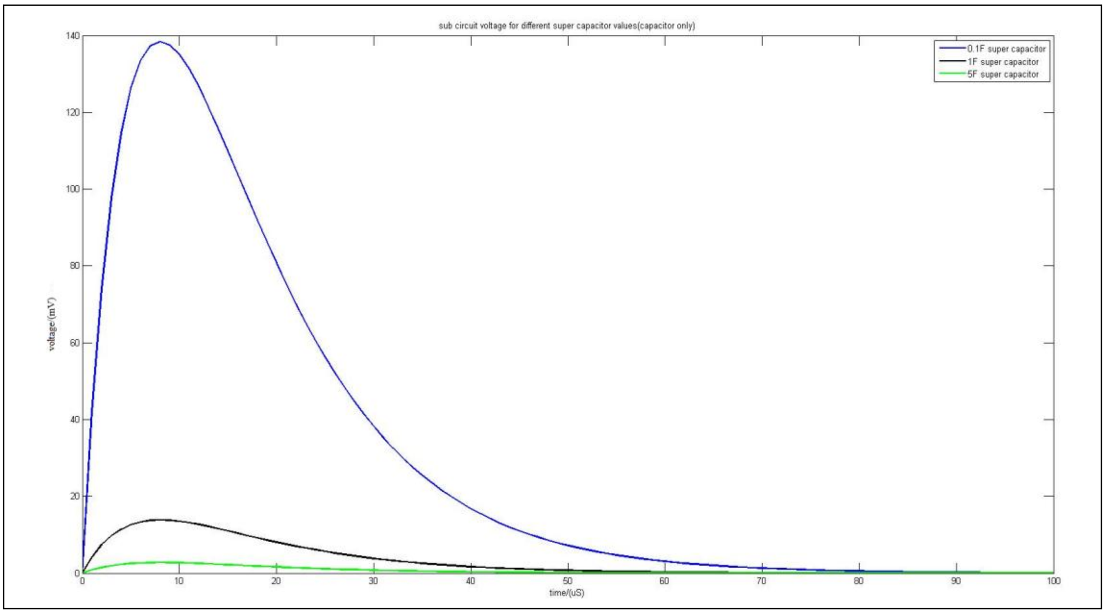


Figure 5.17 : Sub-circuit voltage variation for different capacitors

When capacitor value increased, voltage across sub circuit was decreased.

Sub-circuit voltage variation for different resistors (R+1F sc)

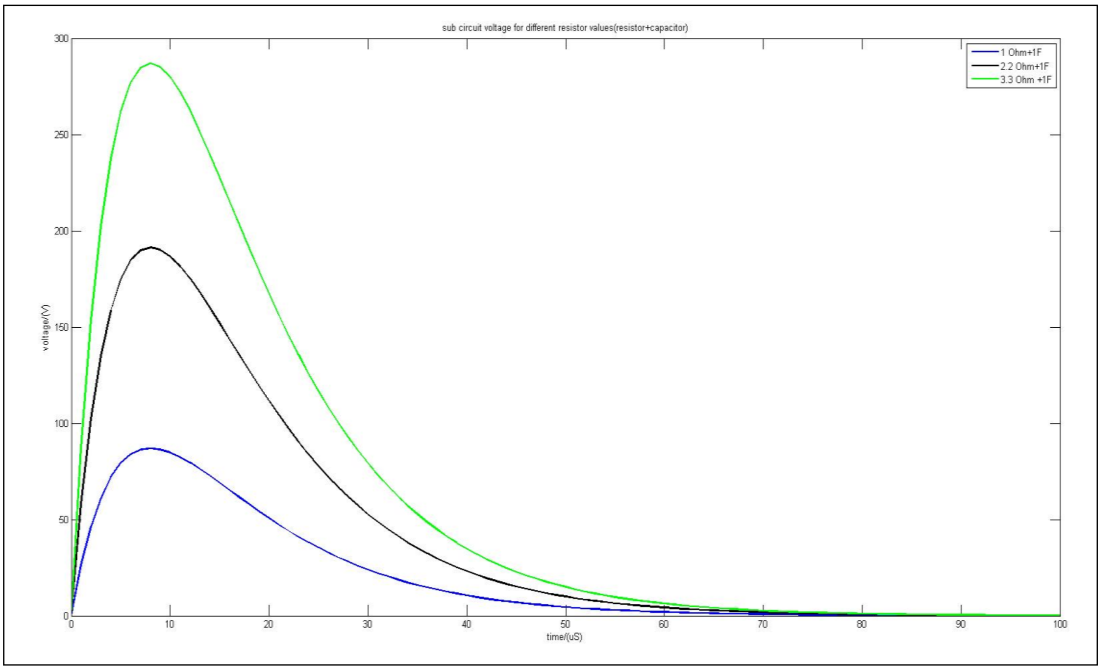


Figure 5.18 : Sub-circuit voltage variation for different resistors

When resistor value increased, voltage across sub circuit was increased.

Sub-circuit voltage variation for different combinations (R+C, C+L, R+C+L)

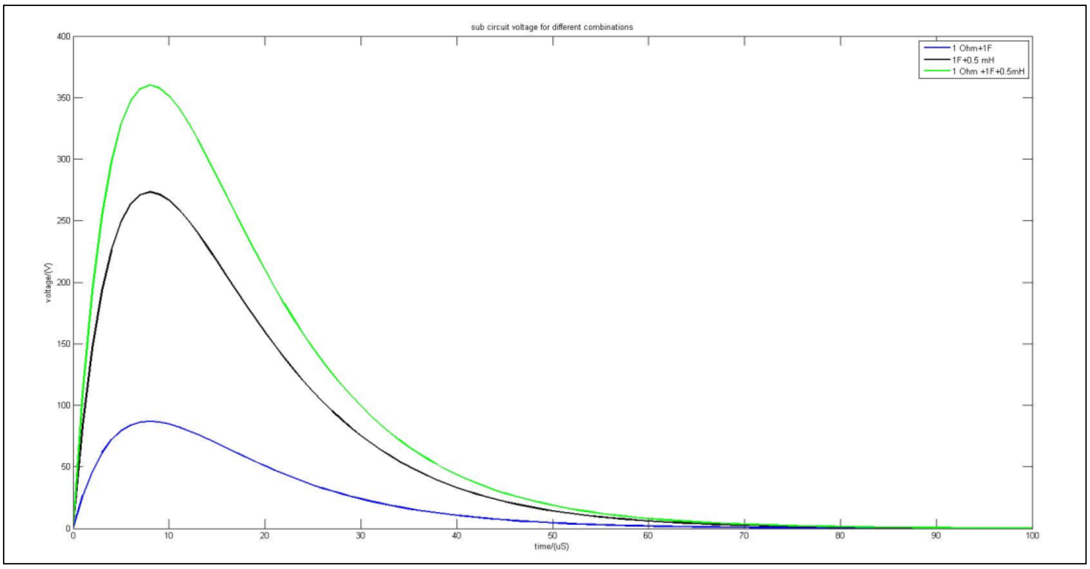


Figure 5.19 : Sub-circuit voltage variation for different combinations

$V_{sub\ (R+C)} < V_{sub\ (C+L)} < V_{sub\ (R+C+L)}$

Power distribution across NLD and sub circuit

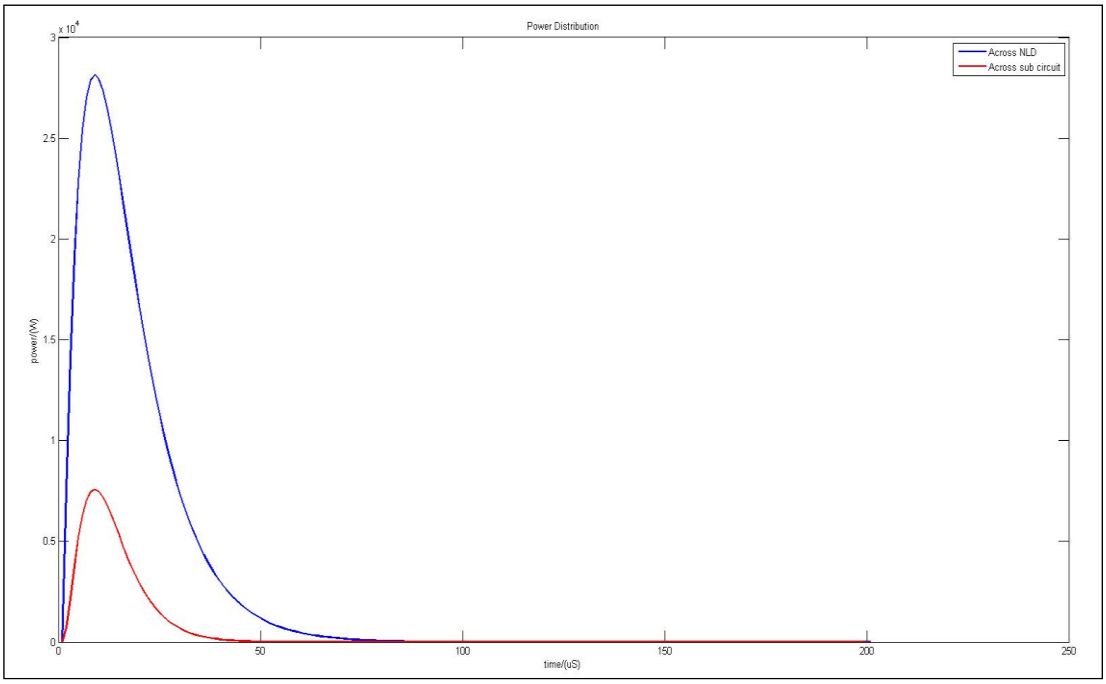


Figure 5.20 : Power distribution across NLD and sub circuit

Total power , across NLD and sub circuit with magnetic core

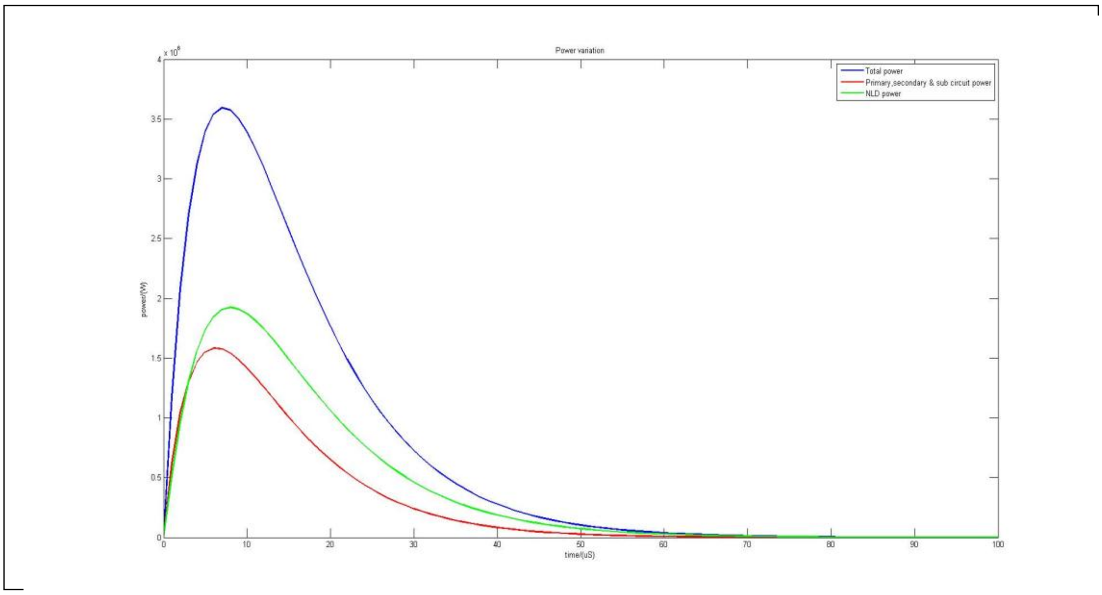


Figure 5.21 : Power distribution – Total, across NLD and sub circuit with magnetic Core

5.3 Energy Calculation

5.3.1 By using powdered core as a transformer

By applying 4 kV and 6 kV, total energy at the input and the energy absorbed by the MOV is calculated using the CSV values from the oscilloscope trace. Tabulated values are shown in Appendix E.

5.3.1.1 For 4 kV Surge

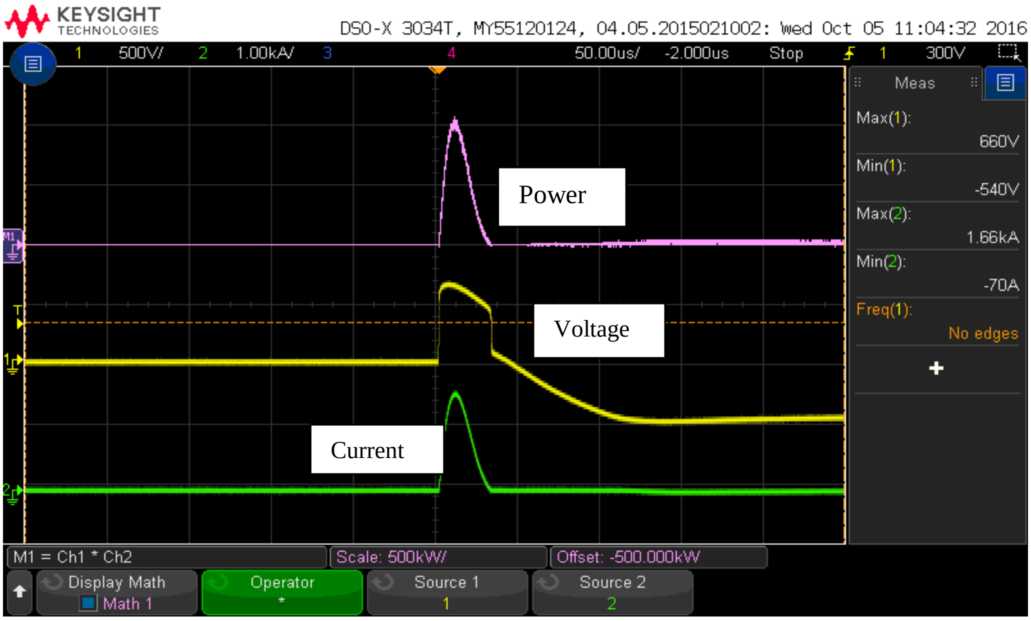


Figure 5.22: Current, voltage & power waveforms across MOV

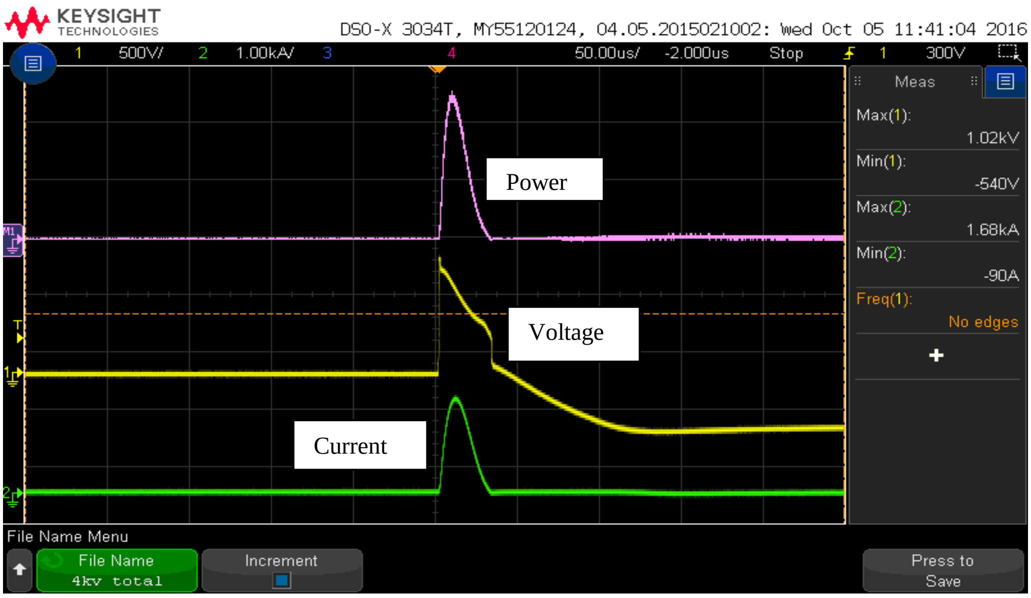


Figure 5.23: Total current, voltage & power waveforms at the input

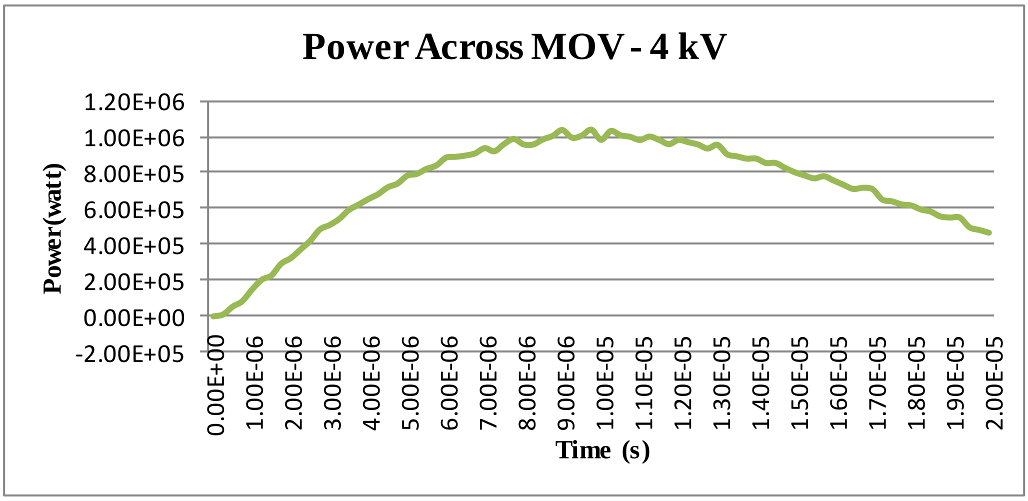


Figure 5.24: Power across MOV

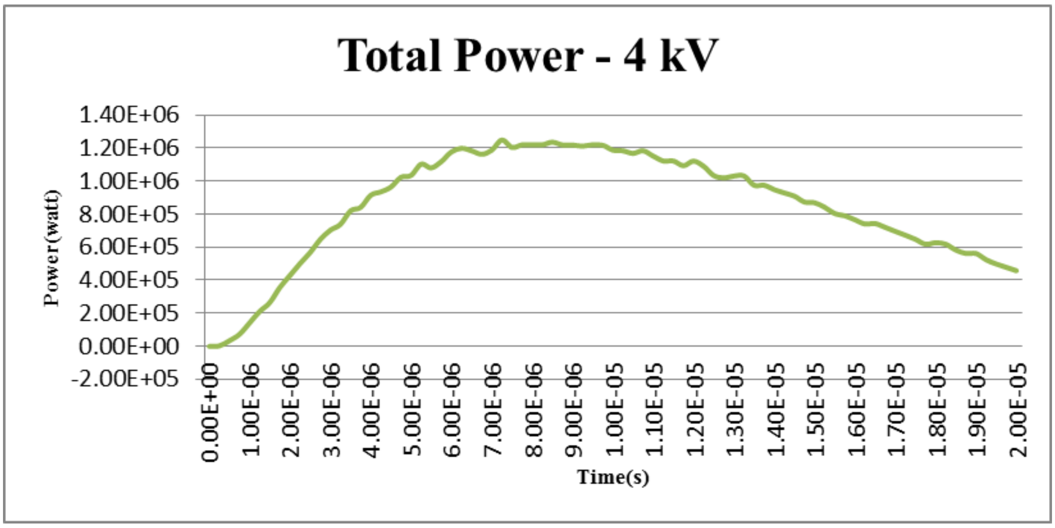


Figure 5.25: Total power at the input

Output clamping voltage = 660 V

Total Energy = 17.2 J

Energy across MOV = 14.6 J

Energy absorbed by the supercapacitor subcircuit = (17.2-14.6) J

= **2.6 J**

5.3.1.2 For 6 kV Surge

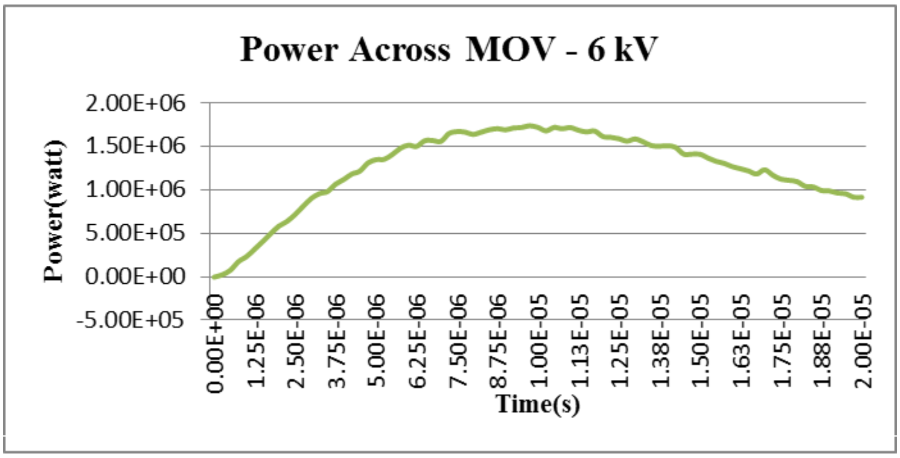


Figure 5.26: Power across MOV

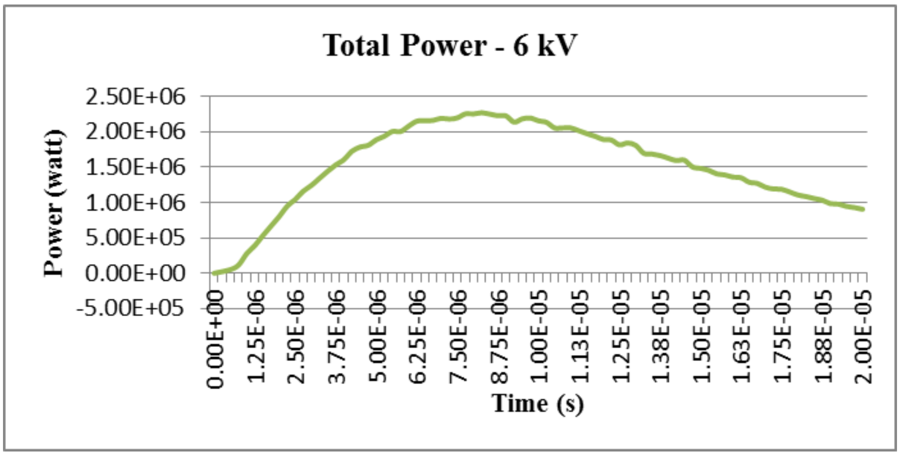


Figure 5.27: Total power at the input

Total Energy = 30.8 J

Output clamping voltage = 720 V

Energy across MOV = 25.2 J

Energy absorbed by the supercapacitor subcircuit = (30.8-25.2) J

= **5.6 J**

Hence, supercapacitor subcircuit plays the role of absorbing part of the surge energy superimposed on the incoming pair of wires and increase the overall life time of the SPD device.

5.3.2 By using ferrite core as a transformer

By applying 4 kV and 6 kV, total energy at the input and the energy absorbed by the MOV is calculated using the CSV values as earlier.

5.3.2.1 For 4 kV Surge

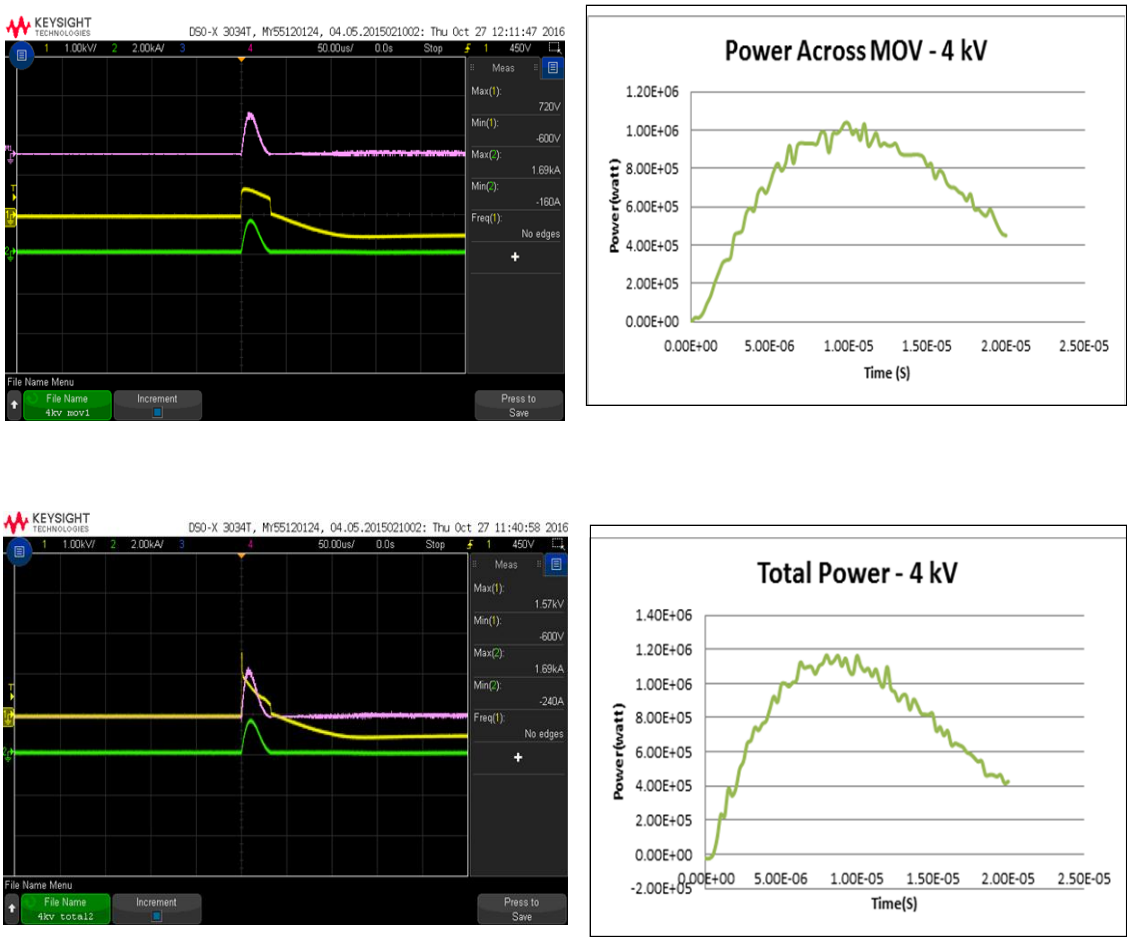


Figure 5.28: Total power at the input and across MOV

Total Energy = 15.7 J

Output clamping voltage = 720 V

Energy across MOV = 14.3 J

Energy absorbed by the supercapacitor subcircuit = (15.7-14.3) J = **<u>1.4 J</u>**

5.3.2.2 For 6 kV Surge

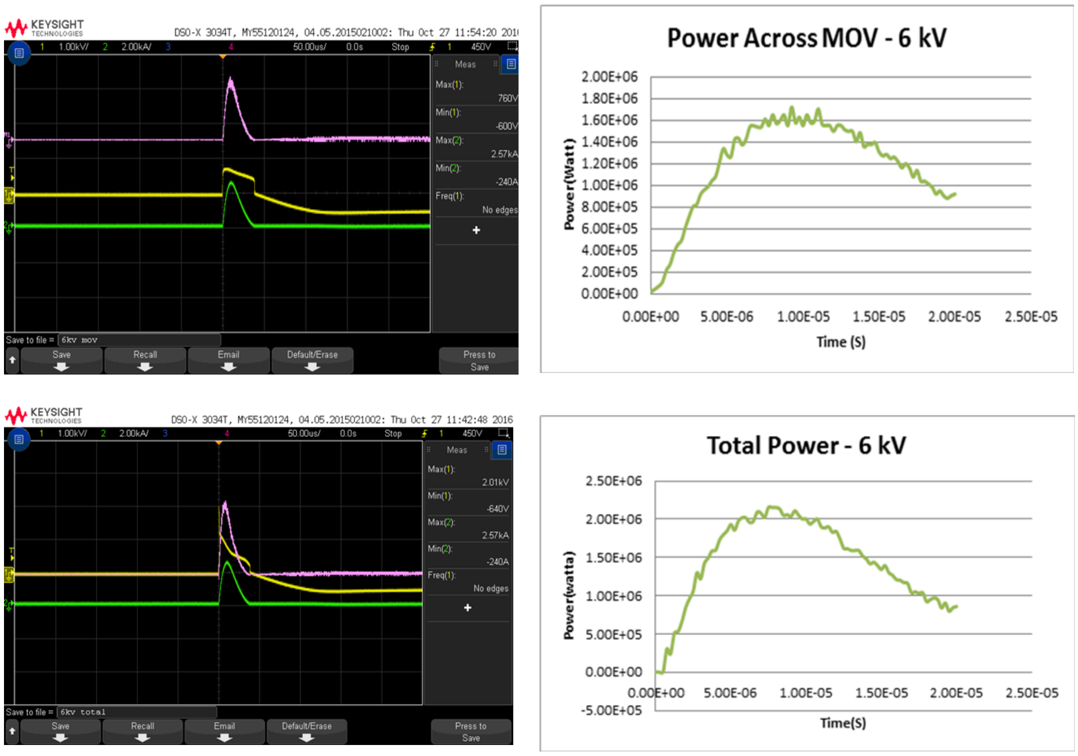


Figure 5.29: Total power at the input and across MOV

Total Energy = 29.1 J

Output clamping voltage = 760 V

Energy across MOV = 24 J

Energy absorbed by the supercapacitor subcircuit = (29.1-24) J = **5.1 J**

5.4 Energy Comparison of Two Different Cores

Surge Voltage (V)	Energy Absorbed by SC Sub-Circuit (J)	
	Powdered Core	Ferrite Core
4000	2.6	1.4
6000	5.6	5.1

Table 5.1 : Energy levels of powdered/ferrite cores

Ferrite core stores less energy from the source which will be absorbed and dissipated by the SC sub-circuit. Hence, powdered core has more capability of absorbing surge energy than the ferrite cores.

5.5 Prototype implementation of the prosed system

5.5.1 Differential Mode

Final prototype implementation of the supercapacitor concept in a differential-mode surge protector circuit is shown in figure 5.30. The SC sub- circuit is formed by a 1 Ω resistor and a 1 F/2.5 V SC in series. The Epcos S-20 MOV with a maximum clamping voltage 595 V together with SC sub- circuit-created input/output waveforms as per Fig 3.2 and 5.22.

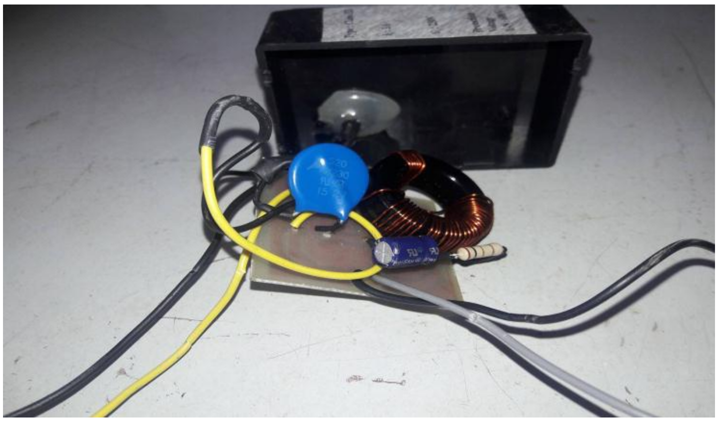


Figure 5.30: Proposed design of SPD (Differential Mode)

The output clamping voltage for the different voltages are tabulated as follows.

Applied Surge Voltage (V)	Output Voltage At Load End L-N (V)
2000	600
4000	675
6000	690

Table 5.2 : Output voltage at load end

5.5.2 Common Mode

Conceptual design of the SPD for common mode which consists of 2.5V /1F SCs, 1Ω resistors, Epcos S-20 MOVs and the powdered core transformers (turns ratio - 6:30) is shown in figure 5.31.

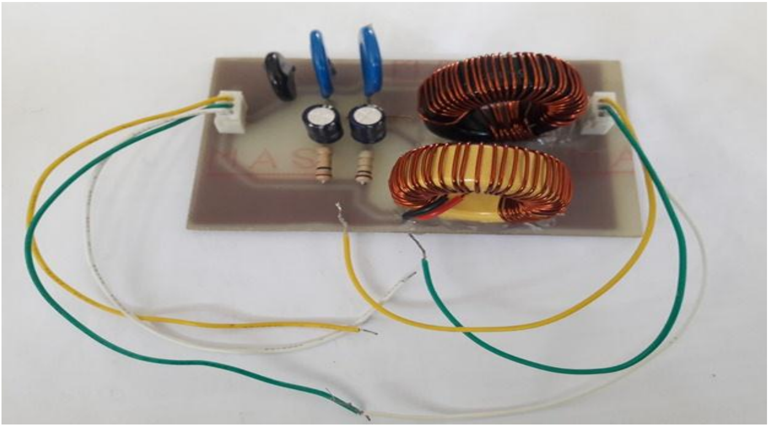


Figure 5.31: Proposed design of SPD (Common Mode)

The output clamping voltage for the different voltages are tabulated as follows.

Applied Surge Voltage (V)	Output Voltage At Load End (V)		
	L-N	L-E	N-E
2000	600	535	535
4000	675	545	583
6000	690	623	607

Table 5.3 : Output voltage at load end

6 CONCLUSION

The research study has been carried out to determine the best configuration of a supercapacitor (SC) to absorb excess energy during a transient. The study has shown that the large value supercapacitors are able to not only handle large amounts of energy but also their large time constants permit this stored energy to be released at a slow rate permitting a longer life to the surge protective device.

Compared to typical non-linear devices used in suge protective device (SPD) circuits, supercapacitors are capable of storing a large amount of energy despite their very low DC voltage rating.In the usual surge protector devices, the high transient energy can cause these non-linear devices to deteriorate and eventually fail. If this energy can be taken out from the non-linear devices their life time will be greatly enhanced.

In this development of SPD, typical non-linear devices (NLDs) such as MOV is combined with a magnetic component and an SC-based sub circuit. However, compared to a typical surge arrestor without supercapacitors, where NLDs are placed directly across the pairs of wires such as the neutral and the live (differential mode) or neutral or live and earth(common mode), the NLD is placed in between the load side end of a primary coil of a transformer and the return wire. Given this configuration, when a surge occurs at the AC input, and when the instantaneous voltage due to surge exceeds the firing voltage of the NLD, high instantaneous current flows through the primary coil, developing a voltage across the primary turns. This in turn develops an induced voltage across the secondary coil, and by winding the secondary coil in the opposite direction, secondary induced voltage has been generated to oppose the surge voltage. This has created a voltage across the critical load to be protected, which is generally less than the instantaneous surge voltage.

The test results indicate that the supercapacitor is not destroyed by the repeated application of high voltage transients and the gradual voltage rise after each hit is in the order of millivolt. Also it still retain its capacitive behavior and is not adversely affected by the transient high voltage at the terminals. Therefore , 1F-2.5 V supercapacitor which has the highest voltage rise with 1 ohm resistor was selected as a supercapacitor sub circuit for this design.

When applied input surge voltage of 6 kV, energy absorbed by the supercapacitor subcircuit with magnetic core is nearly 40% of total energy . Hence, supercapacitor subcircuit plays the role of absorbing part of the surge energy superimposed on the incoming pair of wires and increase the overall life time of the SPD device. Although the clamping voltage of SPD without supercapacitor is nearly 890 V, the supercapacitor assisted surge protective device has a 690 V at its output.

As the test results clearly indicate that the supercapacitor assisted surge protective device forms the basis of an entirely new on non-traditional applications that will yield not only longer life, but also a lower clamping voltage across a critical load to be protected. This proves that the new topology could be used as a base technique to develop full-scale common and differential mode surge capable, fully versatile, commercial surge protectors with better performance than traditional surge protectors with higher component counts. Overall performance of the supercapacitor technique with optimized magnetics is practically used to safeguard electronic systems against transient over-voltage related power quality issues.

Further, this research can be developed to analyse the overall circuit, in order to predict its theoretical performance in detail. This useful ability of supercapacitors can be extended to other major areas such as uninterruptible power supplies and DC-DC converters.

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Appendix A

Cost of implemented unit.

Type	Part No.	Quantity	Price
Resistors			
1Ω / 1 W		3	30.00
Supercapacitors			
1F / 2.5 V	2148494	3	1440.00
Transformer			
Powdered core	0077071A7	3	1080.00
MOV			
Epcos S-20	1004287	4	600.00
Miscellaneous			350.00
		Total (Rs):	**3500.00**

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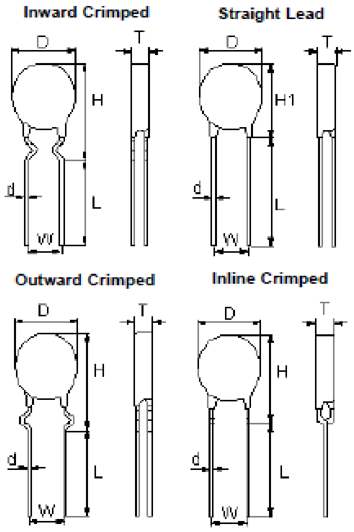

Remark : The lead length (L) is 20 mm minimum unless requested by customers; please refer to lead cutting code in "How to Order"

Dimensions Quick Reference

Series (Maximum)	5D	7D	10D	14D	20D
D	7	9.5	12	16.5	22.5
d*	0.6	0.6	0.8	0.8	1
W**	5	5	7.5	7.5	10
H	12.5	14.5	19	22.5	29
H1	10	12	17	20.5	28
T	4.9	4.9	8.5	8.5	9

* ±0.02
** ±1

Dimensions : Millimetres

Characteristics

High performance transient voltage suppression
Short response time to surge voltage
Low standby power dissipation
Excellent clamping characteristics
High performance withstanding surge currents
High reliability
Disk type : Standard
Lead type : Straight

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Definition of Varistor Terms

Rated RMS Voltage, Rated DC Voltage

The maximum designated values of power system voltage that may be applied continuously between the terminals of a device

Varistor Voltage

Test characteristic that is used to classify varistors by type. A test current of 1 mA DC is typically used to determine varistor voltage classification type. Varistor voltage clamping characteristics can be defined at various test levels

Rated Peak Single Pulse Transient Current

Maximum surge current, 8 / 20 µs waveform which a varistor is rated to withstand for a single surge

Rated Single Pulse Transient Energy

Maximum allowable energy for a single impulse (see specified waveforms)

Maximum Clamping Voltage

Measured peak voltage across the device terminals when a current impulse of specified amplitude and waveform is conducted through the varistor

Typical Capacitance

Typical capacitance values are measured at a test frequency of 1 kHz. Capacitance values are only for reference purpose only, not object to outgoing inspection

Applications

Surge protection in

Consumer electronics
Industrial electronics
Communication electronics
Measuring and controlling systems
Electronic home appliances

Protection against surges induced by lighting striking incoming power lines
Suppression of surges caused by switching inductive loads such as transformers, relays and coils
Protection of rectification diodes, SCRs, power transistors, semiconductor devices, etc

General Characteristics

Storage Temperature	: -55°C to +125°C
Operating Surface Temperature	: 125°C
Operating Ambient Temperature	: -55°C to +85°C (without derating)
Maximum Voltage-Temperature Coefficient	: < -0.05% / °C
Minimum Insulation Resistance	: 1,000 M
Hi Pot (Leads To Case, 1 Minimum)	: 2,500 V dc
Typical Response Time	: <15 Nero-seconds
Epoxy Rating	: 94V-0
Current / Energy Derating (>85 °C)	: -2.5% / °C
DC Leakage Current	: 200 µA maximum (at rated DC working voltage)
Solderability	: MIL-STD-202F

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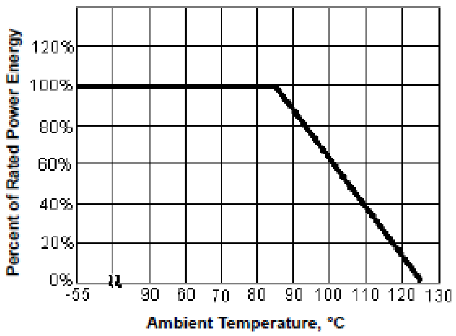
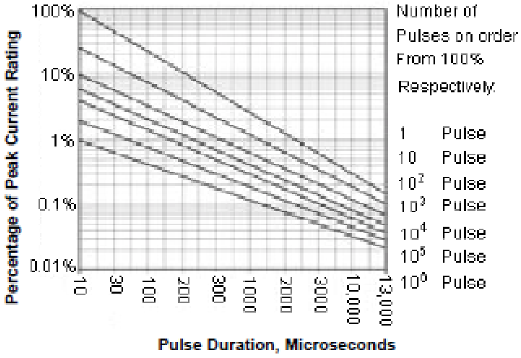
Power Dissipation Ratings (P, in-watts)

Disc Size (mm)	11 V ac to 40 V ac	50 V ac to 680 V ac
5	0.01	0.15
7	0.02	0.25
10	0.05	0.4
14	0.1	0.6
18	-	0.8
20	0.2	1
25	-	1.2
32	-	1.6
34 (Single)	-	2.1
34 (Dual)	-	2.73
40	-	2.1
53	-	2.5

Energy Derating Versus Temperature



Peak Current Per Pulse Versus Pul Seduration



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Specifications Table

Maximum Allowable Voltage		Varistor Voltage		Withstanding Surge Current (8 / 20 µs)	Maximum Claming Voltage (8 / 20 µs)		Maximum Energy		Typical Capacitance	Varistor Voltage	Tolerance (%)	Disk Size (mm)	Part Number
Acrms	DC	DC Volts		1 Time	Vc	Ip	2 ms	10 / 100 µs	at1 KHz				
Volts		Min.	Max.	Amps	Volts	Amps	Joules		PF				
11	14	16	20	100	36	1	0.4	0.6	1,500	18 V	±10	5	MCFT000215
14	18	20	24		43		0.6	0.8	1,260	22 V			MCFT000216
17	22	24	30		53		0.7	0.9	1,050	27 V			MCFT000217
20	26	30	36		65		0.9	1.2	850	33 V			MCFT000218
25	31	35	43		77		1.1	1.3	600	39 V			MCFT000219
30	38	42	52		93		1.4	1.6	500	47 V			MCFT000220
35	45	50	62		110		1.5	1.9	400	56 V			MCFT000221
40	56	61	75		135		1.8	2.3	360	68 V			MCFT000222
50	66	74	90	400	135	5	2.4	3	350	82 V			MCFT000223
75	102	108	132		200		3	5	250	120 V			MCFT000224
95	127	135	165		250		3.5	5.5	180	150 V			MCFT000225
130	175	185	225		340		5	8.5	140	200 V			MCFT000226
150	200	216	264		395		6.5	10	115	240 V			MCFT000227
230	300	324	396		595		9	13	80	360 V			MCFT000228
250	330	351	429		650		10	15	75	390 V			MCFT000229
275	370	387	473		710		11	16	65	430 V			MCFT000230
300	385	423	517		775		13	19	55	470 V			MCFT000231
420	560	612	748		1120		21	30	30	680 V			MCFT000232
11	14	16	20	250	36	2.5	0.8	1	2,900	18 V		7	MCFT000233
14	18	20	24		43		0.9	1.3	2,400	22 V			MCFT000234
17	22	24	30		53		1	1.4	1,800	27 V		5	MCFT000235
20	26	30	36		65		1.2	1.7	1,500	33 V		7	MCFT000236
25	31	35	43		77		1.5	2.1	1,230	39 V			MCFT000237
30	38	42	52		93		1.8	2.5	950	47 V			MCFT000238
35	45	50	62		110		2.2	3.1	890	56 V			MCFT000239
40	56	61	75		135		2.5	3.8	850	68 V			MCFT000240
50	66	74	90	1,200	135	10	3.5	5.5	830	82 V			MCFT000241
75	102	108	132		200		5	7.8	570	120 V			MCFT000242
95	127	135	165		250		6.5	9.7	400	150 V			MCFT000243
130	175	185	225		340		10	13	275	200 V			MCFT000244
150	200	216	264		395		11	16	230	240 V			MCFT000245

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Specifications Table

Maximum Allowable Voltage		Varistor Voltage		Withstanding Surge Current (8 / 20 µs)	Maximum Claming Voltage (8 / 20 µs)		Maximum Energy		Typical Capacitance	Varistor Voltage	Tolerance (%)	Disk Size (mm)	Part Number
Acrms	DC	DC	Volts	1 Time	Vc	Ip	2ms	10 / 100 µs	at1 KHz				
Volts		Min.	Max.	Amps	Volts	Amps	Joules		PF				
230	300	324	396		595		15	25	155	360 V			MCFT000246
250	330	351	429		650		17	26	145	390 V			MCFT000247
275	370	387	473	1,200	710	10	20	28	130	430 V		7	MCFT000248
300	385	423	517		775		21	30	115	470 V			MCFT000249
420	560	612	748		1120		32	45	78	680 V			MCFT000250
11	14	16	20		36		1.5	2.1	6,000	18 V			MCFT000251
14	18	20	24		43		2	2.5	5,000	22 V			MCFT000252
17	22	24	30		53		2.5	3	4,000	27 V			MCFT000253
20	26	30	36	500	65	5	3	4	3,500	33 V			MCFT000254
25	31	35	43		77		3.5	4.6	3,100	39 V			MCFT000255
30	38	42	52		93		4.5	5.5	2,800	47 V			MCFT000256
35	45	50	62		110		5.5	7	2,400	56 V			MCFT000257
40	56	61	75		135		6.5	8.2	2,100	68 V			MCFT000258
50	66	74	90		135		8	12	1,600	82 V		10	MCFT000259
75	102	108	132		200		12	18	1,200	120 V			MCFT000260
95	127	135	165		250		16	22	1,100	150 V	±10		MCFT000261
130	175	185	225		340		20	30	640	200 V			MCFT000262
150	200	216	264	2,500	395	25	25	35	560	240 V			MCFT000263
230	300	324	396		595		35	47	380	360 V			MCFT000264
250	330	351	429		650		40	60	350	390 V			MCFT000265
275	370	387	473		710		45	65	310	430 V			MCFT000266
300	385	423	517		775		46	70	280	470 V			MCFT000267
11	14	16	20		36		3.5	4	15,000	18 V			MCFT000268
14	18	20	24		43		4	5	12,000	22 V			MCFT000269
17	22	24	30		53		5	6	8,500	27 V			MCFT000270
20	26	30	36	1,000	65	10	6	7.5	7,200	33 V			MCFT000271
25	31	35	43		77		7	8.6	6,300	39 V		14	MCFT000272
30	38	42	52		93		8.5	10	5,500	47 V			MCFT000273
35	45	50	62		110		10	11	4,800	56 V			MCFT000274
40	56	61	75		135		12	14	4,000	68 V			MCFT000275
50	66	74	90	4,500	135	50	5	22	3,300	82 V			MCFT000276

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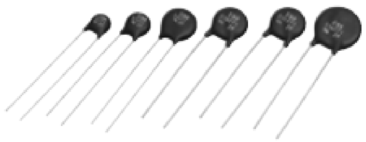
Specifications Table

Maximum Allowable Voltage		Varistor Voltage		Withstanding Surge Current (8 / 20 μs)	Maximum Claming Voltage (8 / 20 μs)		Maximum Energy		Typical Capacitance	Varistor Voltage	Tolerance (%)	Disk Size (mm)	Part Number
Acrms	DC	DC	Volts	1 Time	Vc	Ip	2ms	10 / 100 μs	at1 KHz				
Volts		Min.	Max.	Amps	Volts	Amps	Joules		PF				
75	102	108	132		200		22	34	2,600	120 V			MCFT000277
95	127	135	165		250		30	45	2,000	150 V			MCFT000278
130	175	185	225		340		38	60	1,370	200 V			MCFT000279
150	200	216	264	4,500	395	50	45	66	1,060	240 V		14	MCFT000280
230	300	324	396		595		70	98	725	360 V			MCFT000281
250	330	351	429		650		72	102	665	390 V			MCFT000282
275	370	387	473		710		75	115	600	430 V			MCFT000283
300	385	423	517		775		80	125	570	470 V			MCFT000284
11	14	16	20		36		10	12	27,000	18 V			MCFT000285
14	18	20	24		43		13	15	20,000	22 V			MCFT000286
17	22	24	30		53		15	17	15,000	27 V			MCFT000287
20	26	30	36	2,000	65	20	22	22	12,200	33 V			MCFT000288
25	31	35	43		77		24	26	10,000	39 V	±10		MCFT000289
30	38	42	52		93		30	33	9,350	47 V			MCFT000290
35	45	50	62		110		35	38	8,000	56 V			MCFT000291
40	56	61	75		135		40	43	6,800	68 V			MCFT000292
50	66	74	90		135		37	48	5,600	82 V		20	MCFT000293
75	102	108	132		200		40	55	4,100	120 V			MCFT000294
95	127	135	165		250		50	70	3,200	150 V			MCFT000295
130	175	185	225		340		70	95	2,200	200 V			MCFT000296
150	200	216	264	6,500	395	100	82	110	1,900	240 V			MCFT000297
230	300	324	396		595		120	163	1,320	360 V			MCFT000298
250	330	351	429		650		130	180	1,210	390 V			MCFT000299
275	370	387	473		710		140	190	1,120	430 V			MCFT000300
300	385	423	517		775		50	220	1,000	470 V			MCFT000301

NEW

"ZNR" Transient/Surge Absorbers

Type: **D**
Series: **E**



"ZNR" Transient/Surge Absorber, Series E, Type D features large surge current and energy handling capability for absorbing transient overvoltage in a compact size.

■ Features

- Large withstanding surge current capability in compact sizes
- Large "Energy Handling Capability" absorbing transient overvoltages in compact sizes
- Wide range of varistor voltages
- RoHS compliant

■ Recommended Applications

- Transistor, diode, IC, thyristor or triac semiconductor protection
- Surge protection in consumer electronic equipment
- Surge protection in communication, measuring or controller electronics
- Surge protection in electronic home appliances, gas or petroleum appliances

■ Applicable Standards

- UL1449 (VZCA2/UL, VZCA8/C-UL)
- VDE IEC61051-1, -2, -2-2, IEC60950-1 Annex.Q
- CQC(GB/T10193, GB/T10194, GB4943.1, GB8898)

Refer to pages 2 to 3, and 19 for the details

■ Handling Precautions and Minimum Quantity / Packing Unit

Please see Related Information

■ Explanation of Part Numbers

1	2	3	4	5	6	7	8	9	10	11	12
E	R	Z	E								

1–3: Product Code; 4–6: Series; 7: Lead Configuration; 8–10: Nominal Varistor Voltage; 11–12: Design No.

Series	
E05	Series E5
E07	Series E7
E08	Series E8
E10	Series E10
E11	Series E11
E14	Series E14

Lead Configuration		
Symbol	Lead Configuration	Packaging
A	Straight Lead	Bulk
[1]B	Crimped Lead	Bulk
[2]E	Straight Lead	Taped
[2]F	Crimped Lead	Taped

1) Cut Type, Series E5 to E11
2) Series E5 to E11

Nominal Varistor Voltage
The first two digits are significant figures and the third one denotes the number of zeros following.

■ Reference Guide to Standard Products

Part No.	Applicable Standards		Varistor Voltage at 1 mA	Maximum Allowable Voltage		Clamping Voltage at 8/20μs		Maximum Peak Current at 8/20μs(A)		Recommended Applications
	Type Name	Approvals	(V)	ACrms (V)	DC (V)	max.(V)	Ip (A)	1 time	2 times	
ERZE05A201	E201	○☆◇	200 (185 to 225)	130	170	340	10	1200	600	AC 100 V Line–Line Applications
ERZE07A201	E7201	○☆◇				340	25	2500	1250	
ERZE08A201	E8201	○☆◇				340	25	3500	2500	
ERZE10A201	E10201	○☆◇				340	50	4500	3000	
ERZE11A201	E11201	○◎☆★◇◆				340	50	6000	5000	
ERZE14A201	E14201	○◎☆★◇◆				340	100	10000	7000	
ERZE05A221	E221	○☆◇	220 (198 to 242)	140	180	360	10	1200	600	
ERZE07A221	E7221	○☆◇				360	25	2500	1250	
ERZE08A221	E8221	○☆◇				360	25	3500	2500	
ERZE10A221	E10221	○☆◇				360	50	4500	3500	
ERZE11A221	E11221	○◎☆★◇◆				360	50	6000	5000	
ERZE14A221	E14221	○◎☆★◇◆				360	100	10000	7000	
ERZE05A241	E241	○☆◇	240 (216 to 264)	150	200	395	10	1200	600	AC 100 V to 120 V, Line–Line Applications
ERZE07A241	E7241	○☆◇				395	25	2500	1250	
ERZE08A241	E8241	○☆◇				395	25	3500	2500	
ERZE10A241	E10241	○☆◇				395	50	4500	3000	
ERZE11A241	E11241	○◎☆★◇◆				395	50	6000	5000	
ERZE14A241	E14241	○◎☆★◇◆				395	100	10000	7000	
ERZE05A271	E271	○☆◇	270 (247 to 303)	175	225	455	10	1200	600	
ERZE07A271	E7271	○☆◇				455	25	2500	1250	
ERZE08A271	E8271	○☆◇				455	25	3500	2500	
ERZE10A271	E10271	○☆◇				455	50	4500	3000	
ERZE11A271	E11271	○◎☆★◇◆				455	50	6000	5000	
ERZE14A271	E14271	○◎☆★◇◆				455	100	10000	7000	
ERZE05A331	E331	○☆◇	330 (297 to 363)	210	270	545	10	1200	600	AC 100 V to 120 V, Line–Line Applications Telephone Line Applications, (For DC 250 V Insulation Resistance Test)
ERZE07A331	E7331	○☆◇				545	25	2500	1250	
ERZE08A331	E8331	○☆◇				545	25	3500	2500	
ERZE10A331	E10331	○☆◇				545	50	4500	3000	
ERZE11A331	E11331	○◎☆★◇◆				545	50	6000	4500	
ERZE14A331	E14331	○◎☆★◇◆				545	100	10000	6500	
ERZE05A361	E361	○☆◇	360 (324 to 396)	230	300	595	10	1200	600	
ERZE07A361	E7361	○☆◇				595	25	2500	1250	
ERZE08A361	E8361	○☆◇				595	25	3500	2500	
ERZE10A361	E10361	○☆◇				595	50	4500	3000	
ERZE11A361	E11361	○◎☆★◇◆				595	50	6000	4500	
ERZE14A361	E14361	○◎☆★◇◆				595	100	10000	6500	
ERZE05A391	E391	○☆◇	390 (351 to 429)	250	320	650	10	1200	600	
ERZE07A391	E7391	○☆◇				650	25	2500	1250	
ERZE08A391	E8391	○☆◇				650	25	3500	2500	
ERZE10A391	E10391	○☆◇				650	50	4500	3000	
ERZE11A391	E11391	○◎☆★◇◆				650	50	6000	4500	
ERZE14A391	E14391	○◎☆★◇◆				650	100	10000	6500	
ERZE05A431	E431	○☆◇	430 (387 to 473)	275	350	710	10	1200	600	AC 100 V to 220 V, Line–Line and Line–Ground Applications
ERZE07A431	E7431	○☆◇				710	25	2500	1250	
ERZE08A431	E8431	○☆◇				710	25	3500	2500	
ERZE10A431	E10431	○☆◇				710	50	4500	3000	
ERZE11A431	E11431	○◎☆★◇◆				710	50	6000	4500	
ERZE14A431	E14431	○◎☆★◇◆				710	100	10000	6500	

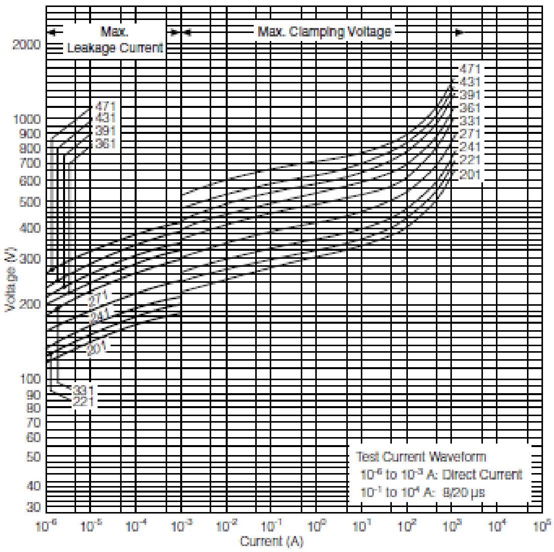
○ : UL1449 (VZCA2/UL, VZCA8/C-UL), ● : UL1449 Type3 (or Code-Connected and Direct plug-in),
◎ : UL1449 Type2 (or Permanently Connected), ☆ : VDE (IEC61051-1, -2, -2-2), ★ : VDE (IEC60950-1 Annex.Q)
◇ : CQC (GB/T10193, GB/T10194), ◆ : CQC (GB4943.1, GB8898)
※ Approval number (File No.) of safety regulations are subject to revision without notice. Ask factory for a copy of the latest file No.

NEW

■ Typical Characteristics

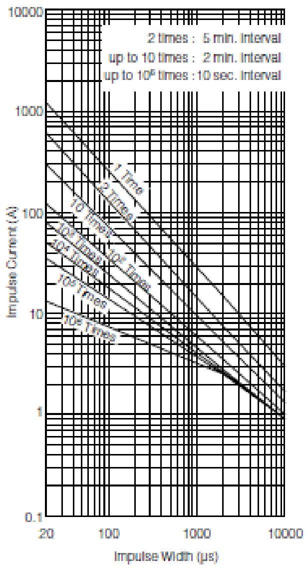
Voltage vs. Current

ERZE05A201 to ERZE05A471

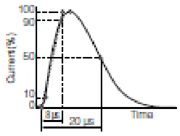


Impulse Derating (Relation between impulse width and impulse current multiple)

ERZE05A201 to ERZE05A471



■ Performance Characteristics (Series E)

	Characteristics		Test Methods/Description	Specifications
	Standard Test Condition		Electrical measurements (initial/after tests) shall be conducted at temperature of 5 to 35 °C, relative humidity of maximum 85 %	———
Electrical	Varistor Voltage		The voltage betwen two terminals with the specified measuring current CmA DC applied is called VC or V_{CmA}. The measurement shall be made as fast as possible to avoid heat affection.	To meet the specified value.
	Maximum Allowable Voltage		The maximum sinusoidal RMS voltage or maximum DC voltage that can be applied continuously.	
	Clamping Voltage		The maximum voltage between two terminals with the specified standard impulse current (8/20 µs) illustrated below applied. 	
	Rated Power		The power that can be applied in the specified ambient temperature.	
	Maximum Energy		The maximum energy within the varistor voltage change of ±10 % when a single impulse current of 2 ms or 10/1000 µs is applied.	
	Maximum Peak Current (Withstanding Surge Current)	2 times	The maximum current within the varistor voltage change of ±10 % when a standard impulse current of 8/20 µs is applied two times with an interval of 5 minutes.	
		1 time	The maximum current within the varistor voltage change of ±10 % with a single standard impulse current of 8/20 µs is applied.	
	Temperature Coefficient of Varistor Voltage		$\frac{V_{CmA} \text{ at } 85\ °C - V_{CmA} \text{ at } 25\ °C}{V_{CmA} \text{ at } 25\ °C} \times \frac{1}{60} \times 100$ (%/°C)	0 to -0.05 %/°C max.
	Capacitance		Capacitance shall be measured at 1 kHz ±10 %, 1 Vrms max. (1 MHz ±10 % below 100 pF), 0 V bias and 20±2 °C.	To meet the specified value
	Withstanding Voltage (Body Insulation)		AC 1500 Vrms shall be applied between both terminals of the specimen connected together and metal foil closely wrapped round its body for 1 minute.	No breakdown
	Impulse Life		The change of VC shall be measured after the impulse current listed below is applied 10000 or 100000 times continuously with the interval of 10 seconds at room temperature.	$\Delta V_{CmA}/V_{CmA} \leq$ 0 to 20 %

Part No. \ Item / Times / Current	Impulse Life (I) ×10^4 Times	Impulse Life (II) ×10^5 Times
	Impulse Current	
ERZE05A201 to ERZE05A471	50 A (8/20 µs)	35 A (8/20 µs)
ERZE07A201 to ERZE07A621	100 A (8/20 µs)	70 A (8/20 µs)
ERZE08A201 to ERZE08A751	150 A (8/20 µs)	85 A (8/20 µs)
ERZE10A201 to ERZE10A112	170 A (8/20 µs)	90 A (8/20 µs)
ERZE11A201 to ERZE11A112	200 A (8/20 µs)	110 A (8/20 µs)
ERZE14A201 to ERZE14A112	250 A (8/20 µs)	120 A (8/20 µs)

■ Performance Characteristics (Series E)

	Characteristics	Test Methods	Specifications
Mechanical	Robustness of Terminations (Tensile)	After gradually applying the force specified below and keeping the unit fixed for 10 seconds, the terminal shall be visually examined for any damage. Terminal diameter / Force: ϕ0.6 mm — 9.8 N ϕ0.8 mm — 9.8 N ϕ1.0 mm — 19.6 N	No remarkable mechanical damage
Mechanical	Robustness of Terminations (Bending)	The unit shall be secured with its terminal kept vertical and the force specified below shall be applied in the axial direction. The terminal shall gradually be bent by 90 ° in one direction, then 90 ° in the opposite direction, and again back to the original position. The damage of the terminal shall be visually examined. Terminal diameter / Force: ϕ0.6 mm — 4.9 N ϕ0.8 mm — 4.9 N ϕ1.0 mm — 9.8 N	No remarkable mechanical damage
Mechanical	Vibration	After repeadly applying a single harmonic vibration (amplitude: 0.75 mm, double amplitude: 1.5 mm) with 1 minute vibration frequency cycles (10 Hz to 55 Hz to 10 Hz) to each of three perpendicular directions for 2 hours. Thereafter, the unit shall be visually examined.	No remarkable mechanical damage
Mechanical	Solderability	After dipping the terminals to a depth of approximately 3mm from the body in a soldering bath of 235±5°C for 2±0.5 seconds, the terminal shall be visually examined.	Approximately 95 % of the termainals shall be covered with new solder uniformly.
Mechanical	Resistance to Soldering Heat	After each lead shall be dipped into a solder bath having a temperature of 260±5 °C to a point 2.0 to 2.5 mm from the body of the unit, using shielding board (t=1.5 mm), be held there for 10±1 s and then be stored at room temperature and normal humidity for 1 to 2 hours. The change of V_{CmA} and mechanical damages shall be examined.	$\Delta V_{CmA}/V_{CmA} < \pm 5$ % No remarkable mechanical damage
Environmental	High Temperature Storage/ Dry Heat	The specimen shall be subjected to 125±2 °C for 1000 hours in a thermostatic bath without load and then stored at room temperature and normal humidity for 1 to 2 hours. Thereafter, the change of V_{CmA} shall be measured.	$\Delta V_{CmA}/V_{CmA} < \pm 5$ %
Environmental	Humidity	The specimen shall be subjected to 40±2 °C, 90 to 95 % RH for 1000 hours without load and then stored at room temperature and normal humidity for 1 to 2 hours. Thereafter, the change of V_{CmA} shall be measured.	$\Delta V_{CmA}/V_{CmA} < \pm 5$ %
Environmental	Temperature Cycle	The temperature cycle shown below shall be repeated five cycles and then stored at room temperature and normal humidity for 1 to 2 hours. The change of V_{CmA} and mechanical damage shall be examined. Step / Temperature (°C) / Period (minutes): 1 — –40±3 — 30±3 2 — Room temperature — 15±3 3 — 125±2 — 30±3 4 — Room temperature — 15±3	$\Delta V_{CmA}/V_{CmA} < \pm 5$ % No remarkable mechanical damage
Environmental	High Temperature Load/ Dry Heat Load	After being continuously applied the Maximum Allowable Voltage at 85±2 °C for 1000 hours, the specimen shall be stored at room temperature and normal humidity for 1 to 2 hours. Thereafter, the change of V_{CmA} shall be measured.	$\Delta V_{CmA}/V_{CmA} < \pm 10$ %
Environmental	Damp Heat Load/ Humidity Load	The specimen shall be subjected to 40±2 °C, 90 to 95 % RH and the Maximum Allowable Voltage for 1000 hours and then stored at room temperature and normal humidity for 1 to 2 hours. Thereafter, the change of V_{CmA} shall be measured.	$\Delta V_{CmA}/V_{CmA} < \pm 10$ %
Environmental	Low Temperature Storage/Cold	The specimen shall be subjected to –40±2 °C without load for 1000 hours and then stored at room temperature and normal humidity for 1 to 2 hours. Thereafter, the change of V_{CmA} shall be measured.	$\Delta V_{CmA}/V_{CmA} < \pm 5$ %

(4) Concerning current fuse

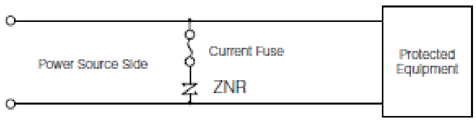
<1> We recommend selecting a ZNR and the rated current of a current fuse as follows.
Finally, please be sure that there is no danger if the ZNR mounted on the equipment breaks.

● Type D, Series E

Standard Part No.	ERZE05A□□□	ERZE07A□□□	ERZE08A□□□	ERZE10A□□□	ERZE11A□□□	ERZE14A□□□
Fuse rated current	5 A max.	7 A max.	7 A max.	10 A max.	10 A max.	10 A max.

✱ Fuses shall use rated voltages appropriate for circuits.

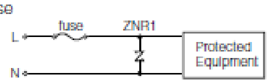
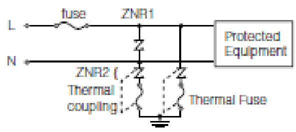
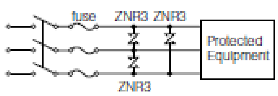
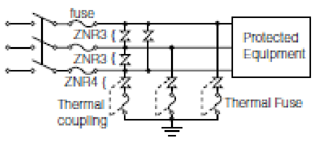
<2> The recommended fuse position is shown in table 1, "Example of ZNR application", however, if the load current of protected equipment is larger than that of the above recommended fuse rated current, install a current fuse at the position shown below.



(5) Concerning thermal fuse

Set a thermal fuse to get high thermal conductivity with ZNR.

Table 1 Example of ZNR application

	Across-the-Line use	Use between Line to ground
Connections example	DC/AC Single-phase 	DC/AC Single-phase 
Connections example	AC 3-phase 	AC 3-phase 

Example of varistor voltage — Across-the-Line use:

ZNR	Source voltage	Nominal varistor voltage
ZNR1 ZNR3	AC100 V	201 to 361*
	AC120 V	241 to 431*
	AC200 V	471 to 621*
	AC220 V	471 to 621*
	AC240 V	511, 621*
	AC380 V	751, 821*

Example of varistor voltage — Use between Line to ground:

ZNR	Source voltage	Nominal varistor voltage
ZNR2 ZNR4	AC100 V AC220 V	471 511 621* 821 and more**
	AC230 V AC240 V	511 621* 821 and more**
	AC380 V	112**

Note : Element size is selected by impulse Condition.

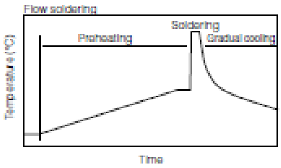
2) Operating environments
  (1) The ZNR is designed to be used indoors. Do not use it exposed outdoors.
  (2) Do not use the ZNR in places exposed to temperatures beyond the operating temperature range, such as places exposed to sunlight and vicinities of heating equipment.
  (3) Do not use the ZNR in places exposed to high temperatures and high humidity, such as places exposed directly to rain, wind, dew condensation, and vapor.
  (4) Do not use the ZNR in dusty and salty places and atmospheres polluted by corrosive gases.

3) Processing conditions
  (1) Do not wash the ZNR by such solvents(thinner, acetone, etc.) as its exterior resin deteriorates.
  (2) Do not apply a strong vibration or shock (by falling, etc.) to the ZNR, cracking to its exterior resin and element may occur.
  (3) When coating the ZNR with resin(including molding), do not use such resin.
  (4) Do not bend the ZNR type D lead wires at the position close to its ZNR type D exterior resin, or apply external force to the position.
  (5) When soldering the ZNR lead wires, follow the recommended conditions and do not melt the solder and insulating materials constituting the ZNR.

	Soldering Method	Recommended Condition	Attention Item
Type D	Flow soldering	260 °C, within 10 sec.	Type D is not Reflow soldering object part.

✱1 Soldering iron temperature should not exceed 400 °C and should not be applied for mor than 5 seconds.
✱2 Profile be careful because there is a margin of error in the way of measuring.
✱3 The temperature depend on the size and the package density of the substrate. Therefore, confirm every kind of the substrate.

● Soldering temperature-time profile to recommend



Preheating	The normal to 130 °C	max. 120s
Soldering	max. 260 °C	max. 10s
Gradual cooling	Gradual cooling	

4) Long-term storage
  (1)Do not store the ZNR under high temperature and high humidity. Store it at a temperature up to 40 °C and at humidity below 75 %RH, and use it within two years.
  Before using the ZNR that has been stored for a long period(two years or longer), confirm the solderability.
  (2) Avoid atmospheres full of corrosive gases(hydrogen sulfide, sulfurous acid, chlorine, ammonia, etc.).
  (3) Avoid direct sunlight and dew condensation.

3. Notices
  3.1 In cases that the ZNR is used in equipment(aerospace equipment, medical equipment, etc.) requiring extremely high reliability, ask us for a selection of Part No., and protection coordination, etc. in advance.
  3.2 Note that we do not take any responsibility for faults and abnormalities resulting from the use not in conformity with the contents of entries in the delivery specification.
  3.3 There is a possibility that the ZNR will unexpectedly cause smoke or ignite because of an abnormal rise of the circuit voltage and invasion of excessive surge. To prevent that accident from spreading over the equipment and not to expand the damage, use multiplex protection such as the adoption of frame-retardant materials for housing parts and structural parts.

PowerStor®

Supercapacitors

B Series

HALOGEN HF FREE · Pb · RoHS

Description

Cooper Bussmann PowerStor® supercapacitors are unique, ultra-high capacitance devices utilizing electrochemical double layer capacitor (EDLC) construction combined with new, high performance materials. This combination of advanced technologies allows Cooper Bussmann to offer a wide variety of capacitor solutions tailored to specific applications that range from a few micro-amps for several days to several amps for milliseconds.

Cylindrical Device

Features & Benefits

- High specific capacitance
- Very low ESR
- Low leakage currents
- Long cycle life
- UL Recognized

Applications

- Main power
- Hybrid battery packs
- Hold-up power
- Pulse power

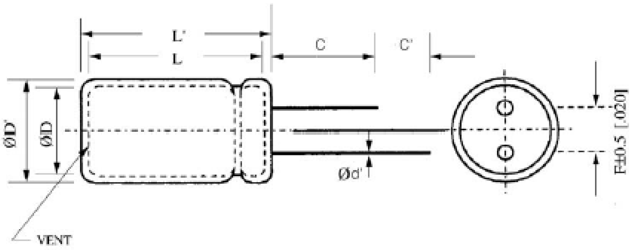
Specifications	
Working Voltage	2.5V
Surge Voltage	3.0V
Capacitance	0.22F to 2.2F
Capacitance Tolerance	-20% to +80% (20°C)
Operating Temperature Range	-25°C to 70°C

Standard Product						
Nominal Capacitance (F)	Part Number	Maximum ESR (Ω) (Equivalent Series Resistance) Measured @ 100Hz	Nominal Leakage Current (μA) After 72 Hours @ 20°C	Nominal Dimensions (mm) Diameter	Nominal Dimensions (mm) Length	Typical Mass (grams/piece)
0.22	B0510-2R5224-R	2.00	2	5	11	0.54
1.0	B0810-2R5105-R	0.50	4	8	13	1.2
1.5	B1010-2R5155-R	0.30	7	10	14	1.9
2.2	B0820-2R5225-R	0.20	9	8	20	1.5

Performance		
Parameter	Capacitance Change (% of initial measured value)	ESR (% of initial specified value)
Life (1000 hrs @ 70°C @ 2.5Vdc)	≤ 30 %	≤ 300 %
Storage - Low and High Temperature (1000 hrs @ -25°C and 70°C)	≤ 30 %	≤ 300 %

Dimensions (mm)								
Part Number	D	D'	L	L'	F	d'	C	C'
B0510-2R5224-R	5.0	5.5	11.5	12.0	2.0	0.50	20.0	5.0
B0810-2R5105-R	8.0	8.5	13.0	13.5	3.5	0.50	20.0	5.0
B1010-2R5155-R	10.0	10.5	14.3	14.8	5.0	0.60	20.0	5.0
B0820-2R5225-R	8.0	8.5	20.5	21.0	3.5	0.50	20.0	5.0
Tolerances	Maximum				± 0.5	± 0.02	Minimum	

Note: Longer lead is positive.



Part Numbering System										
B	□ □	□ □	–	2	R	5	□	□		□
Series Code	Dimensions (mm)			Voltage (V) R is Decimal			Capacitance (μF)			
							Value			Multiplier
B Series	Diameter	Length		2R5 = 2.5V			Example: 155 = 15 x 10⁵μF or 1.5F			

Packaging Information

Packaging:

- Standard packaging: Bulk, 100 units per bag.
- Larger bulk packages available on request.

Part Marking

Manufacturer
Capacitance (F)
Max Operating Voltage (V)
Series Code (or part number)
Polarity

North America
Cooper Bussmann
1225 Broken Sound Parkway NW
Suite F
Boca Raton, FL 33487-3533
Tel: 1-561-998-4100
Fax: 1-561-241-6640
Toll Free: 1-888-414-2645

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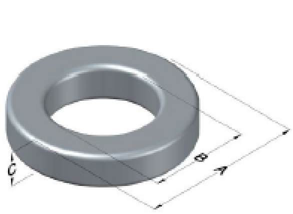
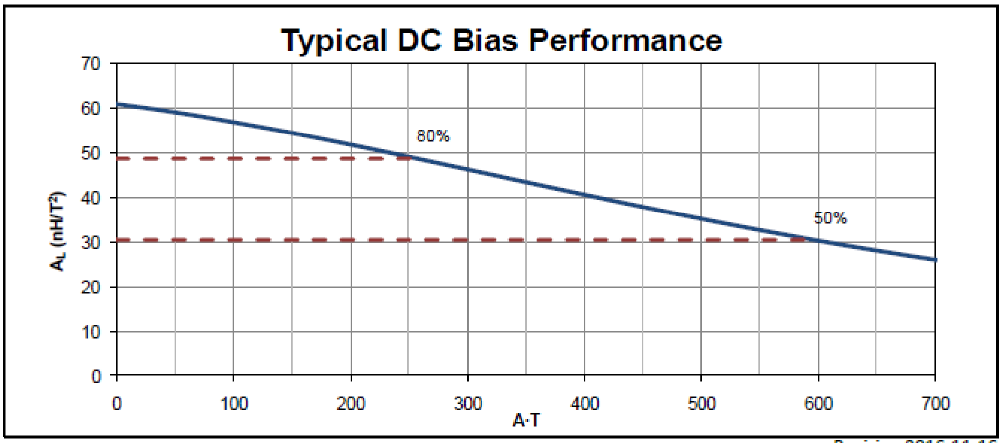


Kool Mμ Permeability (μ)	A_L (nH/T²)	Core Marking			Coating Color
		Lot Number	Part Number	Inductance Grade	
60	61 ± 8%	XXXXXX	77071A7	N/A	Black

Dimensions	Uncoated		Coated Limits			Packaging
	(mm)	(in)	(mm)	(in)		
OD (A)	32.80	1.291	33.66	1.325	max	Cardboard cut-outs Box Qty= 250 pcs
ID (B)	20.1	0.791	19.4	0.766	min	
HT (C)	10.7	0.420	11.5	0.450	max	

Electrical Characteristics			Physical Characteristics							
Watt Loss @ 100 kHz, 100mT max (mW/cm³)	DC Bias min (A·T/cm)		Voltage Breakdown wire to wire min (V_{AC})	Break Strength min (kg)	Window Area W_A(mm²)	Cross Section A_e (mm²)	Path Length L_e (mm)	Volume V_e (mm³)	Weight (g)
	80%	50%							
900	31.0	69.1	2000	49	297	65.6	81.4	5340	32

Winding Information							Temperature Rating
Winding Length Per Turn				Wound Coil Dimensions (mm)			Curie Temp: 500°C
Winding Factor	(mm)	Winding Factor	(mm)	40% Winding Factor	OD	36.8	Coating Temp (Continuous up to): 200°C
					HT	17.8	
				Completely Full Window	Max OD	46.7	Notes:
0%	37.4	40%	47.2		Max HT	28.0	
20%	42.4	45%	48.8	Surface Area (mm²)			
25%	43.5	50%	50.1				
30%	44.7	60%	53.2	Unwound Core	3,100		
35%	46.1	70%	56.7	40% Winding Factor	4,900		



Revision 2016-11-16

Appendix E

4 kV

Time(S)	Volt(V)	Current(A)	Power(W)	Energy(J)
0.00E+00	1.79E+02	-2.90E+01	6.62E+03	-1.66E-03
2.50E-07	5.23E+02	9.99E+00	3.91E+03	9.77E-04
5.00E-07	5.52E+02	9.04E+01	4.78E+04	1.19E-02
7.50E-07	5.68E+02	1.42E+02	7.87E+04	1.97E-02
1.00E-06	5.84E+02	2.50E+02	1.44E+05	3.60E-02
1.25E-06	6.03E+02	3.32E+02	1.98E+05	4.96E-02
1.50E-06	6.03E+02	3.72E+02	2.23E+05	5.57E-02
1.75E-06	6.03E+02	4.81E+02	2.88E+05	7.20E-02
2.00E-06	6.04E+02	5.33E+02	3.20E+05	7.99E-02
2.25E-06	6.03E+02	6.13E+02	3.68E+05	9.20E-02
2.50E-06	6.23E+02	6.72E+02	4.17E+05	1.04E-01
2.75E-06	6.23E+02	7.74E+02	4.80E+05	1.20E-01
3.00E-06	6.23E+02	8.14E+02	5.05E+05	1.26E-01
3.25E-06	6.28E+02	8.63E+02	5.40E+05	1.35E-01
3.75E-06	6.38E+02	9.75E+02	6.20E+05	1.55E-01
4.00E-06	6.43E+02	1.02E+03	6.51E+05	1.63E-01
4.25E-06	6.39E+02	1.06E+03	6.78E+05	1.69E-01
4.50E-06	6.33E+02	1.14E+03	7.17E+05	1.79E-01
4.75E-06	6.29E+02	1.18E+03	7.37E+05	1.84E-01
5.00E-06	6.43E+02	1.22E+03	7.81E+05	1.95E-01
5.25E-06	6.28E+02	1.27E+03	7.92E+05	1.98E-01
5.50E-06	6.34E+02	1.30E+03	8.20E+05	2.05E-01
5.75E-06	6.29E+02	1.34E+03	8.38E+05	2.10E-01
6.00E-06	6.43E+02	1.38E+03	8.82E+05	2.21E-01
6.50E-06	6.33E+02	1.42E+03	8.94E+05	2.24E-01
6.75E-06	6.23E+02	1.46E+03	9.06E+05	2.27E-01
7.00E-06	6.43E+02	1.46E+03	9.36E+05	2.34E-01
7.25E-06	6.28E+02	1.47E+03	9.18E+05	2.30E-01
7.50E-06	6.34E+02	1.52E+03	9.59E+05	2.40E-01
7.75E-06	6.43E+02	1.54E+03	9.87E+05	2.47E-01
8.00E-06	6.23E+02	1.54E+03	9.57E+05	2.39E-01
8.25E-06	6.23E+02	1.54E+03	9.56E+05	2.39E-01
8.50E-06	6.34E+02	1.56E+03	9.85E+05	2.46E-01
8.75E-06	6.38E+02	1.58E+03	1.00E+06	2.51E-01
9.00E-06	6.43E+02	1.62E+03	1.04E+06	2.59E-01
9.25E-06	6.28E+02	1.59E+03	9.94E+05	2.49E-01
9.50E-06	6.23E+02	1.62E+03	1.01E+06	2.51E-01
9.75E-06	6.43E+02	1.62E+03	1.04E+06	2.60E-01

Time(S)	Volt(V)	Current(A)	Power(W)	Energy(J)
1.00E-05	6.23E+02	1.58E+03	9.82E+05	2.46E-01
1.03E-05	6.39E+02	1.62E+03	1.03E+06	2.58E-01
1.05E-05	6.23E+02	1.62E+03	1.01E+06	2.52E-01
1.08E-05	6.23E+02	1.61E+03	9.99E+05	2.50E-01
1.10E-05	6.23E+02	1.58E+03	9.81E+05	2.45E-01
1.13E-05	6.23E+02	1.61E+03	1.00E+06	2.50E-01
1.15E-05	6.23E+02	1.58E+03	9.81E+05	2.45E-01
1.20E-05	6.23E+02	1.58E+03	9.81E+05	2.45E-01
1.23E-05	6.19E+02	1.57E+03	9.69E+05	2.42E-01
1.25E-05	6.23E+02	1.54E+03	9.56E+05	2.39E-01
1.28E-05	6.09E+02	1.54E+03	9.34E+05	2.33E-01
1.30E-05	6.22E+02	1.54E+03	9.54E+05	2.39E-01
1.33E-05	6.03E+02	1.50E+03	9.01E+05	2.25E-01
1.35E-05	6.03E+02	1.48E+03	8.90E+05	2.22E-01
1.38E-05	6.03E+02	1.46E+03	8.77E+05	2.19E-01
1.40E-05	6.03E+02	1.46E+03	8.77E+05	2.19E-01
1.43E-05	6.03E+02	1.42E+03	8.53E+05	2.13E-01
1.45E-05	6.03E+02	1.42E+03	8.53E+05	2.13E-01
1.48E-05	5.83E+02	1.42E+03	8.24E+05	2.06E-01
1.50E-05	5.83E+02	1.38E+03	8.00E+05	2.00E-01
1.53E-05	5.83E+02	1.35E+03	7.82E+05	1.96E-01
1.55E-05	5.83E+02	1.32E+03	7.66E+05	1.92E-01
1.58E-05	5.89E+02	1.33E+03	7.78E+05	1.95E-01
1.60E-05	5.83E+02	1.30E+03	7.54E+05	1.88E-01
1.63E-05	5.83E+02	1.26E+03	7.30E+05	1.83E-01
1.65E-05	5.83E+02	1.22E+03	7.07E+05	1.77E-01
1.68E-05	5.83E+02	1.23E+03	7.14E+05	1.78E-01
1.70E-05	5.82E+02	1.21E+03	7.06E+05	1.76E-01
1.73E-05	5.67E+02	1.14E+03	6.48E+05	1.62E-01
1.75E-05	5.63E+02	1.14E+03	6.38E+05	1.59E-01
1.78E-05	5.68E+02	1.10E+03	6.21E+05	1.55E-01
1.80E-05	5.63E+02	1.10E+03	6.14E+05	1.54E-01
1.83E-05	5.63E+02	1.06E+03	5.92E+05	1.48E-01
1.85E-05	5.63E+02	1.03E+03	5.80E+05	1.45E-01
1.88E-05	5.63E+02	9.86E+02	5.53E+05	1.38E-01
1.90E-05	5.63E+02	9.75E+02	5.47E+05	1.37E-01
1.93E-05	5.63E+02	9.75E+02	5.47E+05	1.37E-01
1.95E-05	5.52E+02	8.94E+02	4.92E+05	1.23E-01
1.98E-05	5.43E+02	8.83E+02	4.77E+05	1.19E-01
2.00E-05	5.43E+02	8.54E+02	4.62E+05	1.15E-01
			Total	1.46E+01

Time(S)	Volt(V)	Current(A)	Power(W)	Energy(J)
0.00E+00	1.78E+02	-7.29E+00	-1.95E+03	-4.88E-04
2.50E-07	9.11E+02	1.51E+00	1.28E+03	3.20E-04
5.00E-07	1.00E+03	3.29E+01	3.22E+04	8.06E-03
7.50E-07	9.88E+02	7.31E+01	7.16E+04	1.79E-02
1.25E-06	9.02E+02	2.34E+02	2.10E+05	5.25E-02
1.50E-06	9.02E+02	2.93E+02	2.63E+05	6.59E-02
1.75E-06	9.02E+02	3.95E+02	3.55E+05	8.89E-02
2.00E-06	9.02E+02	4.75E+02	4.28E+05	1.07E-01
2.25E-06	9.02E+02	5.56E+02	5.00E+05	1.25E-01
2.50E-06	8.92E+02	6.36E+02	5.66E+05	1.42E-01
2.75E-06	9.02E+02	7.16E+02	6.46E+05	1.61E-01
3.00E-06	8.83E+02	7.95E+02	7.02E+05	1.75E-01
3.25E-06	8.82E+02	8.37E+02	7.37E+05	1.84E-01
3.50E-06	8.93E+02	9.17E+02	8.18E+05	2.05E-01
3.75E-06	8.68E+02	9.69E+02	8.40E+05	2.10E-01
4.00E-06	8.82E+02	1.04E+03	9.13E+05	2.28E-01
4.25E-06	8.67E+02	1.08E+03	9.33E+05	2.33E-01
4.50E-06	8.62E+02	1.12E+03	9.63E+05	2.41E-01
4.75E-06	8.62E+02	1.19E+03	1.02E+06	2.56E-01
5.00E-06	8.62E+02	1.20E+03	1.03E+06	2.58E-01
5.25E-06	8.62E+02	1.28E+03	1.10E+06	2.75E-01
5.50E-06	8.33E+02	1.30E+03	1.08E+06	2.70E-01
5.75E-06	8.48E+02	1.32E+03	1.12E+06	2.79E-01
6.00E-06	8.41E+02	1.40E+03	1.18E+06	2.94E-01
6.25E-06	8.38E+02	1.43E+03	1.20E+06	2.99E-01
6.50E-06	8.22E+02	1.44E+03	1.18E+06	2.96E-01
6.75E-06	8.08E+02	1.44E+03	1.16E+06	2.90E-01
7.00E-06	8.02E+02	1.48E+03	1.19E+06	2.97E-01
7.25E-06	8.22E+02	1.52E+03	1.25E+06	3.12E-01
7.50E-06	8.02E+02	1.50E+03	1.20E+06	3.01E-01
8.00E-06	7.82E+02	1.56E+03	1.22E+06	3.05E-01
8.25E-06	7.82E+02	1.56E+03	1.22E+06	3.05E-01
8.50E-06	7.72E+02	1.60E+03	1.23E+06	3.09E-01
8.75E-06	7.62E+02	1.60E+03	1.22E+06	3.04E-01
9.00E-06	7.62E+02	1.60E+03	1.22E+06	3.04E-01
9.50E-06	7.52E+02	1.62E+03	1.22E+06	3.05E-01
9.75E-06	7.42E+02	1.64E+03	1.22E+06	3.04E-01
1.00E-05	7.42E+02	1.60E+03	1.19E+06	2.97E-01

Time(S)	Volt(V)	Current(A)	Power(W)	Energy(J)
1.03E-05	7.21E+02	1.64E+03	1.18E+06	2.96E-01
1.05E-05	7.21E+02	1.62E+03	1.17E+06	2.92E-01
1.08E-05	7.21E+02	1.64E+03	1.18E+06	2.96E-01
1.13E-05	7.01E+02	1.60E+03	1.12E+06	2.80E-01
1.15E-05	6.92E+02	1.62E+03	1.12E+06	2.80E-01
1.18E-05	6.96E+02	1.57E+03	1.09E+06	2.73E-01
1.20E-05	7.01E+02	1.60E+03	1.12E+06	2.80E-01
1.23E-05	6.81E+02	1.60E+03	1.09E+06	2.72E-01
1.25E-05	6.72E+02	1.54E+03	1.03E+06	2.58E-01
1.28E-05	6.61E+02	1.54E+03	1.02E+06	2.55E-01
1.30E-05	6.61E+02	1.56E+03	1.03E+06	2.57E-01
1.33E-05	6.61E+02	1.56E+03	1.03E+06	2.58E-01
1.35E-05	6.41E+02	1.52E+03	9.74E+05	2.43E-01
1.38E-05	6.41E+02	1.52E+03	9.74E+05	2.43E-01
1.40E-05	6.41E+02	1.48E+03	9.47E+05	2.37E-01
1.45E-05	6.32E+02	1.44E+03	9.08E+05	2.27E-01
1.48E-05	6.07E+02	1.44E+03	8.72E+05	2.18E-01
1.50E-05	6.21E+02	1.40E+03	8.68E+05	2.17E-01
1.53E-05	6.05E+02	1.39E+03	8.40E+05	2.10E-01
1.55E-05	5.91E+02	1.36E+03	8.03E+05	2.01E-01
1.58E-05	5.86E+02	1.35E+03	7.89E+05	1.97E-01
1.60E-05	5.81E+02	1.32E+03	7.65E+05	1.91E-01
1.63E-05	5.65E+02	1.31E+03	7.39E+05	1.85E-01
1.65E-05	5.81E+02	1.28E+03	7.42E+05	1.86E-01
1.68E-05	5.81E+02	1.24E+03	7.19E+05	1.80E-01
1.70E-05	5.80E+02	1.20E+03	6.95E+05	1.74E-01
1.73E-05	5.65E+02	1.19E+03	6.71E+05	1.68E-01
1.75E-05	5.50E+02	1.18E+03	6.47E+05	1.62E-01
1.78E-05	5.46E+02	1.13E+03	6.16E+05	1.54E-01
1.80E-05	5.61E+02	1.12E+03	6.26E+05	1.56E-01
1.83E-05	5.56E+02	1.11E+03	6.16E+05	1.54E-01
1.85E-05	5.51E+02	1.06E+03	5.82E+05	1.45E-01
1.88E-05	5.41E+02	1.04E+03	5.61E+05	1.40E-01
1.90E-05	5.41E+02	1.04E+03	5.61E+05	1.40E-01
1.93E-05	5.25E+02	9.98E+02	5.23E+05	1.31E-01
1.95E-05	5.20E+02	9.58E+02	4.97E+05	1.24E-01
1.98E-05	5.20E+02	9.17E+02	4.77E+05	1.19E-01
2.00E-05	5.20E+02	8.77E+02	4.56E+05	1.14E-01
			Total	**1.72E+01**

6 kV

Time(S)	Volt(V)	Current(A)	Power(W)	Energy(J)
0.00E+00	1.34E+02	-3.44E+01	-5.68E+03	-1.42E-03
2.50E-07	5.21E+02	4.47E+01	2.17E+04	5.42E-03
5.00E-07	5.97E+02	1.25E+02	7.32E+04	1.83E-02
7.50E-07	6.08E+02	2.86E+02	1.72E+05	4.31E-02
1.00E-06	6.37E+02	3.66E+02	2.31E+05	5.78E-02
1.25E-06	6.53E+02	4.87E+02	3.16E+05	7.91E-02
1.50E-06	6.47E+02	6.26E+02	4.03E+05	1.01E-01
1.75E-06	6.57E+02	7.57E+02	4.96E+05	1.24E-01
2.00E-06	6.57E+02	8.88E+02	5.81E+05	1.45E-01
2.25E-06	6.57E+02	9.69E+02	6.35E+05	1.59E-01
2.50E-06	6.57E+02	1.09E+03	7.14E+05	1.78E-01
2.75E-06	6.77E+02	1.20E+03	8.10E+05	2.02E-01
3.00E-06	6.77E+02	1.33E+03	8.99E+05	2.25E-01
3.25E-06	6.77E+02	1.41E+03	9.54E+05	2.39E-01
3.50E-06	6.67E+02	1.47E+03	9.79E+05	2.45E-01
3.75E-06	6.77E+02	1.57E+03	1.06E+06	2.66E-01
4.00E-06	6.77E+02	1.65E+03	1.12E+06	2.79E-01
4.25E-06	6.82E+02	1.73E+03	1.18E+06	2.95E-01
4.50E-06	6.77E+02	1.79E+03	1.21E+06	3.03E-01
4.75E-06	6.92E+02	1.89E+03	1.31E+06	3.27E-01
5.00E-06	6.97E+02	1.93E+03	1.35E+06	3.36E-01
5.25E-06	6.82E+02	1.98E+03	1.35E+06	3.37E-01
5.50E-06	6.77E+02	2.08E+03	1.40E+06	3.51E-01
5.75E-06	6.92E+02	2.14E+03	1.48E+06	3.69E-01
6.00E-06	6.97E+02	2.17E+03	1.51E+06	3.78E-01
6.25E-06	6.77E+02	2.22E+03	1.50E+06	3.75E-01
6.50E-06	6.88E+02	2.27E+03	1.56E+06	3.91E-01
6.75E-06	6.83E+02	2.30E+03	1.57E+06	3.91E-01
7.00E-06	6.78E+02	2.30E+03	1.56E+06	3.89E-01
7.25E-06	6.93E+02	2.38E+03	1.64E+06	4.11E-01
7.50E-06	6.97E+02	2.40E+03	1.67E+06	4.17E-01
7.75E-06	6.77E+02	2.46E+03	1.66E+06	4.16E-01
8.00E-06	6.77E+02	2.42E+03	1.64E+06	4.09E-01
8.25E-06	6.77E+02	2.46E+03	1.66E+06	4.16E-01
8.50E-06	6.77E+02	2.50E+03	1.69E+06	4.22E-01
8.75E-06	6.83E+02	2.50E+03	1.70E+06	4.26E-01
9.00E-06	6.77E+02	2.50E+03	1.69E+06	4.22E-01
9.25E-06	6.77E+02	2.53E+03	1.71E+06	4.27E-01
9.50E-06	6.77E+02	2.54E+03	1.72E+06	4.29E-01

Time(S)	Volt(V)	Current(A)	Power(W)	Energy(J)
9.75E-06	6.77E+02	2.57E+03	1.74E+06	4.34E-01
1.00E-05	6.77E+02	2.54E+03	1.72E+06	4.29E-01
1.03E-05	6.62E+02	2.54E+03	1.68E+06	4.19E-01
1.05E-05	6.77E+02	2.54E+03	1.72E+06	4.29E-01
1.08E-05	6.72E+02	2.54E+03	1.70E+06	4.25E-01
1.10E-05	6.77E+02	2.54E+03	1.71E+06	4.29E-01
1.13E-05	6.73E+02	2.51E+03	1.68E+06	4.21E-01
1.15E-05	6.57E+02	2.54E+03	1.67E+06	4.16E-01
1.18E-05	6.72E+02	2.50E+03	1.67E+06	4.19E-01
1.20E-05	6.57E+02	2.46E+03	1.61E+06	4.03E-01
1.23E-05	6.53E+02	2.46E+03	1.60E+06	4.00E-01
1.25E-05	6.47E+02	2.46E+03	1.59E+06	3.97E-01
1.28E-05	6.43E+02	2.43E+03	1.56E+06	3.90E-01
1.30E-05	6.57E+02	2.42E+03	1.58E+06	3.96E-01
1.33E-05	6.53E+02	2.38E+03	1.55E+06	3.87E-01
1.35E-05	6.47E+02	2.34E+03	1.51E+06	3.77E-01
1.38E-05	6.43E+02	2.34E+03	1.50E+06	3.75E-01
1.40E-05	6.57E+02	2.30E+03	1.51E+06	3.76E-01
1.43E-05	6.57E+02	2.26E+03	1.49E+06	3.72E-01
1.45E-05	6.37E+02	2.22E+03	1.41E+06	3.52E-01
1.48E-05	6.37E+02	2.22E+03	1.41E+06	3.52E-01
1.50E-05	6.37E+02	2.21E+03	1.41E+06	3.52E-01
1.53E-05	6.37E+02	2.14E+03	1.36E+06	3.41E-01
1.55E-05	6.28E+02	2.12E+03	1.33E+06	3.32E-01
1.58E-05	6.23E+02	2.09E+03	1.30E+06	3.26E-01
1.60E-05	6.17E+02	2.05E+03	1.27E+06	3.16E-01
1.63E-05	6.17E+02	2.01E+03	1.24E+06	3.10E-01
1.68E-05	6.11E+02	1.93E+03	1.18E+06	2.95E-01
1.73E-05	6.17E+02	1.89E+03	1.17E+06	2.92E-01
1.75E-05	6.06E+02	1.85E+03	1.12E+06	2.80E-01
1.78E-05	6.03E+02	1.84E+03	1.11E+06	2.77E-01
1.80E-05	6.17E+02	1.77E+03	1.09E+06	2.73E-01
1.83E-05	6.01E+02	1.73E+03	1.04E+06	2.60E-01
1.85E-05	5.97E+02	1.73E+03	1.03E+06	2.58E-01
1.88E-05	5.97E+02	1.66E+03	9.91E+05	2.48E-01
1.90E-05	5.98E+02	1.65E+03	9.85E+05	2.46E-01
1.93E-05	5.97E+02	1.61E+03	9.61E+05	2.40E-01
1.95E-05	6.08E+02	1.57E+03	9.53E+05	2.38E-01
1.98E-05	5.97E+02	1.53E+03	9.13E+05	2.28E-01
2.00E-05	5.97E+02	1.53E+03	9.13E+05	2.28E-01
			Total	**2.52E+01**

Time(S)	Volt(V)	Current(A)	Power(W)	Energy(J)
0.00E+00	1.18E+02	-7.29E+00	-1.95E+03	-4.88E-04
2.50E-07	9.98E+02	2.41E+01	2.27E+04	5.68E-03
5.00E-07	1.00E+03	5.18E+01	5.05E+04	1.26E-02
7.50E-07	1.00E+03	1.13E+02	1.13E+05	2.83E-02
1.00E-06	1.00E+03	2.74E+02	2.73E+05	6.84E-02
1.25E-06	9.87E+02	3.95E+02	3.88E+05	9.71E-02
1.50E-06	9.93E+02	5.34E+02	5.29E+05	1.32E-01
1.75E-06	1.00E+03	6.65E+02	6.65E+05	1.66E-01
2.00E-06	1.00E+03	7.97E+02	7.97E+05	1.99E-01
2.25E-06	1.02E+03	9.26E+02	9.46E+05	2.37E-01
2.50E-06	1.02E+03	1.02E+03	1.04E+06	2.60E-01
2.75E-06	1.00E+03	1.16E+03	1.16E+06	2.90E-01
3.00E-06	1.00E+03	1.24E+03	1.24E+06	3.10E-01
3.25E-06	1.02E+03	1.32E+03	1.34E+06	3.36E-01
3.50E-06	1.00E+03	1.44E+03	1.44E+06	3.60E-01
3.75E-06	1.01E+03	1.52E+03	1.53E+06	3.83E-01
4.00E-06	1.00E+03	1.60E+03	1.60E+06	4.01E-01
4.25E-06	1.00E+03	1.72E+03	1.72E+06	4.31E-01
4.50E-06	1.00E+03	1.78E+03	1.78E+06	4.46E-01
4.75E-06	9.83E+02	1.84E+03	1.81E+06	4.52E-01
5.00E-06	9.83E+02	1.92E+03	1.89E+06	4.72E-01
5.25E-06	9.83E+02	1.97E+03	1.94E+06	4.84E-01
5.50E-06	9.72E+02	2.06E+03	2.00E+06	5.01E-01
5.75E-06	9.63E+02	2.08E+03	2.00E+06	5.01E-01
6.00E-06	9.63E+02	2.16E+03	2.08E+06	5.20E-01
6.25E-06	9.63E+02	2.24E+03	2.15E+06	5.37E-01
6.50E-06	9.52E+02	2.27E+03	2.15E+06	5.39E-01
6.75E-06	9.43E+02	2.30E+03	2.16E+06	5.40E-01
7.00E-06	9.43E+02	2.33E+03	2.19E+06	5.48E-01
7.25E-06	9.22E+02	2.36E+03	2.18E+06	5.45E-01
7.50E-06	9.22E+02	2.38E+03	2.20E+06	5.49E-01
7.75E-06	9.22E+02	2.44E+03	2.25E+06	5.63E-01
8.00E-06	9.22E+02	2.44E+03	2.25E+06	5.63E-01
8.25E-06	9.02E+02	2.52E+03	2.27E+06	5.67E-01
8.50E-06	8.92E+02	2.53E+03	2.25E+06	5.63E-01
8.75E-06	8.82E+02	2.53E+03	2.23E+06	5.57E-01
9.00E-06	8.82E+02	2.53E+03	2.23E+06	5.57E-01
9.25E-06	8.46E+02	2.53E+03	2.14E+06	5.34E-01
9.50E-06	8.51E+02	2.57E+03	2.18E+06	5.46E-01
9.75E-06	8.57E+02	2.57E+03	2.19E+06	5.49E-01
1.00E-05	8.41E+02	2.56E+03	2.16E+06	5.39E-01

Time(S)	Volt(V)	Current(A)	Power(W)	Energy(J)
1.03E-05	8.22E+02	2.60E+03	2.13E+06	5.33E-01
1.05E-05	8.02E+02	2.57E+03	2.05E+06	5.14E-01
1.08E-05	8.02E+02	2.57E+03	2.05E+06	5.14E-01
1.10E-05	8.02E+02	2.57E+03	2.05E+06	5.14E-01
1.13E-05	7.86E+02	2.57E+03	2.02E+06	5.04E-01
1.15E-05	7.82E+02	2.53E+03	1.97E+06	4.93E-01
1.18E-05	7.67E+02	2.53E+03	1.94E+06	4.84E-01
1.20E-05	7.62E+02	2.49E+03	1.89E+06	4.73E-01
1.23E-05	7.62E+02	2.48E+03	1.88E+06	4.71E-01
1.25E-05	7.31E+02	2.49E+03	1.81E+06	4.54E-01
1.28E-05	7.42E+02	2.49E+03	1.84E+06	4.60E-01
1.30E-05	7.41E+02	2.44E+03	1.81E+06	4.52E-01
1.33E-05	7.06E+02	2.40E+03	1.70E+06	4.24E-01
1.35E-05	7.01E+02	2.40E+03	1.69E+06	4.21E-01
1.38E-05	7.01E+02	2.38E+03	1.66E+06	4.16E-01
1.40E-05	7.01E+02	2.32E+03	1.63E+06	4.07E-01
1.43E-05	6.86E+02	2.32E+03	1.59E+06	3.98E-01
1.45E-05	7.01E+02	2.28E+03	1.60E+06	4.00E-01
1.48E-05	6.67E+02	2.26E+03	1.50E+06	3.76E-01
1.50E-05	6.61E+02	2.24E+03	1.48E+06	3.71E-01
1.53E-05	6.61E+02	2.20E+03	1.46E+06	3.64E-01
1.55E-05	6.50E+02	2.16E+03	1.40E+06	3.51E-01
1.58E-05	6.55E+02	2.12E+03	1.39E+06	3.48E-01
1.60E-05	6.41E+02	2.12E+03	1.36E+06	3.40E-01
1.63E-05	6.61E+02	2.04E+03	1.35E+06	3.37E-01
1.65E-05	6.30E+02	2.04E+03	1.29E+06	3.22E-01
1.68E-05	6.35E+02	2.00E+03	1.27E+06	3.18E-01
1.70E-05	6.21E+02	1.96E+03	1.22E+06	3.04E-01
1.73E-05	6.21E+02	1.92E+03	1.19E+06	2.98E-01
1.75E-05	6.32E+02	1.88E+03	1.19E+06	2.97E-01
1.78E-05	6.15E+02	1.87E+03	1.15E+06	2.87E-01
1.80E-05	6.01E+02	1.84E+03	1.11E+06	2.77E-01
1.83E-05	6.17E+02	1.76E+03	1.08E+06	2.71E-01
1.85E-05	6.01E+02	1.76E+03	1.06E+06	2.64E-01
1.88E-05	6.01E+02	1.72E+03	1.03E+06	2.58E-01
1.90E-05	6.01E+02	1.64E+03	9.85E+05	2.46E-01
1.93E-05	5.96E+02	1.64E+03	9.77E+05	2.44E-01
1.95E-05	5.91E+02	1.60E+03	9.45E+05	2.36E-01
1.98E-05	5.81E+02	1.60E+03	9.28E+05	2.32E-01
2.00E-05	5.81E+02	1.56E+03	9.04E+05	2.26E-01
			Total	**3.08E+01**

Appendix F

4 kV

Time(S)	Volt(V)	Current(A)	Power(W)	Energy(J)
0.00E+00	2.81E+02	7.54E-01	0.00E+00	0.00E+00
2.50E-07	5.53E+02	4.10E+01	2.29E+04	5.74E-03
5.00E-07	5.63E+02	4.10E+01	2.25E+04	5.62E-03
7.50E-07	6.03E+02	8.12E+01	4.69E+04	1.17E-02
1.00E-06	6.03E+02	1.62E+02	9.57E+04	2.39E-02
1.25E-06	6.33E+02	2.22E+02	1.40E+05	3.49E-02
1.50E-06	6.43E+02	3.22E+02	2.05E+05	5.13E-02
1.75E-06	6.43E+02	4.03E+02	2.58E+05	6.45E-02
2.00E-06	6.43E+02	4.83E+02	3.09E+05	7.71E-02
2.25E-06	6.73E+02	4.83E+02	3.23E+05	8.08E-02
2.50E-06	6.43E+02	5.23E+02	3.35E+05	8.37E-02
2.75E-06	6.43E+02	7.04E+02	4.52E+05	1.13E-01
3.00E-06	6.43E+02	7.24E+02	4.65E+05	1.16E-01
3.25E-06	6.43E+02	7.44E+02	4.78E+05	1.19E-01
3.50E-06	6.43E+02	8.85E+02	5.68E+05	1.42E-01
3.75E-06	6.73E+02	8.85E+02	5.95E+05	1.49E-01
4.00E-06	6.03E+02	9.66E+02	5.80E+05	1.45E-01
4.25E-06	6.43E+02	1.05E+03	6.72E+05	1.68E-01
4.50E-06	6.43E+02	1.09E+03	6.97E+05	1.74E-01
4.75E-06	6.43E+02	1.05E+03	6.72E+05	1.68E-01
5.00E-06	6.43E+02	1.13E+03	7.23E+05	1.81E-01
5.25E-06	6.53E+02	1.21E+03	7.88E+05	1.97E-01
5.50E-06	6.43E+02	1.29E+03	8.26E+05	2.07E-01
5.75E-06	6.43E+02	1.23E+03	7.88E+05	1.97E-01
6.00E-06	6.43E+02	1.29E+03	8.26E+05	2.07E-01
6.25E-06	6.83E+02	1.35E+03	9.20E+05	2.30E-01
6.50E-06	6.43E+02	1.29E+03	8.26E+05	2.07E-01
6.75E-06	6.73E+02	1.37E+03	9.20E+05	2.30E-01
7.00E-06	6.83E+02	1.37E+03	9.34E+05	2.33E-01
7.25E-06	6.43E+02	1.45E+03	9.30E+05	2.32E-01
7.50E-06	6.43E+02	1.45E+03	9.30E+05	2.32E-01
7.75E-06	6.43E+02	1.45E+03	9.30E+05	2.32E-01
8.00E-06	6.43E+02	1.45E+03	9.30E+05	2.32E-01
8.25E-06	6.73E+02	1.47E+03	9.87E+05	2.47E-01
8.50E-06	6.43E+02	1.53E+03	9.82E+05	2.46E-01
8.75E-06	6.03E+02	1.47E+03	8.83E+05	2.21E-01

Time(S)	Volt(V)	Current(A)	Power(W)	Energy(J)
9.00E-06	6.43E+02	1.53E+03	9.82E+05	2.46E-01
9.25E-06	6.43E+02	1.53E+03	9.82E+05	2.46E-01
9.50E-06	6.23E+02	1.61E+03	1.00E+06	2.50E-01
9.75E-06	6.53E+02	1.59E+03	1.04E+06	2.59E-01
1.00E-05	6.43E+02	1.61E+03	1.03E+06	2.58E-01
1.03E-05	6.33E+02	1.55E+03	9.79E+05	2.45E-01
1.05E-05	6.23E+02	1.61E+03	1.00E+06	2.50E-01
1.08E-05	6.13E+02	1.55E+03	9.48E+05	2.37E-01
1.10E-05	6.43E+02	1.61E+03	1.03E+06	2.58E-01
1.13E-05	6.03E+02	1.53E+03	9.20E+05	2.30E-01
1.15E-05	6.03E+02	1.57E+03	9.44E+05	2.36E-01
1.18E-05	6.13E+02	1.61E+03	9.85E+05	2.46E-01
1.20E-05	6.03E+02	1.53E+03	9.20E+05	2.30E-01
1.23E-05	6.03E+02	1.55E+03	9.32E+05	2.33E-01
1.25E-05	6.03E+02	1.53E+03	9.20E+05	2.30E-01
1.28E-05	6.03E+02	1.53E+03	9.20E+05	2.30E-01
1.30E-05	6.43E+02	1.45E+03	9.30E+05	2.32E-01
1.33E-05	6.03E+02	1.47E+03	8.83E+05	2.21E-01
1.35E-05	6.03E+02	1.45E+03	8.71E+05	2.18E-01
1.38E-05	6.03E+02	1.45E+03	8.71E+05	2.18E-01
1.40E-05	6.03E+02	1.45E+03	8.71E+05	2.18E-01
1.43E-05	6.13E+02	1.43E+03	8.73E+05	2.18E-01
1.45E-05	6.03E+02	1.45E+03	8.71E+05	2.18E-01
1.48E-05	6.03E+02	1.43E+03	8.59E+05	2.15E-01
1.50E-05	5.63E+02	1.45E+03	8.14E+05	2.04E-01
1.53E-05	6.03E+02	1.37E+03	8.24E+05	2.06E-01
1.55E-05	5.83E+02	1.29E+03	7.49E+05	1.87E-01
1.58E-05	6.03E+02	1.31E+03	7.88E+05	1.97E-01
1.60E-05	6.03E+02	1.29E+03	7.75E+05	1.94E-01
1.63E-05	5.63E+02	1.29E+03	7.23E+05	1.81E-01
1.65E-05	5.83E+02	1.21E+03	7.02E+05	1.76E-01
1.68E-05	5.53E+02	1.27E+03	6.99E+05	1.75E-01
1.70E-05	5.63E+02	1.21E+03	6.78E+05	1.69E-01
1.73E-05	5.63E+02	1.19E+03	6.67E+05	1.67E-01
1.75E-05	5.63E+02	1.13E+03	6.33E+05	1.58E-01
1.78E-05	5.93E+02	1.13E+03	6.67E+05	1.67E-01
1.80E-05	5.63E+02	1.05E+03	5.88E+05	1.47E-01
1.83E-05	5.63E+02	1.05E+03	5.88E+05	1.47E-01
1.85E-05	5.63E+02	1.01E+03	5.65E+05	1.41E-01

Time(S)	Volt(V)	Current(A)	Power(W)	Energy(J)
1.88E-05	5.63E+02	9.86E+02	5.54E+05	1.39E-01
1.90E-05	5.63E+02	1.05E+03	5.88E+05	1.47E-01
1.93E-05	5.63E+02	9.66E+02	5.43E+05	1.36E-01
1.95E-05	5.63E+02	8.85E+02	4.96E+05	1.24E-01
1.98E-05	5.23E+02	8.85E+02	4.61E+05	1.15E-01
2.00E-05	5.63E+02	8.05E+02	4.51E+05	1.13E-01
			Total	**1.43E+01**

Time(S)	Volt(V)	Current(A)	Power(W)	Energy(J)
0.00E+00	2.81E+02	-7.96E+01	-2.34E+04	-5.86E-03
2.50E-07	1.14E+03	-1.93E+01	-2.34E+04	-5.86E-03
5.00E-07	1.45E+03	7.54E-01	0.00E+00	0.00E+00
7.50E-07	1.53E+03	6.11E+01	9.08E+04	2.27E-02
1.00E-06	1.45E+03	1.62E+02	2.32E+05	5.81E-02
1.25E-06	1.24E+03	1.82E+02	2.22E+05	5.54E-02
1.50E-06	1.07E+03	3.63E+02	3.84E+05	9.59E-02
1.75E-06	1.01E+03	3.42E+02	3.42E+05	8.56E-02
2.00E-06	9.65E+02	4.03E+02	3.87E+05	9.67E-02
2.25E-06	9.55E+02	5.23E+02	5.00E+05	1.25E-01
2.50E-06	9.05E+02	6.04E+02	5.45E+05	1.36E-01
2.75E-06	9.25E+02	7.04E+02	6.49E+05	1.62E-01
3.00E-06	9.25E+02	7.24E+02	6.68E+05	1.67E-01
3.25E-06	9.25E+02	8.05E+02	7.42E+05	1.86E-01
3.50E-06	9.05E+02	8.05E+02	7.27E+05	1.82E-01
3.75E-06	8.84E+02	8.65E+02	7.64E+05	1.91E-01
4.00E-06	8.84E+02	8.85E+02	7.81E+05	1.95E-01
4.25E-06	8.84E+02	9.66E+02	8.52E+05	2.13E-01
4.50E-06	8.84E+02	1.05E+03	9.24E+05	2.31E-01
4.75E-06	8.54E+02	1.05E+03	8.92E+05	2.23E-01
5.00E-06	8.84E+02	1.13E+03	9.94E+05	2.49E-01
5.25E-06	8.44E+02	1.19E+03	1.00E+06	2.50E-01
5.50E-06	8.44E+02	1.17E+03	9.83E+05	2.46E-01
5.75E-06	8.34E+02	1.21E+03	1.01E+06	2.51E-01
6.00E-06	8.44E+02	1.21E+03	1.02E+06	2.54E-01
6.25E-06	8.34E+02	1.35E+03	1.12E+06	2.81E-01
6.50E-06	8.24E+02	1.33E+03	1.09E+06	2.73E-01
6.75E-06	8.04E+02	1.37E+03	1.10E+06	2.74E-01

Time(S)	Volt(V)	Current(A)	Power(W)	Energy(J)
7.00E-06	8.04E+02	1.37E+03	1.10E+06	2.74E-01
7.25E-06	7.74E+02	1.37E+03	1.06E+06	2.64E-01
7.50E-06	7.64E+02	1.45E+03	1.10E+06	2.76E-01
7.75E-06	7.64E+02	1.47E+03	1.12E+06	2.80E-01
8.00E-06	7.64E+02	1.53E+03	1.17E+06	2.92E-01
8.25E-06	7.64E+02	1.47E+03	1.12E+06	2.80E-01
8.50E-06	7.64E+02	1.49E+03	1.13E+06	2.84E-01
8.75E-06	7.34E+02	1.59E+03	1.16E+06	2.91E-01
9.00E-06	7.24E+02	1.53E+03	1.10E+06	2.76E-01
9.25E-06	7.24E+02	1.59E+03	1.15E+06	2.87E-01
9.50E-06	7.24E+02	1.49E+03	1.08E+06	2.69E-01
9.75E-06	6.93E+02	1.53E+03	1.06E+06	2.65E-01
1.00E-05	7.24E+02	1.61E+03	1.16E+06	2.91E-01
1.03E-05	7.24E+02	1.53E+03	1.10E+06	2.76E-01
1.05E-05	7.04E+02	1.53E+03	1.07E+06	2.68E-01
1.08E-05	7.14E+02	1.53E+03	1.09E+06	2.72E-01
1.10E-05	6.83E+02	1.53E+03	1.04E+06	2.61E-01
1.13E-05	6.83E+02	1.59E+03	1.08E+06	2.71E-01
1.15E-05	6.63E+02	1.53E+03	1.01E+06	2.53E-01
1.18E-05	6.43E+02	1.53E+03	9.82E+05	2.46E-01
1.20E-05	6.83E+02	1.61E+03	1.10E+06	2.74E-01
1.23E-05	6.43E+02	1.51E+03	9.69E+05	2.42E-01
1.25E-05	6.23E+02	1.53E+03	9.51E+05	2.38E-01
1.28E-05	6.13E+02	1.47E+03	8.99E+05	2.25E-01
1.30E-05	6.43E+02	1.45E+03	9.30E+05	2.32E-01
1.33E-05	6.43E+02	1.45E+03	9.30E+05	2.32E-01
1.35E-05	6.03E+02	1.41E+03	8.48E+05	2.12E-01
1.38E-05	6.03E+02	1.51E+03	9.08E+05	2.27E-01
1.40E-05	6.03E+02	1.45E+03	8.71E+05	2.18E-01
1.43E-05	6.03E+02	1.37E+03	8.24E+05	2.06E-01
1.45E-05	5.83E+02	1.41E+03	8.19E+05	2.05E-01
1.48E-05	5.73E+02	1.43E+03	8.17E+05	2.04E-01
1.50E-05	6.03E+02	1.37E+03	8.24E+05	2.06E-01
1.53E-05	5.63E+02	1.29E+03	7.23E+05	1.81E-01
1.55E-05	5.63E+02	1.33E+03	7.45E+05	1.86E-01
1.58E-05	5.33E+02	1.31E+03	6.96E+05	1.74E-01
1.60E-05	5.63E+02	1.29E+03	7.23E+05	1.81E-01
1.63E-05	5.23E+02	1.23E+03	6.40E+05	1.60E-01
1.65E-05	5.23E+02	1.25E+03	6.50E+05	1.63E-01

Time(S)	Volt(V)	Current(A)	Power(W)	Energy(J)
1.68E-05	5.23E+02	1.23E+03	6.40E+05	1.60E-01
1.70E-05	5.23E+02	1.21E+03	6.29E+05	1.57E-01
1.73E-05	5.23E+02	1.15E+03	5.98E+05	1.50E-01
1.75E-05	5.23E+02	1.13E+03	5.88E+05	1.47E-01
1.78E-05	5.23E+02	1.09E+03	5.66E+05	1.41E-01
1.80E-05	4.82E+02	1.13E+03	5.43E+05	1.36E-01
1.83E-05	5.23E+02	1.05E+03	5.45E+05	1.36E-01
1.85E-05	4.82E+02	9.66E+02	4.65E+05	1.16E-01
1.88E-05	4.82E+02	9.66E+02	4.65E+05	1.16E-01
1.90E-05	4.82E+02	9.66E+02	4.65E+05	1.16E-01
1.93E-05	4.82E+02	9.45E+02	4.55E+05	1.14E-01
1.95E-05	4.82E+02	9.66E+02	4.65E+05	1.16E-01
1.98E-05	4.72E+02	8.85E+02	4.17E+05	1.04E-01
2.00E-05	4.82E+02	8.85E+02	4.26E+05	1.06E-01
			Total	**1.57E+01**

6 kV

Time(S)	Volt(V)	Current(A)	Power(W)	Energy(J)
0.00E+00	2.81E+02	8.12E+01	2.15E+04	5.37E-03
2.50E-07	5.53E+02	8.12E+01	4.39E+04	1.10E-02
5.00E-07	6.03E+02	1.21E+02	7.13E+04	1.78E-02
7.50E-07	6.33E+02	1.82E+02	1.12E+05	2.81E-02
1.00E-06	6.83E+02	3.22E+02	2.19E+05	5.47E-02
1.25E-06	6.83E+02	4.03E+02	2.73E+05	6.84E-02
1.50E-06	6.83E+02	5.64E+02	3.83E+05	9.57E-02
1.75E-06	6.83E+02	6.64E+02	4.53E+05	1.13E-01
2.00E-06	6.83E+02	7.24E+02	4.94E+05	1.24E-01
2.25E-06	6.93E+02	8.85E+02	6.12E+05	1.53E-01
2.50E-06	6.83E+02	1.05E+03	7.13E+05	1.78E-01
2.75E-06	7.14E+02	1.13E+03	8.03E+05	2.01E-01
3.00E-06	6.83E+02	1.21E+03	8.24E+05	2.06E-01
3.25E-06	7.14E+02	1.29E+03	9.17E+05	2.29E-01
3.50E-06	7.04E+02	1.37E+03	9.59E+05	2.40E-01
3.75E-06	6.83E+02	1.45E+03	9.88E+05	2.47E-01
4.00E-06	6.83E+02	1.53E+03	1.04E+06	2.61E-01
4.25E-06	6.83E+02	1.59E+03	1.08E+06	2.71E-01
4.50E-06	7.04E+02	1.73E+03	1.21E+06	3.03E-01
4.75E-06	7.24E+02	1.85E+03	1.34E+06	3.34E-01
5.00E-06	7.24E+02	1.77E+03	1.28E+06	3.20E-01

Time(S)	Volt(V)	Current(A)	Power(W)	Energy(J)
5.25E-06	6.83E+02	1.85E+03	1.26E+06	3.16E-01
5.50E-06	7.24E+02	1.97E+03	1.42E+06	3.56E-01
5.75E-06	7.14E+02	2.01E+03	1.43E+06	3.58E-01
6.00E-06	6.83E+02	2.01E+03	1.37E+06	3.43E-01
6.25E-06	6.83E+02	2.09E+03	1.43E+06	3.57E-01
6.50E-06	7.24E+02	2.13E+03	1.54E+06	3.85E-01
6.75E-06	7.14E+02	2.17E+03	1.55E+06	3.87E-01
7.00E-06	6.83E+02	2.25E+03	1.54E+06	3.84E-01
7.25E-06	6.83E+02	2.25E+03	1.54E+06	3.84E-01
7.50E-06	7.04E+02	2.29E+03	1.61E+06	4.03E-01
7.75E-06	6.83E+02	2.27E+03	1.55E+06	3.88E-01
8.00E-06	6.83E+02	2.41E+03	1.65E+06	4.12E-01
8.25E-06	6.73E+02	2.33E+03	1.57E+06	3.92E-01
8.50E-06	6.63E+02	2.41E+03	1.60E+06	4.00E-01
8.75E-06	6.83E+02	2.41E+03	1.65E+06	4.12E-01
9.00E-06	6.43E+02	2.41E+03	1.55E+06	3.88E-01
9.25E-06	7.14E+02	2.41E+03	1.72E+06	4.30E-01
9.50E-06	6.43E+02	2.45E+03	1.58E+06	3.94E-01
9.75E-06	6.53E+02	2.49E+03	1.63E+06	4.07E-01
1.00E-05	6.43E+02	2.41E+03	1.55E+06	3.88E-01
1.03E-05	6.83E+02	2.41E+03	1.65E+06	4.12E-01
1.05E-05	6.43E+02	2.45E+03	1.58E+06	3.94E-01
1.08E-05	6.43E+02	2.47E+03	1.59E+06	3.97E-01
1.10E-05	6.83E+02	2.49E+03	1.70E+06	4.26E-01
1.13E-05	6.43E+02	2.43E+03	1.56E+06	3.91E-01
1.15E-05	6.43E+02	2.41E+03	1.55E+06	3.88E-01
1.18E-05	6.43E+02	2.41E+03	1.55E+06	3.88E-01
1.20E-05	6.43E+02	2.33E+03	1.50E+06	3.75E-01
1.23E-05	6.43E+02	2.41E+03	1.55E+06	3.88E-01
1.25E-05	6.43E+02	2.41E+03	1.55E+06	3.88E-01
1.28E-05	6.43E+02	2.35E+03	1.51E+06	3.78E-01
1.30E-05	6.43E+02	2.33E+03	1.50E+06	3.75E-01
1.33E-05	6.43E+02	2.33E+03	1.50E+06	3.75E-01
1.35E-05	6.23E+02	2.25E+03	1.40E+06	3.51E-01
1.38E-05	6.43E+02	2.31E+03	1.49E+06	3.71E-01
1.40E-05	6.03E+02	2.25E+03	1.36E+06	3.39E-01
1.43E-05	6.13E+02	2.25E+03	1.38E+06	3.45E-01
1.45E-05	6.23E+02	2.21E+03	1.38E+06	3.44E-01
1.48E-05	6.43E+02	2.17E+03	1.39E+06	3.49E-01

Time(S)	Volt(V)	Current(A)	Power(W)	Energy(J)
1.50E-05	6.03E+02	2.17E+03	1.31E+06	3.27E-01
1.53E-05	6.03E+02	2.11E+03	1.27E+06	3.18E-01
1.55E-05	6.03E+02	2.13E+03	1.28E+06	3.21E-01
1.58E-05	6.03E+02	2.07E+03	1.25E+06	3.12E-01
1.60E-05	6.03E+02	2.09E+03	1.26E+06	3.15E-01
1.63E-05	6.13E+02	1.99E+03	1.22E+06	3.05E-01
1.65E-05	6.03E+02	1.93E+03	1.16E+06	2.91E-01
1.68E-05	6.03E+02	1.99E+03	1.20E+06	3.00E-01
1.70E-05	6.03E+02	1.93E+03	1.16E+06	2.91E-01
1.73E-05	6.03E+02	1.79E+03	1.08E+06	2.70E-01
1.75E-05	6.03E+02	1.89E+03	1.14E+06	2.84E-01
1.78E-05	5.63E+02	1.85E+03	1.04E+06	2.60E-01
1.80E-05	5.63E+02	1.85E+03	1.04E+06	2.60E-01
1.83E-05	5.73E+02	1.77E+03	1.01E+06	2.53E-01
1.85E-05	5.83E+02	1.69E+03	9.83E+05	2.46E-01
1.88E-05	5.73E+02	1.61E+03	9.20E+05	2.30E-01
1.90E-05	5.63E+02	1.69E+03	9.49E+05	2.37E-01
1.93E-05	5.63E+02	1.61E+03	9.04E+05	2.26E-01
1.95E-05	5.63E+02	1.57E+03	8.82E+05	2.20E-01
1.98E-05	5.93E+02	1.53E+03	9.05E+05	2.26E-01
2.00E-05	6.03E+02	1.53E+03	9.20E+05	2.30E-01
			Total	**2.40E+01**

Time(S)	Volt(V)	Current(A)	Power(W)	Energy(J)
0.00E+00	2.81E+02	7.54E-01	-1.12E-05	-2.79E-12
2.50E-07	1.53E+03	7.54E-01	0.00E+00	0.00E+00
5.00E-07	1.95E+03	7.54E-01	0.00E+00	0.00E+00
7.50E-07	1.89E+03	1.62E+02	3.03E+05	7.57E-02
1.00E-06	1.49E+03	1.62E+02	2.38E+05	5.96E-02
1.25E-06	1.28E+03	4.03E+02	5.12E+05	1.28E-01
1.50E-06	1.21E+03	4.43E+02	5.32E+05	1.33E-01
1.75E-06	1.18E+03	5.64E+02	6.60E+05	1.65E-01
2.00E-06	1.17E+03	7.24E+02	8.42E+05	2.10E-01
2.25E-06	1.17E+03	8.25E+02	9.59E+05	2.40E-01
2.50E-06	1.15E+03	9.25E+02	1.06E+06	2.64E-01
2.75E-06	1.16E+03	1.13E+03	1.30E+06	3.25E-01
3.00E-06	1.09E+03	1.13E+03	1.22E+06	3.05E-01
3.25E-06	1.13E+03	1.27E+03	1.42E+06	3.56E-01

Time(S)	Volt(V)	Current(A)	Power(W)	Energy(J)
3.50E-06	1.13E+03	1.33E+03	1.49E+06	3.73E-01
3.75E-06	1.10E+03	1.45E+03	1.58E+06	3.96E-01
4.00E-06	1.05E+03	1.53E+03	1.60E+06	3.99E-01
4.25E-06	1.08E+03	1.61E+03	1.73E+06	4.32E-01
4.50E-06	1.07E+03	1.69E+03	1.80E+06	4.49E-01
4.75E-06	1.05E+03	1.77E+03	1.85E+06	4.62E-01
5.00E-06	1.05E+03	1.85E+03	1.93E+06	4.83E-01
5.25E-06	1.01E+03	1.85E+03	1.86E+06	4.64E-01
5.50E-06	1.03E+03	1.93E+03	1.98E+06	4.94E-01
5.75E-06	1.01E+03	2.01E+03	2.02E+06	5.05E-01
6.00E-06	1.01E+03	2.01E+03	2.02E+06	5.05E-01
6.25E-06	9.65E+02	2.03E+03	1.96E+06	4.89E-01
6.50E-06	9.45E+02	2.09E+03	1.98E+06	4.94E-01
6.75E-06	9.65E+02	2.17E+03	2.09E+06	5.23E-01
7.00E-06	9.25E+02	2.25E+03	2.08E+06	5.20E-01
7.25E-06	9.25E+02	2.19E+03	2.02E+06	5.06E-01
7.50E-06	9.25E+02	2.33E+03	2.15E+06	5.39E-01
7.75E-06	9.25E+02	2.33E+03	2.15E+06	5.39E-01
8.00E-06	9.25E+02	2.33E+03	2.15E+06	5.39E-01
8.25E-06	8.84E+02	2.41E+03	2.13E+06	5.33E-01
8.50E-06	8.64E+02	2.37E+03	2.05E+06	5.12E-01
8.75E-06	8.54E+02	2.41E+03	2.06E+06	5.15E-01
9.00E-06	8.44E+02	2.41E+03	2.04E+06	5.09E-01
9.25E-06	8.54E+02	2.47E+03	2.11E+06	5.28E-01
9.50E-06	8.24E+02	2.49E+03	2.05E+06	5.13E-01
9.75E-06	8.04E+02	2.49E+03	2.00E+06	5.01E-01
1.00E-05	8.04E+02	2.49E+03	2.00E+06	5.01E-01
1.03E-05	8.04E+02	2.41E+03	1.94E+06	4.84E-01
1.05E-05	8.04E+02	2.45E+03	1.97E+06	4.93E-01
1.08E-05	8.04E+02	2.49E+03	2.00E+06	5.01E-01
1.10E-05	7.64E+02	2.49E+03	1.90E+06	4.76E-01
1.13E-05	7.64E+02	2.47E+03	1.89E+06	4.72E-01
1.15E-05	7.64E+02	2.49E+03	1.90E+06	4.76E-01
1.18E-05	7.34E+02	2.49E+03	1.83E+06	4.57E-01
1.20E-05	7.64E+02	2.41E+03	1.84E+06	4.60E-01
1.23E-05	7.24E+02	2.41E+03	1.74E+06	4.36E-01
1.25E-05	6.83E+02	2.37E+03	1.62E+06	4.05E-01
1.28E-05	6.93E+02	2.33E+03	1.62E+06	4.04E-01
1.30E-05	6.83E+02	2.33E+03	1.59E+06	3.98E-01
1.33E-05	6.83E+02	2.33E+03	1.59E+06	3.98E-01
1.35E-05	6.83E+02	2.33E+03	1.59E+06	3.98E-01

Time(S)	Volt(V)	Current(A)	Power(W)	Energy(J)
1.38E-05	6.53E+02	2.33E+03	1.52E+06	3.80E-01
1.40E-05	6.83E+02	2.17E+03	1.48E+06	3.71E-01
1.43E-05	6.53E+02	2.17E+03	1.42E+06	3.54E-01
1.45E-05	6.63E+02	2.17E+03	1.44E+06	3.60E-01
1.48E-05	6.43E+02	2.17E+03	1.39E+06	3.49E-01
1.50E-05	6.43E+02	2.09E+03	1.34E+06	3.36E-01
1.53E-05	6.43E+02	2.17E+03	1.39E+06	3.49E-01
1.55E-05	6.23E+02	2.09E+03	1.30E+06	3.25E-01
1.58E-05	6.13E+02	2.07E+03	1.27E+06	3.17E-01
1.60E-05	6.03E+02	2.01E+03	1.21E+06	3.03E-01
1.63E-05	5.93E+02	2.03E+03	1.20E+06	3.01E-01
1.65E-05	5.83E+02	2.01E+03	1.17E+06	2.93E-01
1.68E-05	6.03E+02	1.93E+03	1.16E+06	2.91E-01
1.70E-05	5.63E+02	1.85E+03	1.04E+06	2.60E-01
1.73E-05	5.63E+02	1.87E+03	1.05E+06	2.63E-01
1.75E-05	5.83E+02	1.77E+03	1.03E+06	2.58E-01
1.78E-05	5.63E+02	1.85E+03	1.04E+06	2.60E-01
1.80E-05	5.23E+02	1.77E+03	9.24E+05	2.31E-01
1.83E-05	5.63E+02	1.69E+03	9.49E+05	2.37E-01
1.85E-05	5.63E+02	1.73E+03	9.72E+05	2.43E-01
1.88E-05	5.63E+02	1.69E+03	9.49E+05	2.37E-01
1.90E-05	5.23E+02	1.61E+03	8.40E+05	2.10E-01
1.93E-05	5.63E+02	1.61E+03	9.04E+05	2.26E-01
1.95E-05	5.23E+02	1.53E+03	7.97E+05	1.99E-01
1.98E-05	5.53E+02	1.53E+03	8.44E+05	2.11E-01
2.00E-05	5.63E+02	1.53E+03	8.59E+05	2.15E-01
			Total	**2.91E+01**