BEHAVIORAL STUDIES OF SURGE PROTECTION DEVICES BASED ON TRADITIONAL METAL OXIDE VARISTOR / GAS DISCHARGE TUBE AND POWER ELECTRONICS SWITCHES

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DECEMBER 2022

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I hereby declare that this project report is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously concurrently submitted for any other degree or award at UTAR or other institutions.

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ABSTRACT

BEHAVIORAL STUDIES OF SURGE PROTECTION DEVICES BASED ON TRADITIONAL METAL OXIDE VARISTOR / GAS DISCHARGE TUBE AND POWER ELECTRONICS SWITCHES

Teh Jia Kee

The source of this power surge can be classified into internal and external source of surge. Lightning is the most obvious source of surge which can lead to degrade or severe physical damage to electrical device in the circuit. Power surge will also cause damage to devices, for instance computers, servers, telecommunication devices and CCTVs which will result in the damages in the form of network paralysis, data loss, massive physical and financial damage and downtime. Hence, some conventional methods of protection against power surge such as metal oxide varistor (MOV) and gas discharged tube (GDT) are applied in order to prevent any damage or losses caused by surge. However, conventional SPDs are not able to handle continuous and repetitive surge. Therefore, this research replaces the conventional method of surge protection with power electronics for better improvement. The conventional surge protection methods and protection by power electronics are studied in both simulation and hardware. In this research, power electronics is proven to be potential candidate as a surge protection device since the response time of MOSFET is faster than MOV and the clamping voltage level of IGBT is lower than MOV.

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LIST OF SYMBOLS / ABBREVIATIONS

GDT	gas discharge tube
Hz	hertz
IGBT	insulated-gate bipolar transistor
MCOV	maximum continuous operating voltage
MOSFET	metal-oxide semiconductor field effect transistors
MOV	metal oxide varistor
SPD	surge protection device

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Power surge is also known as a transient wave as it is an unexpected alter of voltage, current or power in a circuit that only happened for a short duration of time. Power surge can degrade or damage an electrical device in the circuit and cause significantly lost. The source of this power surge can be classified into internal and external source of surge. Lightning and utility-initiated grid are examples of external source of surge. Meanwhile, internal source of surge consists of switching of inductive and capacitive loads.

1.2 Importance of the Study

Lightning strike can cause damage to devices, for instance, computers, servers, telecommunication devices and CCTVs. This damage caused can be in the form of network paralysis, data loss, massive physical and financial damage and downtime (Tokai Engineering Sdn Bhd, 2019). Hence, some conventional methods of protection against power surge are applied in order to prevent any damage or losses caused by surge. However, there are several drawbacks to the conventional methods being used nowadays. Therefore, this research replaces the conventional method of surge protection with power electronics to eliminate those drawbacks.

1.3 Problem Statement

Overvoltage is limited with the use of surge protection device. Its working principle is to divert surge current away from other electronic devices to prevent damage to those devices. The conventional surge protection device consists of metal oxide varistor and gas discharge tube that shields systems and devices from excess energy. Although conventional SPD has already existed, it is insufficient to withstand continuous surge and repetitive pulses. Due to the advance of power electronics technologies, the improved power capability and switching frequency allow power electronics to be utilized in surge protection to improve its performance as compared to the conventional SPD.

1.4 Aim and Objectives

This research focuses on the studies of the source of lightning and surge. The feasibility of power electronic devices as surge protection will be identified by comparing it with a simulated conventional surge protection method and the behaviour of power electronics in surge protection is analyzed with the use of both MATLAB Simulink and hardware experiment. The prototype will be tested by using a surge generator with $1.2/50\mu s$ voltage surge waveform, $8/20\ \mu s$ current surge waveform and $10/350\ \mu s$ voltage surge waveform. Besides, this project is carried out to evaluate the performance of integrating SPD and external mounted SPD. The evaluation also contains analysis on optimum length of the cable connecting SPD to the protecting system or apparatus including condition of the cable, either twisted or straight to further extend allow the cable to reach greater length while maintaining its performance.

1.5 Scope and Limitation of the Study

In overall, this research identified surge sources and its consequences, analyse the performance of internal and external SPD, build a model of surge generator and simulate it through MATLAB Simulink, study the working principle of the conventional SPDs, simulate the power electronic as SPD in MATLAB Simulink, and then test the prototype with surge generator under standard waveform. The limitation of this study is the surge count and surge interval can only be testing by surge protection hardware test because MATLAB Simulink is not able to simulate the surge count and surge interval as the degradation and damage is not observable in this software. Besides that, components rating which applied in the surge protection hardware test is a limitation of this project since the surge applied is sufficient to burn a small rating component.

1.6 Contribution of Study

This research focus on study surge protection device based on power electronic devices that can help to prevent significant lost or damage to electrical devices by power surge. The goal of this research is to implement power electronics to improve the performance of conventional surge protection devices.

1.7 Outline of Report

Chapter 1 contains information regarding the overview of the project, the problem faced and the tests that will be carry out for this research.

Chapter 2 contains several literatures review on power surge, the working principles, and drawbacks of conventional surge protection devices, the behavior of power electronics as surge protection devices as well as the performance of integrating SPD and external mounted SPD.

Chapter 3 explains the calculations and the surge generator model that are planned to be applied for this project to progress.

Chapter 4 involve discussion on the results obtained and the comparison between the simulated and hardware test result.

Last of all, Chapter 5 contains the conclusion to summarize the overall of this project as well as included recommendation on characteristics and behaviors that can be further studied.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Surge is transient voltage spikes or disturbances to the power waveform which causes damage or failure to electrical appliances. There are two types of surges, which are external power surge such as lightning and internal power surge such as switching of electric loads. However, the most obvious source is from lightning, but the surges still can come from various other sources.

Besides, differences in the magnitude of surge energy and duration will lead to different levels of damage. The natural external source of surge such as lightning will produce a significantly large instantaneous amount of energy as compared to artificially generated surge such as utility-initiated grid. Therefore, the damage triggered by external source of surge such as lightning is severe than the damage caused by artificially generated surge. (Mamoon Alyah, n.d.). Typically, when electrical equipment shows signs of prolonger overheating, for instance melting, an artificial generated surge should be the primary suspect of the equipment failure. On the other hand, lightning should be the primary suspect if the damage is localized and extensive.

2.2 External Source of Surge - Lightning

Lightning is a discharge of electricity caused by imbalances between two different areas of charge (Robinson, n.d.). Dwyer, J.R. and Uman, M.A (2014) have discussed that there was a variety of lightning, which included cloud to ground lightning, ground to cloud lightning, and intracloud lightning. Besides, NEMA Surge Protection Institute (2020) has discussed that the power surges caused by lightning either be lightning directly contact to the building or indirectly that induces power surges onto the electrical system.

One of the most visible source of surge that occurs outside buildings is lightning. The ways of lightning propagate and branches in space and time can be influenced by the polarity of the lightning discharge. There are approximately 9 million flashes of lightning produced within a day across the world. According to the comparative statistics provided by Energy Commission (Suruhanjaya Tenaga) as shown in Table 1, the average number of thunderstorm days per year is 204 days, which is corresponding to 49 strikes per square kilometer per year.

Table 1: Thunderstorm Days per Year Comparative Statistics (Khair, 2015)

Country	Thunderstorm days per year
Argentina	30-80
Brazil	40-200
Hong Kong	90-100
Indonesia	180-260
Malaysia	180-300
Singapore	160-220
Thailand	90-200

Besides that, lightning is an example of a long electric spark that is mostly generated during thunderstorms and can travel anywhere from 5 to 10 km. This can be proved by Newspaper the Star (2006, Oct 8). ‘A lightning strike near the Ipoh Selatan toll exit of the North-South Expressway at 4.46pm yesterday caused a traffic congestion that stretched 8km from the toll plaza. The computerized system suffered a short-circuit forcing PLUS personnel to collect the toll manually from motorists. A check at the scene found that the back-up generator had failed. The traffic jam continued until well after dark.’ However, old data mentioned that successive flashes were on the order of 3 to 4 km, which is only half of the flashes. Therefore, the National Severe Storms Laboratory report conclude the safety distance must be adjusted to at least 10 to 13km instead of 3 to 5 km. Previously, 3 to 5km was used in lightning safety education.”

2.2.1 Cloud to Ground Lightning

There are two types of electrical discharge that take place between the cloud and ground. These electrical discharges were differentiated by the direction of the leader's propagation. The downward flashes were referred to as cloud to ground type. Moreover, cloud to ground lightning was branched to negative cloud to ground lightning and positive cloud to ground lightning as shown in Figure 1 and Figure 2 respectively. Negative cloud to ground lightning is initiated by downward-moving, negatively charged stepped leader and usually consist of multiple "return strokes". Meanwhile, positive cloud to ground lightning is initiated by downward-moving, positively charged leader and normally consist of only one "return strokes". (Robinson, n.d.)

Figure 1: Negative Cloud-to-Ground Lightning

Figure 2: Positive Cloud-to-Ground Lightning

2.2.2 Ground to Cloud Lightning

Refer to Figure 3, the second type of lightning is Ground-to-Cloud Lightning. It is a discharge of electricity that is triggered by imbalances between storm clouds and ground. The kinds of lightning that take place between ground and cloud were distinguished from each other by the direction of the leader's propagation. Ground to cloud lightning is initiated by an upward-moving leader starting from an object on the ground and it is normally occurring on tall towers or mountaintops. (Robinson, n.d.)

Figure 3: Ground-to-Cloud Lightning

2.2.3 Intracloud Lightning

Figure 4 shows the most common type of electrical discharge, which is the intracloud lightning and it is also called sheet lightning. Intracloud lightning was happening within a single storm cloud, jumping between two different areas of charge regions in the cloud and sky will light up with a ‘sheet’ of light when intracloud lightning happened. However, Cloud-to-Cloud Lightning as shown in Figure 5 is different from Intracloud Lightning. Intracloud Lightning happened inside a storm cloud, but Cloud-to-Cloud Lightning was discharged from at least two separate storm clouds. (Robinson, n.d.)

Figure 4: Intracloud Lightning

Figure 5: Cloud-to-Cloud Lightning

2.2.4 Types of Lightning Conduction

Indirect strikes of lightning occurred more commonly as compared to direct strikes. It can be generated through a few conductions such as inductive coupling, capacitive coupling, and resistive coupling.

Inductive Coupling as demonstrated in Figure 6 is a phenomenon that a voltage surge will be induced to the nearby cables due to the huge electromagnetic field generated onto a lightning down conductor from lightning strikes. (Paul Ortmann, 2016)

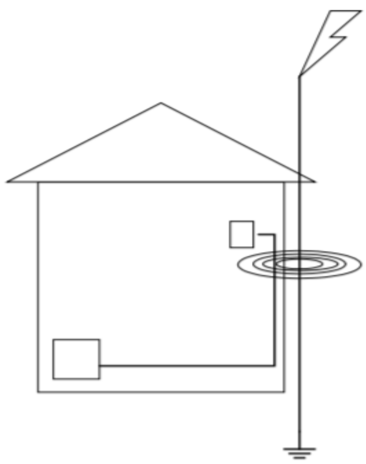


Figure 6: Inductive Coupling (Paul Ortmann, 2016)

Figure 7 shown capacitive coupling and it is produced during lightning strikes between clouds. In capacitive coupling, the transient voltage may be coupled to any adjacent conductors and across transformer windings. (Paul Ortmann, 2016)

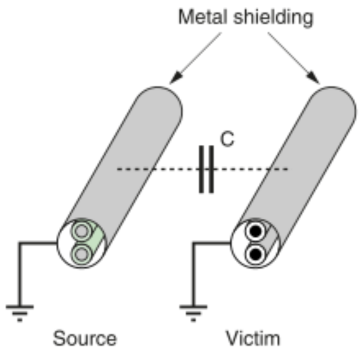


Figure 7: Capacitive Coupling (Paul Ortmann, 2016)

Further, Figure 8 shows resistive coupling which happened when a lightning direct strikes on the ground nearby a building. The ground potential of the adjacent area rises instantaneously once a lightning strike onto it and therefore the lightning will be conducted back into the building through earthing system. Any ground power, telecommunication, or underground piping cables itself is acts as a route for surge current to enter the building. (Paul Ortmann, 2016)

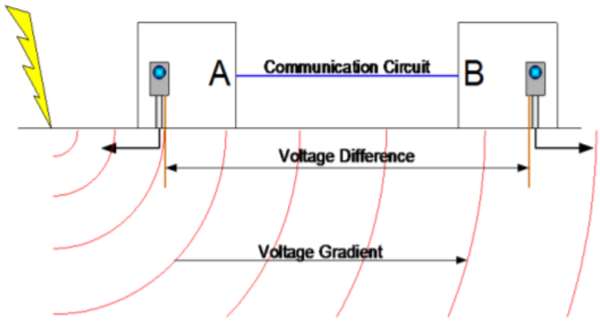


Figure 8: Resistive coupling (Paul Ortmann, 2016)

2.3 External Source of Surge – Utility Initiated Grid

Utility-initiated grid is another external source of surge. A fault will be occurred on a line when it is in the event of a fallen tree and therefore the utility might require to transfer the supply of power to another source in order to clear the fault from the system. There would be temporarily power disturbances occur during the operation of the electric grid in order to clear out the fault. Besides, electric utilities will generate electricity from a few power generating station and distribute the power to specific grids of users. Power disturbances, including transient and under- or over-voltage conditions occurred during the switching of power from one grid to another. (NEMA Surge Protection Institute, 2020)

2.4 Internal Source of Surge

Transients surge can also originate from inside a facility that mostly occurs in commercial and industrial buildings. Air conditioners and refrigerators are the major household items that cause surges but the smaller appliances for example hair dries might also trigger a surge. Magnetic and inductive coupling is one of the internal sources of surge in the electrical system. A magnetic field would be created when electric current flows and the fundamental principle by which transformers work were a voltage will be induced in the second wire if the magnetic field extends to the second wire. Nonetheless, this voltage is undesirable and may lead to transient in nature for the case of nearby building wire. The equipment that can trigger this internal source of surge include elevators and air conditioning system (HVAC with variable frequency drives). (NEMA Surge Protection Institute, 2020)

2.4.1 Internal Source – Switching of Inductive Loads

The internal power surge was normally triggered by the switching of inductive loads. An overvoltage transient will happen due to the current cannot change immediately when unloaded inductive loads is introduced to the system. The deionizing effect of a circuit breaker is extremely powerful. The current will be reduced rapidly to zero before the natural current reached zero and there will be a high voltage transient created across the contacts of circuit breaker. Repetitive strike of voltage referred to the high-frequency transient voltage that occurred during the arcing period. Switching of electrical loads is one of the internal sources of surge in the electrical system and it will not damage the equipment immediately like the externally generated surge. However, switching surge will be disruptive to equipment over time as it happens far more frequently. Further, the sources of switching surge include the relay and circuit breaker operation, loose connections, arcing fault, and discharge of inductive devices such as transformer.

2.4.2 Internal Source – Switching of Capacitive Loads

The internal power surge can also be triggered by the switching of capacitive loads. Switching is an event that takes place relatively frequent in capacitor bank, transformer, generator or motor by protection and control systems. Capacitor switching is the most often switching event. Van Sickle, R. C and Zaborsky, J. (1952) have argued that capacitor switching can control the power flow by improving power factor and enhance the capability of power transmission since capacitors are used for power factor correction in electrical power distribution system. However, as shown in Figure 9, there will be a transient wave observed at the monitoring location when the capacitor switch is closed. The contacts of the capacitor switch will close when the voltage is near to the peak of system voltage. The voltage across the capacitor will be zero whenever the potential difference of switch reaches its maximum value since the insulation of the switch contacts can break down easily. During the starting of charging of capacitor to the system voltage, the voltage across the capacitor increases. The inductive source of the power system lead to the overshoot of voltage across the capacitor and rings at the frequency of the system. The presence of the ringing transient indicates that a capacitor-switching event would be visible to some degree. (Prasadi, P. and Dhote, V.P., 2016)

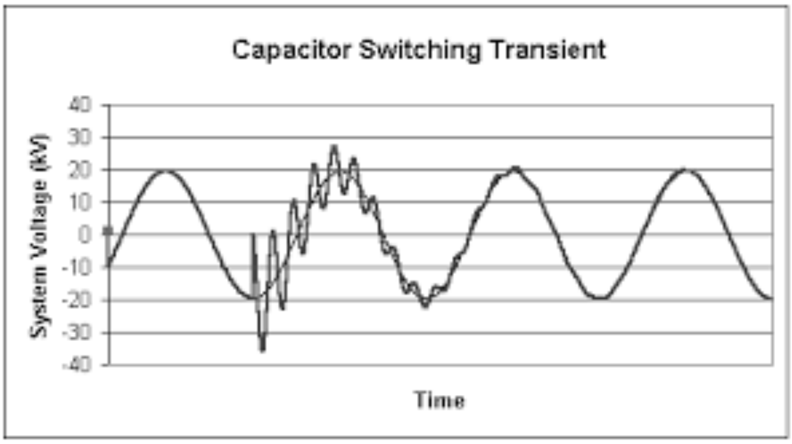


Figure 9: Capacitor Switching Transient Wave (Prasadi, P. and Dhote, V.P., 2016)

2.5 Consequences of Surge

Surge is a transient overvoltage disturbance that may cause a few effects on electronics components which included instant physical damage within industrial facility or within commercial building such as blowing fuses or melting electrical devices. (NEMA Surge Protection Institute, 2020) Voltage will exceed the peak voltage only for a short duration of time during a power surge. However, life spans of appliances can be shortened due to a power surge even surge was only happened for short period.

Moreover, the rise in voltage beyond an electrical device's normal operating voltage may cause an electric discharged within the electrical device which will also raise the operating temperature of the device and can be harmful to it. Further, a power surge may also lead to long-term damage that will gradually degrade the electronic components until they completely damaged and malfunction. (Sunpower Electronics, 2019) The affected electrical devices that undergo degradation is encountered the most severe impact of power surge since the percentage of degradation cannot be measured or evaluated. For example, the working of a motor is influenced by the transient as the motor will operate at a higher temperature with the presence of transient voltage. This transient voltage will produce excessive heat, vibration and noise which can disturb the normal timing and running of the motor. Thus, motor winding insulation is degraded and then leads to failure, and the hysteresis losses which raise the required current to operate the motor are created. Besides, the additional case of degradation is TV might mysteriously stops working by small and repeated power surge, which slowly caused damage to the TV.

Transient activity may also affect the facility of the electrical distribution system. This is because transient can cause the contact surface in the circuit breaker to degrade overtime. "Nuisance tripping" happens in breakers can be produced by transient activity as "fooling" the breaker and heating it into reacting to a non-existent demand of current. The electrical transformers' efficiency drops due to the hysteresis losses and temperature rises beyond normal condition produced by transients. (Agbamu Edward Oghenovo, 2021)

2.6 Lightning Protection Standard

Lightning protection standard was a guidance to be followed for all buildings and utility grid system. Earthing installations are mandatory in Malaysia and must meet the requirements of BS EN/IEC 62305 that was divided into four parts (BS: British Standard and IEC: International Electrical Commission).

Part 1 of the BS EN/IEC 62305 offers the fundamental principles to be obeyed in the protection against lightning of structures involving their installations and contents as well as persons, and services connected to a structure. This part also introduces new concepts for consideration when organizing a lightning protection scheme, such as Lightning Protection Levels

(LPL) and Lightning Protection Zones (LPZ). Four lightning protection levels (I to IV) are introduced. Based on Table 2, every LPL has its own unique lightning current parameter of both maximum and minimum. The radius of rolling sphere represents the area that is protected from lightning strike. Besides that, the area protected from lightning is also affected by several other sources like Lightning Protection System (LPS), Surge Protection Device (SPD), magnetic shield, and shielding wires. Refer to Figure 10, LPZ 0A is an area that has a high chance of getting direct lightning flash and full lightning electromagnetic field meanwhile LPZ 0B is the area shielded from these threats. Then, LPZ 1 defined as the area that surge current is bounded by current sharing and SPDs while LPZ 2 is the area with lower surge current than LPZ 1 as it is even more bounded by current sharing and additional SPDs. (Tokai Engineering Sdn Bhd, 2019)

Table 2: Lightning Protection Levels

LPL	Max kA	Min kA	Rolling Sphere Radius (m)
I	200	3	20
II	150	5	30
III	100	10	45
IV	100	16	60

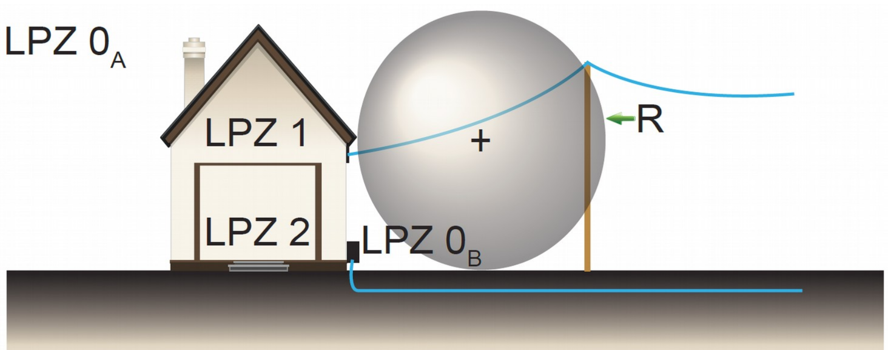


Figure 10: Lightning protection zones

Part 2 of the BS EN/IEC 62305 is useful in risk assessment which provides us with the procedure on how to evaluate the risk of lightning flashes to earth. From the risk assessment, we can determine the tolerable limit for the risk and make proper protection measures according to the limit to further reduce the chance of lightning flashes to earth. (Tokai Engineering Sdn Bhd, 2019)

Part 3 of the BS EN/IEC 62305 describes the conditions meet by the lightning protection system (LPS) to ensure it is able to protect the structure from physical damage and the safety of any living being from touch and step voltage. The characteristics of LPS is influenced by the characteristics of the structure under its protection as well as the lightning protection level that the structure should have. According to Table 3, the LPS in this standard consists of four classes (I to IV) each with respect to a different lightning protection level (I to IV). (Tokai Engineering Sdn Bhd, 2019)

Table 3: Equivalence LPL / LPS

LPL	Class of LPS
I	I
II	II
III	III
IV	IV

Part 4 of the BS EN/IEC 62305 gives guidance on how to design, install, inspect, maintain, and test the Lightning Electromagnetic Impulse (LEMP) protection system for the electrical system of a structure to lower the risk of damage caused by lightning electromagnetic impulse. (Tokai Engineering Sdn Bhd, 2019)

2.6.1 Standard Test Waveforms

According to IEC 61000-4-5, transient overvoltage was generally in the wave shape form of voltage spike, which was categorized into front time (t_f) and tail time (t_t). tf in this waveform was defined as the time taken for the lightning impulse waveform to achieve 90% of its peak value while tail time represents the time required for the lightning impulse waveform to decay to 50% of its peak value. IEC 61000 standards demonstrate transient overvoltage waveform should be in a shape with front time 1.2-250 µs and tail time 50-2500 µs. 10/350µs voltage waveform was applied for a direct strike since the energy of direct strike was much larger as compared to indirect strike. Referred to Figure 11, the time taken for the waveform to reach 90% of its peak value was 10 µs and the time required to decay to 50% of the maximum voltage was 350 µs. Moreover, 8/20µs short-circuit current surge waveform as shown in Figure 12 was applied for an indirect strike as the front time required was 8 µs and tail time was 20 µs. However, 1.2/50 µs open-circuit voltage impulse waveform as demonstrated in Figure 13 was used for an indirect strike. (International Electrotechnical Commission, 2005)

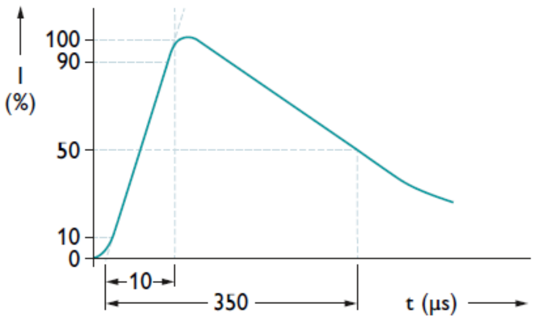


Figure 11: 10/350µs direct voltage surge waveform (International Electrotechnical Commission, 2005)

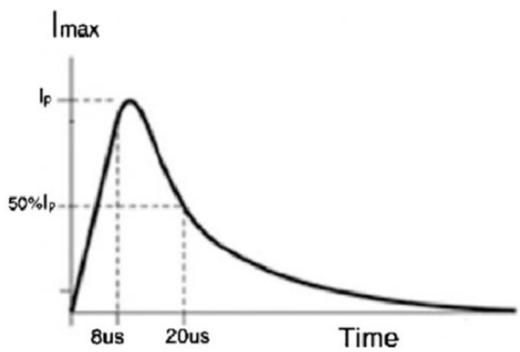


Figure 12: 8/20 µs short circuit current surge waveform (International Electrotechnical Commission, 2005)

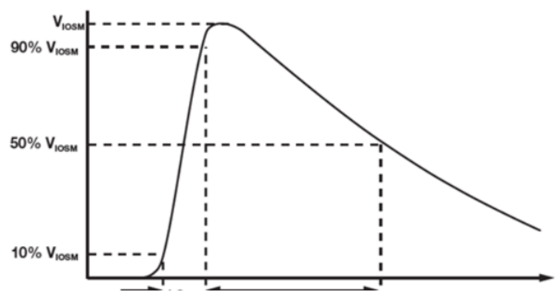


Figure 13: 1.2/50 µs indirect voltage surge waveform (International Electrotechnical Commission, 2005)

2.7 Conventional Protection Methods on Surge

Surge Protection Device (SPD) is a protective device that functions in power protection system as well as connected parallelly to the power supply circuit of the protected loads with the aim to provide an effective type of overvoltage or overcurrent protection at each and every levels of the power supply network. The way that SPD offers efficient type of overvoltage protection in order to prevent harmful to appliances and equipment downtime that might cause by power surge is to limit the amount of transient overvoltage on electrical devices. (Electrical Installation, 2019)

SPD can be categorized into two main modes of operation where a different type of current may possibly flow, which are awaiting mode and diverting mode. During normal power which is when "clean power" is supplied to the electrical distribution system, SPD functions at its minimal state. While in awaiting mode, SPD is at low power consumption where power primarily needs by monitoring circuits. Meanwhile, SPD changes into another mode, which is

Diverting Mode when a transient overvoltage event. The aim of using SPD is to redirect away damaging impulse current from critical loads and lower the overvoltage magnitude to a harmless level. (Sunpower Electronics, 2019)

Likewise, Hitoshi Kijima and Kazuo Murakawa (2012) have argued that SPD is also classified into clamping type and switching type. Switching type SPD is also known as crowbar type SPD. Crowbar device is a device that reduces the impedance state in order to provide a low-impedance path to divert the fault current to ground when there is an occurrence of overvoltage. Hence, the main convenience of crowbar device comes from its low impedance which prevent the development of high energy within the device itself when substantial surge currents flow through the device since the energy can be spent somewhere else in the circuit (Sunpower Electronics, 2019). However, the response of crowbar device is slow and needs a longer response time as it requires time to create a low impedance arcing path during avalanche breakdown process. IEEE Std C62.42.1™-2016 have discussed that gas discharge tube (GDTs) is grouped under switching type SPD.

On the other hand, clamping type SPD is a device that attempts to hold on the input voltage of the protected device at a value that slightly beyond the normal operating voltage whenever conducting and diverting transient currents. Steady-stage voltage that below the clamping level would not affect the circuit by the device no matter before or after the transient if there is a voltage clamping device applied. Variable varistor is an example of clamping type SPD. (Martzloff, 1986)

2.7.1 Gas Discharge Tube

As mentioned in previous subtopic, IEEE Std C62.42.1™-2016 have discussed that Gas Discharge Tube (GDT) is a model of switching type SPD devices. GDT had high current capacity and its response time is slower as compared to Metal Oxide Varistor (MOV) (Littelfuse, 2002). However, GDT is a passive component which will not disturb the communication circuit. Therefore, GDT is extensively applied in telecommunications plant and equipment as it offers reliable and effective protection solutions against transient overvoltage that produced by lightning, power switching and fault conditions.

Figure 14 indicates the property of a GDT in basic switching (Tim Ardley, 2008). Yves Gannac and Guillaume Leduc (2021) have argued that when voltage disturbances achieved the GDT spark-over value, GDT will switch into arc mode, which is a virtual short or partially short of the line with the purpose to divert the extra current to ground via the path provided by GDT and remove the surge from the electrical device. The GDT will remain in a high resistance condition whenever the spark-over voltage is not reached during normal operating mode. As the voltage across its conductor raised, GDT will move into its glow voltage region, which is a region that ionization of gas arises. Moreover, an avalanche effect in gas ionization was created in the glow region with the increase of current flow. This avalanche effect will transition GDT into a virtually short circuit mode and current being passed through the conductors. The potential difference in GDT during short circuit condition is known as arc voltage. The transition time between glow and arc region be determined by the gas composition, pressure of the gas, the available impulse current, the shape and distance of the electrodes, and the exclusive emission coatings. Additionally, GDT will reset to its initial high resistance state once the energy is not enough to keep the device in the arc mode. (B.Sc, 2008)

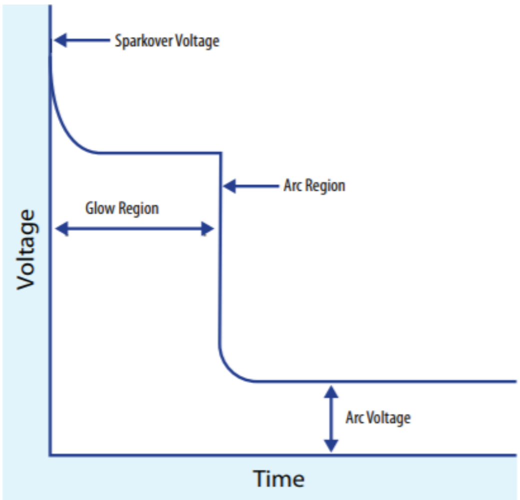


Figure 14: Characteristic curve of GDT (Tim Ardley, 2008)

2.7.2 Metal Oxide Varistor

Metal oxide varistor (MOV) is a solid-state device that is constructed to protect various types of electrical devices from power surges and offers effective transient voltage suppression. (P.Marian, 2011) As mentioned earlier, Martzloff (1996) have discussed that MOV is an example of clamping type SPD. Figure 15 illustrates the clamping voltage characteristic of MOV. Based on Ohm's law, the V-I characteristics curve of a linear resistor always shows linearity. However, the V-I characteristics curve as shown in Figure16 is extremely non-linear for variable resistor as a small change in the voltage of variable resistor will lead to a substantial change in current. According to Figure 16, MOV able to operate in both directions as it has symmetrical bi-directional characteristics which are similar to the characteristics curve of two back-to-back connected Zener diodes. Amount of current flowing through the varistor is nearly zero in the flat area for voltage in the range of 0 V-200 V. (Electronics-project-design.com, 2018) However, there is not much difference in the curve whenever the applied voltage was growing in the range of 200-250V although the value of resistance reduced as well as a few micro-amperes of current flowed.

Figure17 demonstrates the resistance of MOV is inversely proportional to the potential difference across it. (Circuits-Today, 2018) This curve can be also implemented to study the value of resistance that will be across the MOV at various voltage levels. Once exposed to a high transient voltage that exceeds MOV's threshold or clamping voltage (250 V), the resistance drops dramatically to almost zero and the varistor becomes highly conductive for the current to divert through itself in order to protect the electrical device. The potentially destructive energy is absorbed and dissipated as heat to prevent the system damaged. After the transient energy reaches zero, the MOV switch to open circuit again to stay ready for the next transient voltage. (Components 101, 2019)

Hitoshi Kijima and Kazuo Murakawa (2012) have mentioned that the advantage of utilizing MOV in surge protection is due to its quick response time as MOV is able to reach its operating voltage within 0.01 µs. MOV is an active electronic component that can draw current from its source when connected and result in power loss within the circuit. Therefore, due to its low level of losses, it is a suitable device to utilize in power circuit.

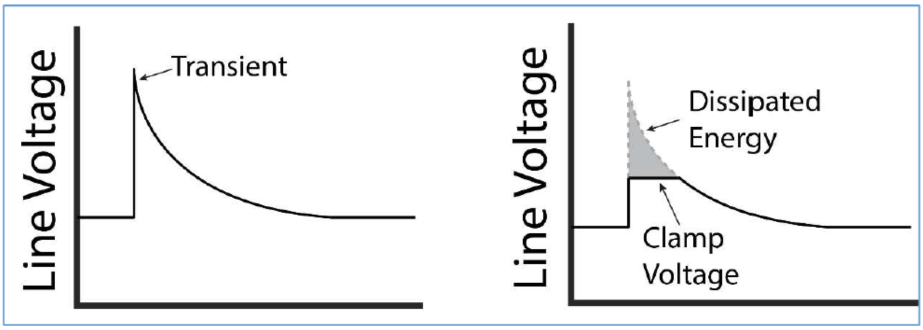


Figure 15: MOV clamping voltage characteristic (Electronics-project-design.com, 2018)

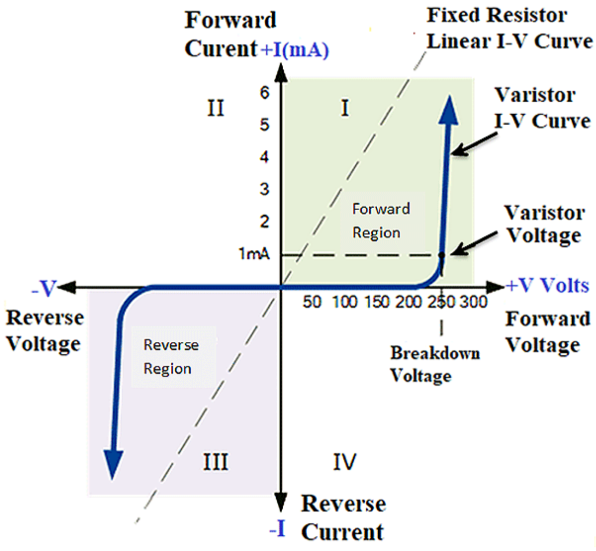


Figure 16: V-I Characteristic Curve of MOV (Electronics-project-design.com, 2018)

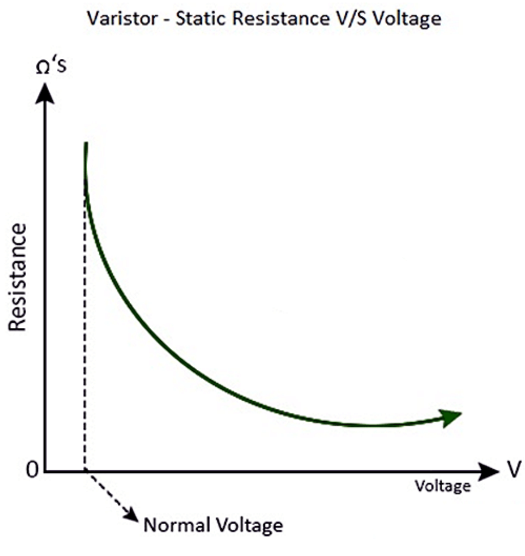


Figure 17: Resistance curve of MOV (Circuits-Today, 2018)

2.7.3 Drawbacks of Conventional Protection Method

Conventional SPD provides effective type of overvoltage or overcurrent protection at each and every levels of the power supply network, however there were several drawbacks of conventional SPD. A problem with typical MOV is under repetitive transient overvoltage, MOV will gradually deteriorate, until it eventually results in a malfunction. (Arati Channe, Vijay Mohale, 2020). During conduction state, SPD will absorb the transient and surge voltages. Thus, SPD must dissipate the energy absorbed during the conduction state as heat. However, the heat energy will not be able to be dissipated effectively, therefore causes SPD to fail if the consecutive conduction happens too frequently. Arati Channe and Vijay Mohale (2020) have classified the SPD failure over a three-year period as shown in Table 4 and conclude that maloperation is the main source of SPD failure.

Table 4: Defect Count of SPD

Type of Defect	Count of Defect
Maloperation	75
Functional Failure	25
Alarm	5
Powering issue	2
Tripping issue	1

As mentioned earlier, Metal Oxide Varistor (MOV) was categorized under conventional SPD. A phenomenon of thermal runaway due to continuous overvoltage will lead a MOV to be spoiled. This phenomenon happened once the normal voltage rises beyond the maximum continuous operating voltage (MCOV) of the MOV and continuous current is initiated through the MOV. MOV will introduce its conductive mode to allows the current to flow through the device whenever the voltage reached its MCOV. Concurrently, the magnitude of this current be determined by the resistance of MOV in the conductive mode, width of transient pulse and number of pulse repetitions. Consequently, a transient pulse with a high pulse width will lead to raise in surge current and cause heating issue, which will ultimately cause the MOV to burn and a serious arcing may be produced. (Anish.k, Bute, & Ranjan, 2008)

As the protection for an electrical device that offered by MOV inside a transient voltage surge suppressor (TVSS) was not completed, MOV may ignore low sustained overvoltage. This low sustained surge may result in damage to that electrical equipment including the protector device. Besides, MOV may also ignore low sustained overvoltage as the protection provided by MOV was incomplete. Furthermore, there is also a junction in metal oxide varistor called metal oxide junction. This junction can be malfunction due to transient overvoltage. The number of destructed junctions be determined by the number of surges encountered by MOV. The more the surge experienced by MOV, the more the number of junctions will be destructed. The increment in the number of damaged junctions will lead to a reduction in energy absorbing capability of

MOV and MCOV, which will then cause the voltage needed for MOV conduction to be reduced. This phenomenon will reduce the lifespan of that MOV but it will not influence the capability of the MOV to clamp surges.

Additionally, peak current rating for maximum single pulse of MOV referred to the maximum energy that is able to withstand by MOV without causing failure to electrical equipment. Each MOV has this rating in order to protect the appliance. Hence, failure might be occurred if the MOV is introduced to the pulse with energy that exceeds its rating. (Lang, M.J., 2011)

2.8 Characteristics of Power Electronics

More advanced technology invented since the technology of power semiconductors is developing. Further, microelectronics chips with high reliability and high performance were available at a reasonable price. These developments were also widening the implementation of switching power electronics due to their improvement in power handling capability and switching frequency. Figure 18 illustrates the power capability and switching frequency of a few types of power electronics. Figure 18 shows that thyristor has the highest power capability. As compared to other types of transistors, MOSFET has the highest operation frequency capability, which is a definite advantage. It also means that MOSFET has the fastest response time. Hence, MOSFET was generally used for high switching frequency applications. Moreover, MOSFETs required only a minimal amount of input current to control the load current as compared to Bipolar Junction Transistors (BJT). (Jiang. W. et al., 2009)

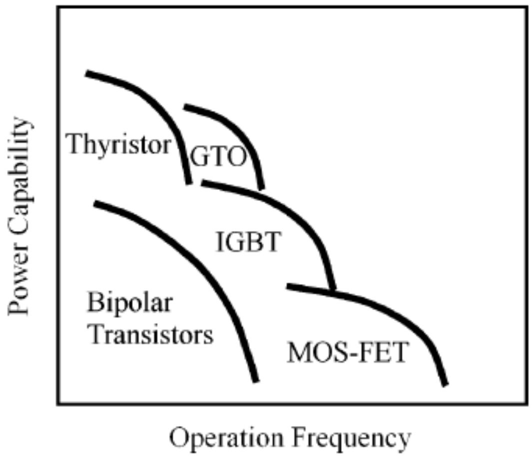


Figure 18: Power and frequency capabilities of different semiconductors (Jiang. W. et al., 2009)

2.8.1 Behaviour of MOSFET

Figure 19 illustrated circuit arrangement of an Enhancement-mode N-channel MOSFET that being used as a switch to turn on or turn off the lamp. MOSFET normally has three terminals, which are gate, drain and source. The current that is operated between the drain and source is monitored by the voltage applied to the gate. The lamp will be "ON" whenever the gate input voltage, V_{GS} reached an appropriate positive voltage level (V_{GS} = +ve). Meanwhile, a zero-voltage level ($V_{GS} = 0$) will turn off the lamp. (Electronics Tutorials, 2014)

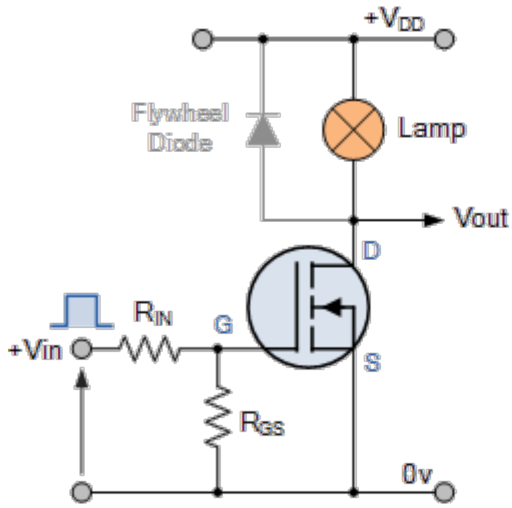


Figure 19: Circuit arrangement of MOSFET (Electronics Tutorials, 2014)

As mentioned in the previous subtopic, MOSFET is a significant power electronics for high switching frequency applications. MOSFET can protect the load from alternating frequency. Therefore, MOSFET was applied as a switch in surge protector device with the purpose to prevent some failure to be happened.

However, the gate-source voltage of MOSFET may create an unpredicted power surge once the voltage or current of the equipment itself varies. Hence, full silicon carbide MOSFET (siC-MOSFET) has been developed and implemented frequently in recent years. SiC-MOSFET was built by replaced resistive load of the device by an inductive load such as coil or solenoid. Further, a flywheel diode was required to be connected with the load parallelly in order to protect the MOSFET from any self-generated back-emf, which is also an unexpected power surge. The advantages over conventional silicon MOSFET are SiC-MOSFETs provide better overall performance, higher efficiency, more compact components and higher switching frequencies, which means smaller peripheral components such as filters, inductors, capacitors and transformers can implemented SiC-MOSFET. In addition, siC-MOSFET may operate at such a high-speed even though the voltage or current of the equipment itself varied. (Wolfspeed, 2019)

2.8.2 Safe Operating Area of MOSFET

MOSFET can only function without any permanent damage or degradation if it works within its safe operating area (SOA). Therefore, MOSFET must not be exposed to conditions outside the SOA although for only an instant time. There is no secondary breakdown as the failure mode that takes place in bipolar junction transistor for the conventional MOSFET. However, the recent MOSFET exhibits secondary breakdown. Hence, the SOA of MOSFET is within its secondary breakdown voltage, maximum drain-source voltage, maximum drain current and thermal limit between them. (Toshiba, 2018)

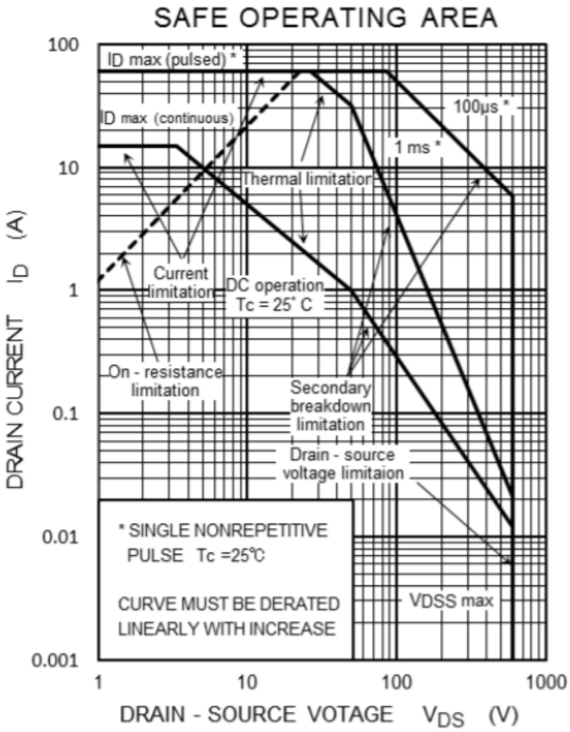


Figure 20: Safe Operating Area of a MOSFET (Toshiba, 2018)

Figure 20 demonstrates the safe operating area of a MOSFET. According to Figure 20, the safe operating area of a MOSFET was classified into five zones, which are thermal limitation, secondary breakdown, current limitation, drain-source voltage limitation and on-state resistance limitation. (Toshiba, 2018) First, the thermal limitation region was defined as the area that bound by maximum power dissipation (P_D) which is constant and has a slope of -1 in a double logarithmic graph while the secondary breakdown limitation area was bound by the secondary breakdown limit. Current limitation region was an area that restricted by the maximum drain current rating, whereas the drain-source limitation region was an area bound by the drain-source voltage (V_{DSS}) limit. Last but not least, an on-state resistance limitation region defined as an area that is theoretically restricted by the on-state resistance ($R_{DS(ON)}$(max)) limit and the I_D is equivalent to $V_{DS}/R_{DS(ON)}$(max). (Toshiba, 2018)

2.8.3 Comparison between Si IGBT and SiC IGBT

In January 2018, Mitsubishi Electric Corporation has announced a full silicon carbide, SiC power semiconductor modeule has been developed. The advantages over conventional silicon IGBT is higher power density, smaller size and lower power loss. Table 5 shows the comparison of conventional IGBT(Si IGBT) and full SiC IGBT module. The rated voltage of full SiC IGBT, which is able to reach 6.5 kV is the highest among Si IGBT module. The chip size can be reduced by combining both diode and MOSFET on a single chip. SiC IGBT also has high heat tolerance and high heat dissipation because it is facilitated by the insulating substrate and bonding technology. The insulating substrate has good thermal properties while the die bonding technology is highly reliable. (Mitsubishi Electric Corporation, 2018)

Table 5: Comparison between Si IGBT and SiC IGBT (Mitsubishi Electric Corporation, 2018)

	Power Density	**Power Loss**
Conventional silicon IGBT module	1.8	1/3
Full SiC IGBT module	1	1

2.8.4 Comparison between SiC MOSFET and Si IGBT

In high-power density applications, Si IGBT may be replaced by SiC MOSFET as SiC MOSFET has high switching speed and low switching loss. Si IGBT and SiC MOSFET have similar design structures on their gated drivers because they have the same MOS-gated structure. Si IGBT is usually used in an application that requires a low switching frequency. Therefore, Sic MOSFET is a suitable replacement for Si IGBT due to its high switching speed which reduces its size and high efficiency that reduces the size of heat sink. In Year 2017, research on comparison between SiC MOSFET and Si IBGT is conducted by Shan Yin and King Jet Tseng. In the research, standard double pulse test (DPT) was utilised, and the results found that SiC MOSFET indeed has a higher switching speed and lower switching loss as compared to a Si IGBT that has a similar voltage and current rating. However, in order to make use of the high switching speed capability of SiC MOSFET, it must be driven with a similarly high-speed switching, so that it can achieve low switching time and loss.

2.9 Types of SPD

SPD eliminates transients in two modes, which are common mode and differential mode. In common mode, the energy conducts to the earth whenever overvoltage exceeds the operating threshold. However, energy is distributed to the other live conductors in the event of a transient exceeding the operating threshold. According to IEC 61643-11 as shown in Table 6, SPD can be categorized into three different types with various purposes and each design is tailored for specific use cases. The SPD consists of Type I, Type II as well as Type III.

Table 6: Three different test classes corresponding to three types of SPDs (Schneider Electric, 2021)

	Direct lightning stroke	Indirect lightning stroke	
IEC 61643-1	Class I test	Class II test	Class III test
IEC 61643-11/2011	Type 1 : T1	Type 2 : T2	Type 3 : T3
EN/IEC 61643-11	Type 1	Type 2	Type 3
Former VDE 0675v	B	C	D
Type of test wave	10/350	8/20	1.2/50 + 8/20

Note 1: There exist T1 + T2 SPD (or Type 1 + 2 SPD) combining protection of loads against direct and indirect lightning strokes.
Note 2: some T2 SPD can also be declared as T3.

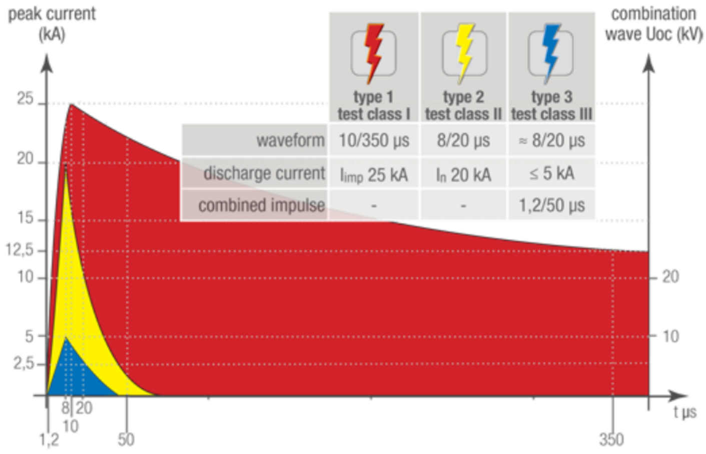


Figure 21: Maximum Discharge Current for three types of SPDs based on IEC 61643-11 (Zotup, 2018)

2.9.1 Type 1 SPD

Figure 22 shows Type 1 SPD with impulse current rating of 25kA. According to IEC 61643-11:2012, Type I SPD, which is also known as 'Class B' functions under 10/350µs current wave to protect electrical appliances from direct lightning strikes by discharging its back-current from earth conductor to the network conductor at a nominal discharge current rating of between 10kA to 20kA. (Nemasurge, 2013) Type 1 SPD is normally applied in the buildings protected by a lightning protection system or a meshed cage such as service-sector or industrial building. (Wenzhou Arrester Electric Co., May 2022)

The Type I SPD can only be utilized without implementing any other external overcurrent protective device. On installing Type 1 SPD, referring to IEC62305, it is ideally placed in transition lightning protection zone (LPZ) 0 - 1 as it is capable of protecting its nearby installations from lightning strikes and internally generated surges or induced transients. Generally, Type 1 SPD to be applied at the origin, for instance, main distribution board. (IET, 2022)

Impulse current (Iimp) is defined as the peak value of a direct current lightning waveform (10/350µs waveform) that the SPD is capable of discharging 5 times. IEC 62305-2 standard defines four protection level. IEC 62305-2 has stated a table of Iimp value based on the building's voltage protection level as shown in Table 7. An impulse current of at least 12.5kA per pole is needed for a three-phase system. Three-phase system is referred to 3P + N system, thus the SPD should be able to withstand Iimp of 100kA coming from the earth bonding. (Schneider Electric, 2021) Moreover, auto extinguish follow current (Ifi) is defined as the current that the SPD is capable of interrupting by itself after flashover, which is applicable to the spark gap technology. Therefore, auto extinguish follow current must exceed the prospective short-circuit current at the point of installation.

Figure 22: Type 1 SPD completed with Iimp of 25 kA (Confly, n.d.)

Table 7: Iimp based on the building's voltage protection level
(Schneider Electric, 2021)

Protection level as per EN 62305-2	External lightning protection system designed to handle direct flash of:	Minimum required Iimp for Type 1 SPD for line-neutral network
I	200 kA	25 kA/pole
II	150 kA	18.75 kA/pole
III / IV	100 kA	12.5 kA/pole

2.9.2 Type 2 SPD

Figure 23 shows Type 2 SPD with impulse current rating of 20kA. According to IEC 61643-11:2012, Type 2 SPD, which is also known as 'Class C' functions under 8/20µs current wave to protect electrical appliances against the effects of indirect lightning strikes and induced voltage at a nominal discharge current rating of 3kA, 5kA, 10kA as well as 20kA. (Nemasurge, 2013)

The Type 2 SPD can be utilized by implementing an external overcurrent protective device or including itself within the SPD. On installing this SPD type, it is ideally placed in transition lightning protection zone (LPZ) 1 – 2 as stated in IEC 62305, as it is capable of protection against indirect lightning effects on low voltage electrical installations. Type 2 SPD is usually to be applied at the low voltage electrical installations, for instance located in each electrical switchboard. This is because Type 2 SPD is able to avoid the spread of transient overvoltage in the electrical installation and protects the loads. Further, Type 2 SPD provides protection against power surge which results from switching or indirect lightning strokes. (IET, 2022)

Nominal discharge current (In) is expressed as the peak value of a short circuit current lightning waveform (8/20µs waveform) that the SPD is capable of discharging a minimum 19 times. The lifespan of a SPD is directly proportional to the nominal discharge current value.

Maximum discharge current (Imax) is expressed as the peak value of a short circuit current lightning waveform (8/20µs waveform) that the SPD is capable of discharging once. Table 8 illustrates the recommended maximum discharge current value based on the exposure level. The maximum discharge current is determined based on the estimated exposure level referring to the building's location.

Figure 24 shows the time versus current characteristic of a SPD connected to low voltage distribution systems which defined by IEC 61643-11. In a case of 2 SPDs with the same nominal discharge current, the SPD with higher maximum discharge current value has a better safety margin, where it is able to withstand a higher surge current.

Table 8: Recommended Maximum Discharge Current Value based on Exposure Level (Schneider Electric, 2021)

	Exposure level		
	Low	**Medium**	**High**
Building environment	Building located in an urban or suburban area of grouped housing	Building located in a plain	Building where there is a specific risk: pylon, tree, mountainous region, wet area or pond, etc.
Recommended Imax value (kÂ)	20	40	65

Figure 23: Type 2 SPD completed with Iimp of 20 kA (Confly, n.d.)

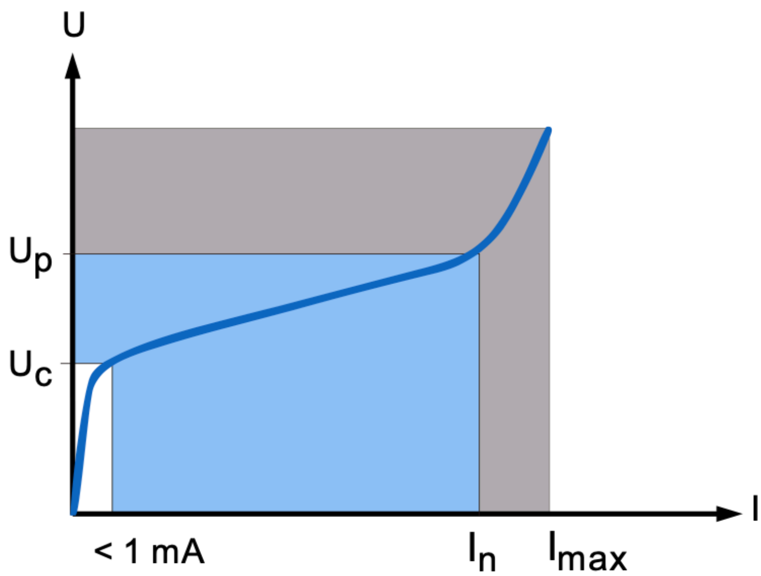


Figure 24: Time/current characteristic of a SPD connected to low voltage distribution systems according to IEC 61643-11 (Wenzhou Arrester Electric Co., May 2022)

2.9.3 Type 3 SPD

Figure 25 demonstrated Type 3 SPD with impulse current rating of 5kA. According to IEC 61643-11:2012, Type 3 SPD, which is also known as Class D or 'Point of Utilization SPD'. The distance from this SPD to the electrical service panel must be exceeded 10 meters unless the evaluation carried out at Type 2 SPDs by receiving a nominal discharge current rating of at least 3kA. (Nemasurge, 2013)

Further, Type 3 SPD is characterized by a combination of 1.2/50µs impulse voltage wave and 8/20µs impulse current wave. Type 3 SPD usually applied for fine protection on sensitive or critical loads against the transient overvoltage, as it has a low discharge capacity. Type 3 SPD must be installed as a supplement to the Type 2 SPD, which is normally installed downstream of Type 2 SPD. Type 3 SPD is the main protection system of sensitive loads such as typically home automation, IT systems and communication networks. Type 3 SPD is intended as a protection for communication networks as it protects telephone networks against external transient overvoltage like lightning as well as internal transient overvoltage to the power supply network such as polluting equipment and switchgear operation. (Schneider Electric, 2021)

Figure 25: Type 3 SPD completed with Iimp of 5 kA (Confly, n.d.)

2.10 Earthing System

The difference between earthing and grounding are often mixed up and confused when describing a reference point of an electrical system. The term “Earthing” defined by IEEE means a circuit that is physically connected to the soil mass (earth), taking the potential of the earth as a reference point. On the other end, “grounding” refers to a reference point where other electrical points of circuits are connected and may not necessarily refer to a physical connection to the soil mass. For instance, the reference point for electrical connection on an eighth floor of a building is the ground where the building itself uses earth as a reference due to its solid connection to the soil mass. (Vijayaraghavan, G., Brown, M., Barnes, M., 2004) Table 9 illustrates the differences between earthing and grounding system.

Table 9: Differences between Earthing and Grounding System

Parameter	Earthing	Grounding
Definition	The non-current carrying parts (body of equipment) is connected to ground in order to protect human beings from electric shocks.	The current carrying part is connected to ground in order to shields the entire power system from malfunctioning
Location	It is located between the equipment body and earth pit which is placed under the earth surface	It is located between the neutral of the equipment and ground
Potential	It consists of zero potential	It does not consist of zero potential
Application	It functions to prevent shocks to human by discharging electricity to earth	It functions to protect electrical system from being damaged or malfunction by providing a return path for the current

Use Note: "Use" is same with "Application"	For preventing the electrical shock	For balancing the unbalanced load.
Colour	The color of earth wire is green	The color of ground wire is black
Examples	The enclosure of the motor, generator, power transformer is connected to the earth.	Neutral of transformer and generator is connected to ground.

2.10.1 Importance of Earthing System

Earthing discharges the electrical energy to the earth through the cables with low resistance whenever faults happen. Earthing system is implemented for two main purposes, which include providing electrical reference as well as providing protection against electrical faults. (BYJUS, 2022)

The measurement of voltage is possible through an electrical earthing system with respect to the electrical reference. A standard reference point is necessary as the voltage across multiple points may be defined inconsistently without it. Therefore, connecting on the same electrical reference allows the electrical system to be maintained on a standardized reference level.

Figure 26 and Figure 27 demonstrates the electrical system with earthing network and electrical system without earthing network respectively. Earthing network able to minimize the chance of electric shock and protecting devices from electrical damage. Earthing network provide an alternative low impedance path for faults currents or discharge the electrical energy to earth instead of flowing through a human body. (Circuit Globe, 2017) For instance, in a case of fault happen in a cooker, the fault current will flow to the earth via the earthing conductors. This will also lead to the protective device such as circuit breaker to turn off the electricity supply to the cooker. Therefore, people who touches this cooker will not experience electric shock.

In contrast, without earthing a metal enclosure of electrical appliances, it will cause electrocution to those who come in contact with the appliances in case of a fault due to exposure of phase wire which comes in contact with the metal enclosure.

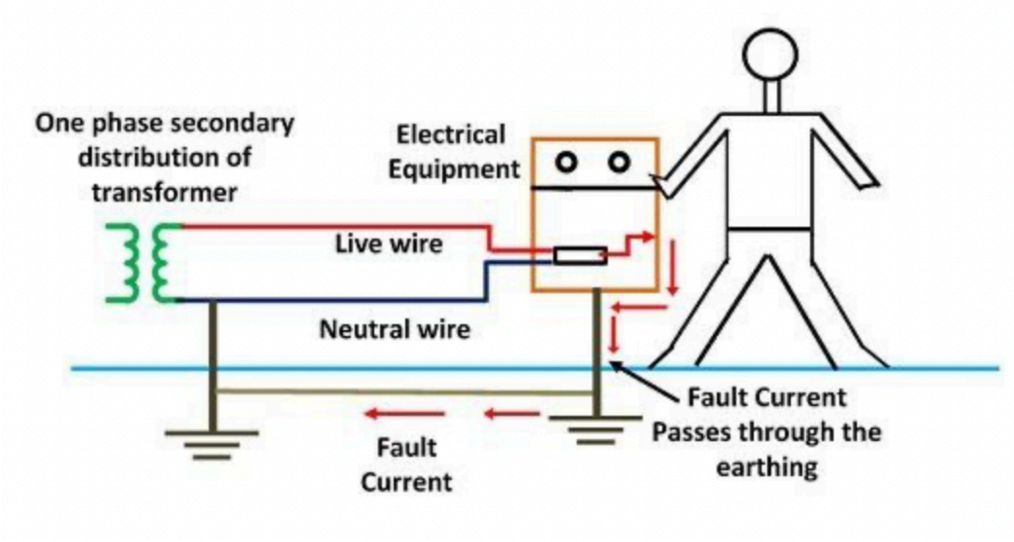


Figure 26: Electrical Network with Earthing System (Circuit Globe, 2017)

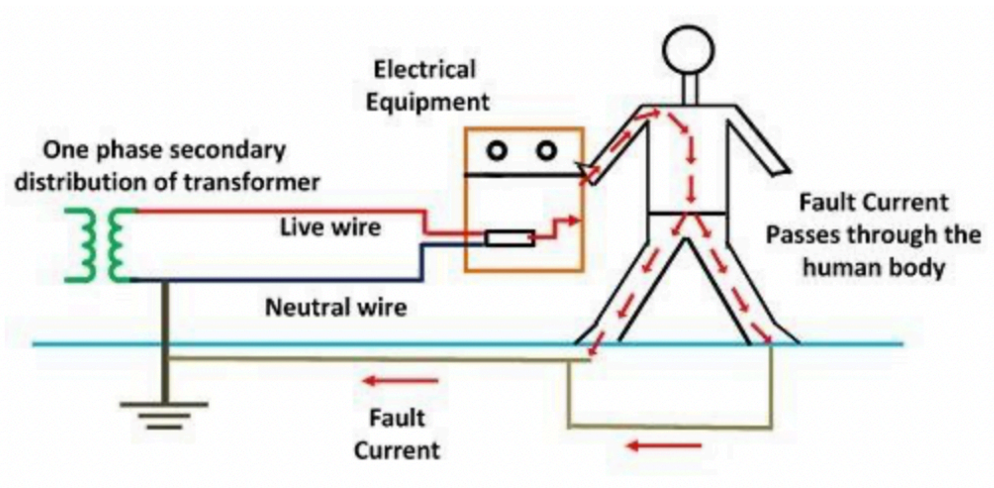


Figure 27: Electrical Network without Earthing System (Circuit Globe, 2017)

2.10.2 5 Types of Earthing System

The IEC 60364-4-41 provides guidelines on protection methods such as protective conductors for indirect surge events. This standard describes that the grounding system for low voltage distribution systems has two different grounding locations where the first is located at the supplier's distribution transformer on the low voltage side, the second is placed at the consumer's electrical installations, both of these grounding locations has its grounding points installed with low impedance electrode. This grounding system includes the TT system, TN-C system, TN-S system, TN-C-S system and IT system. The naming convention for the grounding systems represents its grounding characteristics, the descriptions are as listed below:

The first letter is reserved for grounding conditions at the source side. "T" which derived from the word "Terra", the word "earth" from ancient Greek, means the system is connected directly to the source side earth. "I" indicates that the system is isolated from the earth or connected through a high impedance.

The second letter is reserved for grounding conditions at the load side. "T" indicates that electrical installation is directly grounded, the letter "N" means it is connected to the transformer's grounding point of the source through a neutral conductor.

The third letter, which exists for certain systems and not for others, describes the connection patterns for neutral and protective conductors. “C” indicates that both neutral and protective conductors are combined. On the contrary, “S” indicates a separated neutral and protective conductor.

2.10.2.1 TT Earthing System

TT grounding systems consist of two grounding points located at source and load each as shown in Figure 28. This system is applied in Malaysia where it is commonly found in housing areas, telecommunication sites, agricultural areas and places with overhead facilities because it provides reduction in conducted interference and noise as well as the earth conductor remains grounded instead of turning into live in case of a connection with fallen tree or branches. In the TT system, the distributor will provide grounding for the source while the consumer provides its own grounding point by placing a suitable ground electrode close to the installation. The advantages of this system include its simplicity where few calculations are required during installation, no calculations required for extension, its low fault current, and require little maintenance. However, its disadvantages are its higher cost as RCDs are required on every outgoing line to obtain horizontal discrimination, contains risk of false tripping, and its level of safety is dependent on value of the earth connections.

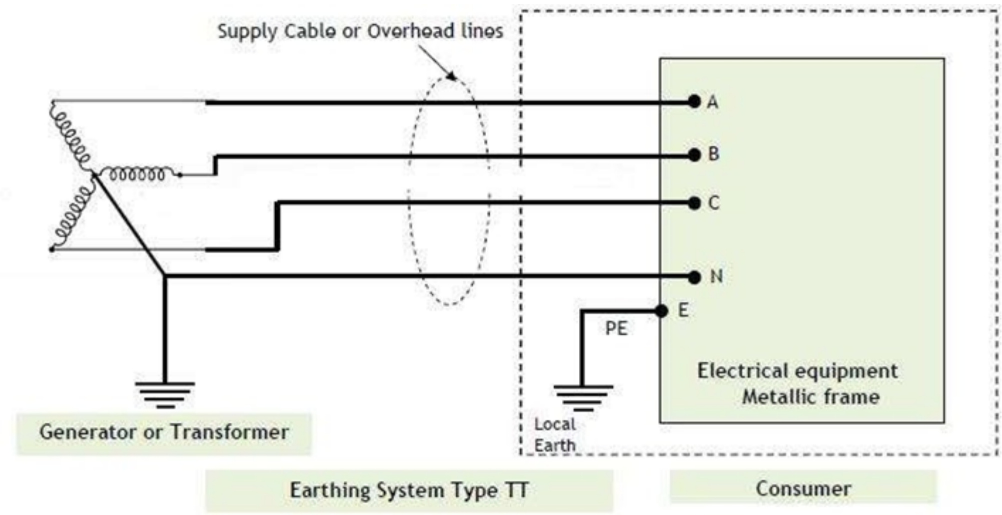


Figure 28: TT Earthing System

2.10.2.2 IT Earthing System

Figure 29 illustrates the structure of IT grounding system. IT grounding systems consist of two remote grounding points, where the source is isolated due to its high impedance that separates the transformer’s neutral point and the ground. The advantage of the TT system is its ability to keep other loads operated even if one of the loads is compromised by a fault event as it diverts the fault current to earth while the circuit breaker remains unactivated where only an LED alarm is triggered to assist in locating the fault location for maintenance service. In the case of a second fault while the first fault remains, the fault will trigger the system circuit breakers. Due to this ability, this system is commonly applied to facilities that require electricity for critical use such as the hospitals, military defense facilities, and data centers.

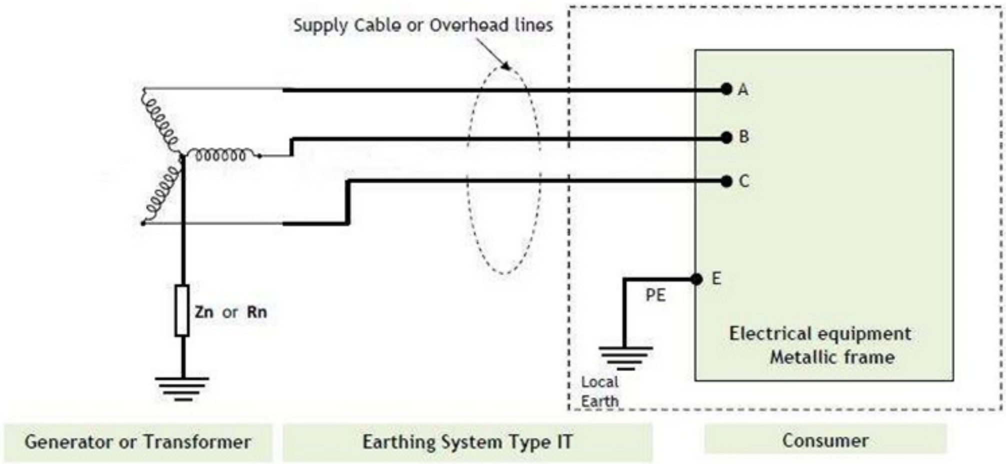


Figure 29: IT Earthing System

2.10.2.3 TN-C Earthing System

Figure 30 shows the structure of TN-C grounding system. TN-C grounding system has the grounding point on the source connected through a low impedance earth electrode and a combined PEN conductor connects the earth on load side to the source. The downside to this system is its combined PE and N cable that leads to damaging the PEN which will affect the whole earthing system.

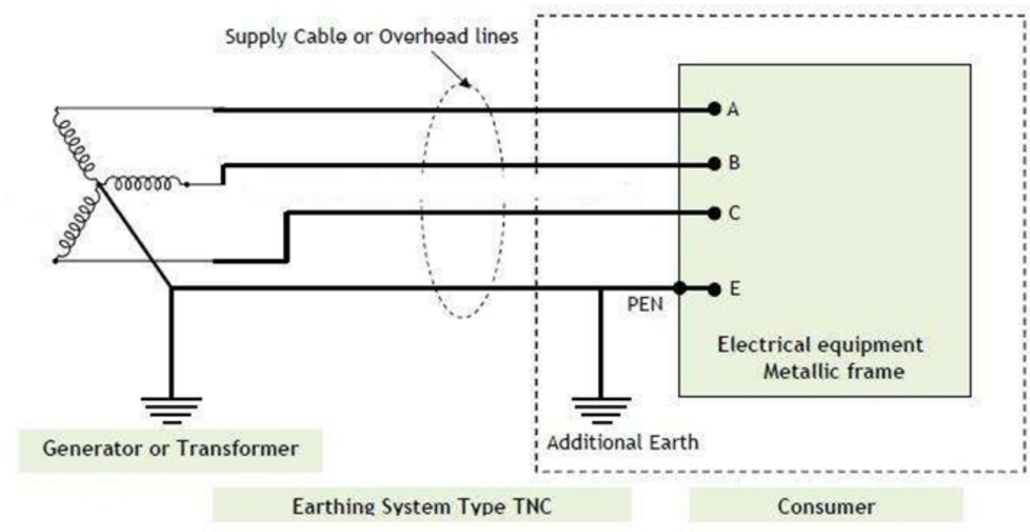


Figure 30: TN-C Earthing System

2.10.2.4 TN-S Earthing System

Figure 31 demonstrates the structure of TN-S grounding system. TN-S system is similar to TN-C system where the grounding point on the source is connected through a low impedance electrode, however the PE and N conductors are separated on both the source and load side where the N conductor is connected to the neutral for both transformer of the source and consumer's electrical installation while the PE conductor is connected to the neutral of the source's transformer and connected to the earth of the consumer's electrical installation. In the event of a fault, the fault current is able to flow through the PE or N conductor back to the source grounding point. This system is ideal for underground power supplies, consumers with one or more step down transformers, and places where the load is above 1 MA.

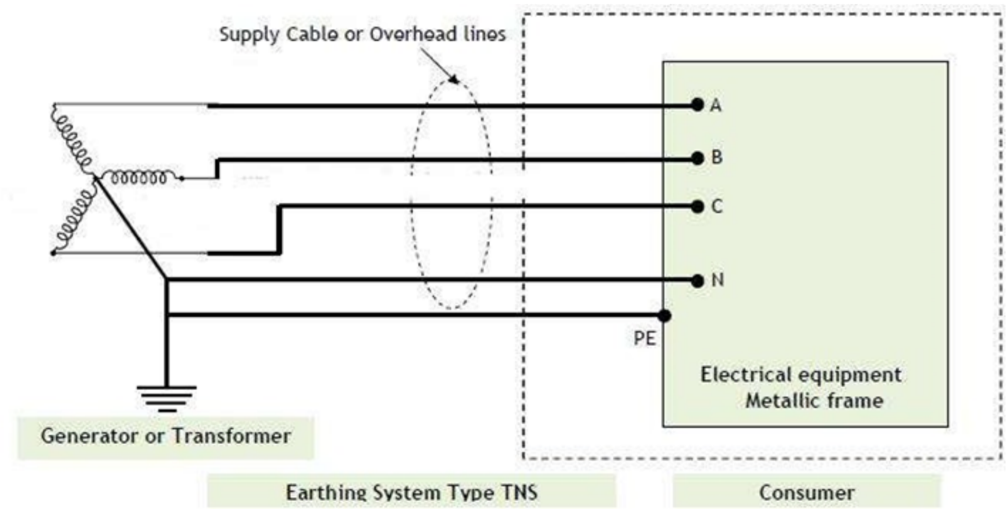


Figure 31: TN-S Earthing System

2.10.2.5 TN-C-S Earthing System

Figure 32 shows the structure of TN-C-S grounding system. TN-C-S system has a grounded source transformer through a low impedance electrode, a combined PEN conductor that is connected to the transformer's neutral point and remains unseparated if connection at the consumer side is not required. In the case where connection to the consumer side is necessary, the PE and N conductor are separated where the PE and N conductor connects to the earth and neutral respectively to the conductor of the electrical installation. This system is suitable to be applied around the existence of electromagnetic compatibility problems, in places such as the radio tower, cell tower, and power distribution network as the PEN conductor provides reduction on voltage drop during power transmission which in turn reduces cabling cost.

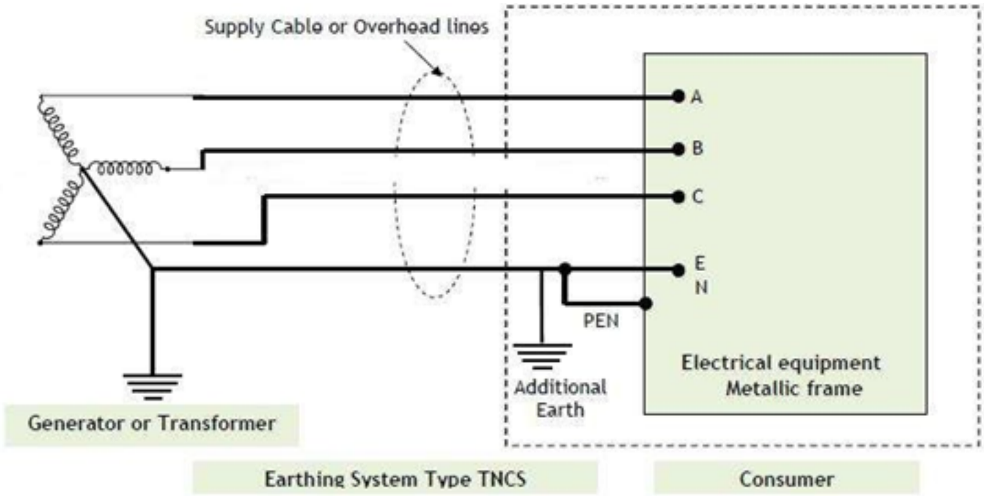


Figure 32: TN-C-S Earthing System

2.11 Coordination between SPD and Overcurrent Protection Device (OCPDs)

Though a Surge Protection Device (SPD) serves to protect systems or other devices from damage, the SPD itself also requires protection in case of overcurrent. As defined within BS 7671 Section 534, an overcurrent protection device (OCPDs) is necessary on every installed SPDs to protect it against short-circuit in circumstances such as end-of-life of SPDs. The majority of SPDs are installed in parallel to the supply load, meaning that the SPDs are independent to their respective supply load current therefore using a load of 100A or 1000A is fine on the same SPD or the same cross-sectional area of the connecting leads to SPDs and not needed to be sized equivalent to the load current.

According to Section 534, the minimum cross-sectional area of the connecting cables for SPD has to be 16mm2 for high energy Type 1 SPD and 4mm2 for Type 2 and Type 3 SPDs. The cross-sectional area value is dependent on the surge current that these SPDs are required to carry, not of the supply load current. These parallelly connected SPD to the supply load often does not draw any current, however in the event of overload fault condition, an internal overload protection such as a thermal disconnection is required by standard from BS EN 61643 to protect the connecting conductor to the SPD from short-circuit through utilizing OCPD in-line with the connecting cables.

The SPD is protected by the in-line OCPD following the equation I2t = k2S2. The details on I2t which relates to OCPD is obtainable through manufacturer's data while k2S2 which relates to the connecting cable indicates the thermal capacity of the cable where k is obtainable from BS 7671 or cable manufacturer's data and S is the nominal cross-sectional area of the cable in mm2. In order to protect the connecting cable, I2t should not exceed k2S2. (Beama, 2014)

The coordination between SPD and OCPD is to be considered within the design for protection of SPDs within a system. The OCPD and SPD should be coordinated to function as intended and discrimination between the SPD, OCPD and upstream OCPDs is achieved in every installation. Functioning in coordination allows maximum SPD surge current without triggering OCPD to operate as they are installed in-line with each other meaning the surge current of the SPD also flows through OCPD. To achieve this, BS EN 61643 SPD product standard stipulates SPD manufacturers to define the maximum OCPD rating to safely use on their SPDs. Hence, the declared maximum rating on OCPD from the SPD manufacturer is never to be exceeded and the maximum OCPD value should be implemented irrespective of the discrimination of this OCPD with upstream OCPDs.

2.11.1 Residual Current Devices (RCD)

Earth fault is a fault that occurred between a live conductor and earth. The electrical system short circuit during earth faults. The short circuit current flows through the system and returns through the earth or any electrical devices, which will then damage the devices. Furthermore, earth fault also interrupts the continuity of the supply as well as shocking the user. Therefore, fault protection devices such as residual current devices (RCD) should be installed in order to protect the electrical equipment and human safety.

RCD provides earth fault protection by comparing the current in live and neutral conductor. If the current in live conductors is not equivalent to the neutral conductors, RCD will break the circuit. RCD compare the current by comparing the magnetic fields produced by live and neutral conductors.

Besides, RCD can prevent electric shock when the current between live and neutral conductor is imbalanced. For instance, whenever a person touches the live conductors, some of the current will flow through the body which will lead to current in the live conductor exceeding the current in the neutral conductor. This imbalance in current produces a magnetic field in the core which will then trigger a signal for RCD to operate. However, RCD does not protect from electrocution in a condition that the current between live and neutral conductors remains balanced. For example, a person accidentally touched both the live and neutral conductor. Hence, RCD does not replace MCB or fuse even though it is similar compared to a miniature circuit breaker (MCB) as RCD will not react on overload or short circuit in that case currents in live and neutral conductors remain balanced.

2.11.2 Coordination between SPD and RCD

Insulation faults between live conductors and exposed conductive parts, also known as fault protection, which provided by RCD requires coordination between the types of power supply, earthing system, impedance values of protective wiring system and protection device characteristics. This is due to the incorporation between the power distribution system and RCD transient activity which may cause RCDs to operate as well as interrupts the continuity of power supply. According to IEC 62305-4, two configurations between SPD and RCD are allowed, which are SPD installed upstream of RCDs and SPD installed downstream of RCDs.

The configuration of SPD installed upstream of RCDs as shown in Figure 33 also refers to SPD installed on the supply side of RCD. This configuration is preferred as it can avoid nuisance tripping caused by transient overvoltage. According to Figure 33, the SPDs are installed between the live conductors to neutral conductors instead of between the live conductors and protective conductor. The RCD being downstream of the SPD would not function when the SPD becomes defective as it would create a short-circuit current instead of an earth fault current. However, this configuration of SPD would ensure the OCPD which connected in-line with the SPD to safely operate within the required disconnection times of OCPDs whenever short circuit current is encountered in case of the SPD becoming defective.

Meanwhile, Figure 34 demonstrated the configuration of SPD installed downstream of RCDs, which also refers to SPD installed on load side of RCD. RCD that applied in this configuration should be S-type with minimum surge currents rating of 3kA 8/20. (Beama, 2014) Nonetheless, the RCD may trip and lead to a disturbance in power supply in case of surge currents exceeding 3kA 8/20. This configuration is not preferred as it may lead to nuisance tripping of the RCD at regular intervals. This is due to a lightning transient that passed through the RCD along the line as an inward current. However, there is no current returned whenever SPD diverts the lightning transient to earth. Consequently, RCD misidentifies this condition as an earth fault, which will then lead to unwanted tripping of the RCD.

In a nutshell, installation of SPD on the source side of earth fault current tripping devices such as RCD is recommended as it can prevent nuisance tripping to occur.

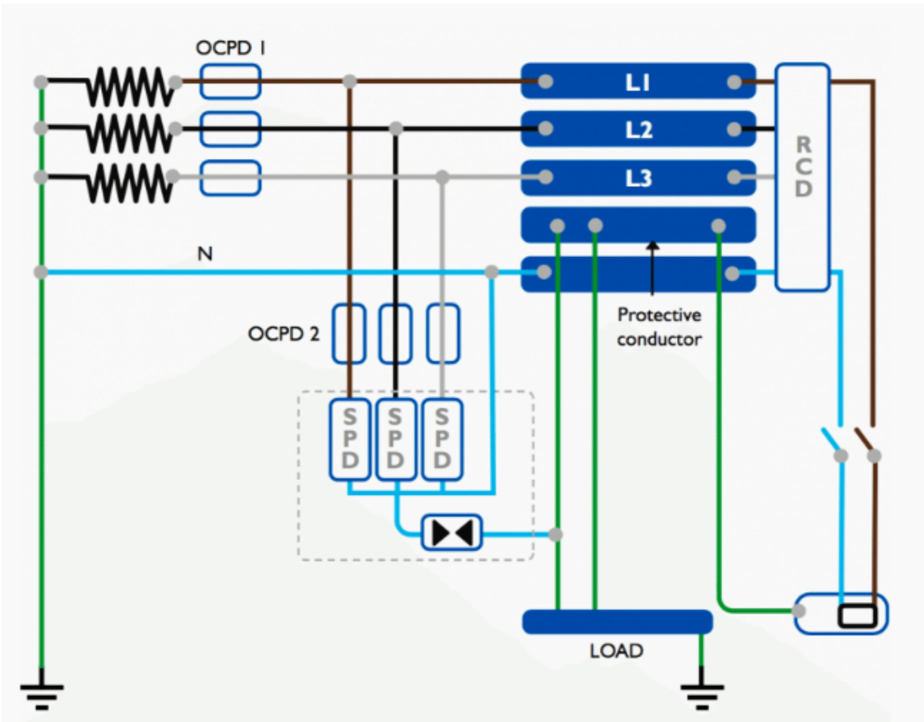


Figure 33: Configuration of SPD Installed Upstream of RCDs (Beama, 2014)

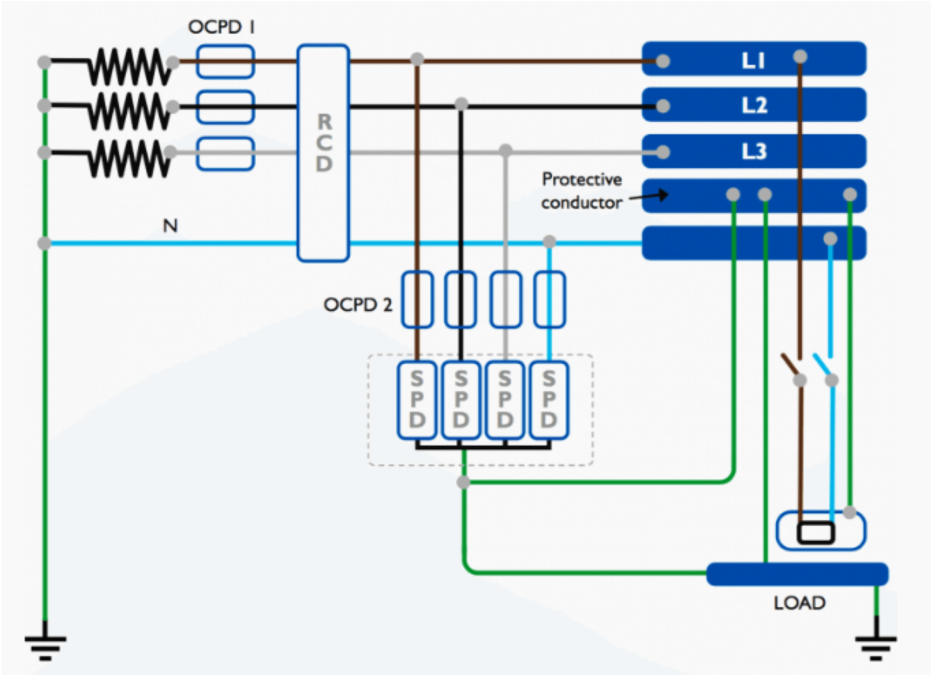


Figure 34: Configuration of SPD Installed Downstream of RCDs (Beama, 2014)

2.11.3 Arrangements of SPD

The low voltage power line SPDs usually are connected in shunt in order to be independent of the steady-state current rating of the supply as well as independent of the steady-state and short circuit current rating of the load. SPD which is connected in parallel with the load can also apply separate overcurrent protection from the load.

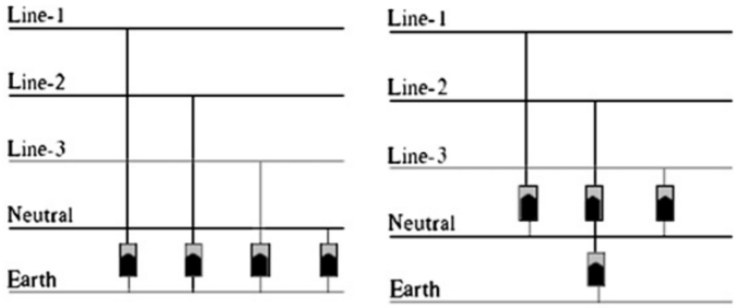
The operation of SPD is twofold with the purpose of creating a condition of voltage equalization. In an event of a ground potential rise or overvoltage, SPD should switch itself from high impedance mode to low impedance mode in order to allow the transient to pass into earth.

Meanwhile, SPD should switch back to high impedance mode after the fault is removed.

Two arrangements of SPD are available as shown in Figure 35. Based on the SPD type 2 connection that demonstrated in Figure X, neutral connection is present in this connection. As discussed above, the function of SPD is not only to divert surges to ground through the least resistance path, SPD is also utilized to equalize the earth, neutral and line potentials. Neutral wire is a non-energized wire as it is not connected to any active energy source from the incoming services. A balanced system is required to meet several criteria, which include equivalent current among each line as well as a consistent power factor in which the phase angle of each current is consistent with respect to their phase voltages. In a 3-phase balanced system, the voltage at the star point of the three-phase is as the stable reference, the voltage between each phase and the star point intended to be the same as that of the supply.

A neutral wire is implemented to carry out of the balance current in unbalanced loads to ensure equivalent voltage and current across each phase in order to achieve a balanced system. In a case of neutral connection being eliminated from the SPD system, the star point will no longer be referenced to the ground. This will then cause the potential at the star point tend to increase towards the potential of the phase with the greatest load. For instance, whenever the potential of one phase is approached, the potential between the other phases and the star point will rise proportionally with the purpose to achieve potential equilibrium. This process will lead to an exhibited sign of overheating and failure on SPDs of the two phases, meanwhile the remaining phase is undamaged. Hence, instabilities conditions such as unstable voltage, unexpected current as well as dangers of electric shock will happen in the system if neutral connection is removed. Therefore, SPD type 2 connection that demonstrated in Figure X is more preferred than SPD type 1 connection. (Chandima Gomes, 2016)

SPDs from each line to neutral are labeled as SPD1, SPD2 and SPD3 respectively. SPD4 indicated the SPD which connected from neutral to earth. The operation of this type of connection is discussed in the event of a voltage impulse propagating in Line-1. During response time T1, SPD1 switches to low impedance mode allowing Line-1 voltage flows to neutral as potential difference across SPD1 is developed with the presence of voltage impulse at Line-1. Therefore, there is a potential difference created between neutral and Line-2, Line-3 and earth. The SPD2, SPD 3 and SPD4 will then switch to zero impedance mode after response time T2, T3 and T4 respectively in order to equalize the earth, neutral and line potentials. Hence, a decision can be made that the potential of Line-1, Line-2, Line-3 and earth is equalized with time periods T1+T2, T1+T3 and T1+T4 respectively. These time intervals should be sufficiently short to avoid insulation breakdown between the respective lines, neutral or earth.



Type 1 Connection Type 2 Connection

Figure 35: Two Arrangements of SPD (Chandima Gomes, 2016)

2.11.4 SPD in TT Earthing System

Figure 36 demonstrates the SPD installed in TT earthing system. Fault protection in TT networks consists in the connection of exposed conductive parts with earth and in using earth for conducting fault current to the supply node. Generally, the response time of a protective system must be sufficiently short to prevent insulation breakdown. This can be achieved by ensuring the earth resistance of protective earthing of an electric equipment is low.

Special attention is required for TT systems due to its high earth impedances. One of the risk factors in the TT system is that high earth impedances of the TT system will lead to reduction in earth fault currents and an increase in the disconnection times of overcurrent protective devices (OCPDs). Hence, RCDs are utilized as earth fault protection in order to achieve the requirements for safe disconnection time. One of the risk factors in a TT network is extremely high touch voltage which will lead to major electric shock, considerably more severe than usual in case of a fault in a TN network. The supply voltage of the TT system is divided in the proportion of wiring impedance and earthing resistance. Therefore, the exposed conductive part in a TT network is exposed to an extremely high touch voltage whenever fault happens. Moreover, two RCDs connected in series are endorsed in the TT network in order to prevent the failure of an RCD to occur, on which the fault tripping is directly dependent. The primary RCD to be utilized in series is the main building RCD meanwhile the other RCD to be used is sensitive type for final circuits with I<=30mA. (Beama, 2014)

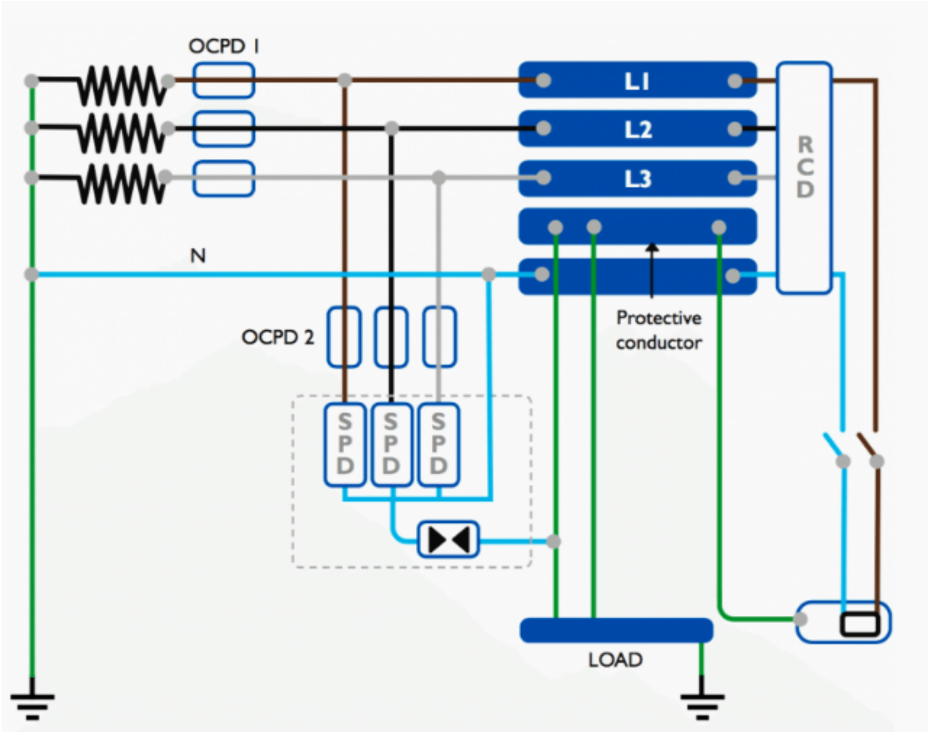


Figure 36: SPD Installed in TT Earthing System (Beama, 2014)

2.11.5 SPD in TN Earthing System

TN-C earthing system the most commonly used type of supply network. RCD is prohibited to be utilized in the TN-C network due to its neural and protective wire being one shared conductor. RCD provides earth fault protection by comparing the current in live and neutral conductor. If the current in live conductors is not equivalent to the neutral conductors, RCD will break the circuit. In a case that neutral and protective conductor are combined, RCD is not able to function, which will then lead to the malfunction of circuit breaker as no tripping signal is given by RCD. Hence, interconnection between protective conductor and neutral conductor in the installation behind RCD is prohibited. Based on BS7671, SPDs are allowed to be installed in the supply side (TN-C) of the TN-C-S system. However, SPD should be installed within 0.5m of the PEN split to N and PE as well as omit the N to PE SPD protection mode. (Beama, 2014)

Figure 37 shows the installation of SPDs as part of the lightning protection zones for a TN-C-S network. TN-C network is converted to TN-S network once the PEN conductor is separated to protective conductor and neutral conductor in the main switchboard. In the TN network, SPDs can only be utilized in the TN-S side, which is the consumer side of the TN-C-S system. In the TN-C-S network, SPDs are usually installed at the main distribution board. As the protective conductor and neutral conductor are separated, the distance between the SPD installation point and the PEN split always exceeds 0.5m. Therefore, SPD is required to be utilized between the protective conductor and neutral conductor of the TN-S system.

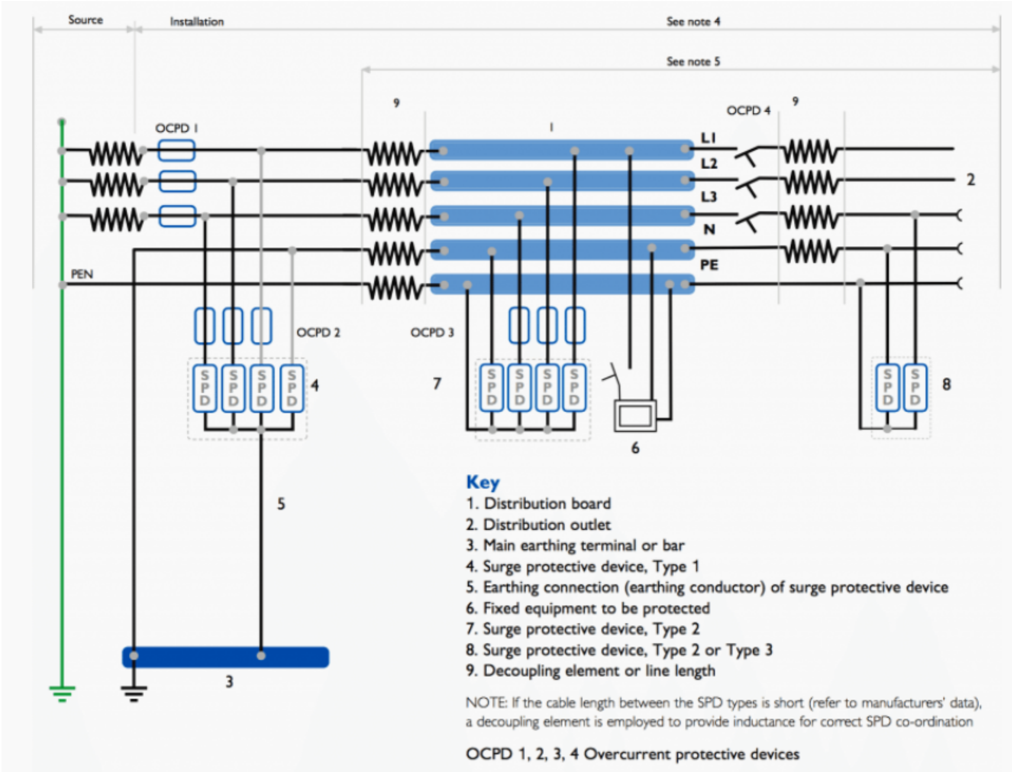


Figure 3 – Installation of Types 1, 2 and 3 SPDs, for example in TN-C-S systems (click to expand scheme)

Figure 37: SPD Installed in TN Earthing System (Beama, 2014)

2.11.6 SPD in IT Earthing System

IT grounding systems are usually applied to facilities that require electricity for critical use such as hospitals and data centre due to it providing high reliability and safety in the electricity supply. IEC 60364-7-710 stated the specific requirements for the electrical installation in a medical insulated network (MIS).

One of the advantages of an IT network is the ability of the safe function. For an ideal IT network, all the parts are isolated from the earth except the conductive parts of the electrical equipment is earthed. Therefore, the IT network will become an earthed TN network in the case of occurrence of first earth connection. The overload protection device will not trip as there is no current flowing to the earth. However, practically, there is a small amount of leaking current flowing in the network.

In the case of first occurrence of first earth connection, the IT network is able to keep the other parts of the system operated even if one of the loads is compromised by a fault. In case of the first earth connection, the IT network diverted the fault current to earth without activating the circuit breaker. In order to ensure the safety of the work, insulation monitoring devices (IMD) and residual current monitors (RCM) are applied to determine the first earth connection. IMD and RCM will provide audible and light signals during the first failure to identify the occurrence of first failure as well as assist in locating the fault location for maintenance services. (Eaton, 2017)

The first failure in an IT network will create a short circuit current. Therefore, the overcurrent protective devices must trip in the case of occurrence of second earth connection at another location. In order to ensure the safety and reliability of supply, protection must be ensured by RCDs in case of a second failure. However, RCD is not able to provide protection whenever the second earth connection happens after it. Figure 38 and Figure 39 illustrates the appropriate and inappropriate use of sensitive RCD in an IT earthing system respectively. Thus, the fundamental rule for implementing RCDs in an IT system is as shown in Figure 38, where the wiring after the RCD must be shorter than the installation before it.

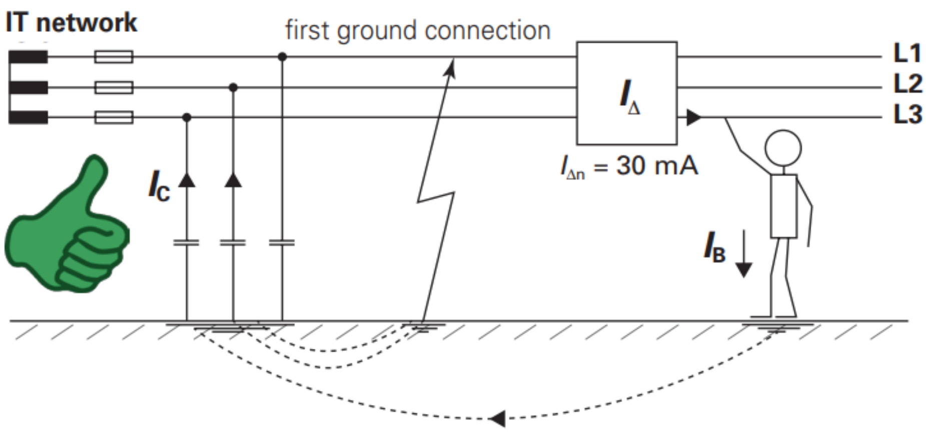


Figure 38: Appropriate Use of Sensitive RCD in an IT Earthing System (Eaton, 2017)

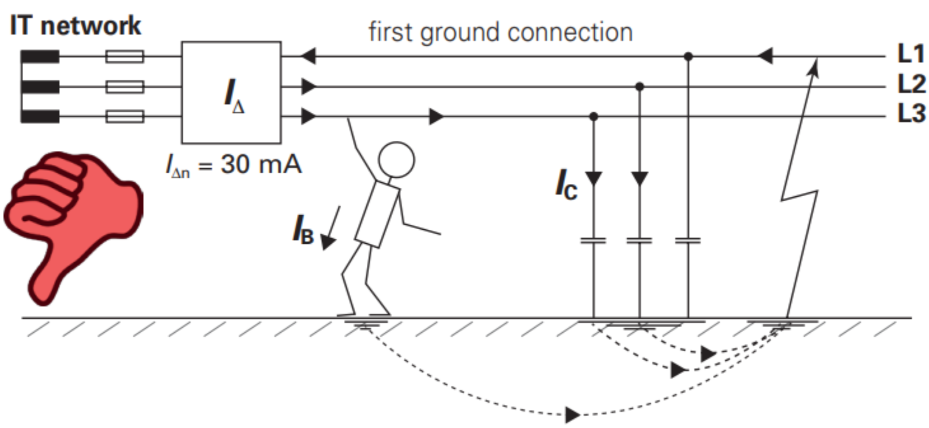


Figure 39: Inappropriate Use of Sensitive RCD in an IT Earthing System (Eaton, 2017)

2.12 Harmonics

In the alternating current (AC) system, both the voltage and current waveform will be pure sinusoidal waveform, which also means that the phase difference between the sinusoids is zero. Harmonics is a result of a non-linear load as it does not demonstrate 'linear' characteristic, which also means that voltage and current are not synchronous. The positive integer multiple of the fundamental frequency is known as the harmonics frequency of a voltage and current sinusoidal waveform. The waveform frequencies out of the harmonics frequency will form an irregular and non-repeating waveform.

Harmonics are higher frequency waveforms superimposed onto the fundamental frequency, that is the frequency of the circuit. The type, quantity and shape of the harmonics present can affect the amount of harmonic distortion applied to the fundamental wave. Harmonic distortion is present whenever the current and voltage waveforms deviate from the sinusoidal wave due to the increment in the base frequency as harmonic is the multiplication between the system's base frequency and the voltage or current.

Harmonics frequency merges with the fundamental frequency (50Hz or 60Hz) supply to create a distorted waveform for both voltage and current, where the resulting distorted waveform is also known as the complex waveform that has adverse effect on the electrical system.

2.12.1 Complex Waveform

In the alternating voltages and currents system, a pure sinusoidal waveform can be generated whenever only fundamental frequency is present in the system. In Malaysia, this fundamental frequency is set at 50 Hz. Harmonics are the multiplication between an integer and fundamental frequency. As an illustration, the fundamental frequency is designated at 50 Hz. Therefore, the 2nd harmonics would be a frequency twice that of the fundamental, which is 100 Hz. Besides, a 3rd harmonic has a frequency three times the fundamental, which is 150 Hz, a 4th at 200 Hz, a 5th at 250 Hz and so on. In other words, harmonics can be expressed as 2f, 3f, 4f, etc as harmonics are multiples of the fundamental frequency.

A phase difference between voltage and current waveform also means the current flowing through an electrical circuit is not proportional to the applied voltage. A complex waveform is the result of combining the harmonic content and fundamental waveform. Figure 40 demonstrated the formation of complex waveforms.

A complex waveform is formed whenever the fundamental waveform and the harmonic waveform is combined. The shape of the complex waveform depends on the number and amplitude of the harmonic frequencies present as well as the phase relationship between the fundamental frequency and each harmonic frequency.

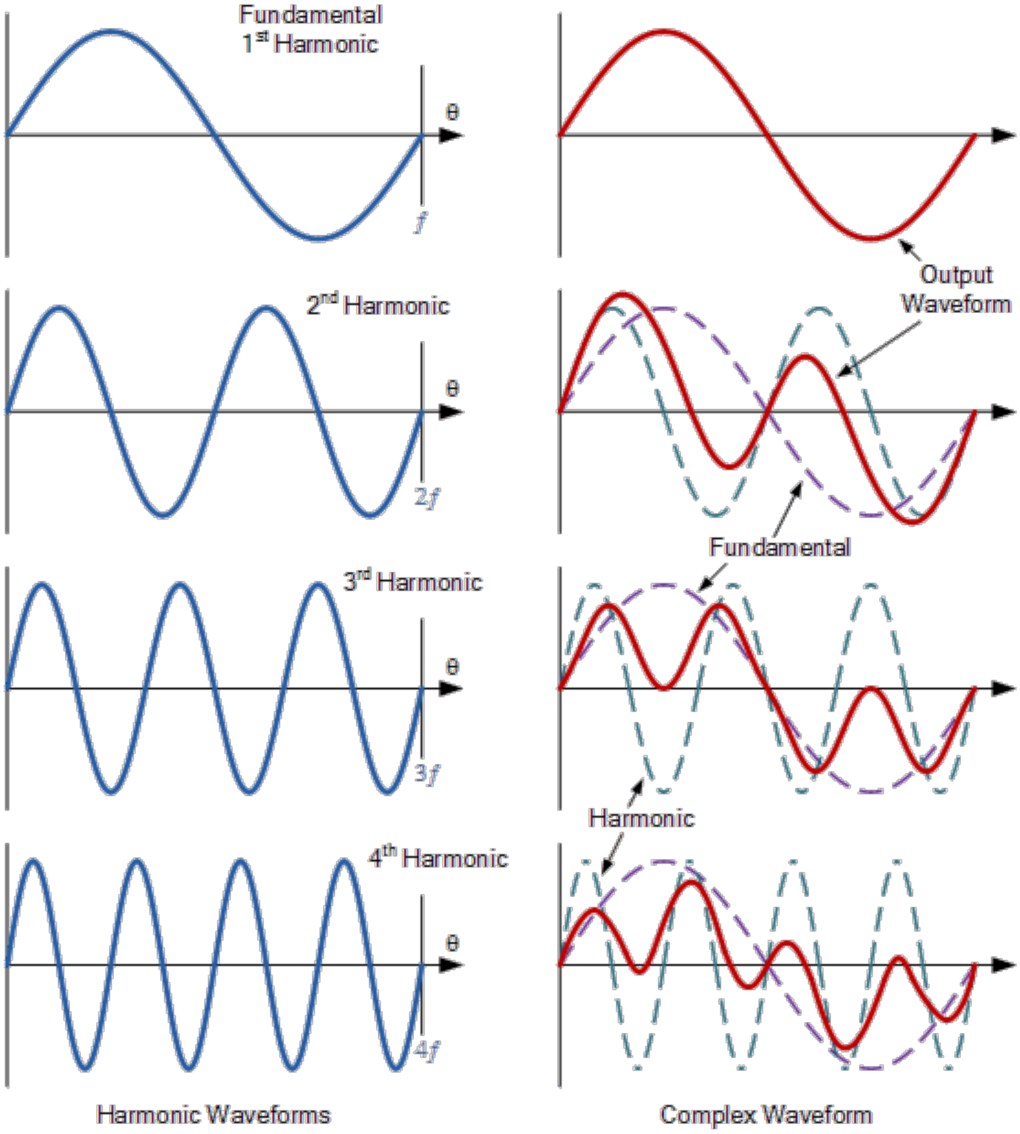


Figure 40: Complex Waveforms Due to Harmonics (Electronics Tutorials, 2022)

2.12.2 Harmonics Sequence

In a balanced 3-phase 4-wire system, harmonic sequence indicated the phasor rotating direction of the harmonic voltages and currents with respect to the fundamental waveform. There are three types of harmonic sequence, which include positive sequence harmonics, negative sequence harmonics and zero sequence harmonics.

Based on Table 10, harmonic frequencies such as 4th, 7th and 10th are classified positive sequence harmonics. Positive sequence harmonics rotates in the same direction with the fundamental waveform, which is in the forward direction. Hence, an additional waveform is added to the fundamental waveform. This will lead to undesired conditions such as overheating of conductors, power lines and transformers.

On the other hand, harmonic frequencies such as 2nd, 5th and 8th are categorized as negative sequence harmonics. The rotating direction of these harmonic frequencies is in a reverse direction, which is in the opposite direction of the fundamental waveform. This will then weaken the rotating magnetic field required by motors and reduce the amount of mechanical torque produced.

Lastly, the last harmonic sequence is identified as zero-sequence harmonics. Zero-sequence harmonics is also known as triplen harmonics. Zero sequence harmonics are multiples of third harmonics such as 3re, 6th and 9th. It only rotates between the phase and neutral or ground as well as shifted in the sequence of zero. Instead of cancelling out each other similar to positive and negative harmonic currents, the triplen harmonics add up arithmetically in the common neutral wire depending on the amplitude of current from all three phases, resulting in less efficient and overheat due to up to 3 times the amplitude of the phase current at the fundamental frequency within the neutral wire.

Table 10: Harmonic Sequencing

Name	Fund.	2nd	3rd	4th	5th	6th	7th	8th	9th
Frequency, Hz	50	100	150	200	250	300	350	400	450
Sequence	+	–	0	+	–	0	+	–	0

Table 11: Harmonic Effect (Electrical Volt, 2019)

Sequence	Rotation	Harmonic Effect
+	Forward	Excessive Heating Effect
–	Reverse	Motor Torque Problems
0	None	Adds Voltages and/or Currents in Neutral Wire causing Heating

2.12.3 Impact of Harmonics

Harmonic distortion is an undesirable phenomenon since it reduces the performance of power system equipment such as transformers and motors due to additional heat produced. These harmonic currents increase the RMS current value which will then affect the performance of protective equipment as the tripping mechanism of the protective equipment is sensitive to the RMS current. An incorrect operation of protective equipment may occur due to the high RMS current value. Further, heating issues on protective equipment such as circuit breakers or fuses take place whenever the RMS current is distorted. Thus, the fuse will act faster and melt. These harmonic currents may also lead to interference with telecommunication lines and errors in power metering.

2.12.4 Impact of Harmonic Distortion on Transformer

Harmonic distortion contributes significantly to additional losses as well as overheating effect on the transformer. Generally, a transformer is sized according to the apparent power requirements of the load. Harmonic currents may result in the transformer RMS current exceeding its rating current. This will then result in increased conductor losses. Besides, eddy current is induced inside a transformer because of the presence of harmonic components in load current. These eddy currents may affect the losses at the transformer as it flows in the windings, core as well as other conducting bodies, depending on the magnetic field of the transformer. The existence of eddy current will result in an overheating issue at the transformer, where the voltage supplied to the load will then be affected as the power quality is influenced by the power loss and overheating issue.

2.12.5 Impact of Harmonic Distortion on Motor

Harmonic voltage distortion which take places at the motor terminal is converted into harmonic fluxes within the motor. First, harmonic distortion will reduce the performance of the motor as it causes the copper and iron between the stator and rotor more difficult to be magnetized, which will then lead to hysteresis losses as well as higher eddy current is induced. These extra losses will result in an overheating issue at the motor. Overheating may degrade winding insulation, reduce the lifespan of the motor and also may cause nuisance tripping of the thermal protection system in the motor. Besides, bearing currents will be induced due to the existence of harmonic distortion at the motor. This bearing current creates a rougher surface with high friction losses, where the risk of bearing to seize increases and speeds up the lubricant breakdown along with the failure of bearings. Further, winding insulation of the motor will be degraded due to the presence of harmonics with high rates of change in voltage as it may create partial discharge arcing in the windings. Lastly, the existence of high harmonics with low power factor may diminish performance of the motor and also increase the power consumption of the motor. (Plant Engineering, 2018)

2.13 Difference between Peak Current, Inrush Current and Steady-State Current

Overcurrent is a condition where the current goes over the rated amperage capacity of the circuit or the connected electrical appliances such as motor on the circuit. Possible causes for overcurrent included overload, short circuit, a ground fault as well as an arc fault.

An overcurrent condition can be occurred in a motor circuit whenever the current flowing within the normal circuit path is exceeded the motor's normal Full Load Amps (FLA). (Cooper Bussmann, 2005) A short circuit is an overcurrent which is extremely higher than the normal full load current of the circuit.

Figure 41 shows the difference between an inrush, peak and steady state current of a circuit. Peak current is defined as the maximum value of current obtained by a waveform either in a positive or negative region, meanwhile steady-state current is reached when di/dt = 0, which also means that the current remains constant with respect to time. Further, inrush current is defined as the maximal instantaneous input current drawn by an electrical device which is higher than the rated value of the circuit that occurs instantaneously when the device is turned on.

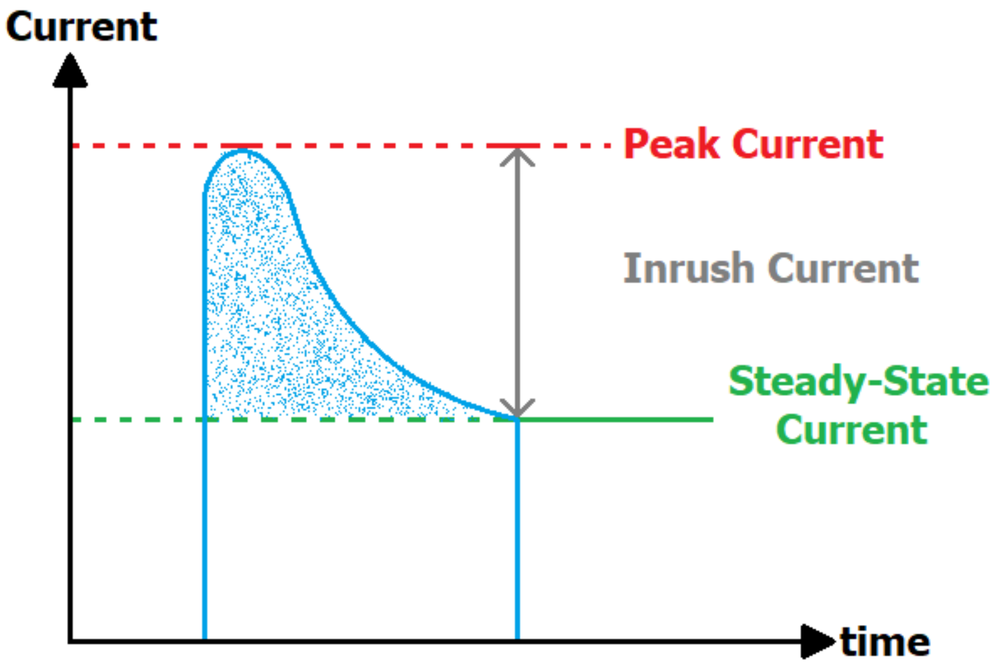


Figure 41: Difference Between Peak Current, Inrush Current and Steady-State Current (Circuit Digest, 2019)

2.13.1 Inrush Current

Inrush current is also known as 'switch-on surge', 'input surge current' along with 'locked rotor current'. (DCCWiki, 2022) This current is referred to as 'switch-on surge' in view of the fact that an excessive current is drawn, which is often in excess of 20 times the normal fill current required during the initial half cycle the motor begins to switch on. After the first half- cycle motor begins to energize, the starting current will be reduced to 4 to 8 times the normal current and then the current level will gradually reduce to steady state current level on any occasion the motor reaches running speed. (Cooper Bussmann, 2005) Inrush current will only exist for a short time of span, which is about a few cycles of the input power until the motor returns to a normal running state. Therefore, the protection system becomes more complicated when high inrush current as the protection system must respond quickly to overload or short circuit faults but must not interrupt the circuit during the flowing of harmless level inrush current.

2.13.2 Inrush Current in Transformer

Transformer inrush current is defined as a spike in current that occurs when the transformer is initially switched ON. This spike can be up to 10 times higher than normal current which can harm the magnetic core and result in unwanted switching of the transformer circuit breaker. (Circuit Digest, 2019) Figure 42 shows a transformer draws inrush current that higher than the saturation current affecting the magnetic property of the core. Based on Figure 42, the inrush current magnitude be determined by the point of AC wave at which the transformer is switched ON at no load condition, where there is no inrush current if AC voltage is at its peak. On the contrary, if the AC voltage is passing through zero, the magnitude of the inrush current will be high which exceeds the saturation current.

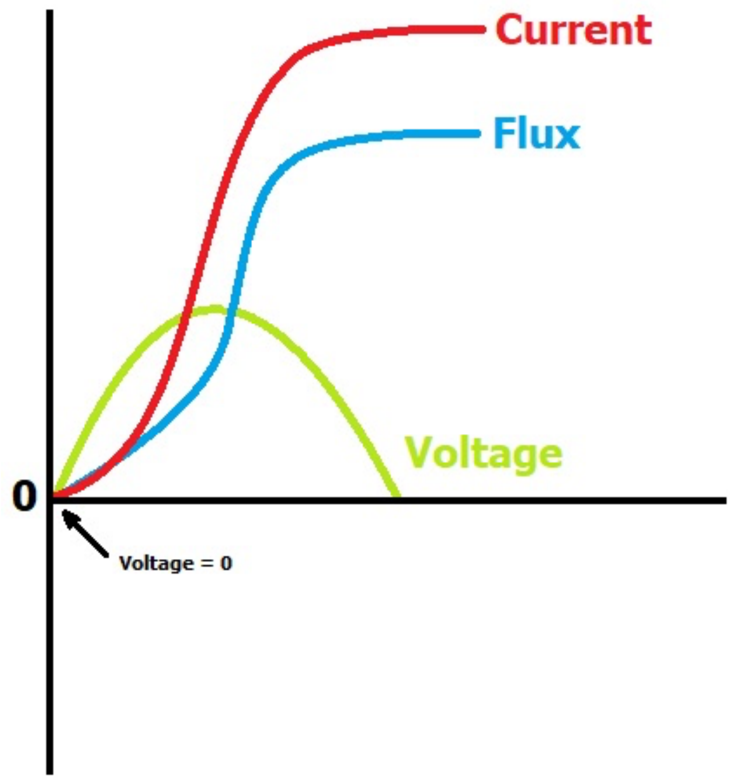


Figure 42: A transformer draws inrush current that higher than the saturation current affecting the magnetic property of the core (Circuit Digest, 2019)

This spike of current causes distortion to the harmonic voltage and current waveform which in turn cause problems such as interference on the operation of circuits and harm to the transformer's magnetic core. The inrush current requires proper management by the use of SPD to avoid failure of circuit components, gradual degradation of the transformer or even damage. (Ametherm, 2015) Therefore, SPD is necessary within the transformer.

2.13.3 Inrush Current in Motors

Similar to the transformers, induction motors do not have a continuous magnetic path. Due to the air gap between the rotor and the stator, induction motor experience high reluctance. Henve, its high reluctance needs high magnetizing current to produce the rotating magnetic field at starting. High initial current is required at the startup to begin the rotation of a de-energized motor shaft as large amounts of current are required to charge the capacitors or inductors of the electrical devices such as the transformer. (Stan Turkel, 2019) This process is similar to the overloaded condition of a motor as extreme current is drawn for the moment in order to overcome an idle motor shaft.

Figure 43 shows the full voltage starting characteristics of the motor. According to the diagram, both initial starting current and starting torque are very high. The high starting current or also known as the inrush current, can cause damage to the electrical system while the initial high torque can affect the mechanical system of the motor due to damage to insulation, fatigue damage to rotor and stress on the complete machine and transmission system which ultimately reduces the lifespan of the machine. To avoid this potential damage to the system, a soft start power supply circuit or soft starter is used where the reason being 75% reduction of the motor torque when initial voltage value reduces by 50%. (Faraday Predictive, 2020) An SPD is required to protect the motor from inrush current by clamping the transient overvoltage to its protected voltage level. The motor will still work if the SPD clamping voltage level is higher than the voltage required by the motor. However, the motor cannot be started if the SPD clamping voltage level is lower than the voltage required by the motor.

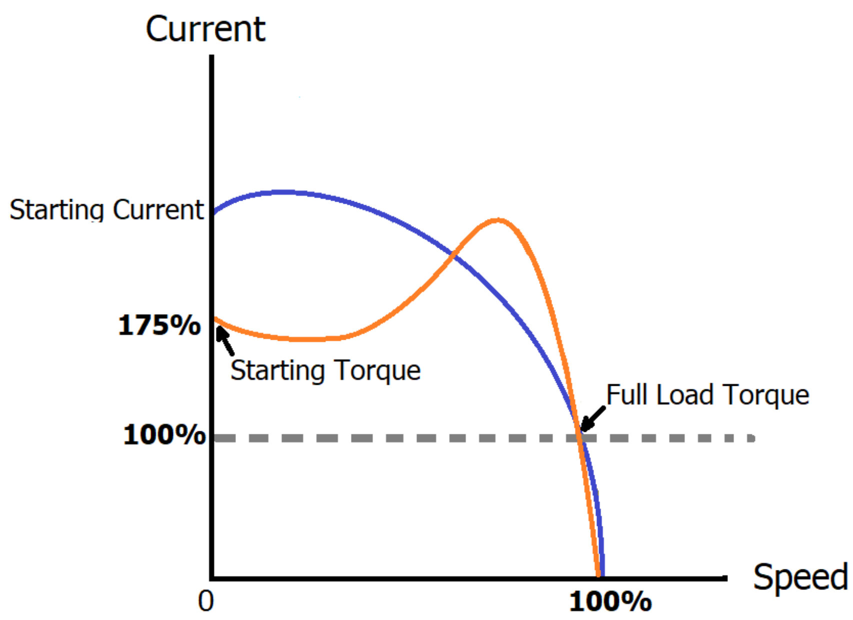


Figure 43: Typical Induction Motor Current and Torque vs Speed (Faraday Predictive, 2020)

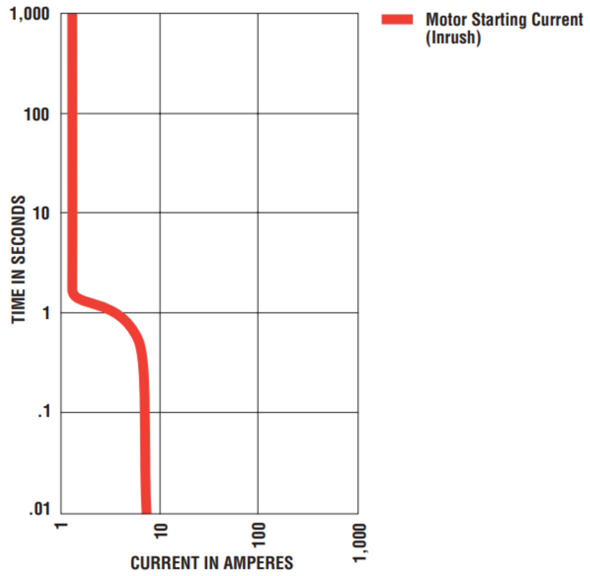


Figure 44: Typical Motor Starting Characteristic (Jade Learning, 2019)

Circuit breaker works based on its response curve. Circuit Breaker will not protect an electrical system against inrush current due to inrush current only existing for an extremely short duration and it often falls outside the response curve of the circuit breaker. (HyTEPS, 2022) Therefore, circuit breakers will not trip even if the inrush current level exceeds the rating of the circuit breaker. An electrical equipment could bever be started if a circuit breaker provides protection against inrush current. However, inrush current is a silent killer just like harmonics for electrical equipment. High inrush currents can increase the risk of ground faults and installation circuit breaker failure as well as voltage dips, which in turn may also result in failure and excessive wear of electrical equipment. Hence, an SPD is utilized with the purpose to protect the electrical equipment against input surge current.

2.13.4 Protection of Drives

A drive system may be damaged by voltage surge. Therefore, a surge protection device (SPD) can be applied to minimize the damage to the drive system. To explain the application of SPDs to a drive system, refer to the block diagram of a typical drive layout as shown in Figure 45. The incoming power is usually in delta connection while the incoming voltage is 480V. The incoming power is normally stepped down to a lower voltage to supply the control circuit as it consists of sensitive electronics.

External events such as lightning and switching surges created at the utility side may propagate to the downstream of the electrical system. Therefore, a parallel SPD is recommended located at the drive input in order to protect the drive system from surge damage due to events propagated on the electrical system from upstream sources.

Secondly, protecting the control circuit is also an essential step in protecting the drive system as the control circuit consists of sensitive elements that can be damaged by surges from external sources. Based on Figure 45, a series connected SPD should be located at the control circuit part as this circuit is isolated by a step-down transformer.

Thirdly, a parallel SPD should be installed at the drive output in a condition of the length between the drive and motor, which is labeled “L” in Figure 45, exceeds 15 meters. This is because reflected waves may require a long distance to occur as the signal from drive output reaches the motor and is then reflected back and forth between the drive and the motor. This reflected wave may cause the formation of voltage piling as the reflected voltage adds to the nominal voltage. The SPD will reduce the peak voltage of the reflected waves at the drive output.

In other hand, a parallel SPD should also be installed whenever connection is routed along an external wall or outdoors. One reason for protecting at the drive output when the connection between the drive and the motor along a path that is exposed to the environment or outdoors is due to the external surge such as lightning. Although the motor input is protected, surges can still cause failure to the drive. Therefore, SPD is needed to reduce the damage to the drive system.

A protection system must also be applied at the motor input part to avoid surge damage due to events propagated from the drive output to the motor input. A SPD is installed at the motor input part in order to extend the life of the motor by preventing damage or degradation to the windings as well as the bearings of the motor due to surges.

In conclusion, an internal SPD must be applied in a drive system in order to protect the drive system from inrush current or surges propagated on the electrical system from upstream sources.

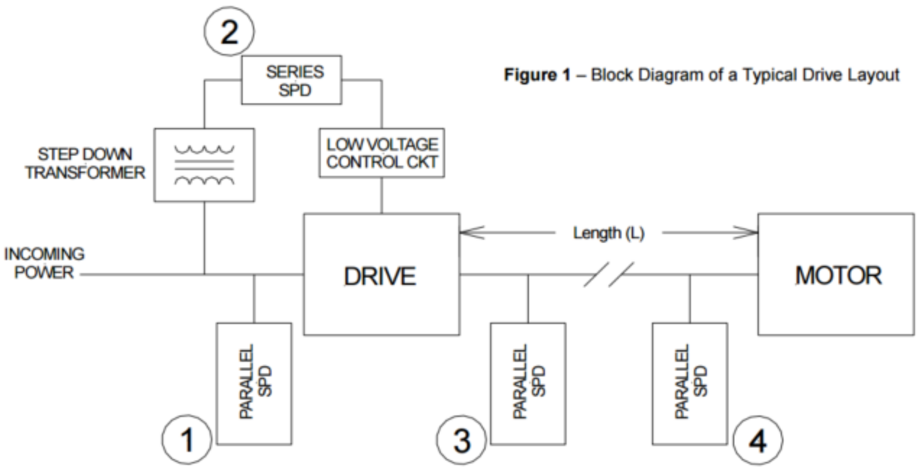


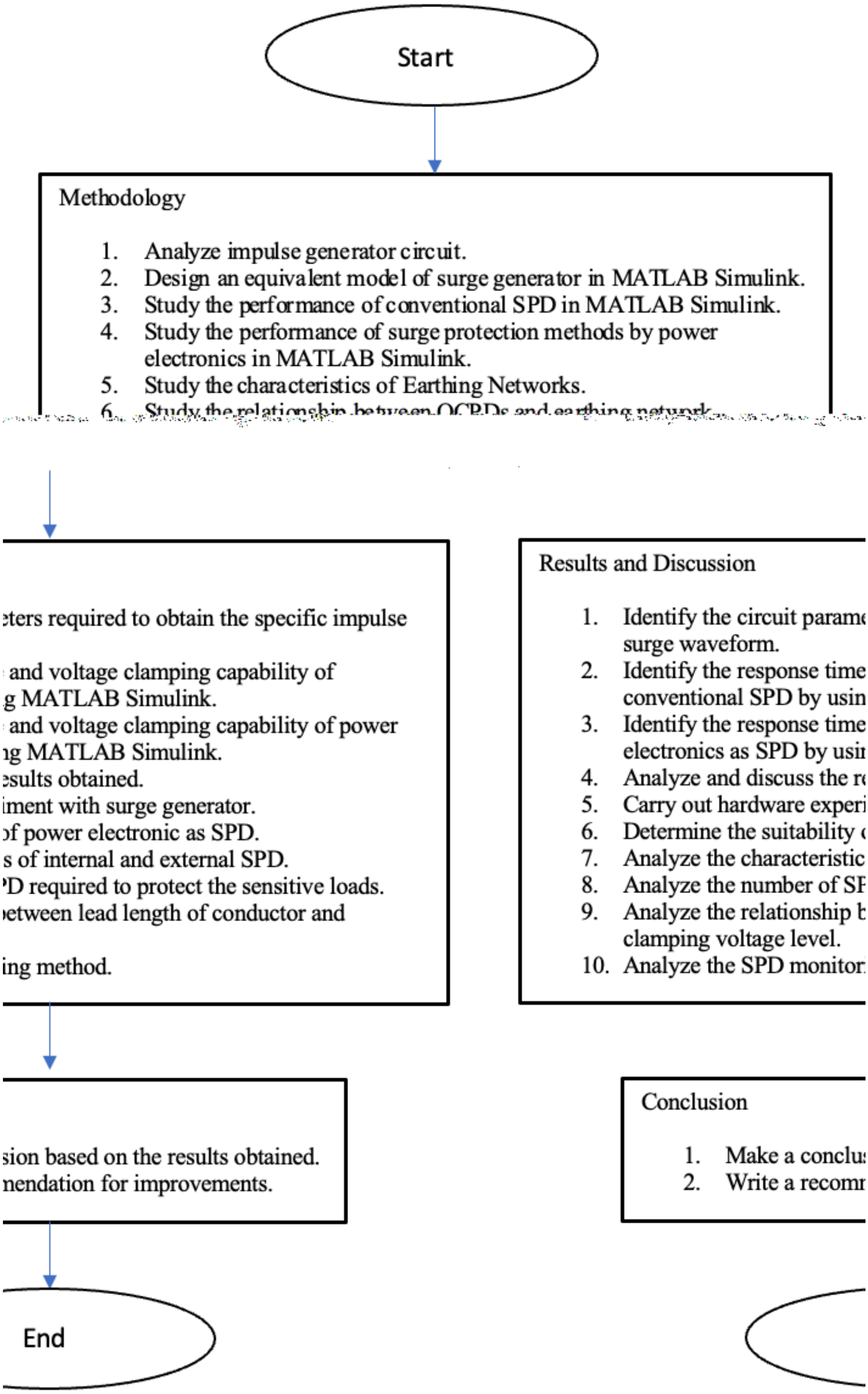
Figure 45: Block Diagram of Typical Drive Layout
(Ronald W. Hotchkiss, 2022)

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

In this project, the equivalent model of surge generator was designed, and MATLAB Simulink was chosen as the simulation tool. The formula is derived with the purpose to determine the capacitors, resistors and voltage level of the surge generator circuit constructed. Moreover, the weakness of conventional SPDs and the behaviour of power electronic devices such as MOSFET and IGBT were also studied in this project. The project flow is as shown below:


Start
Methodology
1. Analyze impulse generator circuit.
2. Design an equivalent model of surge generator in MATLAB Simulink.
3. Study the performance of conventional SPD in MATLAB Simulink.
4. Study the performance of surge protection methods by power electronics in MATLAB Simulink.
5. Study the characteristics of Earthing Networks.
eters required to obtain the specific impulse
and voltage clamping capability of
g MATLAB Simulink.
and voltage clamping capability of power
ng MATLAB Simulink.
esults obtained.
iment with surge generator.
of power electronic as SPD.
s of internal and external SPD.
D required to protect the sensitive loads.
between lead length of conductor and
ing method.
Results and Discussion
1. Identify the circuit param
surge waveform.
2. Identify the response time
conventional SPD by usin
3. Identify the response time
electronics as SPD by usi
4. Analyze and discuss the r
5. Carry out hardware experi
6. Determine the suitability
7. Analyze the characteristic
8. Analyze the number of SP
9. Analyze the relationship b
clamping voltage level.
10. Analyze the SPD monitor
sion based on the results obtained.
nendation for improvements.
Conclusion
1. Make a conclu
2. Write a recomm
End

3.2 Analysis of Impulse Generator Circuit

The lightning impulse waveform can be expressed in a double exponential waveform equation. These double exponential waveform equations can be acquired by constructing a variety combination of RCL or RC circuits. Figure 46 shows four various circuits that generate impulse waves. The inductance in the combination of series RCL circuit as shown in circuit (a) will trigger oscillations in the front and tail parts of an impulse waveform. Thus, circuit (a) is only limited to model generator and it is not chosen for this simulation study since it is inflexible. Besides that, the front and tail time of the waveform are adjustable where the front time (β) can be adjusted by controlling the resistance value while the tail time (α) can be adjusted by controlling the inductance value.

On the other hand, circuit (b), circuit (c) and circuit (d) are normally used for commercial generators. However, normally circuit (b) and (c) are used to generate the impulse wave as their front and tail parts can be independently adjusted by controlling R_1 and R_2 separately. C_2 was formed due to the test objects are mainly capacitive in nature. Moreover, circuit (d) provides more flexibility as compared to the other circuits as it is the combination of circuit (b) and (c) where the resistance R_1 is positioned at the left and the right side of R_2.

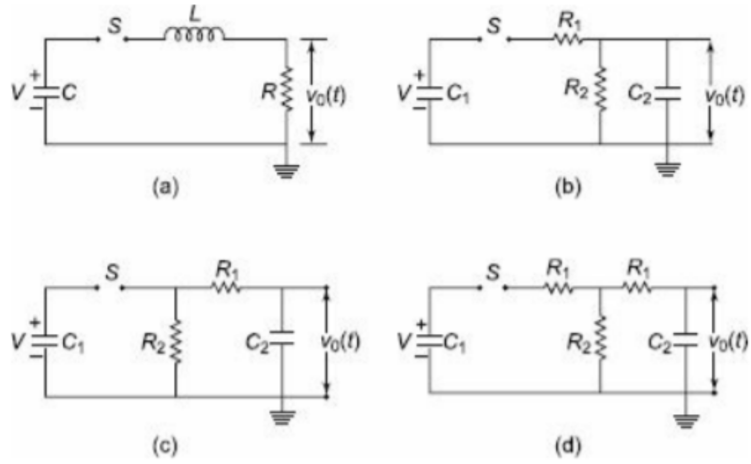


Figure 46: Circuits for producing impulse waves

3.2.1 Calculation of Impulse Generator Circuit

The formula for circuit (b) will be discussed in first part of this section.

By implement Laplace transform, the impedance of circuit:

$$Z(s) = R_1 + \frac{1}{C_1 s} + \frac{R_2}{R_2 C_2 s+1}$$

$$Z(s) = \frac{R_1 R_2 C_1 C_2 s^2 + (R_1 C_1 + R_2 C_2 + R_2 C_1)s + 1}{C_1 s\,(R_2 C_2 s+1)} \quad (3.1)$$

The current of the circuit:

$$I(s) = \frac{V_{in}}{sZ(s)} \quad (3.2)$$

Substitute equation 3.1 into equation 3.2,

Hence,

$$I(s) = \left(\frac{V_{in}}{s}\right)\left[\frac{C_1 s(R_2 C_2 s+1)}{R_1 R_2 C_1 C_2 s^2 + (R_1 C_1 + R_2 C_2 + R_2 C_1)s + 1}\right] \quad (3.3)$$

Output voltage of the circuit:

$$v(s) = I(s)\left[\frac{R_2}{sR_2 C_2+1}\right] \quad (3.4)$$

Substitute equation 3.3 into equation 3.4:

$$v(s) = \frac{V_{in} R_2 C_1}{R_1 R_2 C_1 C_2 s^2 + (R_1 C_1 + R_2 C_2 + R_2 C_1)s + 1} \quad (3.5)$$

Hence, the output voltage can be further simplified into

$$v(s) = \left[\frac{V_{in}R_2C_1}{R_1R_2C_1C_2}\right]\left[\frac{1}{s^2 + as + b}\right]$$

$$v(s) = \left[\frac{V_{in}}{R_1C_2}\right]\left(\frac{1}{(s + \alpha - \beta)(s + \alpha + \beta)}\right) \quad (3.6)$$

By comparing equation 3.5 and equation 3.6,

$$\mathrm{a} = \frac{1}{R_2C_2} + \frac{1}{R_1C_1} + \frac{1}{R_1C_2}$$

$$\mathrm{b} = \frac{1}{R_1C_1R_2C_2}$$

$$\alpha = \left(\frac{a}{2}\right)$$

$$\beta = \sqrt{\left(\frac{a}{2}\right)^2 - b}$$

By using Inverse Laplace Transform, output voltage of the circuit:

$$V(t) = \left(\frac{V_{in}}{2\beta R_1C_2}\right)\left[e^{-(\alpha - \beta)t} - e^{-(\alpha + \beta)t}\right] \quad (3.7)$$

Output voltage of the circuit can also be written as:

$$V(t) = \left[\frac{V_{in}}{2\beta R_1C_2}\right]\{e^{-\alpha_1 t_f} - e^{-\alpha_2 t_f}\} \quad (3.8)$$

Vin is input voltage source whereas V(t) is output voltage magnitude at a specific time, t

By comparing equation 3.7 and equation 3.8,

$$\alpha_1 = \alpha - \beta = \left(\frac{a}{2}\right) - \sqrt{\left(\frac{a}{2}\right)^2 - b}$$

$$\alpha_2 = \alpha + \beta = \left(\frac{a}{2}\right) + \sqrt{\left(\frac{a}{2}\right)^2 - b}$$

Front time of the waveform, t_f:

$$t_f = \left(\frac{1}{2\beta}\right) \ln\left[\frac{\alpha + \beta}{\alpha - \beta}\right]$$

Tail time of the waveform, t_t:

$$t_t = \mathrm{K}\ t_f$$

Hence,

$$\mathrm{K} - 1 = \frac{0.7}{(\alpha - \beta)t_f}$$

Besides that, the formula for circuit (c) are analysed as below:

Output voltage of circuit (c):

$$v(t) = \left(\frac{V_o}{2\beta R_1 C_2}\right)\left[e^{-(\alpha - \beta)t} - e^{-(\alpha + \beta)t}\right]$$

Output voltage of circuit (c) can also be written as:

$$v(t) = \left[\frac{V_o}{2\beta R_1 C_2}\right]\{e^{-\alpha_1 t_f} - e^{-\alpha_2 t_f}\}$$

where

$$\mathrm{a} = \frac{1}{R_1 C_1} + \frac{1}{R_2 C_1} + \frac{1}{R_1 C_2}$$

$$\mathrm{b} = \frac{1}{R_1 C_1 R_2 C_2}$$

$$\alpha = \left(\frac{a}{2}\right)$$

$$\beta = \sqrt{\left(\frac{a}{2}\right)^2 - b}$$

$$\alpha_1 = \alpha - \beta = \left(\frac{a}{2}\right) - \sqrt{\left(\frac{a}{2}\right)^2 - b}$$

$$\alpha_2 = \alpha + \beta = \left(\frac{a}{2}\right) + \sqrt{\left(\frac{a}{2}\right)^2 - b}$$

Front time of the waveform, t_f:

$$t_f = \left(\frac{1}{2\beta}\right) \ln\left[\frac{\alpha + \beta}{\alpha - \beta}\right]$$

Tail time of the waveform, t_t:

$$t_t = \mathrm{K}\, t_f$$

Hence,

$$\mathrm{K} - 1 = \frac{0.7}{(\alpha - \beta)t_f}$$

Nevertheless, circuit (c) was chosen as it is the most suitable circuit in order to analyse the lightning overvoltage surge. The reason being that some of the voltage discharged from capacitor C1 in circuit (b) will drop at resistor R1 and therefore result in a lower voltage drop at resistor R2. However, in circuit (c), there is no resistor in between capacitor C1 and resistor R2 and therefore, we will be able to obtain the voltage value of similar to voltage discharge by capacitor C1 drop at resistor R2. Therefore, circuit (c) is the better choice.

3.3 Combined Surge Generator Model

In this project, MATLAB SIMULINK was used as the simulation tool in order to study the performance of SPDs. A surge generator model as shown in Figure 47 was constructed and simulated by using MATLAB SIMULINK. An indirect voltage surge waveform (1.2/50μs), short circuit current surge waveform (8/20μs) and direct voltage surge waveform (10/350 μs) are simulated from this circuit. Besides that, power electronics such as MOSFET and IGBT are involved in the surge generator model constructed with the purpose to improve the performance of conventional SPD. The behaviour of the surge protection method by power electronics is studied with the surge generator model in Figure 48.

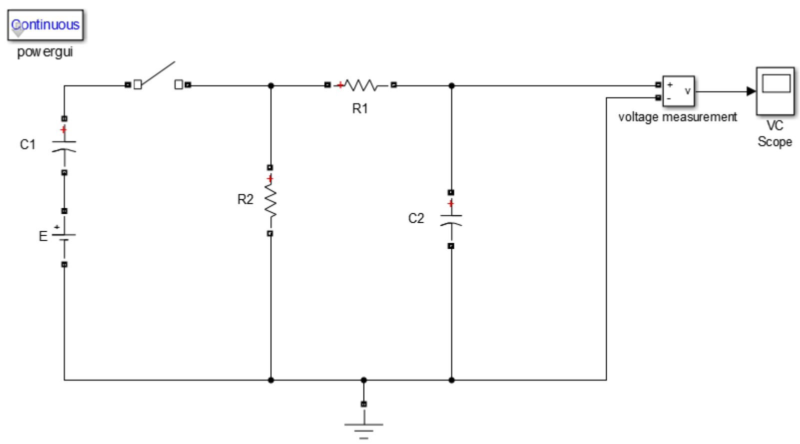


Figure 47: Combined Surge Generator Model

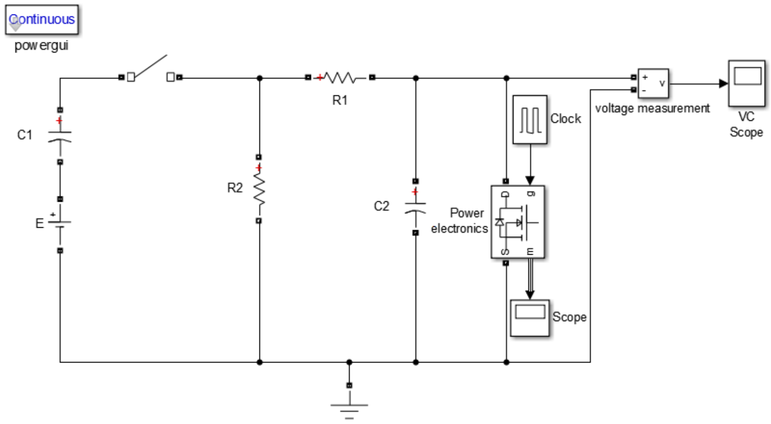


Figure 48: Combined Surge Generator Model with power electronics

3.4 Surge Protection Hardware Test Waveform

Figure 49 shows the setup of surge protection hardware test. A surge generator with surge amplitude of maximum 6kV and a current transformer with ratio of 1000:1 was applied in this experiment. Besides that, the differential probe ratio was adjusted to 1000:1 throughout this experiment. The function of test chamber in this experiment is to fix the components and to isolate the explosion area if the component is burnt.

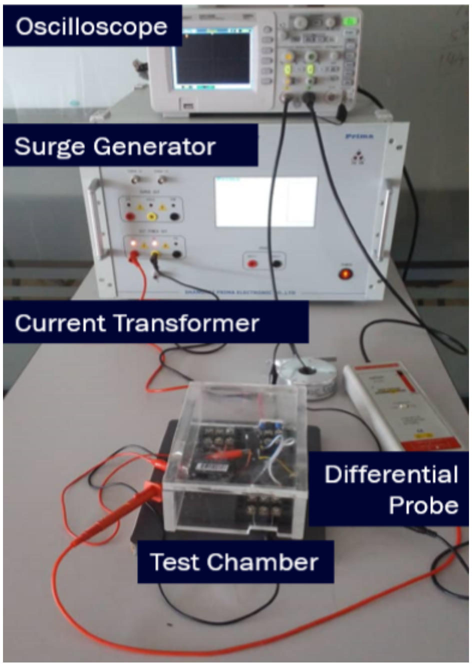


Figure 49: setup of surge protection hardware test

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, we study the behaviour of conventional SPDs and power electronics as SPD. We utilise MATLAB Simulink to build a surge generator circuit to simulate the behaviour of different components. We capture the waveform with scope and time recorded with cursor. To ensure the safety of this test, we construct a test chamber to conduct the hardware test. In this test, we studied the test waveform, effect of surge, clamping voltage of SPDs, and the response time of SPDs.

4.2 Software Simulation

A surge generator model was constructed and simulated by MATLAB SIMULINK. The surge waveforms generated is similar to the IEC 61000-4-5 Standard test waveforms.

4.3 Calculation and Simulation Results

Standard Lightning Impulse Generator circuit is constructed and simulated in MATLAB SIMULINK. The circuits parameters are calculated and tabulated in Table 1.

4.3.1 Generate 1.2/50 μs Standard Lightning Impulse Generator Circuit Model

In order to get desired peak impulse voltage level (6 kV), the capacitance values were assumed where $C_1 = 0.125\ \mu F$ while $C_2 = 1\ nF$.

$$R_2 = \frac{1}{C_1(\alpha - \beta)}$$

$$K - 1 = \frac{0.7}{(\alpha - \beta)t_f} \quad (4.1)$$

$$t_t = \mathrm{k}t_f \quad (4.2)$$

Substitute equation 4.3.2 into equation 4.3.1,

$$\frac{t_t}{t_f} - 1 = \frac{0.7}{(\alpha - \beta)t_f}$$

Since $t_f = 1.2\ \mu s$ and $t_t = 50\ \mu s$,

$$\frac{50\ \mu s}{1.2\ \mu s} - 1 = \frac{0.7}{(\alpha - \beta)\ (1.2\ \mu s)}$$

$$40.6667 = \frac{0.7}{(\alpha - \beta)\ (1.2 \times 10^{-6})}$$

$$4.88 \times 10^{-5}\ (\alpha - \beta) = 0.7$$

$$\alpha - \beta = \frac{0.7}{4.88 \times 10^{-5}} = 14344.2623$$

Therefore, $R_2 = \frac{1}{0.125\ \mu F(14344.2623)} = 557.7143\ \Omega$

$$t_f = \left(\frac{1}{2\beta}\right)\ln\left[\frac{\alpha + \beta}{\alpha - \beta}\right]$$

$$1.2 \times 10^{-6} = \left(\frac{1}{2\beta}\right)\ln\left[\frac{\alpha + \beta}{14344.2623}\right] \quad (4.3)$$

$$1.2 \times 10^{-6} = \left(\frac{1}{2\beta}\right)\ln\left[\frac{14344.2623 + 2\beta}{14344.2623}\right] \quad (4.4)$$

$$\beta = 2428185.9290$$

By comparing equation 4.1.3 and equation 4.1.4,

$$\alpha + \beta = 14344.2623 + 2\beta$$

$$\alpha + \beta = 14344.2623 + 2(2428185.9290)$$

$$\alpha + \beta = 4870716.1200$$

$$R_1 = \frac{1}{C_1(\alpha + \beta)} + \frac{1}{C_2(\alpha + \beta)}$$

$$R_1 = \frac{1}{(0.125 \times 10^{-6})(4870716.1200)} + \frac{1}{(1 \times 10^{-9})(4870716.1200)}$$

$$R_1 = 206.9511\ \Omega$$

Find discharged voltage (V_{in}) by desired $V(t)$ is 6 kV:

$$V(t) = \left(\frac{V_{in}}{2\beta R_1 C_2}\right)\left[e^{-(\alpha-\beta)t_f} - e^{-(\alpha+\beta)t_f}\right]$$

$$V_{in} = \left[\frac{V(t)(2\beta R_1 C_2)}{e^{-(\alpha-\beta)t_f} - e^{-(\alpha+\beta)t_f}}\right]$$

$$V_{in} = \left[\frac{(6\times10^3)(2)(2428185.9290)(206.9511)(1\times10^{-9})}{e^{-(14344.2623)(1.2\times10^{-6})} - e^{-(4870716.1200)(1.2\times10^{-6})}}\right]$$

$$V_{in} = 6153\ V$$

The parameter used for $1.2/50\ \mu s$ impulse waveform:

Table 12: Circuits parameters used for $1.2/50\ \mu s$ impulse waveform

(Peak voltage at 6 kV)

R_1	$206.9511\ \Omega$
R_2	$557.7143\ \Omega$
C_1	$0.125\ \mu F$
C_2	$1\ nF$
V_{in}	$6153\ V$

The value of R_1, R_2, C_1, C_2 and V_{in} for peak voltage at 6 kV are calculated and tabulated in Table 12. A $1.2/50\ \mu s$ indirect voltage surge waveform can be generated by the generator circuit model with the parameter value calculated.

Figure 50 shows the standard lightning impulse generator circuit model with circuit parameters calculated whereas Figure 51 and Figure 52 show the simulation result obtained for $1.2/50\ \mu s$ voltage surge.

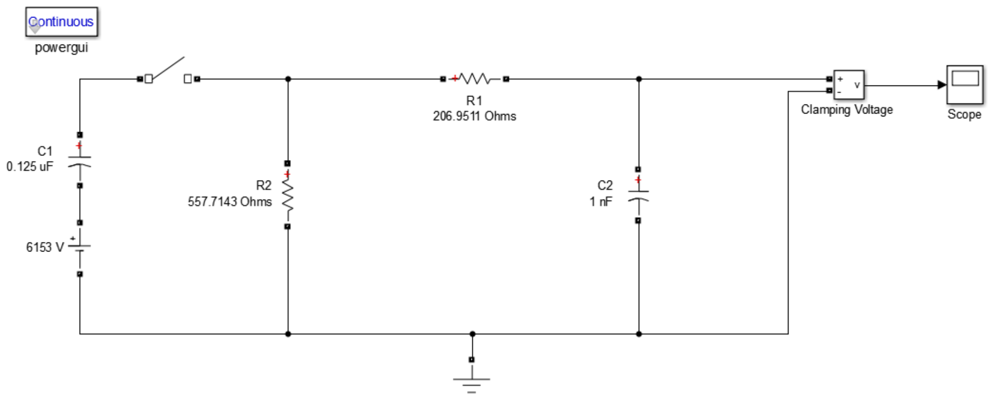


Figure 50: Surge Generator Equivalent Circuit for 1.2/50 µs voltage surge waveform

(Peak voltage at 6kV)

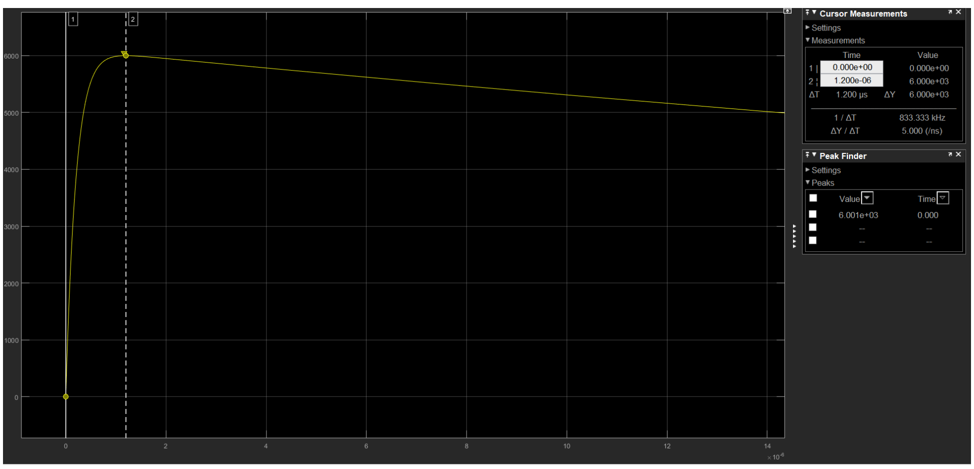


Figure 51: Front time of 1.2/50 µs voltage surge waveform for $V(t) = 6kV$

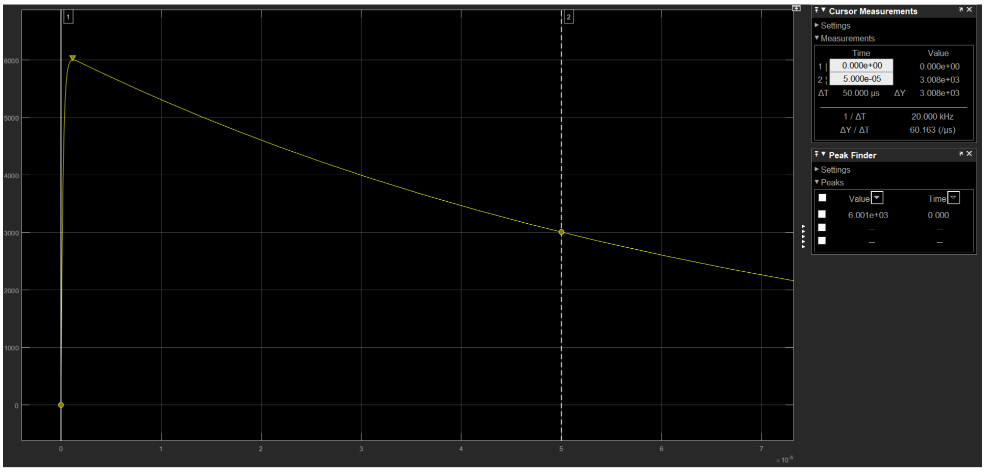


Figure 52: Tail time of 1.2/50 μs voltage surge waveform for $V(t) = 6kV$

Find discharged voltage (V_{in}) by desired $V(t)$ is 1 kV:

$$V(t) = \left(\frac{V_{in}}{2\beta R_1 C_2}\right)\left[e^{-(\alpha-\beta)t_f} - e^{-(\alpha+\beta)t_f}\right]$$

$$V_{in} = \left[\frac{V(t)(2\beta R_1 C_2)}{e^{-(\alpha-\beta)t_f} - e^{-(\alpha+\beta)t_f}}\right]$$

$$V_{in} = \left[\frac{(1\times 10^3)(2)(2428185.9290)(206.9511)(1\times 10^{-9})}{e^{-(14344.2623)(1.2\times 10^{-6})} - e^{-(4870716.1200)(1.2\times 10^{-6})}}\right]$$

$$V_{in} = 1026\,V$$

The parameter used for $1.2/50\ \mu s$ impulse waveform:

Table 13: Circuits parameters used for $1.2/50\ \mu s$ impulse waveform

(Peak voltage at 1 kV)

R_1	$206.9511\ \Omega$
R_2	$557.7143\ \Omega$
C_1	$0.125\ \mu F$
C_2	$1\ nF$
V_{in}	$1026\ V$

According to Table 13, the calculated input voltage (V_{in}) is 1026 V and 6153 V for output peak voltage 1 kV and 6 kV respectively. Figure 53 shows the surge generator equivalent circuit for 1.2/50 μs voltage surge waveform for peak output voltage at 1 kV. After injecting the parameter value calculated, simulation results are as shown in Figure 54 and Figure 55. Based on the simulation results obtained, the front time and tail time of 1.2/50 µs voltage surge waveform for $V(t) = 6\ kV$ and $V(t) = 1\ kV$ are similar. However, the peak voltage of both waveforms is different.

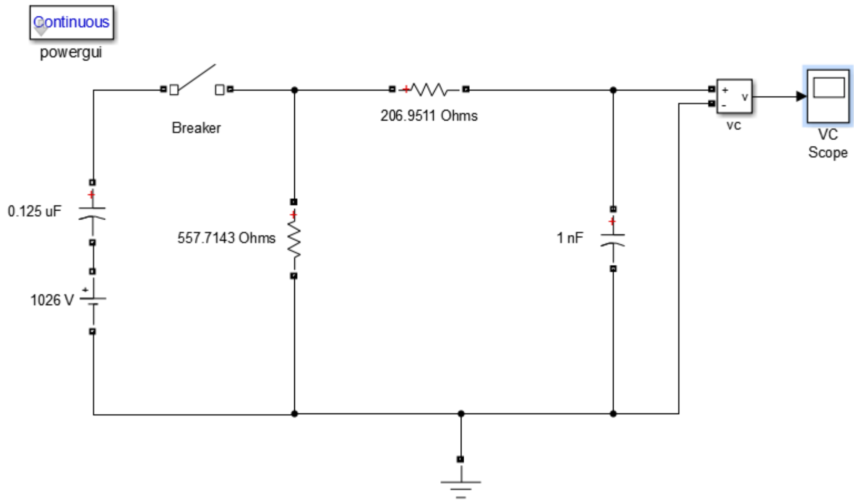


Figure 53: Surge Generator Equivalent Circuit for 1.2/50 µs voltage surge waveform (Peak voltage at 1 kV)

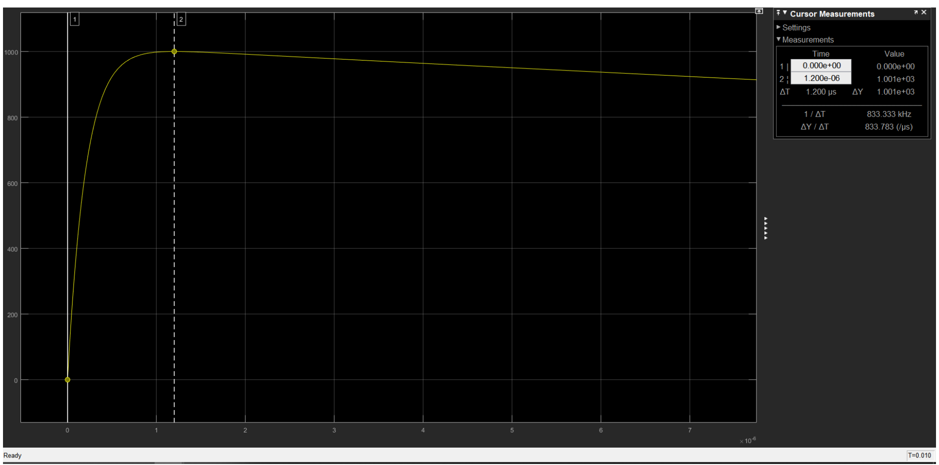


Figure 54: Front time of 1.2/50 µs voltage surge waveform for $V(t) = 1\ kV$

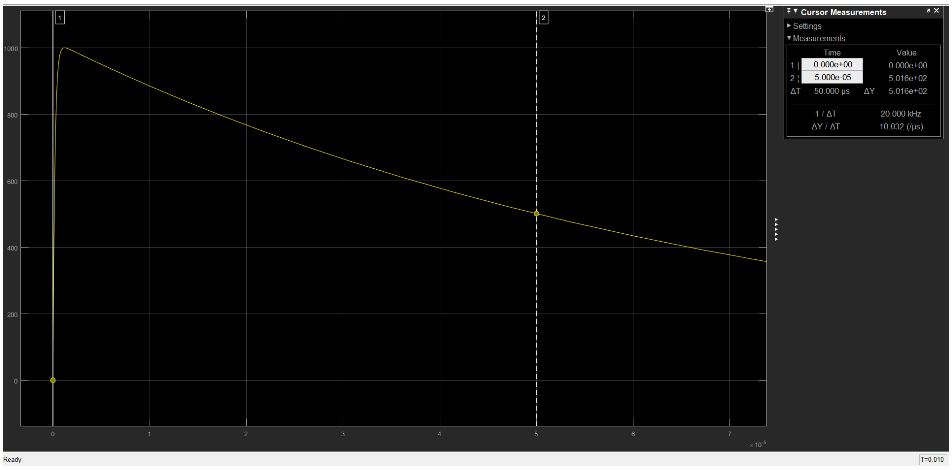


Figure 55: Tail time of 1.2/50 µs voltage surge waveform for $V(t) = 1\ kV$

4.3.2 Generate 8/20 µs Standard Lightning Impulse Generator Circuit Model

An 8/20 µs lightning impulse waveform can be generated by repeating the calculation with front time of 8 µs and tail time of 20 µs.

The parameter used for $8/20\ \mu s$ impulse waveform:

Table 14: Circuits parameters used for $8/20\ \mu s$ impulse waveform (Peak voltage at 6 kV)

R_1	$4390.0777\ \Omega$
R_2	$137.1429\ \Omega$
C_1	$0.125\ \mu F$
C_2	$1\ nF$
V_{in}	$9645\ V$

Table 14 shows the calculated value of R_1, R_2, C_1, C_2 and V_{in}. By substituting the circuit parameter calculated into the surge generator equivalent circuit model that was constructed and simulated in MATLAB SIMULINK as shown in Figure 56. The simulation result obtained for $8/20\ \mu s$ voltage surge were as shown in Figure 57 and Figure 58.

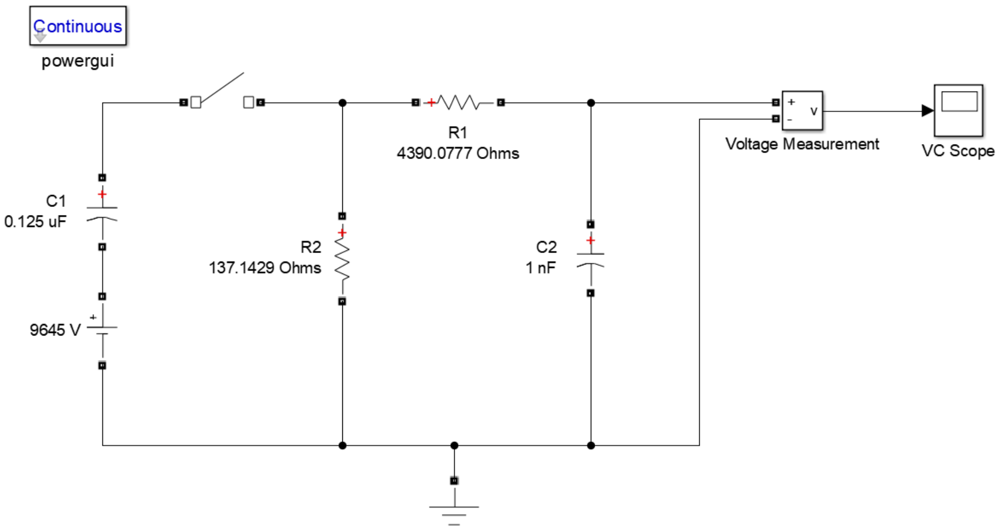


Figure 56: Surge Generator Equivalent Circuit for 8/20 µs current surge waveform

(Peak voltage at 6 kV)

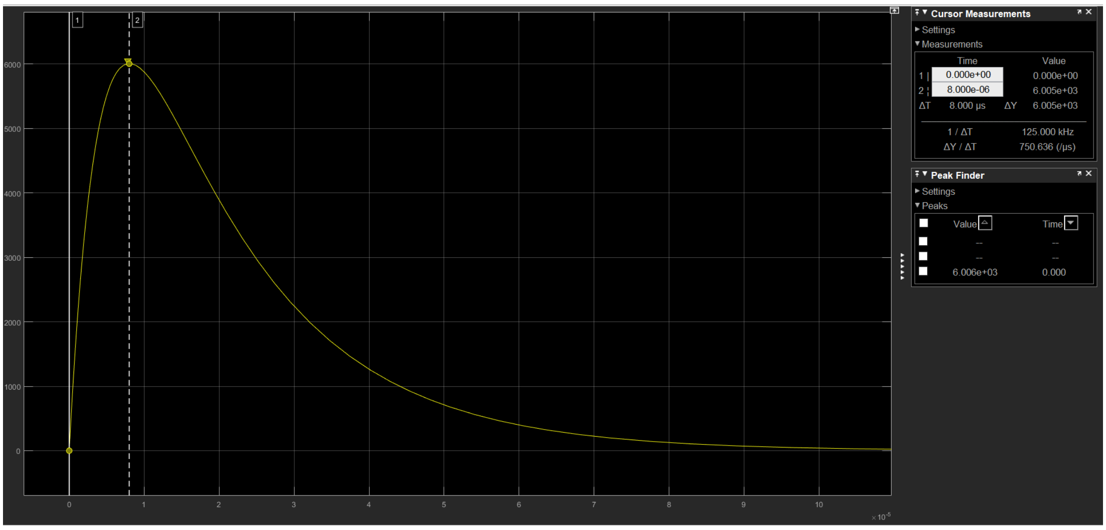


Figure 57: Front time of 8/20 µs current surge waveform for $V(t) = 6\ kV$

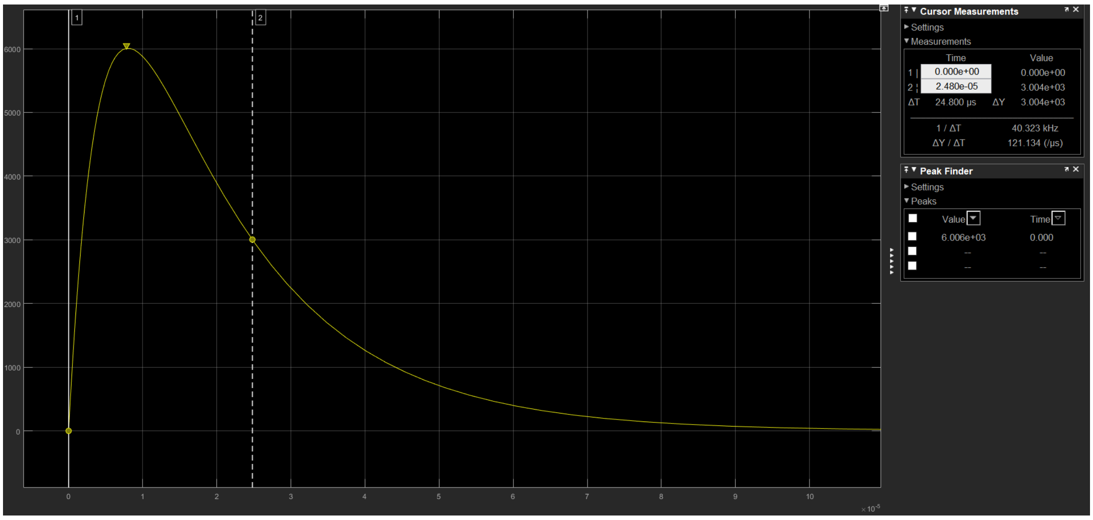


Figure 58: Tail time of 8/20 μs current surge waveform for $V(t) = 6\ kV$

Find discharged voltage (V_{in}) by desired $V(t)$ is 1 kV:

$$V(t) = \left(\frac{V_{in}}{2\beta R_1 C_2}\right)\left[e^{-(\alpha-\beta)t_f} - e^{-(\alpha+\beta)t_f}\right]$$

$$V_{in} = \left[\frac{V(t)(2\beta R_1 C_2)}{e^{-(\alpha-\beta)t_f} - e^{-(\alpha+\beta)t_f}}\right]$$

$$V_{in} = \left[\frac{(1\times 10^3)(2)(85637.6806)(4390.0777)(1\times 10^{-9})}{e^{-(58333.3333)(8\times 10^{-6})} - e^{-(229068.6911)(8\times 10^{-6})}}\right]$$

$$V_{in} = 1610\ V$$

The parameter used for $8/20\ \mu s$ impulse waveform:

Table 15: Circuits parameters used for $8/20\ \mu s$ impulse waveform

(Peak voltage at 1 kV)

R_1	$4390.0777\ \Omega$
R_2	$137.1429\ \Omega$
C_1	$0.125\ \mu F$
C_2	$1\ nF$
V_{in}	$1610\ V$

Table 15 shows the circuits parameters used for $8/20\ \mu s$ impulse waveform when peak voltage at 1 kV. Based on Table 3 and Table 4, the calculated input voltage (V_{in}) is 1026 V and 6153 V for output peak voltage 1 kV and 6 kV respectively. Figure 36 shows the surge generator equivalent circuit for 8/20 µs current surge waveform for peak output voltage at 1 kV. Refer to Figure 59, after injecting the parameter value calculated into the surge generator equivalent circuit model that constructed in MATLAB Simulink, the simulation results are as shown in Figure 60 and Figure 61. Based on the simulation results obtained, the front time and tail time of 8/20 µs current surge waveform for $V(t) = 6\ kV$ and $V(t) = 1\ kV$ are alike. However, the peak voltage of both waveforms is different.

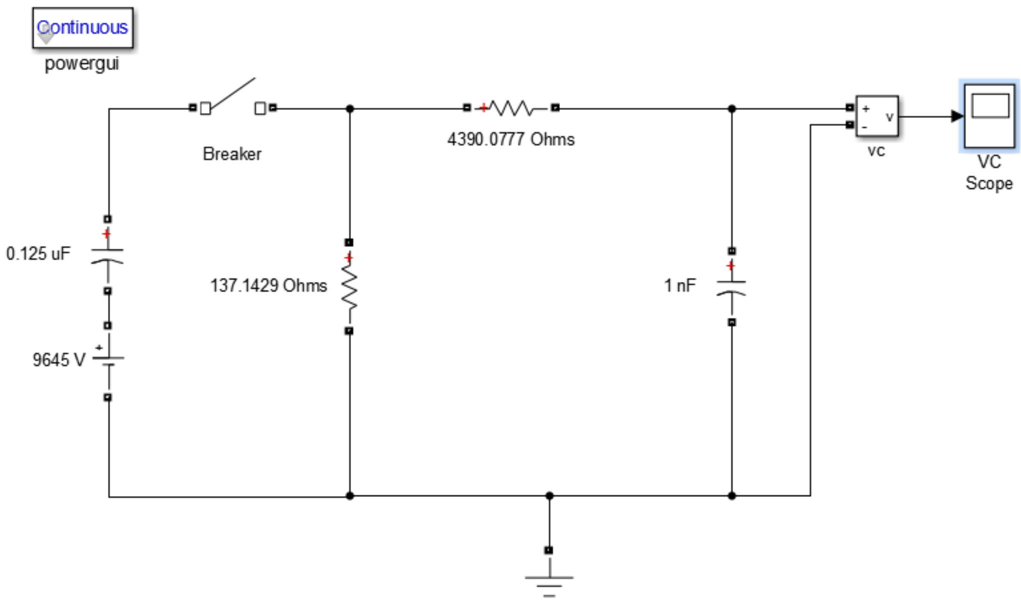


Figure 59: Surge Generator Equivalent Circuit for 8/20 µs current surge waveform (Peak voltage at 1 kV)

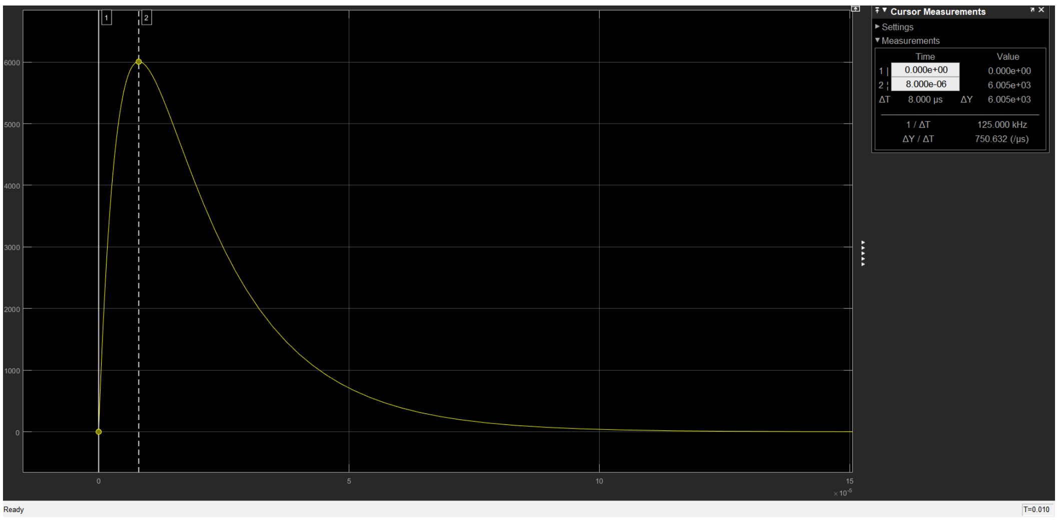


Figure 60: Front time of 8/20 µs current surge waveform for $V(t) = 1\ kV$

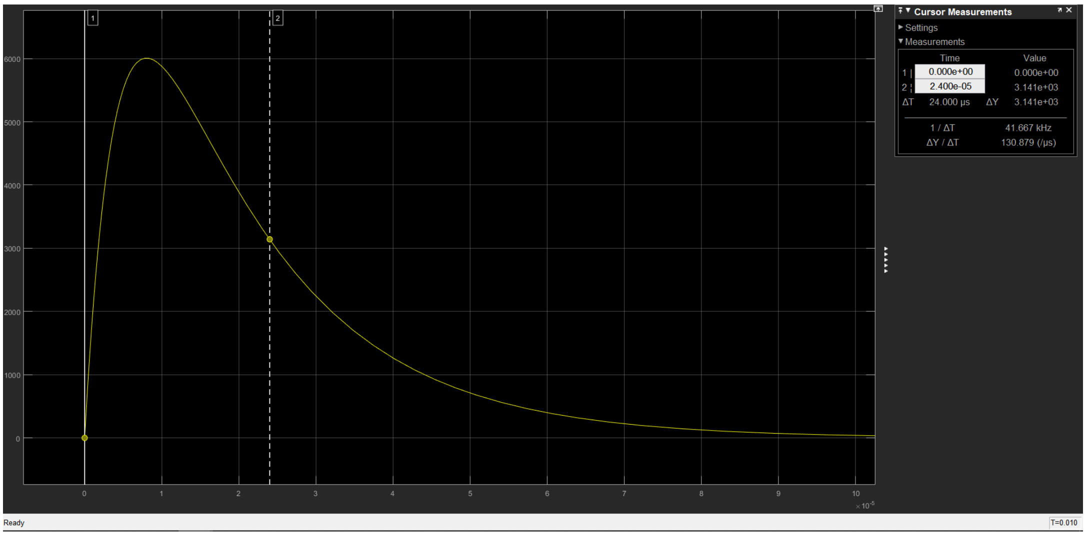


Figure 61: Tail time of 8/20 μs current surge waveform for $V(t) = 1\ kV$

4.3.3 Generate 10/350 µs Standard Lightning Impulse Generator Circuit Model

An 10/350 µs lightning impulse waveform can be generated by repeating the calculation with front time of 10 µs and tail time of 350 µs.

The parameter used for $10/350\ \mu s$ impulse waveform:

Table 16: Circuits parameters used for $10/350\ \mu s$ impulse waveform (Peak voltage at 6 kV)

R_1	$1789.7386\ \Omega$
R_2	$3885.7143\ \Omega$
C_1	$0.125\ \mu F$
C_2	$1\ nF$
V_{in}	$6174\ V$

Refer to Table 16, the circuit parameters can be obtained by repeating calculation with desired front time ($t_f = 10$µs) and tail time ($t_f = 350$ µs). Hence, an $10/350$ µs direct voltage surge waveform was simulated from the standard lightning generator circuit model constructed in MATLAB SIMULINK as shown in Figure 62. Voltage surge waveform with desired front time and tail time were as shown in Figure 63 and Figure 64 respectively.

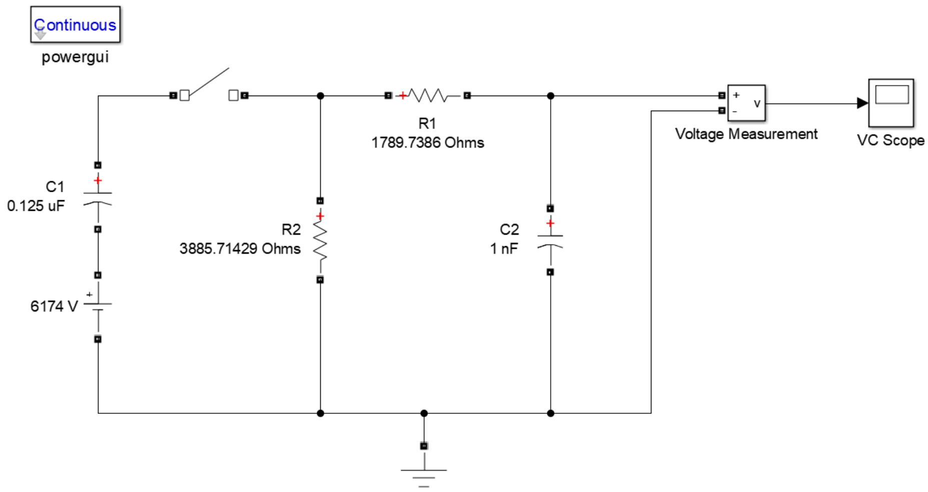


Figure 62: Surge Generator Equivalent Circuit for 10/350 µs voltage surge waveform (Peak voltage at 6 kV)

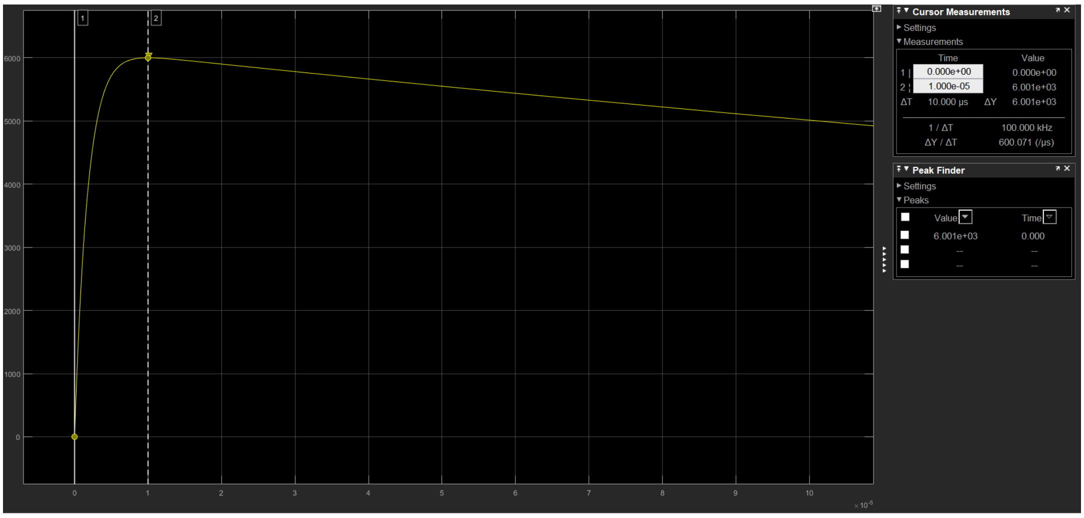


Figure 63: Front time of 10/350 µs voltage surge waveform for $V(t) = 6\ kV$

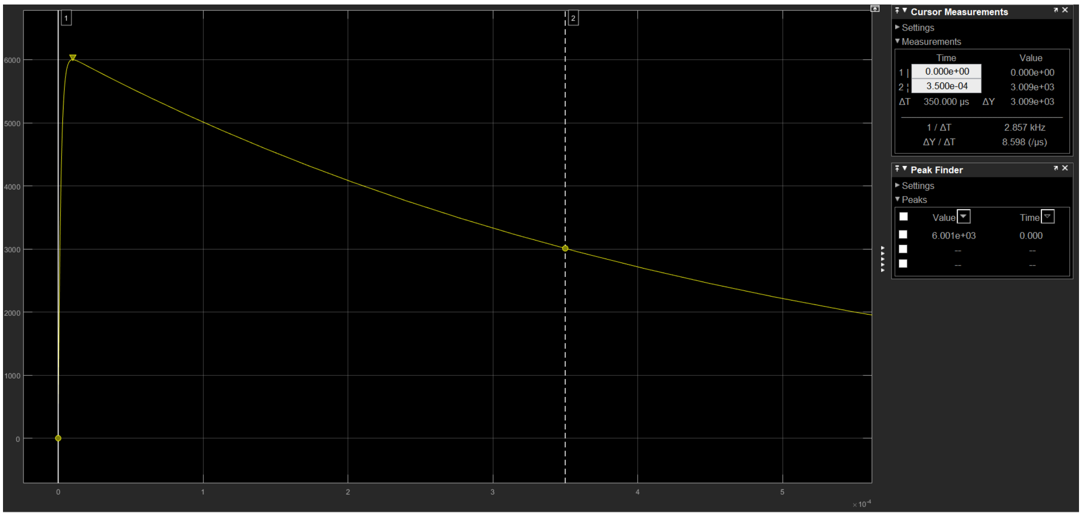


Figure 64: Tail time of 10/350 μs voltage surge waveform for $V(t) = 6\ kV$

Find discharged voltage (V_{in}) by desired $V(t)$ is 1 kV:

$$V(t) = \left(\frac{V_{in}}{2\beta R_1 C_2}\right)\left[e^{-(\alpha-\beta)t_f} - e^{-(\alpha+\beta)t_f}\right]$$

$$V_{in} = \left[\frac{V(t)(2\beta R_1 C_2)}{e^{-(\alpha-\beta)t_f} - e^{-(\alpha+\beta)t_f}}\right]$$

$$V_{in} = \left[\frac{(1\times 10^3)(2)(280575.9578)(1789.7386)(1\times 10^{-9})}{e^{-(2058.8235)(10\times 10^{-6})} - e^{-(563210.7391)(10\times 10^{-6})}}\right]$$

$$V_{in} = 1029\,V$$

The parameter used for $10/350\ \mu s$ impulse waveform:

Table 17: Circuits parameters used for $10/350\ \mu s$ impulse waveform

(Peak voltage at 1 kV)

R_1	$1789.7386\ \Omega$
R_2	$3885.7143\ \Omega$
C_1	$0.125\ \mu F$
C_2	$1\ nF$
V_{in}	$1029\ V$

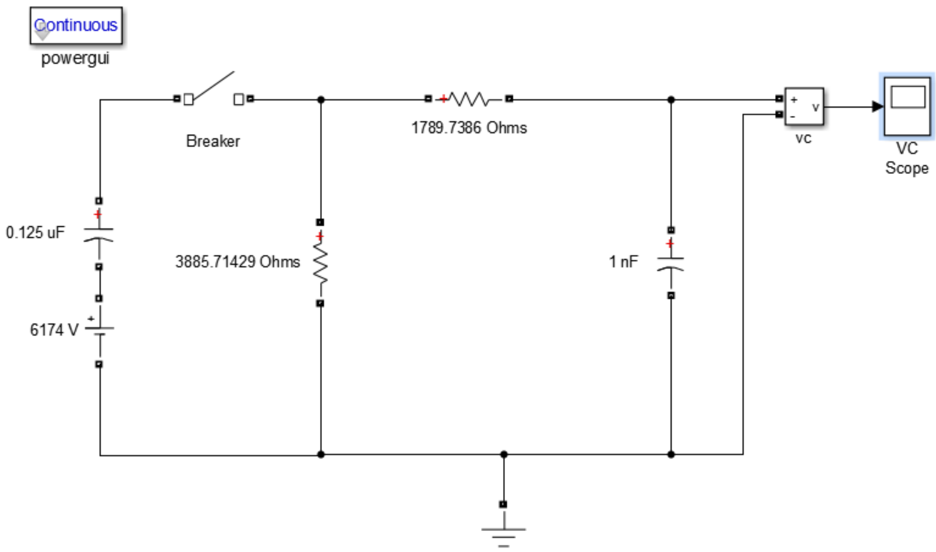


Figure 65: Surge Generator Equivalent Circuit for 10/350 µs voltage surge waveform

(Peak voltage at 1 kV)

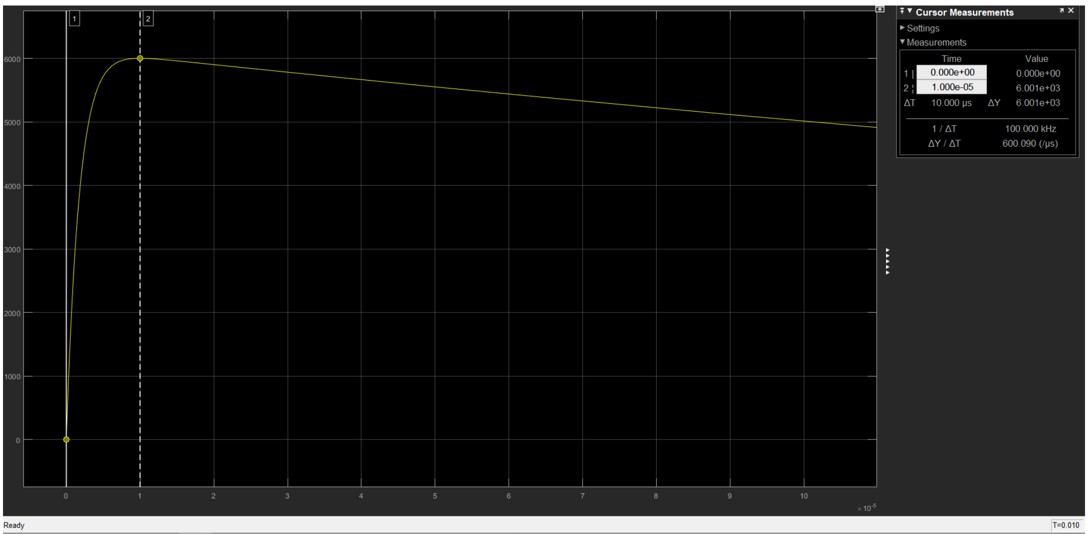


Figure 66: Front time of 10/350 µs voltage surge waveform for $V(t) = 1\ kV$

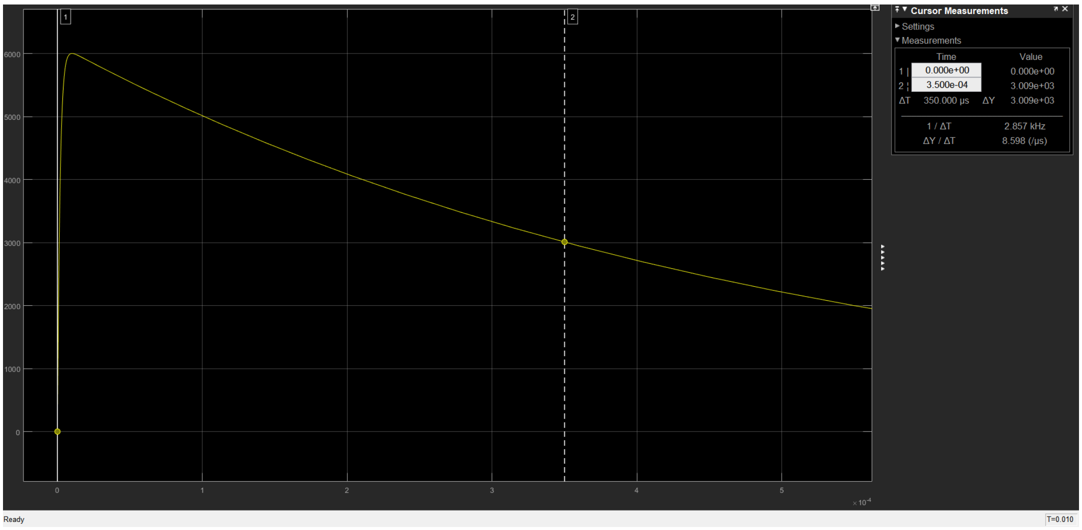


Figure 67: Tail time of 10/350 µs voltage surge waveform for $V(t) = 1\ kV$

The parameter value in Table 17 was injected into the surge generator equivalent circuit model constructed in MATLAB Simulink as shown in Figure 65. Based on the simulation results obtained in Figure 66 and Figure 67, it shows the impulse waveforms obtained is compliance with IEC standard waveforms. The front time (t_f) is measured at the peak amplitude whereas the tail time (t_t) is measured at 50 % of the peak amplitude. These results proved the peak voltage of the impulse waveforms is adjustable by the input voltage source. Table 18 illustrates the circuit parameters of surge generator equivalent circuit for peak voltage at 6 kV whereas Table 19 demonstrates the circuit parameters of surge generator equivalent circuit for peak voltage at 1 kV.

Table 18: Circuit parameters of surge generator equivalent circuit

(Peak voltage at 6 kV)

Impulse Standard of 6 kV	$R_1(\Omega)$	$R_2(\Omega)$	$C_1(\mu F)$	$C_2(nF)$	V_{in}
$1.2/50\ \mu s$	206.9511	557.7143	0.125	1	6153
$8/20\ \mu s$	4390.0777	137.1429	0.125	1	9645
$10/350\ \mu s$	1789.7386	3885.7143	0.125	1	6174

Table 19: Circuit parameters of surge generator equivalent circuit

(Peak voltage at 1 kV)

Impulse Standard of 6 kV	$R_1(\Omega)$	$R_2(\Omega)$	$C_1(\mu F)$	$C_2(nF)$	V_{in}
$1.2/50\ \mu s$	206.9511	557.7143	0.125	1	1026
$8/20\ \mu s$	4390.0777	137.1429	0.125	1	1610
$10/350\ \mu s$	1789.7386	3885.7143	0.125	1	1029

4.3.4 Standard Lightning Impulse Generator Circuit Model with MOV Protection

Figure 68 demonstrated the surge generator equivalent circuit model with MOV protection. The voltage protection level of the MOV is designated to be 4.5 kV as the peak value of input lightning overvoltage surge is 6kV. Voltage protection level is defined as the maximum voltage across the terminals of the SPD when it is active while clamping voltage is defined as the voltage level that can be maintained by MOV once overvoltage happened. Thus, the level of protection voltage may be different from the level of clamping voltage. The voltage protection level set must be lower than the overvoltage withstands capability of the loads. Hence, in case of a lightning strike, the voltage across the MOV will not exceed the level of protection voltage.

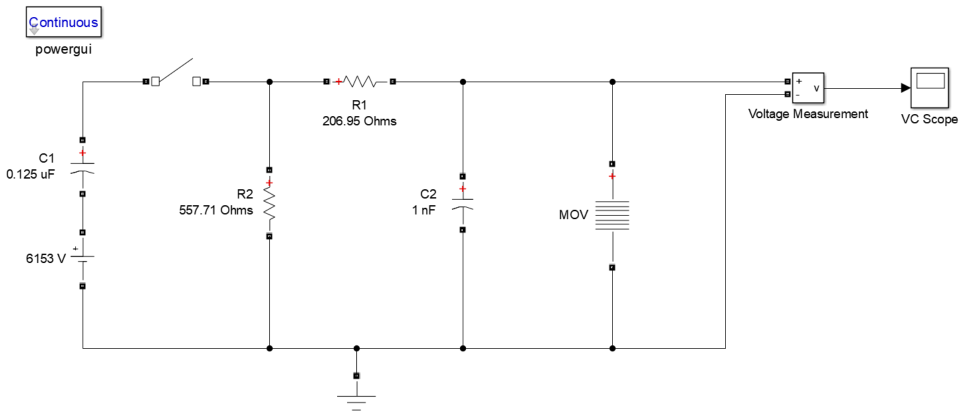


Figure 68: Surge Generator Equivalent Circuit with MOV Protection Model

Based on the result obtained in Figure 69, the maximum voltage across the MOV is 3.9 kV, which is less than the voltage protection level set. Then, the result shows that voltage is clamped at 3.8 kV immediately after 3.9kV is detected. Therefore, this test proves the working principle and the purpose of using MOV.

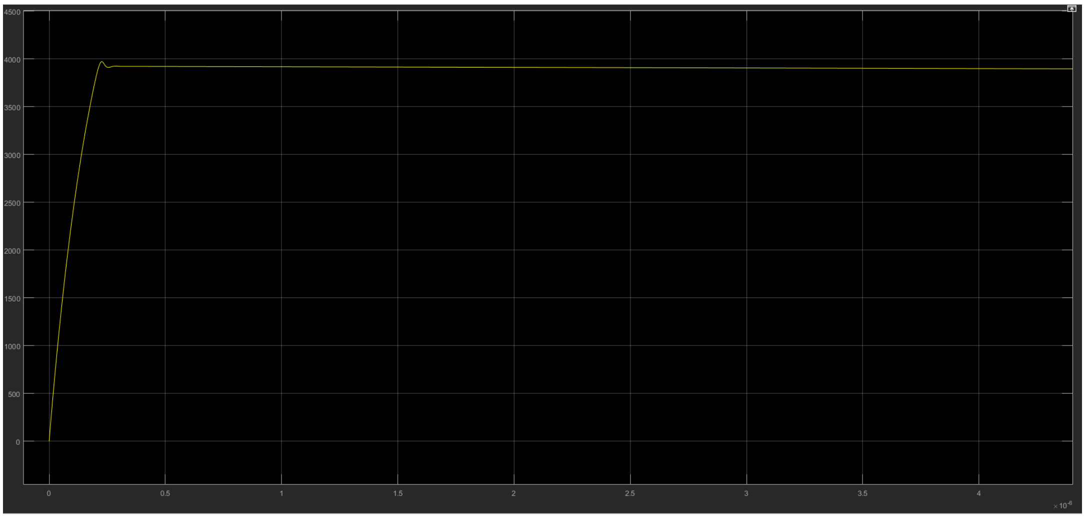


Figure 69: Clamping voltage of MOV (Voltage protection level at 4.5 kV)

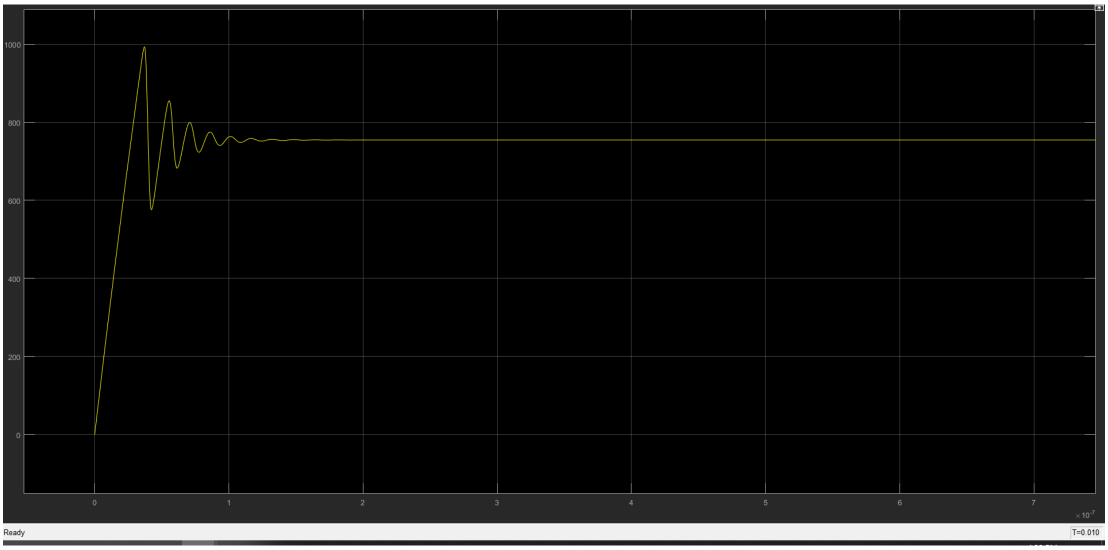


Figure 70: Clamping voltage of MOV (Voltage protection level at 850 V)

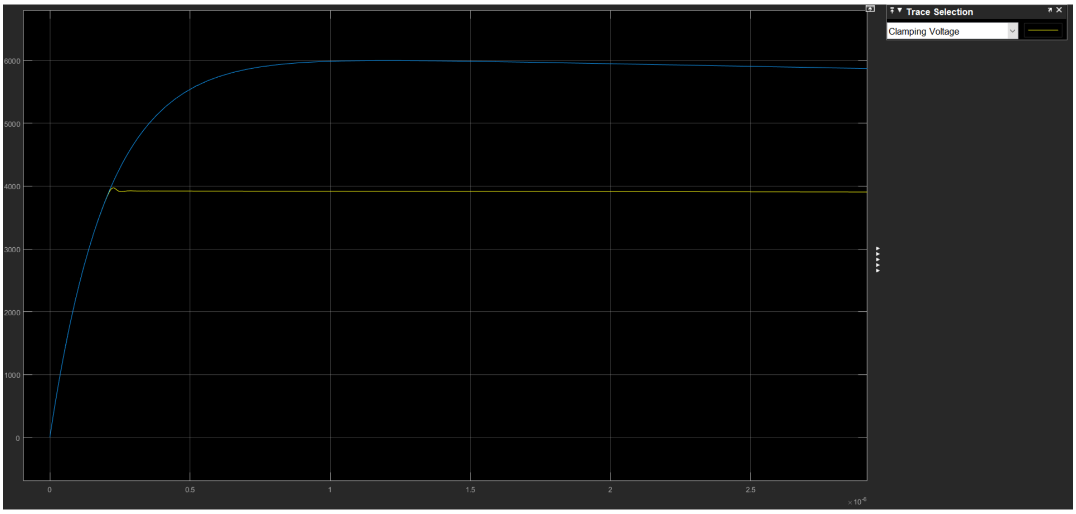


Figure 71: Comparison between indirect voltage surge and clamping voltage level (Voltage protection level of MOV at 4.5 kV)

Figure 70 demonstrates the simulation result obtained whenever the voltage protection level of the MOV is designated to be 800 V. Besides, Figure 71 shows the comparison between indirect voltage surge (1.2/50 μs) and clamping voltage level. The blue line indicates an input overvoltage surge and this surge is following the standard of 1.2/50 μs indirect voltage surge waveform. Meanwhile, the yellow line indicates the voltage level clamped by MOV. Based on this result, the indirect voltage surge will go up to its peak voltage level, which is 6 kV before it is conducted to ground. However, the voltage will be clamped at 3.8 kV by the MOV with the purpose to hold the input voltage of the protected device within the voltage protection level to prevent severe damage happened.

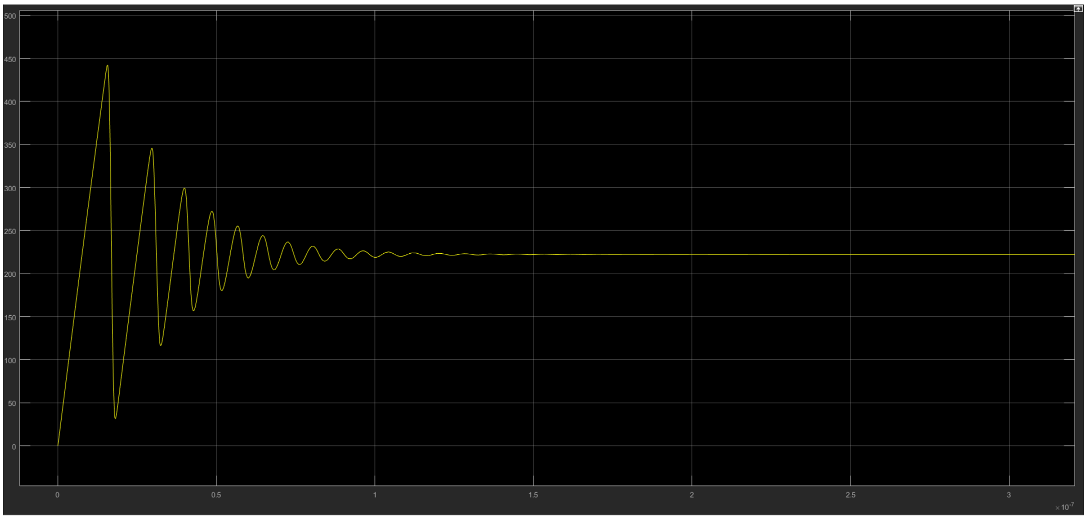


Figure 72: Overvoltage surge is clamp at 225V with oscillatory transient

Figure 72 shows the case where the difference between the over surge peak magnitude and the surge arrester clamping voltage level is large. This large difference will cause overshoot oscillation at the clamping voltage level that damp overtime. The voltage protection level of MOV designated at 250 V. The result shown in the figure has an input overvoltage surge of 6kV where the oscillation damps toward 225V, the clamping voltage level and stabilize after 0.18μs.

4.3.5 Standard Lightning Impulse Generator Circuit Model with MOSFET Protection

Refer to Figure 73, MOV in the Surge Generator Equivalent Circuit is replaced with MOSFET as a switch to conduct surge energy to ground. A surge generator was used to initiate the MOSFET. The surge generator is used as a detector for surge detection as it will transmit a triggering signal to turn ON MOSFET when it detects the voltage level of the surge is close to the voltage protection level.

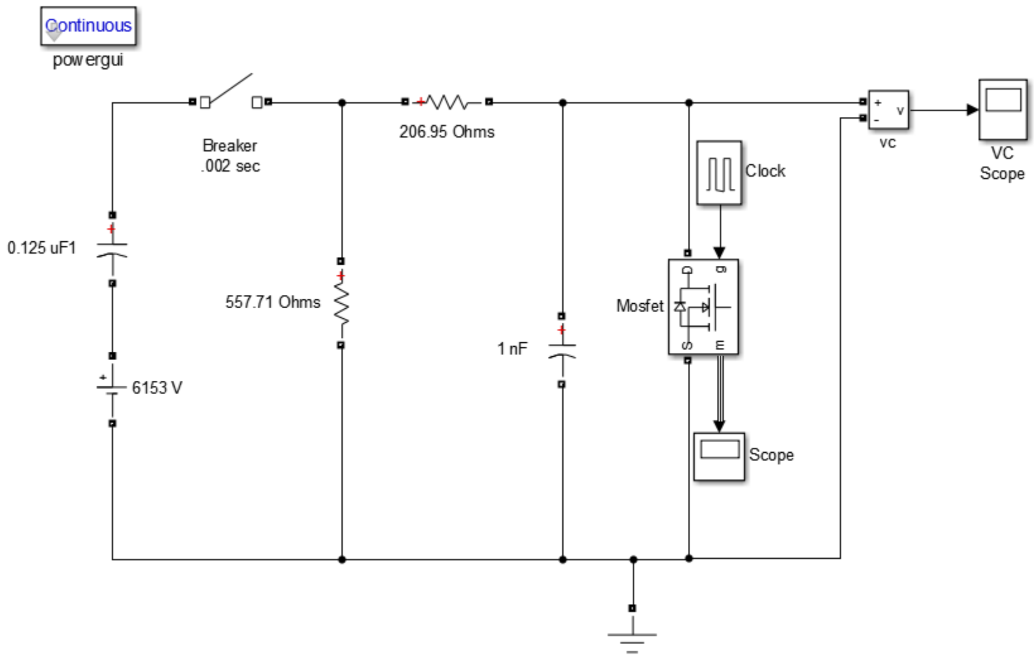


Figure 73: Surge Generator Equivalent Circuit with MOSFET Protection Model

Figure 74 and Figure 75 shows the simulation result of MOV and MOSFET respectively. The result obtained shows that MOSFET can function similarly as the MOV to clamp voltage surge at a specific level. However, MOSFET is better as compared to MOV as the clamping voltage of MOSFET is lower than MOV. This is due to the lower internal resistance of MOSFET compare to MOV. In addition, the response time of MOSFET is faster than MOV as the simulated result demonstrated in Table 20 shows MOSFET response within 0.001 μs while MOV is slower at 0.23 μs.

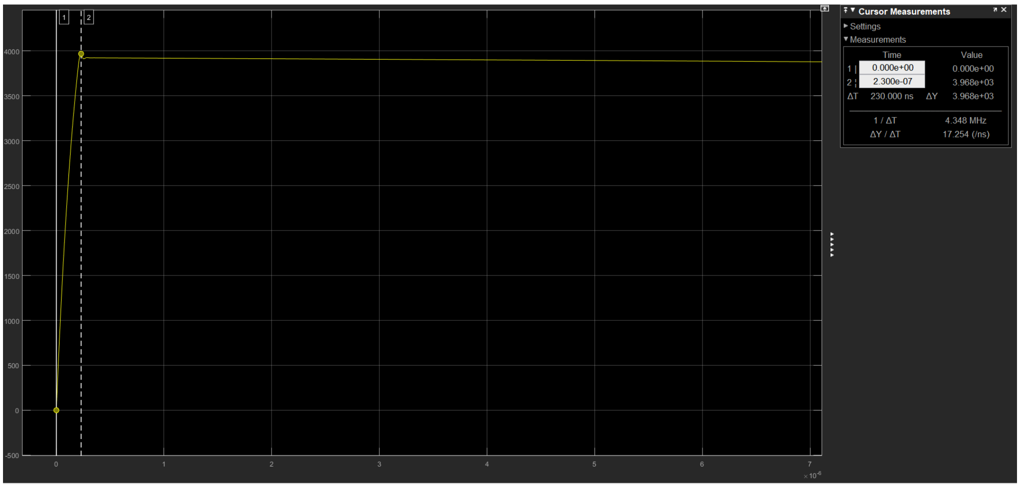


Figure 74: Response time of MOV

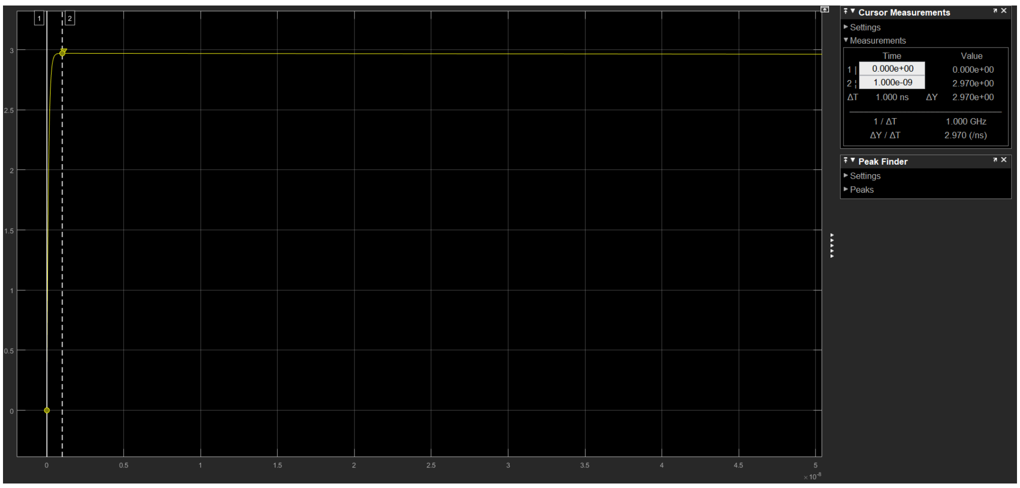


Figure 75: Response time of MOSFET

Table 20: Comparison between the response time of MOV an MOSFET

Circuit with MOV	0.23 μs
Circuit with MOSFET	0.001 μs

4.3.6 Standard Lightning Impulse Generator Circuit Model with IGBT Protection

The MOSFET in Surge Generator Equivalent Circuit is replaced with IGBT as shown in Figure 76. A surge generator was implemented to initiate the IGBT. Based on the result obtained, IGBT is able to function similarly as the MOV to clamp voltage surge at a specific level. Figure 77 shows the clamping level of IGBT is 1 V while Figure 70 shows the clamping level of MOV is 780 V. Moreover, the clamping level of MOSFET is 3 V as shown in Figure 75. Based on these results, the clamping voltage level of IGBT is the lowest among MOV and MOSFET. This is due to the lower internal resistance of IGBT compare to both the MOV and MOSFET.

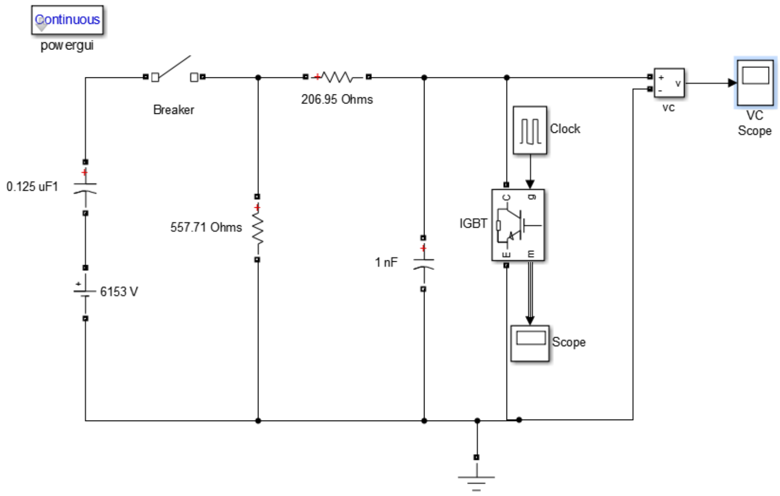


Figure 76: Surge Generator Equivalent Circuit with IGBT Protection Model

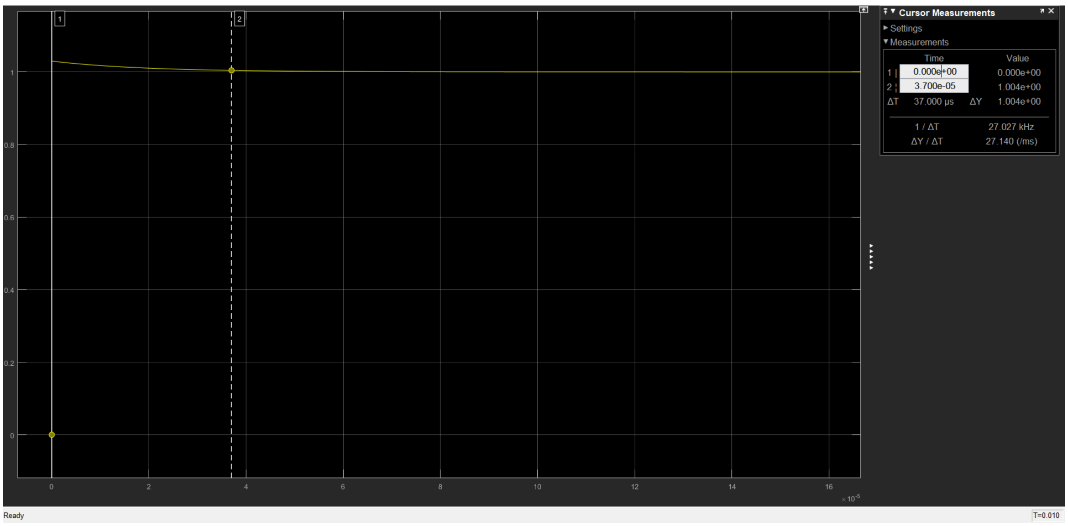


Figure 77: Simulation result of IGBT

4.4 Surge Protection Hardware Test

A surge protection hardware test was carried out with the use of surge generator. Voltage and current are measured by differential probe and current transformer respectively while resistance is measured with a use of multimeter. Besides that, an oscilloscope was applied in this experiment to capture the generated waveforms. Figure 78 and Figure 79 shows the voltage surge waveform and current surge waveform that generated in this experiment respectively.

Figure 78: voltage surge waveform

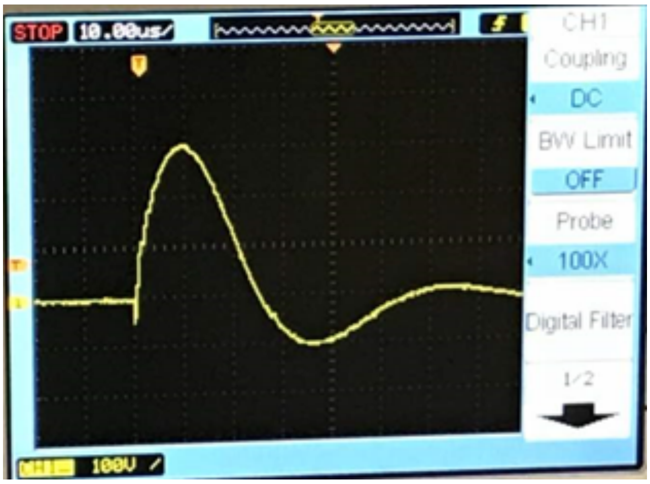


Figure 79: current surge waveform

4.4.1 Consequences of Surge Applied on Resistance

A resistor will be burnt by surge if it is not protected by surge protection device. Figure 80 shows that from the left to right, the value of resistor placed from smallest resistance value to largest resistance value. It can be observed that resistor with smallest value result in the most severe burnout. Therefore, a conclusion can be made that a smaller resistance value will get burnt more easier than the higher resistance value. Besides that, Figure 81 shows the resistor burnout waveform. According to Figure 81, green line indicates voltage waveform while yellow line indicates current waveform. Current only flows through the resistor whenever the breakdown occurred meanwhile there is no potential difference across the resistor. However, there is a large voltage applied across the resistor before the breakdown. Besides that, different amount of energy is required to burn different resistors. The results obtained for the amount energy required to break the resistors are measured and recorded as shown in Table 21, then graph was plotted as shown in Figure 82. Based on the results obtained, the energy required to break the resistance is linearly proportional to the resistance value.

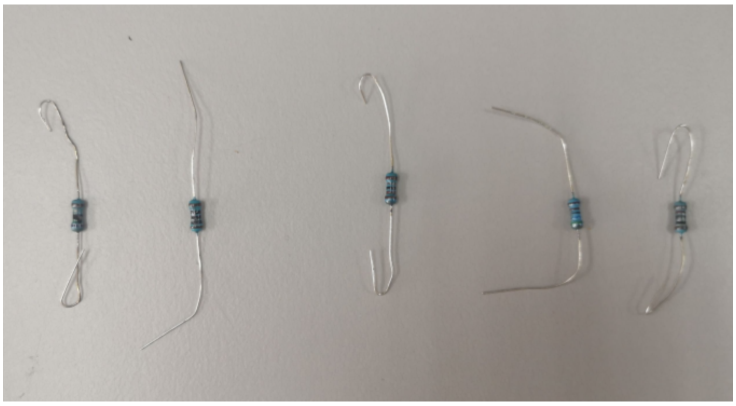


Figure 80: Resistors after suffered surge

Figure 81: Resistor burnout waveform

Table 21: Energy required to break different resistance

Resistor (Ω)	Energy required to break the resistor (J)
75	13.5
100	19.5
1800	76.8
5600	93.3
10000	100

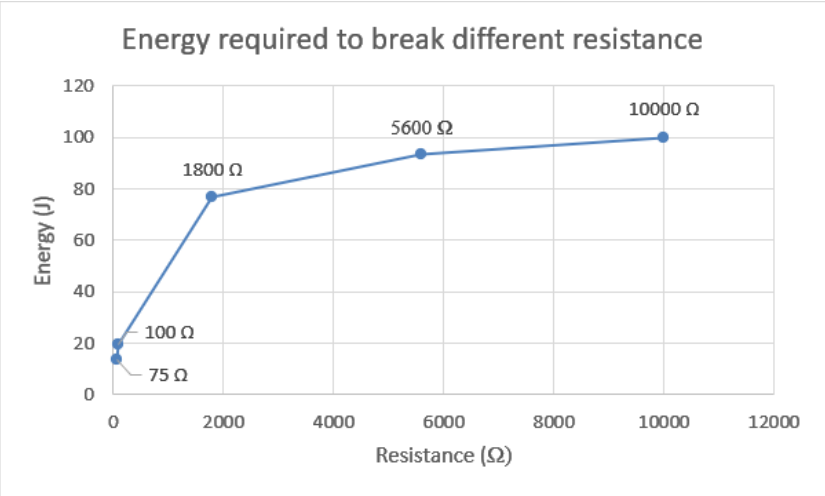


Figure 82: Energy required to break different resistance

4.4.2 Repetitive test

The condition of a 5.57 kΩ resistor after 4kV repetitive surge applied on it was observed and recorded in Table 22. Figure 83 demonstrates the graph plotted based on Table 22 and it shown the value of resistances is maintained within a range from

5.52kΩ to 5.80 kΩ. However, the resistance became 8.24 kΩ after the fifth pulse of 4kV surge applied. Repetitive surge will increase the temperature of resistor which will lead to damage to the resistor and cause the circuit became open circuit. Therefore, the resistance value will rise tremendously when the circuit became open circuit after multiple surges applied on it. Furthermore, based on the results obtained, breakdown and melt of resistor occurred and results in a slight drop after the sixth pulse of 4kV surge applied.

Table 22: Condition of resistor after 4 kV repetitive surge

Number of pulses (4kV)	Resistance (kΩ)
1	5.52
2	5.53
3	5.60
4	5.76
5	5.80
6	8.24
7	7.30

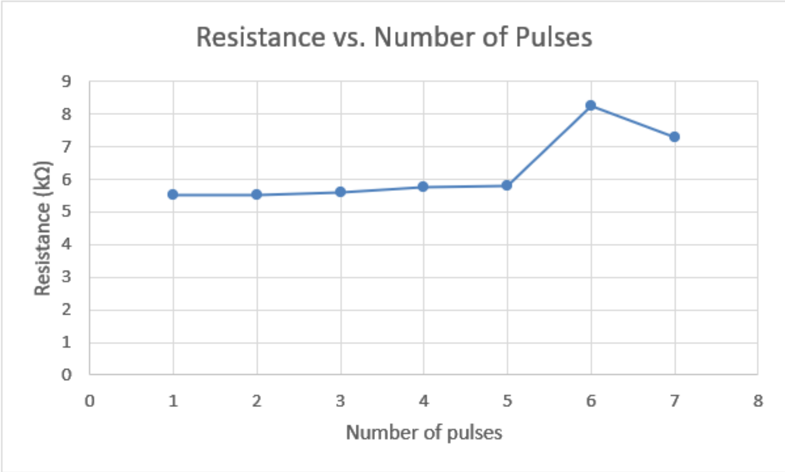


Figure 83: Resistance value after 4 kV repetitive surge

4.4.3 Performance of MOV

MOV is a clamping type of SPD which constructed to protect various types of electrical devices from power surges and offers effective transient voltage suppression. In this experiment, a resistance of 220 kΩ was protected by a MOV. The setup of MOV and resistor was shown in Figure 84. Besides, the result obtained from this experiment as shown in Figure 85 demonstrated the waveform of MOV during surge. The green line indicates voltage waveform while the yellow line indicates current waveform, which is generated by the current flowing through the MOV. MOV is able to clamp the input voltage of the protected device within the voltage protection level as well as conducting and diverting all the transient currents to ground. However, MOV is not able to deal with multiple surges. This is because the multiple surges applied will increase the temperature of MOV which will lead to slower in its response time. Then, the degradation of MOV will affect the resistance value. The changes in resistance value after multiple surges applied was presented as a graph in Figure 86. Based on the results obtained, the changes in the resistance value is small for the first 80 surge counts, this is because the resistor is protected by the MOV. On the contrary, the changes in resistance value will be tremendously whenever the MOV has been burnout by the surge that passes through it. Therefore, the failure mode of MOV can be judged as an open-circuit and it will cause the value of resistance to rise to infinity. Furthermore, Figure 87 shows the burnt MOV after multiple surges applied.

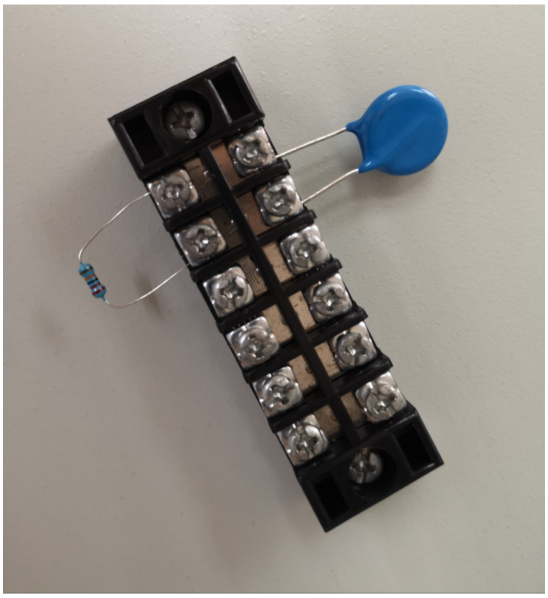


Figure 84: Setup of MOV and resistor

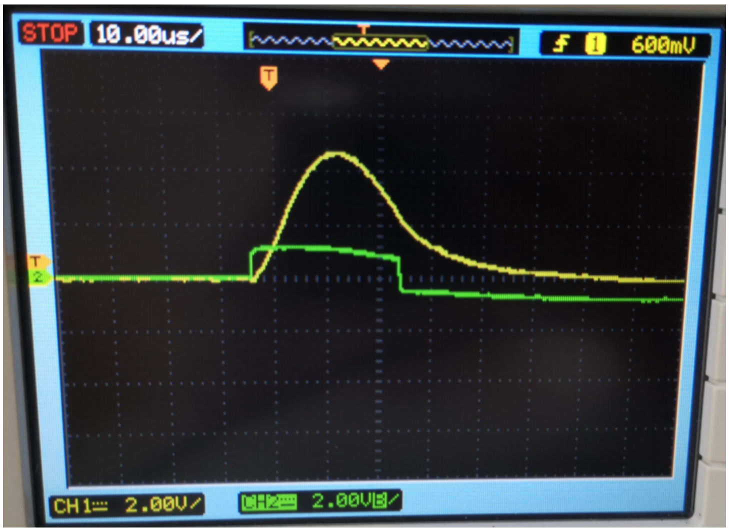


Figure 85: Clamping waveforms of MOV

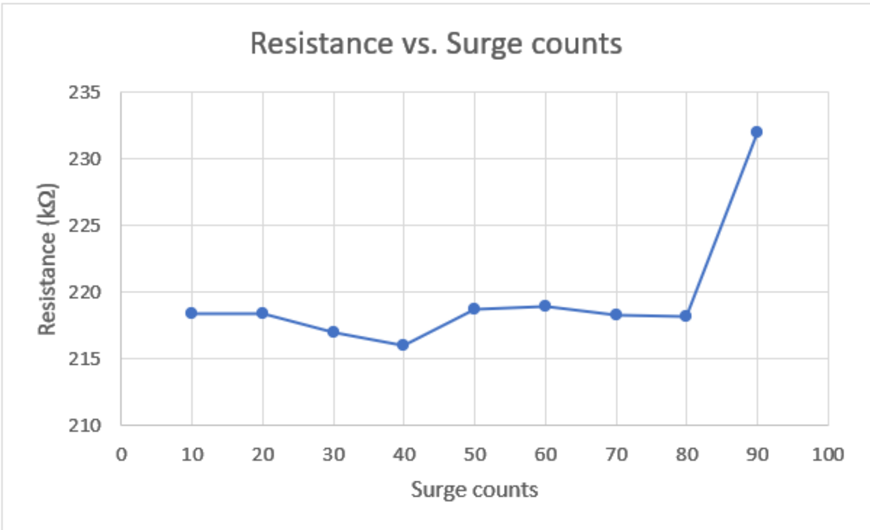


Figure 86: Graph of resistance versus surge counts

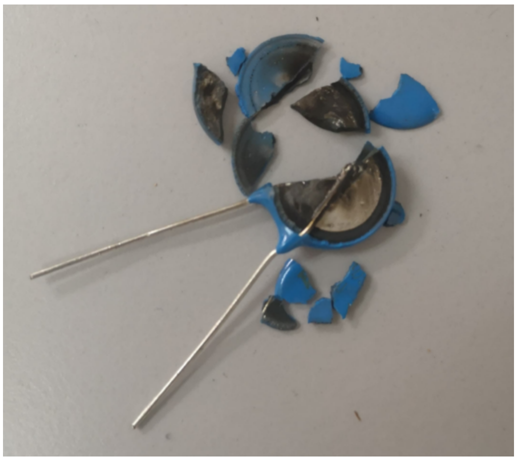


Figure 87: Burnt MOV

4.4.4 Performance of Power Electronics

Power electronics such as MOSFET and IGBT are able to clamp the surge voltage within the voltage protection level and divert all the surge current to ground. Both the MOSFET and IGBT have on-mode and off-mode as they have three terminals. For MOSFET, it will only be on-mode whenever the gate input voltage, V_{GS} reached an appropriate positive voltage level (V_{GS} = +ve). Meanwhile, a zero-voltage level (V_{GS} = 0) will turn the MOSFET into OFF-mode. Besides that, IGBT will be in ON-mode when the gate input voltage, V_{GE} reached an appropriate positive voltage level (V_{GE} = +ve) while it will be in OFF-mode when there is no gate input voltage supplied (V_{GE} = 0).

The waveform of MOSFET and IGBT obtained in ON-mode are shown in Figure 88 and Figure 89 respectively. The yellow line indicates current waveform generated by the current across the power electronic while green waveform shows the voltage across the power electronics. These results proved that the clamping voltage of power electronics is lower as compared to MOV as well as the clamping voltage of IGBT is lower than MOSFET. Besides that, different values of surge voltage applied will result in different voltage clamping level. Hence, an experiment was conducted by applying different surge voltage on power electronics with the purpose to observe the changes in their voltage clamping level. The changes in voltage clamping level of both MOSFET and IGBT at different surge amplitude are presented as a graph in Figure 90 and it shows that the clamping voltage level is linearly proportional to the amount of surge voltage applied.

Furthermore, Figure 91 and Figure 92 demonstrate the burnt MOSFET and burnt IGBT respectively. Both the MOSFET and IGBT burnt because they were in OFF-mode as no gate input voltage supplied to them.

Figure 88: Clamping waveform of MOSFET

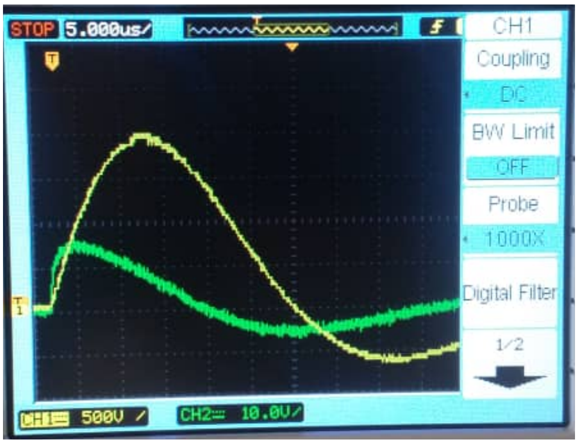


Figure 89: Clamping waveform of IGBT

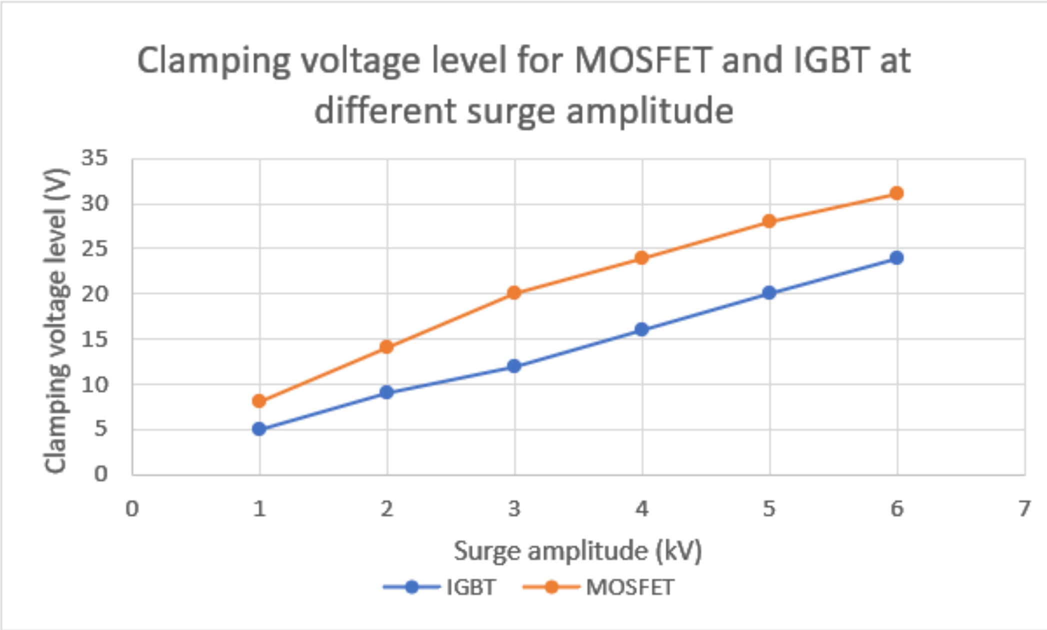


Figure 90: Graph of clamping voltage for MOSFET and IGBT

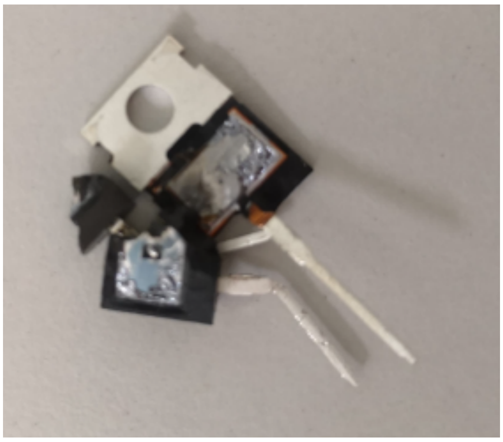


Figure 91: Burnt MOSFET

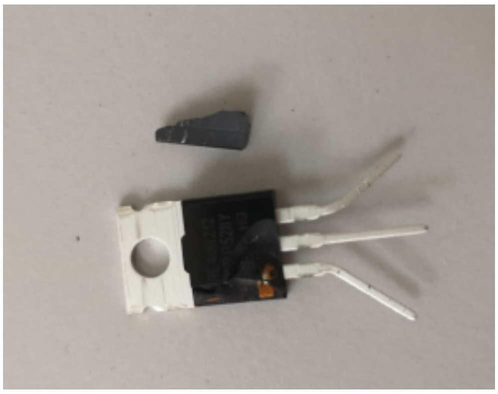


Figure 92: Burnt IGBT

4.4.5 Response time of MOV and MOSFET

Figure 93 and Figure 94 demonstrate the waveform of MOV and MOSFET respectively. The response time of MOV and MOSFET can be obtained from these voltage waveforms. The response time of MOV and MOSFET are 4 μs and 2 μs respectively. It proved that MOSFET has a faster response time as compared to MOV. By comparing the response time obtained from simulation results and hardware test, there is a large different between them. This is because the specific rating of MOV and MOSFET that applied in MATLAB Simulink are different from the one in the surge protection hardware test.

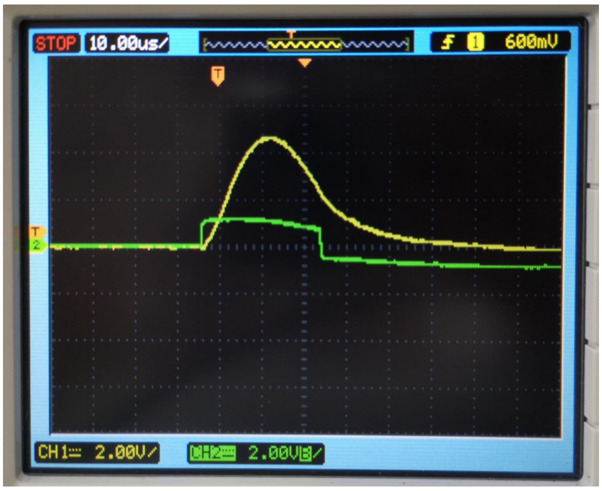


Figure 93: Response time of MOV

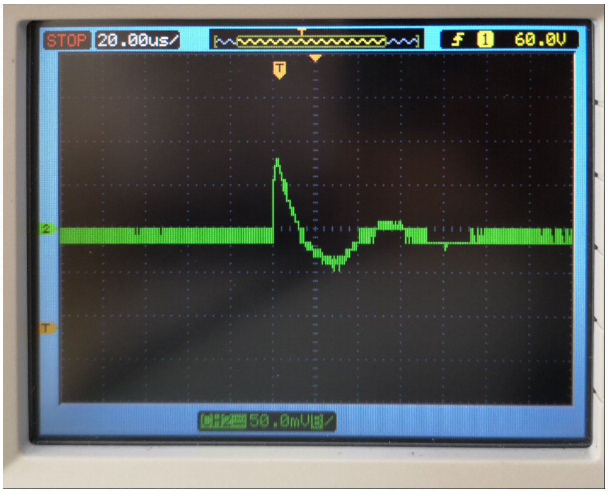


Figure 94: Response time of MOSFET

4.5 Internal vs. External SPD

Article 8.2.4.5 of IEEE Std. 1100-2005 stated that SPD can be installed at the outside of the service equipment through a hardwire external surge panel or mounted inside the service equipment. The National Electrical Code (NEC) stated that service equipment is a necessary equipment which normally contains circuit breakers or fused switches equipped to cut off the supply. The examples of service equipment are switchboard and panelboard.

An internal SPD provides two kinds of protection, which are overcurrent protection and surge protection. Internal SPD will also cut down the service equipment installation cost as the SPD is part of the service equipment. Besides, the shorter the length of the SPD connections between the network and the earthing terminal block, the more effective the protection. Another benefit is that it may minimize the lead length of SPD, which will then optimize the performance and effectiveness of the devices. The lead length of the internal SPD conductor is shorter as an integrated SPD installed directly to the service entrance conductor, which will result in lower let-through voltage. Let-through voltage is the allowable amount of voltage that can be reached to the connected electrical equipment whenever a surge happens. However, IEC C62.72 expressed that a low let-through rating of SPD may lead to frequent interventions as well as speed up the aging of the protective devices. Therefore, SPD with lowest let-through voltage not surely is the best SPD.

NEC code declared that overcurrent protective devices shall not be placed closely to combustible materials. IEC PC62.72 concerned that the switchboard or panel may be damaged due to the failure of SPD whenever the SPD is mounted inside the switchboards or panels. One drawback of an internal SPD is the risk of combustion is high. This is due to Metal Oxide Varistor (MOV), which is made up of combustible materials and is usually incorporated in both the internal and external SPD products as mentioned in IEC C62.72. In a fault condition, combustible materials that are installed within the electrical service equipment may lead to severe damage to the components inside the panels such as circuit breaker. Furthermore, transient overvoltage generated by the lightning strike may trigger the MOV's within an SPD to conduct current continuously and divert the current to ground. Additional heat which may damage the MOV is produced due to this continuous current condition. Therefore, a combustible event will take place if the SPD is not sized appropriately. Another disadvantage of internal SPD is the maintenance work for internal SPD is more complicated. One of the factors is that maintenance or repair work on integrated SPD are forced to be conducted in powered condition. Besides, the purpose of service entrance conductors is to house the overcurrent protective devices. Hence, limited space is available whenever the cabinet with overcurrent protection devices is utilized to house an SPD as well as input conductors.

On the other hand, external SPD has its own benefits, one of them is ease of maintenance. The externally installed SPD can connect to the panel through a circuit breaker, meaning that the SPD can be replaced or maintained with no impact to the facility power by simply turning off the breaker. Limited risk of conductive residue is another benefit of an external SPD. The reason being that in an event of a surge that causes MOV failure and smoke, the residue from the damage will less likely to contaminate the protecting facility or equipment resulting in arc flash or downtime. An externally mounted SPD also isolates the damage in case of a failure due to it being contained within its own electrical panel, therefore reduces the risk for facility downtime. However, a few circuit breakers are required to be installed in between the external SPD and the service equipment in order for SPD to protect the down-line loads from transient overvoltage

4.5.1 SPD Protection Distributed Levels

The number of SPD required to be installed depends on the size of the site and the sensitivity of the electrical equipment. SPD is usually installed at the incoming end of every subdistribution board for a large site in order to protect all the loads from power surge. It is also determined by the distance between the loads and incoming end of a SPD. Additional SPDs are required to be installed as a fine protection whenever the distance from the loads to the existing incoming end of the existing SPD is more than 10 meters. This is due to the propagation of a lightning wave increasing from a distance of 10 meters. Besides, the number of SPD required is also subject to the risk of exposure. In the case of a very exposed site, a Type 2 SPD is usually as a supplement to Type 1 SPD as the incoming end of Type 1 SPD cannot ensure both a high flow of lightning current and a sufficiently low voltage protection level.

Further, additional coordinated SPD must be installed if the stipulated voltage protection level cannot be achieved by the incoming-end SPD or if sensitive loads are remote. The purpose to install this additional coordinated SPD is to achieve the required protection level.

Figure 95 demonstrates the fine protection architecture of several SPD. As mentioned previously, Type 1 SPD provides protection against transient overvoltage instigated from direct lightning strike while Type 2 SPD provides protection mainly for low voltage electrical installations. Further, Type 3 SPD offers fine protection on sensitive and critical loads due to its low discharge capacity. Based on Figure X, a few numbers of SPD with different protection levels are required to distribute energy among these SPDs. According to Figure 95, Type 1 SPD is installed at the main LV switchboard for incoming protection meanwhile Type 2 SPD is installed at each sub distribution board to absorb residual overvoltage. Moreover, Type 3 SPD is usually installed as a supplement to Type 2 SPD where it offers fine protection on sensitive equipment, and it is installed very near to the sensitive equipment. Type 3

SPD is also usually applied as hard-wire devices and combined with Type 2 SPD for fixed installations.

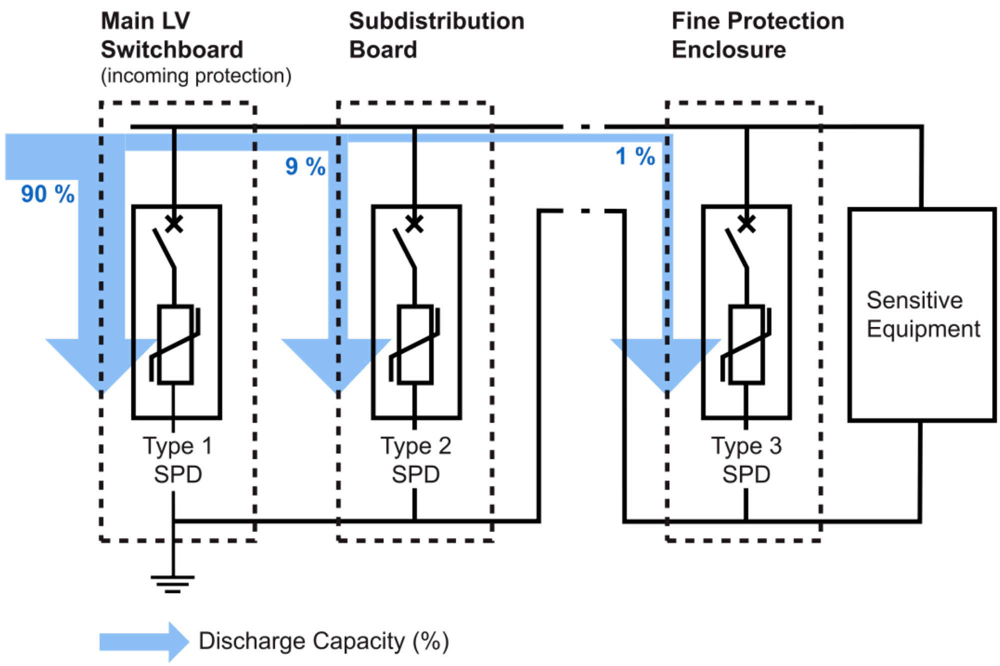


Figure 95: SPD Protection Distributed Levels (Wenzhou Arrester Electric Co., 2022)

Referring to a university building as an example, the building comprises multiple classrooms, offices and laboratories each with their necessary amenities such as air-conditioning, computers, projectors, as well as laboratories specific sensitive equipment/devices. Under these circumstances the SPD Protection Distributed Levels is covering the building as described below:

Type 1: Install to cover the entire building to protect it in overall from surge by clamping the surge voltage or current to 10% as illustrated within Figure X.

Type 2: Install each at every available room within the building to further clamp the surge from the remaining 10% down to 1%

Type 3: Only install within rooms containing sensitive equipment/devices such as the AHU and laboratories to further clamp down the remaining 1% of surge voltage or current. The reason being sensitive equipment is easily decalibrated, degraded or damaged with even a small amount of surge.

4.5.2 Application Example of Integrating SPD

Figure 96 shows the method of typical SPD switchgear installation. Based on Figure 96, the integrating SPD is installed at separate and isolated compartments within the switchgear in order to reduce the risk of collateral damage to the components inside the panels such as circuit breaker. The item 1 as shown in Figure 96 is a main disconnect which feeds the internal bus bar, meanwhile item 2 which is located in another switchgear compartment usually contains mechanical or electrical protection devices such as circuit breaker with adjustable trip mechanism. Further, item 3 as demonstrated in Figure 96 is an SPD. Based on Figure 96, SPD is installed in a separate compartment within the switchgear with purpose to minimize the effect of an SPD failure on the distribution equipment. External overcurrent protection devices such as circuit breakers are usually implemented by SPD as short circuit protection. Meanwhile, internal overcurrent devices such as fuses are also implemented by a limited number of SPD. However, a disconnector is usually installed upstream of the SPD to provide short circuit protection to the SPD and disconnect the SPD in the case of end-of-life of SPD. One of the examples which provide this protection to SPD is external Short Circuit Protection Device (SCPD).

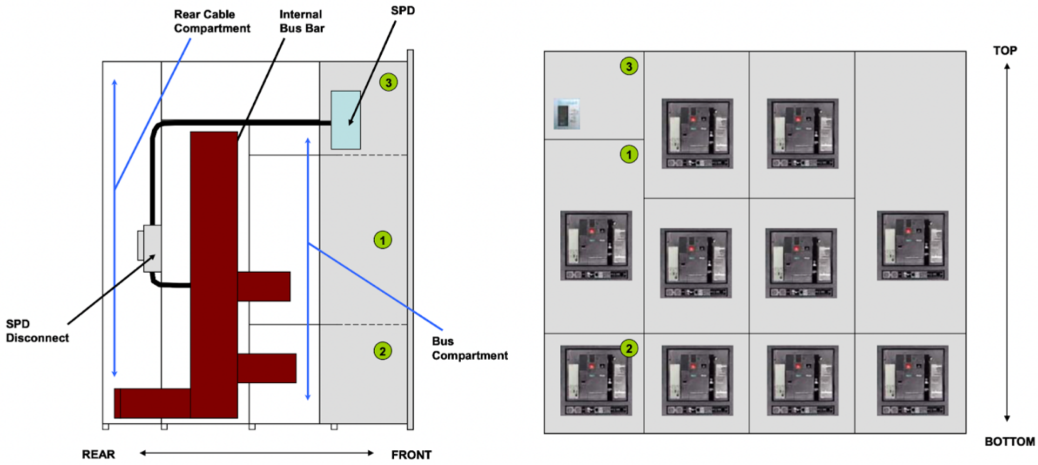


Figure 96: Method of Typical SPD Switchgear Installation (Emerson Network Power, 2010)

An external SPD is safer as compared to integrated SPD. As mentioned previously, a failure of integrated SPD may lead to a combustible event. An SPD which is connected to service equipment through a hardwire external surge panel may diminish the risk of arc flash, combustion as well as the equipment downtime. Besides, the maintenance work for an external SPD is easier as compared to internal SPD. This is due to the repair work of the external SPD can be conducted on a safe de-energized surge panel by turning off the circuit breaker. Another advantage of external SPD is that it is furnished with visual surge protection status.

The purpose of SPD installation is to protect the down-line load against power surges. Circuit breakers consist of designed-in isolation characteristics which helps in avoiding exposure to live parts during a surge event. Besides, the circuit breaker may function as a disconnect for the down-line SPD. Therefore, an external SPD needs to distribute dedicated circuit breakers internal to the service equipment. In a fault condition, the circuit breaker disconnect within the SPD will be turned off with the purpose to prevent the damage to the service equipment since the down-line electronics do not need the SPD to complete the network.

4.5.3 External Short Circuit Protection Device (SCPD) (Citation)

SPD provides protection to electrical equipment against power surge by diverting the transient overvoltage to the ground. Every SPD has its lifespan, therefore they require to be replaced in order to provide protection continuously. In order to prevent the risk at the end of life of the SPDs and to provide the status of the SPD, a device called end-of-life indicators is installed. The end-of-life indicators consist of an internal disconnector and external short circuit protective device (SCPD). In order to guarantee reliable functioning, end-of-life indicators must be coordinated with the SPD. Coordination between end-of-life indicators and SPD will guarantee continuity of service as well as ensure effective protection against overcurrent since it is able to withstand lightning surge and will not create excessive residual voltage.

Internal disconnector is applied in a case of natural end of life due to aging. The protection type for this case shall be thermal type. Therefore, SPD with varistors must consist of an internal disconnector in order to disconnect the SPD whenever the SPD reaches its lifespan. (Eaton Powering Business Worldwide, 2017)

Short circuit fault is one of the causes of end of life of the SPDs. Occurrence of short circuit fault may be due to maximum discharge capacity exceeded. Besides, a fault due to gradual deterioration of the resistor may result in an impedant short circuit. Internal disconnector as discussed previously is thermal-based working principle. Therefore, an external short circuit protective device (external SCPD) is required to be installed with the purpose to eliminate the short circuit and prevent the heat dissipated from the impedant short circuit to damage the SPD. However, depending on the system or apparatus that it is protecting, not every SPD requires the use of external SCPD as a second layer of protection. For example, apparatus that are simple and does not contain complex or sensitive electrical system such as kitchen appliances, SPD is sufficient without the use of external SCPD.

Based on IEC 61643-11, SCPD must be coordinated with the SPD, tested as well as guaranteed by the SPD manufacturer to ensure the protection. This external SCPD must coordinate with the SPD to guarantee the design meets two constraints which include lightning current withstand and short-circuit current withstand. The external SCPD must be able to withstand upon 15 successive impulse currents at nominal discharge current, In created by lightning without interruption. Besides, IEC 62304 stated that the breaking capacity of external SCPD must be designed equal or greater than the prospective short-circuit current Isc at the installation point.

Further, two installation modes for external SPD are available, which are series mode and parallel mode. Figure 97 demonstrates the SCPD connected in series mode where the protection is provided by the general protection device of the system to be protected. For instance, the protection is provided by connecting the circuit breaker upstream of an installation. Meanwhile, Figure 98 shows the SCPD installed in parallel mode where the protection is provided specifically by a protection device associated with the SPD. Figure 99 shows the SPDs with external SCPD. This protective device may or may not be integrated into the SPD. If the protection device applied is a circuit breaker, the external SCPD is also known as “disconnecting circuit breaker”.

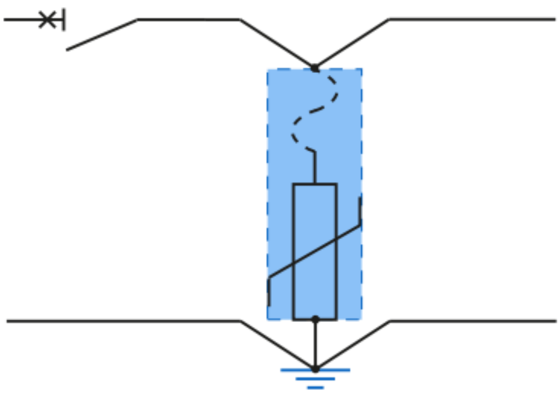


Figure 97: Series installation mode for external SCPD (Eaton Powering Business Worldwide, 2017)

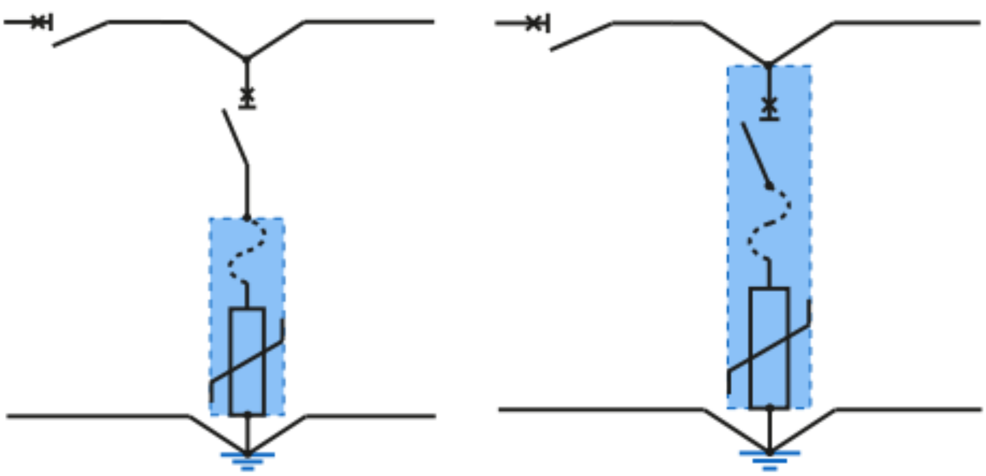


Figure 98: Parallel installation mode for external SCPD (Eaton Powering Business Worldwide, 2017)

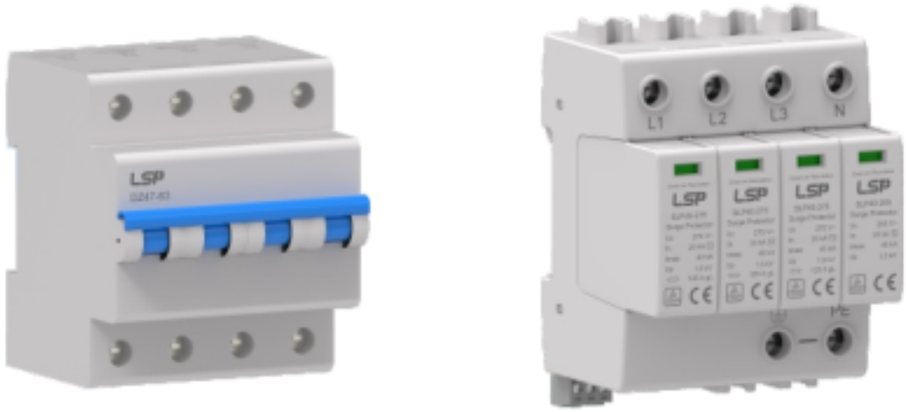
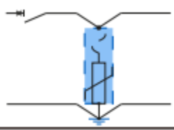
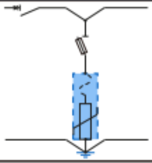
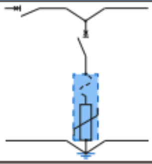
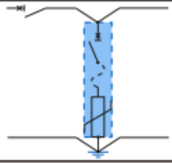


Figure 99: SPDs with external SCPD

The IEC 60947-3 standard must be applied whenever switch-disconnector or fuse protection is involved in a design. A switch-disconnector offers an isolation function when it is in an open position. In contrast, a switch-disconnector switches on the current under a close position. Based on Table 23, the protection is provided by fuse and circuit breaker such as MCB due to the absence of overcurrent release in a switch-disconnector. The short circuit capacity of the combination of switch and circuit breaker is referred to as rated conditional short circuit current. It is defined as the level of the prospective short-circuit current of the switch-disconnector, protected by a short-circuit protective device (SCPD), able to withstand. Therefore, the switch disconnector must have the ability to withstand the magnitude of current limited by the SCPD.

Table 23: Features of End-of-life Protection based on External SCPDs

Installation mode for the external SCPD	In series	In parallel		
		Fuse protection associated	Circuit breaker protection associated	Circuit breaker protection integrated
				
Surge protection of equipment	=	=	=	=
	SPDs protect the equipment satisfactorily whatever the kind of associated external SCPD			
Protection of installation at end of life	-	=	+	++
	No guarantee of protection possible	Manufacturer's guarantee		Full guarantee
		Protection from impedant short circuits not well ensured	Protection from short circuits perfectly ensured	
Continuity of service at end of life	- -	+	+	+
	The complete installation is shut down	Only the SPD circuit is shut down		
Maintenance at end of life	- -	=	+	+
	Shutdown of the installation required	Change of fuses	Immediate resetting	

4.5.3.1 Cabling Rules of SCPD

Figure 100 and Figure 101 demonstrated SPD with separate external SCPD and SPD with integrated external SCPD respectively. Based on Figure 100, the length of SPD connection between the network and the earthing terminal block must be less than 50 cm. Meanwhile, for SPD with integrated external SCPD, the length of SPD connection between the network and the earthing terminal block must be less than 35 cm as shown in Figure 101.

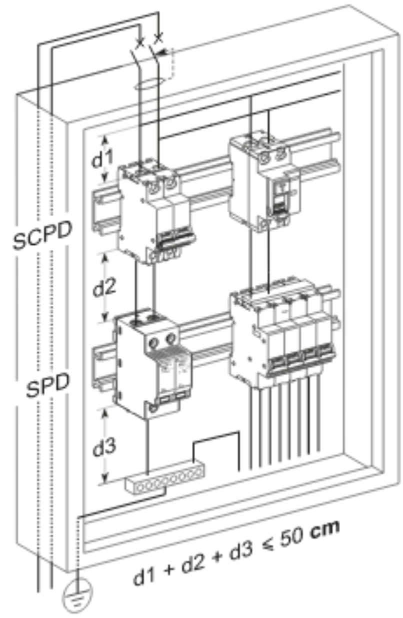


Figure 100: SPD with separate external SCPD (Eaton Powering Business Worldwide, 2017)

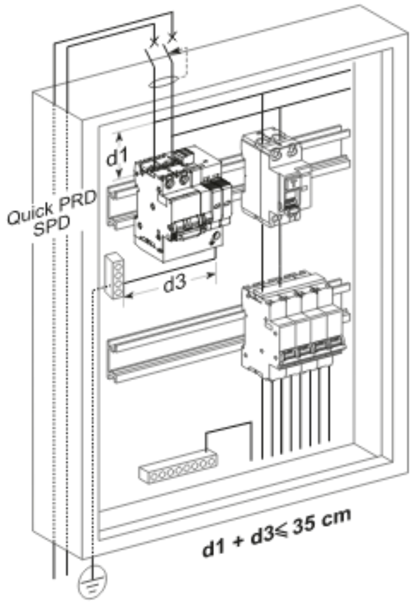


Figure 101: SPD with separate external SCPD (Eaton Powering Business Worldwide, 2017)

Second cabling rule of SCPD is to minimize the loop surface by locating the incoming feeder phase, neutral and protection (PE) conductors at the same side as shown in the right side of Figure 102. The frames of enclosures must also be earthed through very short connections. Further, the incoming conductors of the SPD should be remote from the protected outgoing conductors to avoid polluting them by coupling as demonstrated in Figure 102.

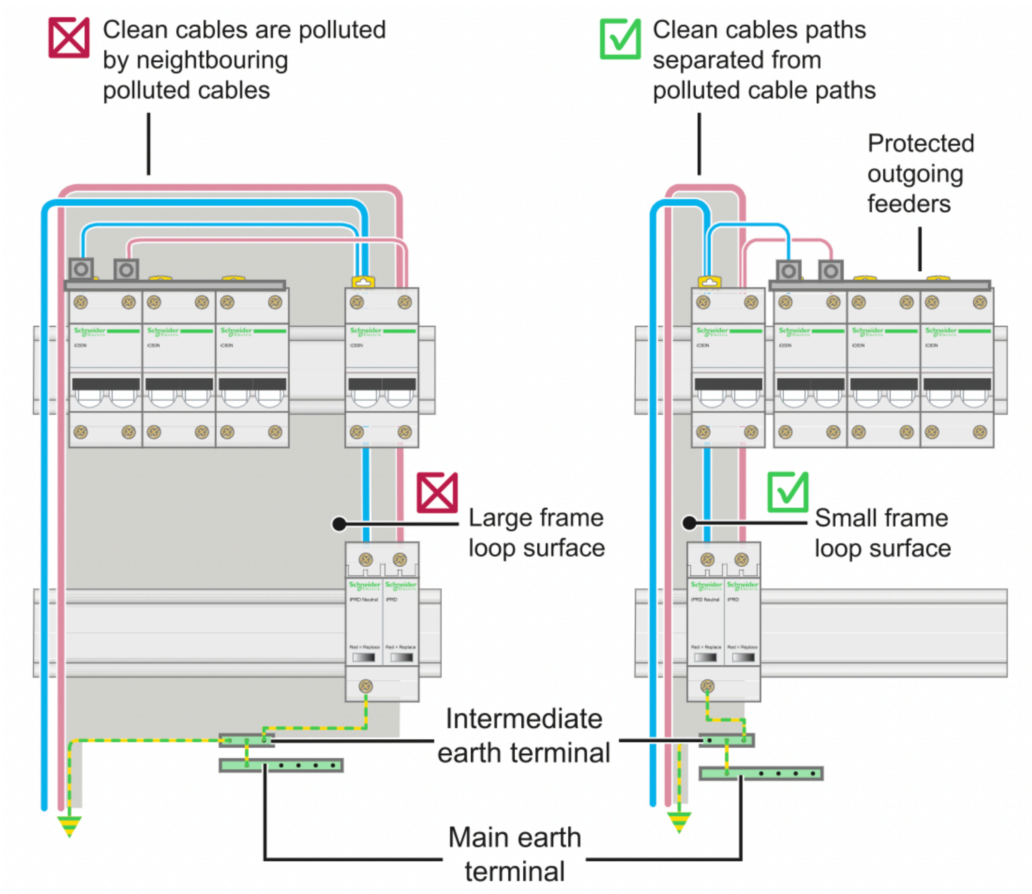


Figure 102: Cabling Rules of SCPD for improvement of EMC

4.6 Proper Installation Practices and Effects of Excessive Lead length on SPD

Voltage protection level of a SPD can be determined by voltage protection ratings (VPR). In order to protect the downstream load from transient overvoltage, the VPR is usually set at the value that is less than five times of the rated voltage.

The lead length of SPD may also affect the clamping voltage level. The clamping voltage level is directly proportional to the lead length of SPD. Therefore, a longer lead length will bring down the effectiveness and performance of SPD in protecting downstream electronics. The fundamental cause of this is high inductance present in the circuit, which will then introduce higher impedance to the high frequency surge event. In contrast, shorter wire leads bring down the effective voltage protection rating, which offers better protection. Table 24 shows the effect of let-through voltage of SPD based on size of conductor. Based on Table 24, a conductor with smaller size has low voltage drop across the conductor, which also means that conductor with smaller size has higher let-through voltage. This high let-through voltage of the installed SPD will reduce the effectiveness and reliability of the SPD to protect the connected loads.

Table 24: Effects of Let-through Voltage if SPDs Based on Size of Conductor (Jeremy Lieland, 2021)

Peak Amplitude of 8/20 μs Surge Current (Amperes)	Voltage Drop of Conductor (12 inches)	Voltage Drop of Conductor (36 inches)
500	22	66
1,000	44	132
3,000	132	395
10,000	439	1316
15,000	658	1974
25,000	1097	3290

A test was carried out to evaluate the wire lead length effects in different installation conditions. For the first test, the wire leads were separated by 25mm as shown in Figure 103. Two wire leads with different length are utilized for this test. Table 25 demonstrates the results obtained from this test for the two wire leads. According to Table 25, Sample 1 can be performed at or better than the rated voltage protection rating only up to 6 inches for the L-N mode while 12 inches for the L-L mode. The voltage protection rating for sample 2 is 700V and 1000V for L-N mode and L-L mode respectively. Based on Table 25, Sample 2 can be performed effectively up to 12 inches for the L-N mode and 15 inches for L-L mode. Further, Table 25 demonstrated the results obtained for conductor length up to 36 inches. The increased wire lengths exceeding 36’’ will keep on increasing the voltage protection rating of the SPD system and lead to ineffective at protecting downstream electronics.

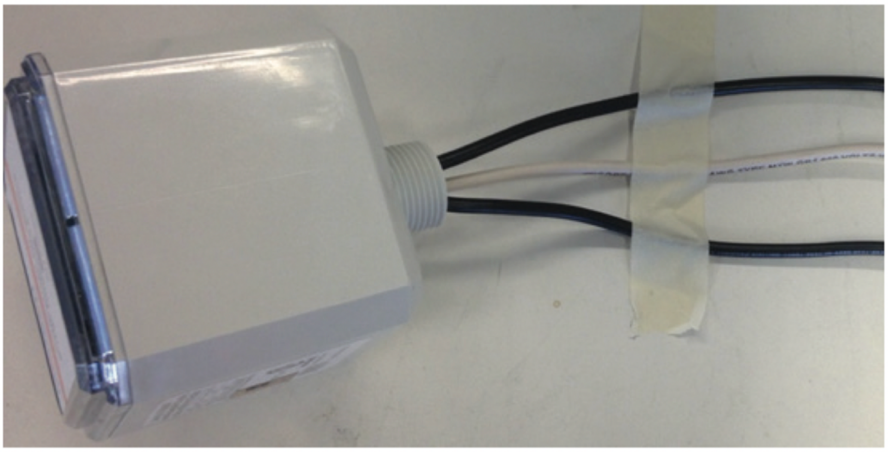


Figure 103: Wire Lead Separated by 25mm, Straight Wire (Jeremy Lieland, 2021)

Table 25: Voltage protection Rating for Different Wire Lead Length, Straight Wire, Separated by 25mm (Jeremy Lieland, 2021)

Conductor Length	Sample 1 L-N Test Result VPR=600	Sample 1 L-L Test Result VPR=1000	Sample 2 L-N Test Result VPR=700	Sample 2 L-N Test Result VPR=1000
36"	1200	1800	1200	1500
33"	1000	1500	1200	1500
30"	1200	1500	1000	1500
27"	900	1500	1000	1200
24"	900	1500	900	1200
21"	900	1200	800	1200
18"	800	1200	800	1200
15"	800	1200	800	1000
12"	700	1000	700	1000
9"	700	1000	700	1000
6"	600	900	600	900
3"	600	900	600	900

The second test performed is shown in Figure 104 where the wire leads were tie-wrapped. Tie wrapping may reduce the inductance in the circuit as it allows the magnetic fields produced by the current flow to be canceled. Table 26 demonstrates the results obtained from this test. According to Table 26, Sample 1 is able to hold the standard voltage protection rating up to 18 inches for L-N mode as well as up to 24 inches for L-L mode. The increased wire lengths exceeding these lengths will lead to ineffective at protecting downstream electronics. Besides, by comparing the results obtained from Test 1 and Test 2, the maximum length of wire lead for tie-wrapped cable is longer as compared to wire leads separated by 25mm.

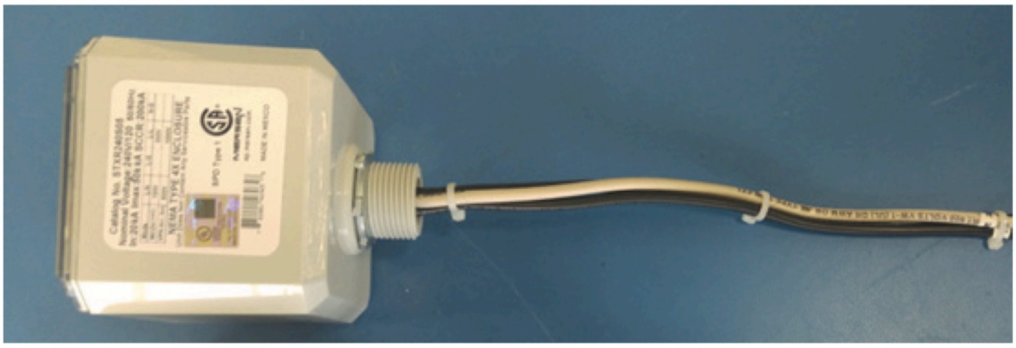


Figure 104: Straight Tie Wrapple Cable (Jeremy Lieland, 2021)

Table 26: Voltage protection Rating for Different Wire Lead Length, Straight Wire, Tie-wrapped (Jeremy Lieland, 2021)

Conductor Length	Sample 1 L-N Test Result VPR=600	Sample 1 L-L Test Result VPR=1000	Sample 2 L-N Test Result VPR=700	Sample 2 L-N Test Result VPR=1000
36"	800	1200	800	1200
33"	700	1200	800	1200
30"	700	1200	800	1200
27"	700	1200	800	1200
24"	700	1000	800	1200
21"	700	1000	700	1000
18"	600	1000	700	1000
15"	600	1000	700	1000
12"	600	900	700	1000
9"	600	900	700	1000
6"	500	900	600	900
3"	500	900	600	900

Further, the third test is conducted by using twisted cable as shown in Figure 105. Twisted may negate the effects of inductance in the circuit. Table 27 demonstrates the results obtained from this test. Based on Table 27, Sample 1 is able to perform at or better than the rated voltage protection rating up to 14 inches in L-N mode and 36 inches in L-L mode. Meanwhile, sample 2 is able to hold the standard voltage protection rating up to 21 inches for both the L-N mode and L-L mode. From the results obtained, twisted cable offered a longer length of wire with small effects to the voltage protection rating.

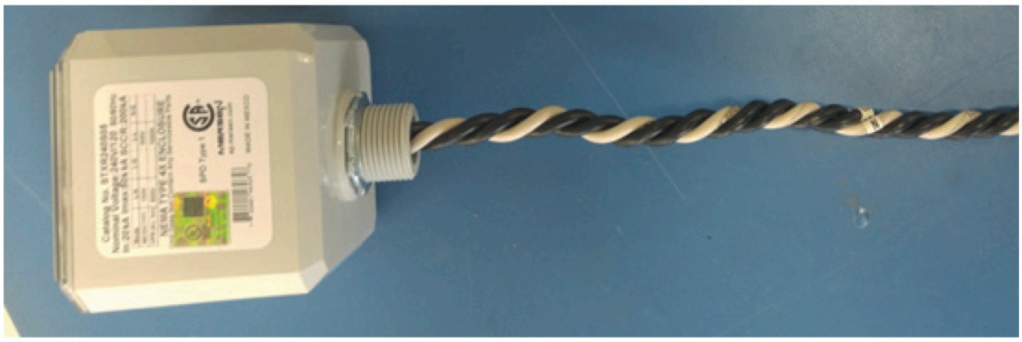


Figure 105: Twisted Cable (Jeremy Lieland, 2021)

Table 27: Voltage Protection Rating for Twisted Wire (Jeremy Lieland, 2021)

Conductor Length	Sample 1 L-N Test Result VPR=600	Sample 1 L-L Test Result VPR=1000	Sample 2 L-N Test Result VPR=700	Sample 2 L-N Test Result VPR=1000
36"	700	1000	800	1200
33"	700	1000	800	1200
30"	700	1000	800	1200
27"	700	1000	800	1200
24"	600	1000	800	1200
21"	600	1000	700	1000
18"	600	900	700	1000
15"	600	900	700	1000
12"	600	900	700	1000
9"	500	900	700	1000
6"	500	900	600	900
3"	500	900	600	900

Moreover, a conductor with sharp bends will significantly increase the let through voltage of the SPD. This is because bends in wiring introduce a wire loop which will contribute a significant increment in inductance. The increment in the circuit inductance will lead to increasing in the voltage protection rating. Therefore, wires are recommended to be laid in straight and the bends in wiring must not be greater than the recommended bend radius in order to hold the added inductance to a minimum.

The recommended distance for installing an SPDs is to make it as close to the protecting system or equipment as possible with the cable connecting in between and be as straight as possible. The straight cable will avoid additional inductive impedance to the system. In addition, with the cable tie wrapped allows the device to function within the Voltage Protection Rating (VPR). This is proven to be true from Table 24 and Table 25 showing the result of a tie wrapped and separated straight cable with tie wrapped cable achieving double the distance with similar VPR. If the cable exceeds 6 inches, it should be twisted to further maintain its VPR with greater length as shown in Table 26 where it could reach up to 18 inches in length. In case it needs to be bent, the bend radius should be within normal bend radii and not be looped.

4.7 Methods to Monitor the Operational Status of SPD (Citation)

As discussed previously, SPD can be installed externally through a hardwire external surge panel or mounted inside the distribution equipment. SPDs are usually connected in parallel, so that the failure of SPD will not be immediately noticed by the consumer. Therefore, a monitoring device must be installed to ensure the SPD is able to operate correctly. Several types of monitoring devices can be applied to evaluate the operating status of the SPD.

The monitoring devices can be audible or visual such as Light Emitting Diodes (LEDs). Both the audible and visual monitoring devices are only useful for small areas. Visual monitoring devices are the most popular type in the field while audible monitoring devices such as alarms are usually applied in a low-traffic area. Further, remote monitoring devices are useful for a building system or remote location as the dry contacts will change state if a surge event occurs.

4.7.1 Types of SPD Monitoring Devices

Several types of monitoring devices are available to monitor the operational status of the SPD. These monitoring devices have their advantages and disadvantages based on the application needs. Though there are several types of faults such as short circuit, open circuit and high impedance fault, among all these, short circuit fault is the most common and severe fault. Therefore, short circuit fault is taken as a reference for SPD monitoring devices to monitor against. A few examples of monitoring devices which use short circuit faults as reference are the visual monitoring devices, audible alarms, electrical monitoring devices, surge counter, and event recording.

4.7.1.1 Visual Monitoring Devices

Visual monitoring devices provide visual signals to specify the operational status of SPD. A light-emitting diodes (LED) or neon lamps are usually applied as visual monitoring devices.

A SPD without an internal disconnector will result in a short circuit current. This short circuit current will trip the upstream breaker but resetting the upstream breaker might not necessarily pinpoint the problem to the failed SPD. A SPD complete with an internal disconnector might coordinate with the upstream breaker and disconnect the SPD in the case of a surge event. After resetting the upstream breaker, the power system will be returned to a no-fault condition but without providing any surge protection. Therefore, a visual on or off indication is required to indicate the operational status of SPD.

The lifespan of neon lights is around one to two years. The SPD will be transformed to a model without any monitoring devices after the neon lights are burnt out. A more advanced visual indicator, which is known as two-state light, is applied as visual monitoring devices of SPD. Lifespan of LEDs is longer as compared to a neon light. Two-state light includes green LED and red LED. Green

LED illustrates the SPD is operating correctly while red LED illustrates a fault condition. Thus, SPD will switch off the green LED and switch on the red LED in a surge event. Further, three-state light can be built by connecting an extra yellow LED.

However, an issue faced in visual monitoring devices is that the meaning of the lighting is not standardized. This may lead to misunderstanding in the meaning of these lights and the failure of the SPD is not aware. (Martzloff, 1998) Therefore, a clear explanation which indicates the functioning of the monitoring device must be listed within the instruction manual in order to ensure the maintenance staff fully understand the meaning of the lights.

4.7.1.2 Audible Alarms

One of the limitations of visual monitoring devices is that users might not notice the lighting signal. Audible alarms are monitoring devices which produce sound signals to notify users in the case of failure of SPD. Sound signals are easier to be noticed by the user as compared to visual signals. In general, the sound of alarms can be heard in the corridor beside the electrical room, even through a wall or closed door. Nevertheless, a buzzer with small size is usually implemented in SPD monitors where it is easily swamped by a noisy environment.

4.7.1.3 Electrical Monitoring Devices

Form C relay is usually applied as SPD electrical monitoring devices. It has one set of contacts that consist of a normally-open and normally-close contact with a common terminal. In the case of a fault occurring, the normally-open contact will switch to close position while the normally-close contact will become open. A normal condition of a SPD refers to an unpowered condition. The Form C relay markings are in contrast to the SPD. For instance, in the case of the normal condition for the SPD is powered, the Form C relay must be installed in such a way that it tells the system that it is not faulted when powered. A visual indicator such as red lamp or audible alarms such as horn is connected through the normally open circuit in order to alert the maintenance staff of the problem. As mentioned earlier, the normally-open terminal of Form C relay will become closed during a fault condition. Therefore, the relay will close and trigger on the lamp and horn once the unit changes state with the purpose to announce the fault visually or audibly.

However, one of the limitations of Form C relay is that the electrical ratings provided by the manufacturer which included maximum voltage, current, power and VA ratings should not be exceeded. This does not affect dry contact monitoring devices as low power and voltage is applied. However, there is an issue that arises when external loads are connected due to the electrical ratings that can easily be exceeded whenever extra loads are added. This will cause damage to the relay and lead to improper monitoring works. (James, Funke, 2004)

4.7.1.4 Surge Counter

A surge counter is a monitoring device that measures the voltage and records voltages over preset level as a surge were depending on the preset level, it could be configured to detect either lightning surge, switching surge or transformer transient surge due to their difference in magnitude of surge current and voltage. To protect a system from these different types of surges, it will require to install multiple surge counters each with a preset level to detect specific surges. The surge counter uses the combination of frequency and voltage or current to decide if a surge is to be recorded. This device is installed in series with SPD with the purpose of ensuring the SPD is functioning properly as it should to reduce the impact on the distribution system as a surge event occurs. An ideal SPD will reduce the effect of a surge onto the distribution system to the point where there is no noticeable change. In the event that an SPD fails to respond to a surge, the surge counter will detect the high surge voltage or current and record its occurrence. The records can then be reviewed to ensure the system is protected from surge, for example a site with 3 surges each month over the past years experiences 20 surges in last months should be looked at on the well-being of the SPD. While the surge counter does not function to actively protect the system from surge like an SPD does, it serves a purpose to tell if a distribution system is vulnerable to a surge in the near future from the number of surges it encounters in the past. (James, Funke, 2004)

4.7.1.5 Protection or Life Remaining

Monitoring the remaining lifespan of an SPD is another way of ensuring a distribution system is surge protected. Ideally, an SPD with infinite lifespan is desirable, unfortunately that would be impractical as the device will either be too expensive or too high in voltage protection level to protect downstream equipment or both. However, on small SPDs, its remaining lifespan is shown by an indication light of varying color in red and green to indicate life at 0% and 100% respectively. On larger SPDs, those utilize multiple internal surge components where each is fused or monitored to determine its remaining life through counting the number of active internal components based on its nominal number of internal components. Its remaining life can then be indicated through indication lights of red, yellow and green or showing the remaining percentage. The other approach is through measuring the aspect of the surge protection such as the voltage let-through, leakage current, or voltage at fixed current. This approach requires the effect of the distribution system to be removed as well as the SPD to be disconnected from the system to measure those aspects. Therefore, this method is less preferred due to the additional maintenance and time required to consistently and repeatedly obtain the parameters to determine the SPDs lifespan.

4.7.1.6 Event Recording

The surge counter or event counter is improved to not only allow the record of surge count but also its magnitude, date and time of its occurrence. The reason for this additional feature is to provide detail to users on when each surge event occurs to provide users with logs to review events occurred in the past week or year or even one second prior to a shutdown caused by an event. In addition, the record of surge magnitude that shutdown a system further helps in fixing the problem. Therefore, event recording is more useful compared to event counting. (James, Funke, 2004)

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In a nutshell, source of surge can be classified into external power surge and internal power surge. The external power surge is normally results from lightning which is the most obvious source of surge. However, the internal power surge result from switching and this surge can be induced into building by inductive, capacitive and resistive coupling.

Based on the simulation results obtained, it demonstrated that the waveform generated by the equivalent model of surge generator designed in MATLAB Simulink is compliant with IEC standard. The front time and time of the lightning surge waveform can be controlled by circuit parameters of surge generator equivalent circuit such as α, β and the value of resistors and capacitors. The lightning surge waveforms of MOV, power electronics which included MOSFET and IGBT are also generated by the equivalent model of surge generator. Furthermore, the prototype is built and tested with surge generator in the hardware prototype experiment. The behaviours of MOV, MOSFET and IGBT are studied from the standard lightning surge waveform obtained in the hardware prototype experiment.

The results obtained in the hardware prototype experiment is similar to the simulation results obtained in MATLAB Simulink. Both results proved that power electronics can function similarly as the conventional SPD to clamp voltage surge at a specific level. However, the clamping voltage level of power electronics is lower than conventional SPD.

The failure mode of MOV is considered to be open circuit as the resistance value increased tremendously when MOV burnt. On the contrary, the failure mode of MOSFET is short circuit. Therefore, the setup equipment of the MOSFET can be protected from surge during failure mode since its failure mode is short circuit. According to the result obtained, it proved that the response time of power electronics is faster as compared to conventional SPD. In a nutshell, power electronic is proven to be a potential candidate as a surge protection device as it has better performance and able to overcome the drawbacks of conventional protection method.

By comparing the characteristics of the internal and external SPD, it is obvious that external SPD provides more advantages related to safety. This is because in the case of damage caused by a surge event, an externally mounted electrical panel will be able to contain the damage and isolate itself from spreading the damage onto other components within a facility. In an event of a surge that causes MOV failure and smoke within an external SPD, the residue from the damage will be less likely to contaminate the protecting facility or equipment resulting in arc flash or downtime. Further, the number of SPD required to be installed depends on the size of the site and the sensitivity of the electrical equipment. Although several types of SPD are introduced, the ultimate goal and purpose of these remain focused on clamping surge voltage or current down to a specified voltage protection rating.

The clamping voltage level can be affected by the lead length of SPD. An increment in lead length of SPD will lead to an increment in clamping voltage level. The recommended distance for installing an SPDs is to make it as close to the protecting system or equipment as possible with the cable connecting in between and be as straight as possible. Amongst the cables, twisted is able to achieve the longest distance while maintaining within its voltage protection rating.

5.2 Recommendation

In this project, only the behavior and performance of MOV, MOSFET and IGBT are studied. However, further study in other electronics such as Gas Discharge Tube (GDT) and Bipolar Junction Transistor (BJT) can be performed. The failure mode related to temperature and surge count can be further investigated. Under repetitive pulse test, MOV will be heated up after multiple surges are applied whereas MOSFET and IGBT would not. Hence, the temperature of MOV can be used to measure to further study on the health condition of MOV and a surge generator with smaller surge interval can be applied on power electronic to increase its temperature as the power electronic are not able to cool down within the short period. Last but not least, the response time for conventional SPD and SPD by power electronics to turn off after the surge is over can be further studied as this research was only investigated the turn-on time.

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APPENDIX

APPENDIX A: BS_EN_IEC_62305 Lightning Protection Standard

Guide to BS EN/IEC 62305 Introduction

BS EN/IEC 62305 Lightning protection standard

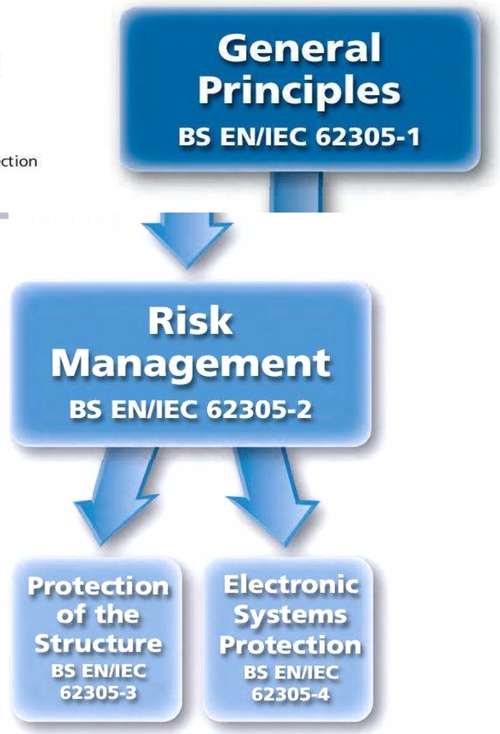
The BS EN/IEC 62305 Standard for lightning protection was originally published in September 2006, to supercede the previous standard, BS 6651:1999.

For a finite period BS EN/IEC 62305 and BS 66
ı in parallel, but as of August 2008, BS 6651 has
en withdrawn and now BS EN/IEC 63205 is the
:ognised standard for lightning protection.

e BS EN/IEC 62305 standard reflects increased
entific understanding of lightning and its effects
er the last twenty years, and takes stock of the
owing impact of technology and electronic systems
our daily activities. More complex and exacting
an its predecessor, BS EN/IEC 62305 includes four
tinct parts - general principles, risk management,
ysical damage to structures and life hazard, and
ctronic systems protection.

ese parts to the standard are introduced here. In
10 these parts underwent periodic technical review,
th updated parts 1, 3 and 4 released in 2011.
dated part 2 is currently under discussion and is
pected to be published in late 2012.

y to BS EN/IEC 62305 is that all considerations for
htning protection are driven by a comprehensive
d complex risk assessment and that this assessment
t only takes into account the structure to be
otected, but also the services to which the structure
onnected. In essence, structural lightning protection
n no longer be considered in isolation, protection
ainst transient overvoltages or electrical surges is
egral to BS EN/IEC 62305.



ructure of BS EN/IEC 62305

e BS EN/IEC 62305 series consists of four parts, of which need to be taken into consideration. ese four parts are outlined below:

rt 1: General principles

EN/IEC 62305-1 (part 1) is an introduction to the
ner parts of the standard and essentially describes
w to design a Lightning Protection System (LPS) in
:ordance with the accompanying parts of the
ndard.

rt 2: Risk management

EN/IEC 62305-2 (part 2) risk management approach,
es not concentrate so much on the purely physical
mage to a structure caused by a lightning discharge,
t more on the risk of loss of human life, loss of
vice to the public, loss of cultural heritage and
onomic loss.

Part 3: Physical damage to structures and life hazard

BS EN/IEC 62305-3 (part 3) relates directly to the major part of BS 6651. It differs from BS 6651 in as much that this new part has four Classes or protection levels of LPS, as opposed to the basic two (ordinary and high-risk) levels in BS 6651.

Part 4: Electrical and electronic systems within structures

BS EN/IEC 62305-4 (part 4) covers the protection of electrical and electronic systems housed within structures. It embodies what Annex C in BS 6651 conveyed, but with a new zonal approach referred to as Lightning Protection Zones (LPZs). It provides information for the design, installation, maintenance & testing of a Lightning Electromagnetic Impulse (LEMP) protection system (now referred to as Surge Protection Measures - SPM) for electrical/electronic systems within a structure.

Key points **Guide to BS EN/IEC 62305**

The following table gives a broad outline as to the key variances between the previous standard, BS 6651, and the BS EN/IEC 62305.

BS 6651 standard (withdrawn August 2008)	**BS EN/IEC 62305 standard**
Document structure	
118 page document, including 9 pages devoted to risk assessment	Over 470 pages in 4 parts, including over 150 pages devoted to risk assessment (BS EN/IEC 62305-2)
Focus on Protection of Structures against Lightning	Broader focus on Protection against Lightning including the structure and services connected to the structure
Specific tables relating to choice and dimension of LPS components and conductors	Specific tables relating to sizes and types of conductor and earth electrodes. LPS components - specifically related to BS EN 50164/ IEC 62561 testing regimes
Annex B - guidance on application of BS 6651	BS EN/IEC 62305-3 Annex E - extensive guidance given on application of installation techniques complete with illustrations
Annex C - general advice (recommendation) for protection of electronic equipment with separate risk assessment	BS EN/IEC 62305-4 is devoted entirely to protection of electrical and electronic systems within the structure (integral part of standard) and is implemented through single separate risk assessment (BS EN/IEC 62305-2)
Definition of risk	
Risk (of death/injury) level set at 1 in 100,000 (1×10^{-5}) based on comparable exposures (smoking, traffic accidents, drowning etc)	3 primary risk levels defined (BS EN 62305): R_1 loss of human life 1 in 100,000 (1×10^{-5}) R_2 loss of service to the public 1 in 10,000 (1×10^{-4}) R_3 loss of cultural heritage 1 in 10,000 (1×10^{-4})
Protection measures	
Mesh arrangement is promoted as the commonly used means of air termination network	Mesh arrangement, protective angle method, catenary system, extensive use of air finials, all form part of or all of air termination network
2 levels of Lightning Protection mesh design: (20 m x 10 m; 10 m x 5 m)	4 sizes of mesh defined according to structural class of Lightning Protection System: Class I 5 m x 5 m Class II 10 m x 10 m Class III 15 m x 15 m Class IV 20 m x 20 m
2 levels of down conductor spacing: 20 m & 10 m	4 levels of down conductor spacing dependent on structural class of Lightning Protection System: Class I 10 m Class II 10 m Class III 15 m Class IV 20 m
Use of bonds promoted to minimise side flashing	Extensive sections/explanations provided on equipotential bonding
10 ohm overall earthing requirement, achieved by 10 x number of down conductors	10 ohms overall earthing requirement achieved either by Type A arrangement (rods) or Type B arrangement (ring conductor)
Requirement to bond all metallic services, (gas, water, electricity etc) to main earth terminal along with external down conductor	Requirement to bond all metallic services to main equipotential bonding bar. 'Live' electrical conductors (e.g. power, data, telecoms) bonded via Surge Protective Devices (SPDs)
Rolling sphere concept on structures over 20 m tall: 20 m sphere used on highly flammable contents/ electronic equipment within building 60 m sphere all other buildings	4 sizes of rolling sphere concept defined according to structural class of Lightning Protection System: Class I 20 m Class II 30 m Class III 45 m Class IV 60 m

BS EN/IEC 62305-1 General principles

This opening part of the BS EN/IEC 62305 suite of standards serves as an introduction to the further parts of the standard. It classifies the sources and types of damage to be evaluated and introduces the risks or types of loss to be anticipated as a result of lightning activity.

Furthermore, It defines the relationships between damage and loss that form the basis for the risk assessment calculations in part 2 of the standard.

Lightning current parameters are defined. These are used as the basis for the selection and implementation of the appropriate protection measures detailed in parts 3 and 4 of the standard.

Part 1 of the standard also introduces new concepts for consideration when preparing a lightning protection scheme, such as Lightning Protection Zones (LPZs) and separation distance.

Damage and loss

BS EN/IEC 62305 identifies four main sources of damage:

S1 Flashes to the structure

S2 Flashes near to the structure

S3 Flashes to a service

S4 Flashes near to a service

Each source of damage may result in one or more of three types of damage:

D1 Injury of living beings due to step and touch voltages

D2 Physical damage (fire, explosion, mechanical destruction, chemical release) due to lightning current effects including sparking

D3 Failure of internal systems due to Lightning Electromagnetic Impulse (LEMP)

The following types of loss may result from damage due to lightning:

L1 Loss of human life

L2 Loss of service to the public

L3 Loss of cultural heritage

L4 Loss of economic value

The relationships of all of the above parameters are summarised in Table 5.

Figure 12 on page 271 depicts the types of damage and loss resulting from lightning.

For a more detailed explanation of the general principles forming part 1 of the BS EN 62305 standard, please refer to our full reference guide 'A Guide to BS EN 62305.' Although focused on the BS EN standard, this guide may provide supporting information of interest to consultants designing to the IEC equivalent. Please see page 283 for more details about this guide.

Point of strike	Source of damage	Type of damage	Type of loss
Structure	S1	D1 D2 D3	L1, L4** L1, L2, L3, L4 L1*, L2, L4
Near a structure	S2	D3	L1*, L2, L4
Service connected to the structure	S3	D1 D2 D3	L1, L4** L1, L2, L3, L4 L1*, L2, L4
Near a service	S4	D3	L1*, L2, L4

* Only for structures with risk of explosion and for hospitals or other structures where failures of internal systems immediately endangers human life.
** Only for properties where animals may be lost.

Table 5: Damage and loss in a structure according to different points of lightning strike (BS EN/IEC 62305-1 Table 2)

Scheme design criteria

The ideal lightning protection for a structure and its connected services would be to enclose the structure within an earthed and perfectly conducting metallic shield (box), and in addition provide adequate bonding of any connected services at the entrance point into the shield.

This in essence would prevent the penetration of the lightning current and the induced electromagnetic field into the structure.

However, in practice it is not possible or indeed cost effective to go to such lengths.

This standard thus sets out a defined set of lightning current parameters where protection measures, adopted in accordance with its recommendations, will reduce any damage and consequential loss as a result of a lightning strike. This reduction in damage and consequential loss is valid provided the lightning strike parameters fall within defined limits, established as Lightning Protection Levels (LPL).

Lightning Protection Levels (LPL)

Four protection levels have been determined based on parameters obtained from previously published technical papers. Each level has a fixed set of maximum and minimum lightning current parameters. These parameters are shown in Table 6.

The maximum values have been used in the design of products such as lightning protection components and Surge Protective Devices (SPDs).

The minimum values of lightning current have been used to derive the rolling sphere radius for each level.

LPL	I	II	III	IV
Maximum current (kA)	200	150	100	100
Minimum current (kA)	3	5	10	16

Table 6: Lightning current for each LPL based on 10/350 μs waveform

For a more detailed explanation of Lightning Protection Levels and maximum/minimum current parameters please see the Furse Guide to BS EN 62305.

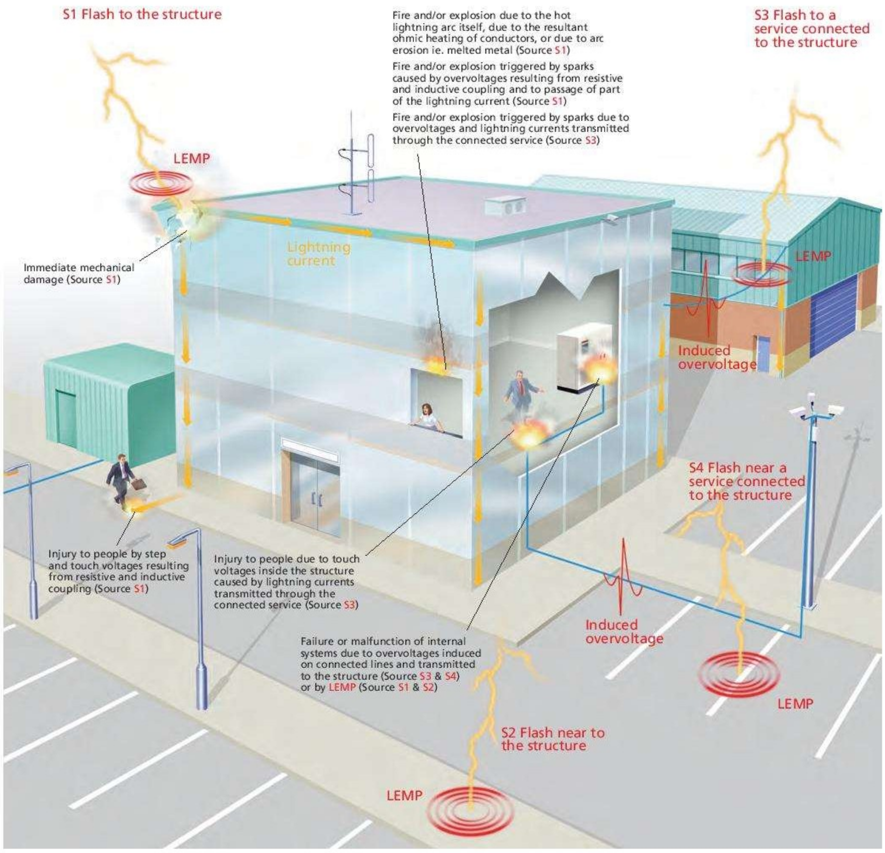


Figure 12: The types of damage and loss resulting from a lightning strike on or near a structure

Lightning Protection Zones (LPZ)

The concept of Lightning Protection Zones (LPZ) was introduced within BS EN/IEC 62305 particularly to assist in determining the protection measures required to establish protection measures to counter Lightning Electromagnetic Impulse (LEMP) within a structure.

The general principle is that the equipment requiring protection should be located in an LPZ whose electromagnetic characteristics are compatible with the equipment stress withstand or immunity capability.

The concept caters for external zones, with risk of direct lightning stroke (LPZ 0_A), or risk of partial lightning current occurring (LPZ 0_B), and levels of protection within internal zones (LPZ 1 & LPZ 2).

In general the higher the number of the zone (LPZ 2; LPZ 3 etc) the lower the electromagnetic effects expected. Typically, any sensitive electronic equipment should be located in higher numbered LPZs and be protected against LEMP by relevant Surge Protection Measures ('SPM' as defined in BS EN 62305:2011).

SPM were previously referred to as a LEMP Protection Measures System (LPMS) in BS EN/IEC 62305:2006.

Figure 13 highlights the LPZ concept as applied to the structure and to SPM. The concept is expanded upon in BS EN/IEC 62305-3 and BS EN/IEC 62305-4.

Selection of the most suitable SPM is made using the risk assessment in accordance with BS EN/IEC 62305-2.

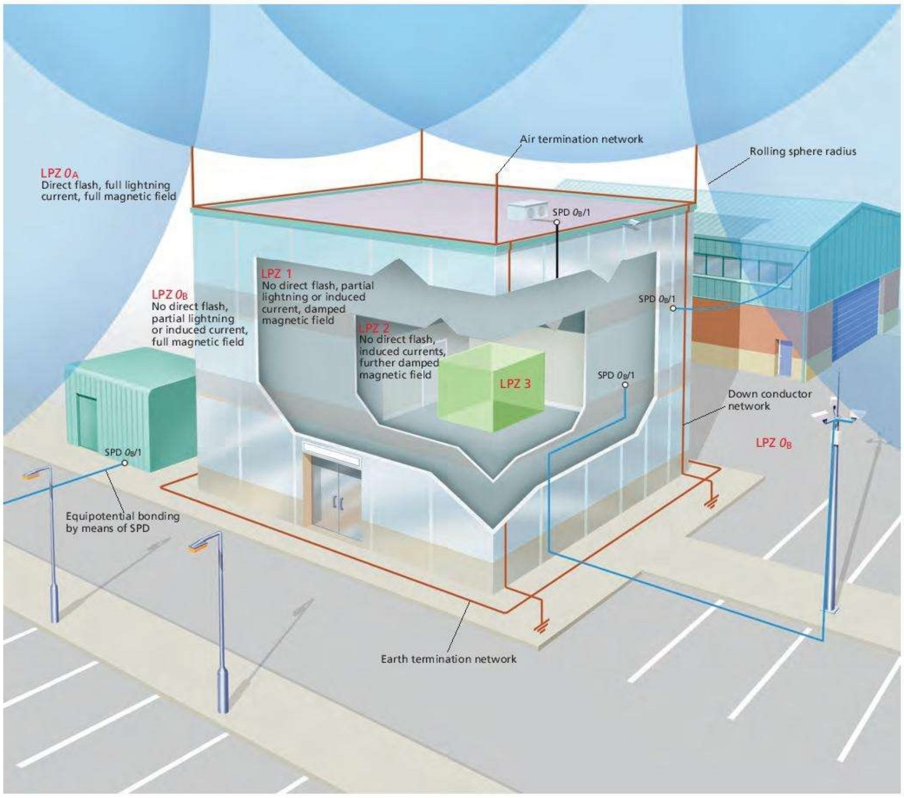


Figure 13: The LPZ concept

BS EN/IEC 62305-2 Risk management

BS EN/IEC 62305-2 is key to the correct implementation of BS EN/IEC 62305-3 and BS EN/IEC 62305-4. The assessment and management of risk is now significantly more in depth and extensive than the approach of BS 6651.

BS EN/IEC 62305-2 specifically deals with making a risk assessment, the results of which define the level of Lightning Protection System (LPS) required. While BS 6651 devoted 9 pages (including figures) to the subject of risk assessment, BS EN/IEC 62305-2 currently contains over 150 pages.

The first stage of the risk assessment is to identify which of the four types of loss (as identified in BS EN/IEC 62305-1) the structure and its contents can incur. The ultimate aim of the risk assessment is to quantify and if necessary reduce the relevant primary risks i.e.:

R_1 **risk of loss of human life**

R_2 **risk of loss of service to the public**

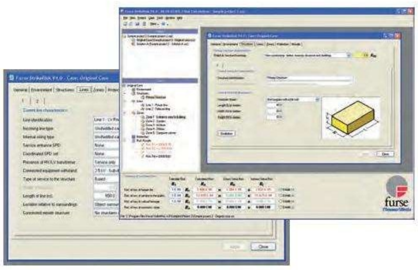
R_3 **risk of loss of cultural heritage**

R_4 **risk of loss of economic value**

For each of the first three primary risks, a tolerable risk (R_T) is set. This data can be sourced in Table 7 of IEC 62305-2 or Table NK.1 of the National Annex of BS EN 62305-2.

Each primary risk (R_n) is determined through a long series of calculations as defined within the standard. If the actual risk (R_n) is less than or equal to the tolerable risk (R_T), then no protection measures are needed. If the actual risk (R_n) is greater than its corresponding tolerable risk (R_T), then protection measures must be instigated. The above process is repeated (using new values that relate to the chosen protection measures) until R_n is less than or equal to its corresponding R_T.

It is this iterative process as shown in Figure 14 that decides the choice or indeed Lightning Protection Level (LPL) of Lightning Protection System (LPS) and Surge Protective Measures (SPM) to counter Lightning Electromagnetic impulse (LEMP).



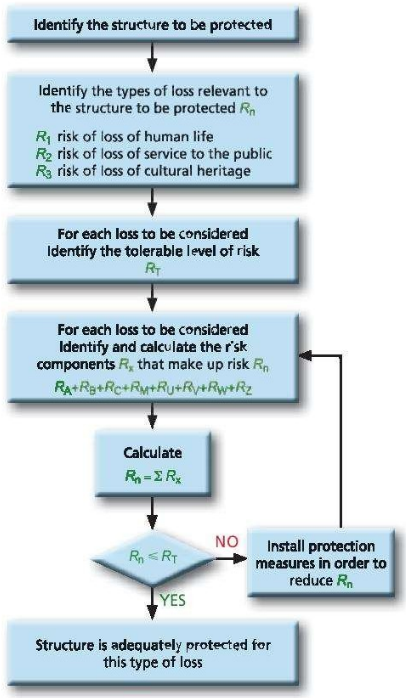


Figure 14: Procedure for deciding the need for protection (BS EN/IEC 62305-1 Figure 1)

StrikeRisk risk management software

An invaluable tool for those involved in undertaking the complex risk assessment calculations required by BS EN 62305-2, StrikeRisk facilitates the assessment of risk of loss due to lightning strikes and transient overvoltages caused by lightning.

Quick & easy to use, with full reporting capability, StrikeRisk automates risk assessment calculations and delivers results in minutes, rather than the hours or days it would take to do the same calculations by hand.

Contact Furse for more details about StrikeRisk.

BS EN/IEC 62305-3 Physical damage to structures and life hazard

This part of the suite of standards deals with protection measures in and around a structure and as such relates directly to the major part of BS 6651.

The main body of this part of the standard gives guidance on the design of an external Lightning Protection System (LPS), internal LPS and maintenance and inspection programmes.

Lightning Protection System (LPS)

BS EN/IEC 62305-1 has defined four Lightning Protection Levels (LPLs) based on probable minimum and maximum lightning currents. These LPLs equate directly to classes of Lightning Protection System (LPS).

The correlation between the four levels of LPL and LPS is identified in Table 7. In essence, the greater the LPL, the higher class of LPS is required.

LPL	Class of LPS
I	I
II	II
III	III
IV	IV

Table 7: Relation between Lightning Protection Level (LPL) and Class of LPS (BS EN/IEC 62305-3 Table 1)

The class of LPS to be installed is governed by the result of the risk assessment calculation highlighted in BS EN/IEC 62305-2.

External LPS design considerations

The lightning protection designer must initially consider the thermal and explosive effects caused at the point of a lightning strike and the consequences to the structure under consideration. Depending upon the consequences the designer may choose either of the following types of external LPS:

- Isolated
- Non-isolated

An Isolated LPS is typically chosen when the structure is constructed of combustible materials or presents a risk of explosion.

Conversely a non-isolated system may be fitted where no such danger exists.

An external LPS consists of:

- Air termination system
- Down conductor system
- Earth termination system

These individual elements of an LPS should be connected together using appropriate lightning protection components (LPC) complying (in the case of BS EN 62305) with BS EN 50164 series (note this BS EN series is due to be superceded by the BS EN/IEC 62561 series). This will ensure that in the event of a lightning current discharge to the structure, the correct design and choice of components will minimize any potential damage.

Air termination system

The role of an air termination system is to capture the lightning discharge current and dissipate it harmlessly to earth via the down conductor and earth termination system. Therefore it is vitally important to use a correctly designed air termination system.

BS EN/IEC 62305-3 advocates the following, in any combination, for the design of the air termination:

- Air rods (or finials) whether they are free standing masts or linked with conductors to form a mesh on the roof
- Catenary (or suspended) conductors, whether they are supported by free standing masts or linked with conductors to form a mesh on the roof
- Meshed conductor network that may lie in direct contact with the roof or be suspended above it (in the event that it is of paramount importance that the roof is not exposed to a direct lightning discharge)

The standard makes it quite clear that all types of air termination systems that are used shall meet the positioning requirements laid down in the body of the standard. It highlights that the air termination components should be installed on corners, exposed points and edges of the structure.

The three basic methods recommended for determining the position of the air termination systems are:

- The rolling sphere method
- The protective angle method
- The mesh method

These methods are detailed over the following pages.

The rolling sphere method

The rolling sphere method is a simple means of identifying areas of a structure that need protection, taking into account the possibility of side strikes to the structure. The basic concept of applying the rolling sphere to a structure is illustrated in Figure 15.

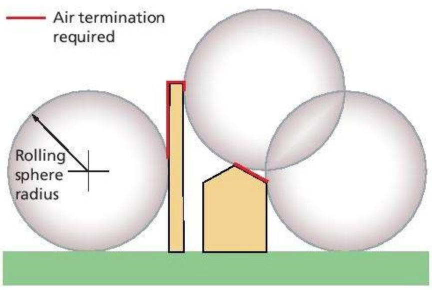


Figure 15: Application of the rolling sphere method

The rolling sphere method was used in BS 6651, the only difference being that in BS EN/IEC 62305 there are different radii of the rolling sphere that correspond to the relevant class of LPS (see Table 8).

Class of LPS	Rolling sphere radius (m)
I	20
II	30
III	45
IV	60

Table 8: Maximum values of rolling sphere radius corresponding to the Class of LPS

This method is suitable for defining zones of protection for all types of structures, particularly those of complex geometry.

The protective angle method

The protective angle method is a mathematical simplification of the rolling sphere method. The protective angle (a) is the angle created between the tip (A) of the vertical rod and a line projected down to the surface on which the rod sits (see Figure 16).

The protective angle afforded by an air rod is clearly a three dimensional concept whereby the rod is assigned a cone of protection by sweeping the line AC at the angle of protection a full 360° around the air rod.

The protective angle differs with varying height of the air rod and class of LPS. The protective angle afforded by an air rod is determined from Table 2 of BS EN/IEC 62305-3 (see Figure 17).

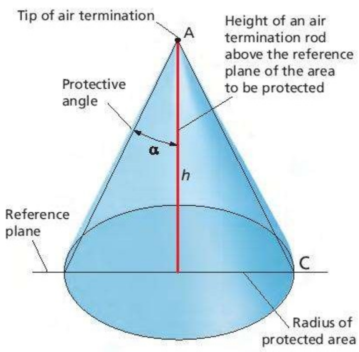
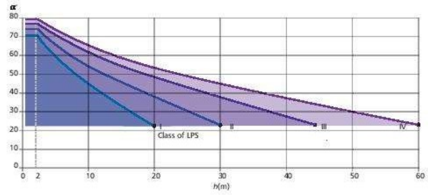


Figure 16: The protective angle method for a single air rod

Varying the protection angle is a change to the simple 45° zone of protection afforded in most cases in BS 6651. Furthermore the new standard uses the height of the air termination system above the reference plane, whether that be ground or roof level (See Figure 18).



Note 1 Not applicable beyond the values marked with ●
Only rolling sphere and mesh methods apply in these cases

Note 2 *h* is the height of air-termination above the reference plane of the area to be protected

Note 3 The angle will not change for values of *h* below 2m

Figure 17: Determination of the protective angle (BS EN/IEC 62305-3 Table 2)

The protective angle method is suitable for simple shaped buildings. However this method is only valid up to a height equal to the rolling sphere radius of the appropriate LPL.

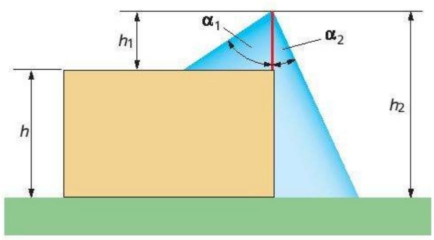


Figure 18: Effect of the height of the reference plane on the protection angle

The mesh method

This is the method that was most commonly used under the recommendations of BS 6651. Again, within BS EN/IEC 62305 four different air termination mesh sizes are defined and correspond to the relevant class of LPS (see Table 9).

Class of LPS	Mesh size (m)
I	5 x 5
II	10 x 10
III	15 x 15
IV	20 x 20

Table 9: Maximum values of mesh size corresponding to the Class of LPS

This method is suitable where plain surfaces require protection if the following conditions are met:

- Air termination conductors must be positioned at roof edges, on roof overhangs and on the ridges of roof with a pitch in excess of 1 in 10 (5.7°)
- No metal installation protrudes above the air termination system

Modern research on lightning inflicted damage has shown that the edges and corners of roofs are most susceptible to damage.

So on all structures particularly with flat roofs, perimeter conductors should be installed as close to the outer edges of the roof as is practicable.

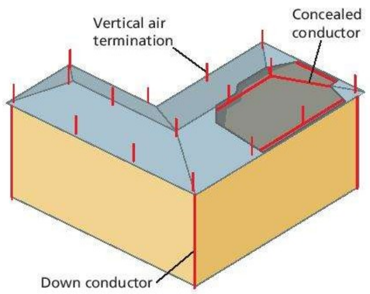


Figure 19: Concealed air termination network

As in BS 6651, the current standard permits the use of conductors (whether they be fortuitous metalwork or dedicated LP conductors) under the roof. Vertical air rods (finials) or strike plates should be mounted above the roof and connected to the conductor system beneath. The air rods should be spaced not more than 10 m apart and if strike plates are used as an alternative, these should be strategically placed over the roof area not more than 5 m apart.

Non-conventional air termination systems

A lot of technical (and commercial) debate has raged over the years regarding the validity of the claims made by the proponents of such systems.

This topic was discussed extensively within the technical working groups that compiled BS EN/IEC 62305. The outcome was to remain with the information housed within this standard.

BS EN/IEC 62305 states unequivocally that the volume or zone of protection afforded by the air termination system (e.g. air rod) shall be determined only by the real physical dimension of the air termination system.

This statement is reinforced within the 2011 version of BS EN 62305, by being incorporated in the body of the standard, rather than forming part of an Annex (Annex A of BS EN/IEC 62305-3:2006).

Typically if the air rod is 5 m tall then the only claim for the zone of protection afforded by this air rod would be based on 5 m and the relevant class of LPS and not any enhanced dimension claimed by some non-conventional air rods.

There is no other standard being contemplated to run in parallel with this standard BS EN/IEC 62305.

Natural components

When metallic roofs are being considered as a natural air termination arrangement, then BS 6651 gave guidance on the minimum thickness and type of material under consideration.

BS EN/IEC 62305-3 gives similar guidance as well as additional information if the roof has to be considered puncture proof from a lightning discharge (see Table 10).

Class of LPS	Material	Thickness(1) t (mm)	Thickness(2) t' (mm)
I to IV	Lead	-	2.0
	Steel (stainless, galvanized)	4	0.5
	Titanium	4	0.5
	Copper	5	0.5
	Aluminium	7	0.65
	Zinc	-	0.7

(1) Thickness t prevents puncture, hot spot or ignition.
(2) Thickness t' only for metal sheets if it is not important to prevent puncture, hot spot or ignition problems.

Table 10: Minimum thickness of metal sheets or metal pipes in air termination systems (BS EN/IEC 62305-3 Table 3)

Down conductors

Down conductors should within the bounds of practical constraints take the most direct route from the air termination system to the earth termination system. The greater the number of down conductors the better the lightning current is shared between them. This is enhanced further by equipotential bonding to the conductive parts of the structure.

Lateral connections sometimes referred to as coronal bands or ring conductors provided either by fortuitous metalwork or external conductors at regular intervals are also encouraged. The down conductor spacing should correspond with the relevant class of LPS (see Table 11).

Class of LPS	Typical distances (m)
I	10
II	10
III	15
IV	20

Table 11: Typical values of the distance between down conductors according to the Class of LPS (BS EN/IEC 62305-3 Table 4)

There should always be a minimum of two down conductors distributed around the perimeter of the structure. Down conductors should wherever possible be installed at each exposed corner of the structure as research has shown these to carry the major part of the lightning current.

Natural components

BS EN/IEC 62305, like BS 6651, encourages the use of fortuitous metal parts on or within the structure to be incorporated into the LPS.

Where BS 6651 encouraged an electrical continuity when using reinforcing bars located in concrete structures, so too does BS EN/IEC 62305-3. Additionally, it states that reinforcing bars are welded, clamped with suitable connection components or overlapped a minimum of 20 times the rebar diameter. This is to ensure that those reinforcing bars likely to carry lightning currents have secure connections from one length to the next.

When internal reinforcing bars are required to be connected to external down conductors or earthing network either of the arrangements shown in Figure 20 is suitable. If the connection from the bonding conductor to the rebar is to be encased in concrete then the standard recommends that two clamps are used, one connected to one length of rebar and the other to a different length of rebar. The joints should then be encased by a moisture inhibiting compound such as Denso tape.

If the reinforcing bars (or structural steel frames) are to be used as down conductors then electrical continuity should be ascertained from the air termination system to the earthing system. For new build structures this can be decided at the early construction stage by using dedicated reinforcing bars or alternatively to run a dedicated copper conductor from the top of the structure to the foundation prior to the pouring of the concrete. This dedicated copper conductor should be bonded to the adjoining/adjacent reinforcing bars periodically.

If there is doubt as to the route and continuity of the reinforcing bars within existing structures then an external down conductor system should be installed. These should ideally be bonded into the reinforcing network of the structures at the top and bottom of the structure.

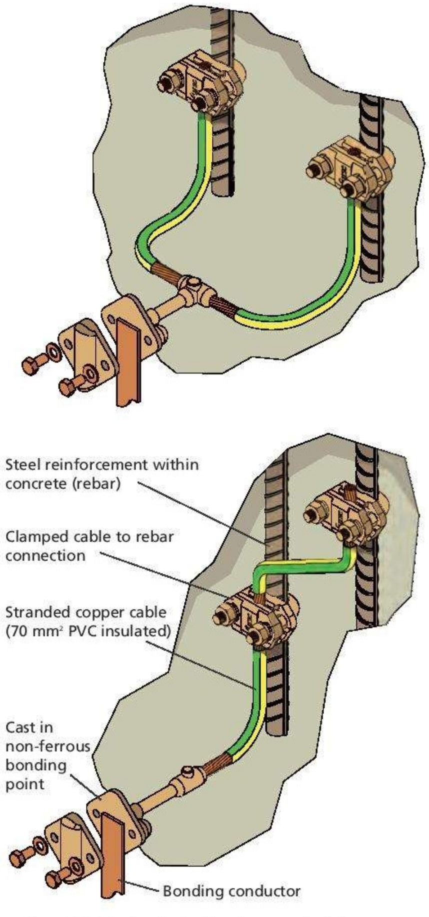


Figure 20: Typical methods of bonding to steel reinforcement within concrete

Earth termination system

The earth termination system is vital for the dispersion of lightning current safely and effectively into the ground.

In line with BS 6651, the new standard recommends a single integrated earth termination system for a structure, combining lightning protection, power and telecommunication systems. The agreement of the operating authority or owner of the relevant systems should be obtained prior to any bonding taking place.

A good earth connection should possess the following characteristics:

- Low electrical resistance between the electrode and the earth. The lower the earth electrode resistance the more likely the lightning current will choose to flow down that path in preference to any other, allowing the current to be conducted safely to and dissipated in the earth
- Good corrosion resistance. The choice of material for the earth electrode and its connections is of vital importance. It will be buried in soil for many years so has to be totally dependable

The standard advocates a low earthing resistance requirement and points out that it can be achieved with an overall earth termination system of 10 ohms or less.

Three basic earth electrode arrangements are used.

- Type A arrangement
- Type B arrangement
- Foundation earth electrodes

Type A arrangement

This consists of horizontal or vertical earth electrodes, connected to each down conductor fixed on the outside of the structure. This is in essence the earthing system used in BS 6651, where each down conductor has an earth electrode (rod) connected to it.

Type B arrangement

This arrangement is essentially a fully connected ring earth electrode that is sited around the periphery of the structure and is in contact with the surrounding soil for a minimum 80% of its total length (i.e. 20% of its overall length may be housed in say the basement of the structure and not in direct contact with the earth).

Foundation earth electrodes

This is essentially a type B earthing arrangement. It comprises conductors that are installed in the concrete foundation of the structure. If any additional lengths of electrodes are required they need to meet the same criteria as those for type B arrangement. Foundation earth electrodes can be used to augment the steel reinforcing foundation mesh.

A sample of Furse high quality earthing components.

Separation (isolation) distance of the external LPS

A separation distance (i.e. the electrical insulation) between the external LPS and the structural metal parts is essentially required. This will minimise any chance of partial lightning current being introduced internally in the structure.

This can be achieved by placing lightning conductors sufficiently far away from any conductive parts that have routes leading into the structure. So, if the lightning discharge strikes the lightning conductor, it cannot `bridge the gap' and flash over to the adjacent metalwork.

BS EN/IEC 62305 recommends a single integrated earth termination system for a structure, combining lightning protection, power and telecommunication systems.

Internal LPS design considerations

The fundamental role of the internal LPS is to ensure the avoidance of dangerous sparking occurring within the structure to be protected. This could be due, following a lightning discharge, to lightning current flowing in the external LPS or indeed other conductive parts of the structure and attempting to flash or spark over to internal metallic installations.

Carrying out appropriate equipotential bonding measures or ensuring there is a sufficient electrical insulation distance between the metallic parts can avoid dangerous sparking between different metallic parts.

Lightning equipotential bonding

Equipotential bonding is simply the electrical interconnection of all appropriate metallic installations/parts, such that in the event of lightning currents flowing, no metallic part is at a different voltage potential with respect to one another. If the metallic parts are essentially at the same potential then the risk of sparking or flashover is nullified.

This electrical interconnection can be achieved by natural/fortuitous bonding or by using specific bonding conductors that are sized according to Tables 8 and 9 of BS EN/IEC 62305-3.

Bonding can also be accomplished by the use of surge protective devices (SPDs) where the direct connection with bonding conductors is not suitable.

Figure 21 (which is based on BS EN/IEC 62305-3 fig E.43) shows a typical example of an equipotential bonding arrangement. The gas, water and central heating system are all bonded directly to the equipotential bonding bar located inside but close to an outer wall near ground level. The power cable is bonded via a suitable SPD, upstream from the electric meter, to the equipotential bonding bar. This bonding bar should be located close to the main distribution board (MDB) and also closely connected to the earth termination system with short length conductors. In larger or extended structures several bonding bars may be required but they should all be interconnected with each other.

The screen of any antenna cable along with any shielded power supply to electronic appliances being routed into the structure should also be bonded at the equipotential bar.

Further guidance relating to equipotential bonding, meshed interconnection earthing systems and SPD selection can be found in the Furse guidebook.

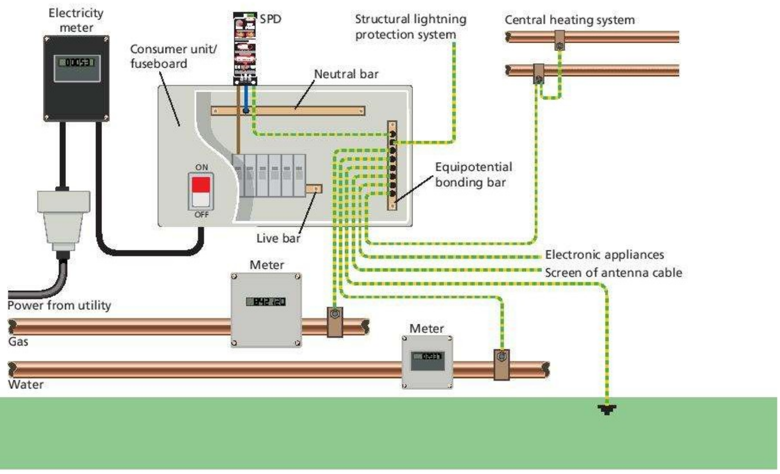


Figure 21: Example of main equipotential bonding

BS EN/IEC 62305-4 Electrical and electronic systems within structures

Electronic systems now pervade almost every aspect of our lives, from the work environment, through filling the car with petrol and even shopping at the local supermarket. As a society, we are now heavily reliant on the continuous and efficient running of such systems. The use of computers, electronic process controls and telecommunications has exploded during the last two decades. Not only are there more systems in existence, the physical size of the electronics involved has reduced considerably (smaller size means less energy required to damage circuits).

BS EN/IEC 62305 accepts that we now live in the electronic age, making LEMP (Lightning Electromagnetic Impulse) protection for electronic and electrical systems integral to the standard through part 4. LEMP is the term given to the overall electromagnetic effects of lightning, including conducted surges (transient overvoltages and currents) and radiated electromagnetic field effects.

LEMP damage is so prevalent such that it is identified as one of the specific types (D3) to be protected against and that LEMP damage can occur from ALL strike points to the structure or connected services - direct or indirect - for further reference to the types of damage caused by lightning see Table 5 on page 270. This extended approach also takes into account the danger of fire or explosion associated with services connected to the structure, e.g. power, telecoms and other metallic lines.

Lightning is not the only threat...

Transient overvoltages caused by electrical switching events are very common and can be a source of considerable interference. Current flowing through a conductor creates a magnetic field in which energy is stored. When the current is interrupted or switched off, the energy in the magnetic field is suddenly released. In an attempt to dissipate itself it becomes a high voltage transient.

Motors create switching events

The more stored energy, the larger the resulting transient. Higher currents and longer lengths of conductor both contribute to more energy stored and also released!

This is why inductive loads such as motors, transformers and electrical drives are all common causes of switching transients.

Significance of BS EN/IEC 62305-4

Previously transient overvoltage or surge protection was included as an advisory annex in the BS 6651 standard, with a separate risk assessment. As a result protection was often fitted after equipment damage was suffered, often through obligation to insurance companies. However, the single risk assessment in BS EN/IEC 62305 dictates whether structural and/or LEMP protection is required hence structural lightning protection cannot now be considered in isolation from transient overvoltage protection - known as Surge Protective Devices (SPDs) within this new standard. This in itself is a significant deviation from that of BS 6651.

Indeed, as per BS EN/IEC 62305-3, an LPS system can no longer be fitted without lightning current or equipotential bonding SPDs to incoming metallic services that have "live cores" - such as power and telecoms cables - which cannot be directly bonded to earth. Such SPDs are required to protect against the risk of loss of human life by preventing dangerous sparking that could present fire or electric shock hazards.

Lightning current or equipotential bonding SPDs are also used on overhead service lines feeding the structure that are at risk from a direct strike. However, the use of these SPDs alone "provides no effective protection against failure of sensitive electrical or electronic systems", to quote BS EN/IEC 62305 part 4, which is specifically dedicated to the protection of electrical and electronic systems within structures.

Lightning current SPDs form one part of a coordinated set of SPDs that include overvoltage SPDs - which are needed in total to effectively protect sensitive electrical and electronic systems from both lightning and switching transients.

Lightning Protection Zones (LPZs)

Whilst BS 6651 recognised a concept of zoning in Annex C (Location Categories A, B and C), BS EN/IEC 62305-4 defines the concept of Lightning Protection Zones (LPZs). Figure 22 illustrates the basic LPZ concept defined by protection measures against LEMP as detailed within part 4.

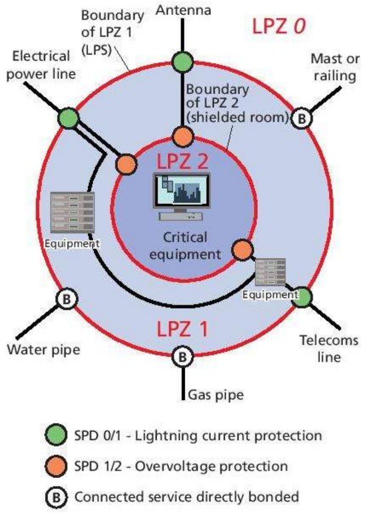


Figure 22: Basic LPZ concept - BS EN/IEC 62305-4

Within a structure a series of LPZs are created to have, or identified as already having, successively less exposure to the effects of lightning.

Successive zones use a combination of bonding, shielding and coordinated SPDs to achieve a significant reduction in LEMP severity, from conducted surge currents and transient overvoltages, as well as radiated magnetic field effects. Designers coordinate these levels so that the more sensitive equipment is sited in the more protected zones.

The LPZs can be split into two categories - 2 external zones (LPZ 0_A, LPZ 0_B) and usually 2 internal zones (LPZ 1, 2) although further zones can be introduced for a further reduction of the electromagnetic field and lightning current if required.

External zones

LPZ 0_A is the area subject to direct lightning strokes and therefore may have to carry up to the full lightning current.

This is typically the roof area of a structure. The full electromagnetic field occurs here.

LPZ 0_B is the area not subject to direct lightning strokes and is typically the sidewalls of a structure.

However the full electromagnetic field still occurs here and conducted partial lightning currents and switching surges can occur here.

Internal zones

LPZ 1 is the internal area that is subject to partial lightning currents. The conducted lightning currents and/or switching surges are reduced compared with the external zones LPZ 0_A, LPZ 0_B.

This is typically the area where services enter the structure or where the main power switchboard is located.

LPZ 2 is an internal area that is further located inside the structure where the remnants of lightning impulse currents and/or switching surges are reduced compared with LPZ 1.

This is typically a screened room or, for mains power, at the sub-distribution board area.

Protection levels within a zone must be coordinated with the immunity characteristics of the equipment to be protected, i.e., the more sensitive the equipment, the more protected the zone required.

The existing fabric and layout of a building may make readily apparent zones, or LPZ techniques may have to be applied to create the required zones.

Surge Protection Measures (SPM)

Some areas of a structure, such as a screened room, are naturally better protected from lightning than others and it is possible to extend the more protected zones by careful design of the LPS, earth bonding of metallic services such as water and gas, and cabling techniques. However it is the correct installation of coordinated Surge Protective Devices (SPDs) that protect equipment from damage as well as ensuring continuity of its operation - critical for eliminating downtime. These measures in total are referred to as Surge Protection Measures (SPM) (formerly LEMP Protection Measures System (LPMS)).

When applying bonding, shielding and SPDs, technical excellence must be balanced with economic necessity. For new builds, bonding and screening measures can be integrally designed to form part of the complete SPM. However, for an existing structure, retrofitting a set of coordinated SPDs is likely to be the easiest and most cost-effective solution.

Coordinated SPDs

BS EN/IEC 62305-4 emphasises the use of coordinated SPDs for the protection of equipment within their environment. This simply means a series of SPDs whose locations and LEMP handling attributes are coordinated in such a way as to protect the equipment in their environment by reducing the LEMP effects to a safe level. So there may be a heavy duty lightning current SPD at the service entrance to handle the majority of the surge energy (partial lightning current from an LPS and/or overhead lines) with the respective transient overvoltage controlled to safe levels by coordinated plus downstream overvoltage SPDs to protect terminal equipment including potential damage by switching sources, e.g. large inductive motors. Appropriate SPDs should be fitted wherever services cross from one LPZ to another.

Coordinated SPDs have to effectively operate together as a cascaded system to protect equipment in their environment. For example the lightning current SPD at the service entrance should handle the majority of surge energy, sufficiently relieving the downstream overvoltage SPDs to control the overvoltage.

Appropriate SPDs should be fitted wherever services cross from one LPZ to another

Poor coordination could mean that the overvoltage SPDs are subject to too much surge energy putting both itself and potentially equipment at risk from damage.

Furthermore, voltage protection levels or let-through voltages of installed SPDs must be coordinated with the insulating withstand voltage of the parts of the installation and the immunity withstand voltage of electronic equipment.

Enhanced SPDs

Whilst outright damage to equipment is not desirable, the need to minimize downtime as a result of loss of operation or malfunction of equipment can also be critical. This is particularly important for industries that serve the public, be they hospitals, financial institutions, manufacturing plants or commercial businesses, where the inability to provide their service due to the loss of operation of equipment would result in significant health and safety and/or financial consequences.

Standard SPDs may only protect against common mode surges (between live conductors and earth), providing effective protection against outright damage but not against downtime due to system disruption.

BS EN 62305 therefore considers the use of enhanced SPDs (SPD*) that further reduce the risk of damage and malfunction to critical equipment where continuous operation is required. Installers will therefore need to be much more aware of the application and installation requirements of SPDs than perhaps they may have been previously.

Superior or enhanced SPDs provide lower (better) let-through voltage protection against surges in both common mode and differential mode (between live conductors) and therefore also provide additional protection over bonding and shielding measures.

Such enhanced SPDs can even offer up to mains Type 1+2+3 or data/telecom Test Cat D+C+B protection within one unit. As terminal equipment, e.g. computers, tends to be more vulnerable to differential mode surges, this additional protection can be a vital consideration.

Furthermore, the capacity to protect against common and differential mode surges permits equipment to remain in continued operation during surge activity - offering considerable benefit to commercial, industrial and public service organisations alike.

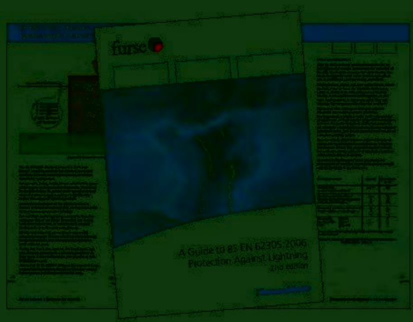
All Furse SPDs offer enhanced SPD performance with industry leading low let-through voltages (voltage protection level, U_p), as this is the best choice to achieve cost-effective, maintenance-free repeated protection in addition to preventing costly system downtime. Low let-through voltage protection in all common and differential modes means fewer units are required to provide protection, which saves on unit and installation costs, as well as installation time.

All Furse SPDs offer enhanced SPD performance with industry leading low let-through voltage

Conclusion

Lightning poses a clear threat to a structure but a growing threat to the systems within the structure due to the increased use and reliance of electrical and electronic equipment. The BS EN/IEC 62305 series of standards clearly acknowledge this. Structural lightning protection can no longer be in isolation from transient overvoltage or surge protection of equipment. The use of enhanced SPDs provides a practical cost-effective means of protection allowing continuous operation of critical systems during LEMP activity.

A Guide to BS EN 62305 Protection Against Lightning



Further to this summary on BS EN/IEC 62305, we have available a comprehensive guide to the BS EN 62305 standard for those interested in learning more about the new developments governing lightning protection design and installation. This A4 Guide helps to explain in clear terms the requirements of BS EN 62305. Following the 4 sections of the standard (Part 1 - General principles; Part 2 - Risk management; Part 3 - Physical damage to structures and life hazard; and Part 4 - Electrical and electronic systems within structures) the Guide provides the information necessary to enable the reader to identify all risks and calculate the required level of protection in accordance with BS EN 62305.

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