STUDIES AND COMPARISON OF SURGE PROTECTION DEVICES (SPDS)

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

Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

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DECLARATION

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

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"STUDIES AND COMPARISON OF SURGE PROTECTION DEVICES (SPDS)"** was prepared by **LOH KWONG SENG** has met the required standard for submission in partial fulfilment of the requirements for the award of Master of Engineering (Electrical) at Universiti Tunku Abdul Rahman.

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STUDIES AND COMPARISON OF SURGE PROTECTION DEVICES (SPDS)

ABSTRACT

Lightning is one of most destructive natural phenomena in the world. The damage it bring can be lethal to any life and also equipment. This research included the study of internal and external overvoltage transient factors, several type of lightning surge protection technologies lightning impulse generator circuits and also the calculation procedure to obtain the circuit components parameter values in order to get the desired peak voltage. MATLAB Simulink was used to investigate the overvoltage surge clamping characteristics of conventional SPD (MOV) and power electronic SPD (MOSFET). The simulation results conclude that formulas are valid and also verified the impulse waveform peak voltage level, front time and tail time can be controlled by the input voltage, capacitors and resistors values. The desired impulse waveform (1.2/50 μs or 8/20 μs) can be designed according to different calculated parameter as show in report Table 1. In addition, MOV protection circuit occurs overshot oscillatory in transient time when there is big different between in impulse peak voltage and clamping voltage level (protection voltage level). Results also show MOSFET has faster response time than MOV.

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LIST OF SYMBOLS / ABBREVIATIONS

C	capacitance
I	current
IGBT	Insulated-Gate Bipolar Transistor
LPL	Lightning Protection Level
LPS	Lightning Protection System
LPZ	Lightning Protection Zone
MOSFET	Metal-Oxide-Semiconductor Field-effect Transistor
MOV	Metal-Oxide Varistor
t_f	front time
t_t	tail time
R	resistor
t	time
V	voltage
Z	Impedance

LIST OF APPENDICES

1. INTRODUCTION

1.1 Background Study

Power surges are abnormally high voltage spikes riding on the AC power system in very short time. It is also known as the overvoltage surge or transients overvoltage. Overvoltage surges carry high energy content that can lead to fatal or deadly damage equipment connected to line or to the person who is doing the maintenance. Besides, the overvoltage surge also can damage the electronic devices which are very sensitive to the voltage level variation as their thermal capacity normally are very low. Figure 1-1 shows the damage on sensitive electronic devices due to overvoltage surges

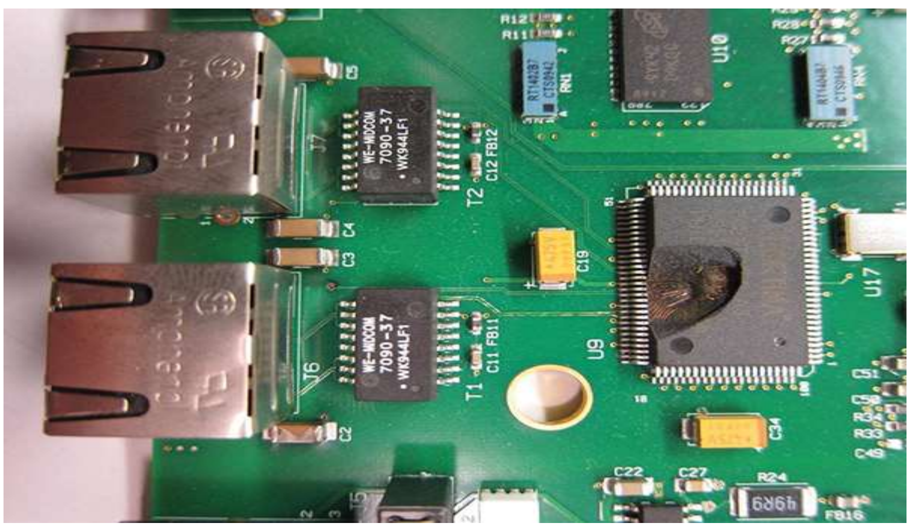


Figure 1-1 Damage on Semiconductor Electronic Devices Due to Overvoltage Surges

Overvoltage surge caused by lightning sometime can cause to fatal issue such as power equipment damage or power outages. Malaysia is a country that encounters more than 70% of power surges due to lightning. The effects of the lightning on electrical network cost over RM250 millions due to equipment damage, data losses, downtime, malfunctioning of control and most importantly thousands of human injuries and deaths. (Kadir et al., 2012).

Figure 1-2 shows lightning caused a CIPS transformer explosion at America and Figure 1-3 shows annual business losses in billions due to overvoltage surges. Figure 1-4 shows an overview of duration of power outage in worldwide.

Figure 1-2 An Ameren CIPS transformer is shown exploding caused by lightning

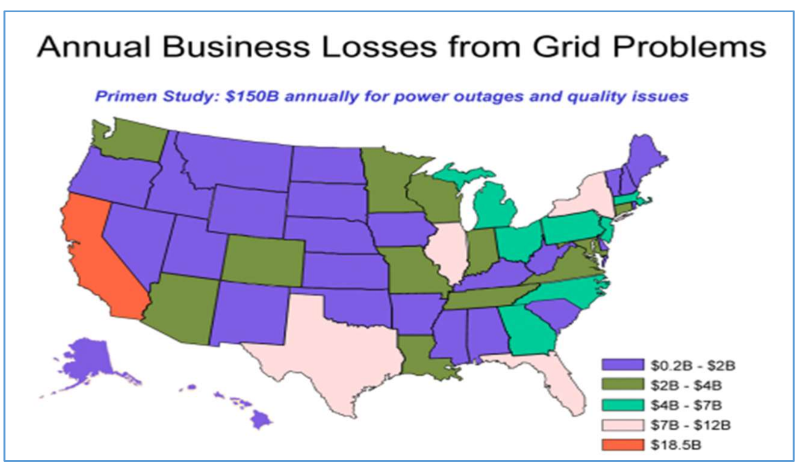


Figure 1-3 Annual Business Losses from Grid Problems in USA

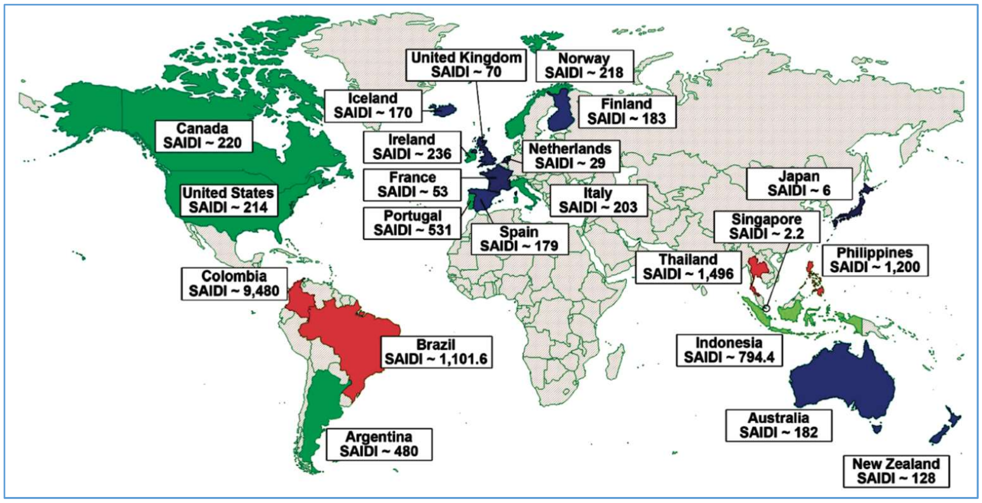


Figure 1-4 Overview over minutes of International Power Outage Comparison (data from 1992-2001)

1.2 Problem Statement

Circuit without surge protection function will be having many negative impacts or damages caused by voltage surge such as power quality issue, damaging to electronic devices, increase the risk of fire, loss of power plant, and etc. SPD is a protection device used to minimize or eliminate these losses or damages. This research study the different type of SPDs and also compare response time of conventional and power electronic SPD via MATLAB Simulink.

1.3 Aims and Objectives

This research will be going through by investigate the different type of overvoltage surge source,

The objectives of this research are:

1) Investigate different source of overvoltage surges.
2) Investigate different surge arrester technology and type.
3) Investigate lightning impulse generator circuit.
4) Compare the response time of conventional and power electronic surge arresters characteristics in term of response time.

2 LITERATURE REVIEW

2.1 Introduction

Capacitor switching and lightning are two main origins of transient overvoltages on power system. The waveform of current or voltage transient can be grouped into two categories, oscillatory and impulsive.

Impulsive transient is a sudden, non-power frequency change in the steady state condition of voltage, current or both. It is unidirectional in polarity and normally characterized by their rise and decay time and the typical example is lightning surge. Oscillatory transient can be produced when impulse transient agitate the natural frequency of power system circuit. Oscillatory transient is similar with impulsive transient, but it vary in positive and negative polarity. (Roger C. Dugan, 2012). Figure 2-1 show the typical characteristic of impulsive and oscillatory transient waveforms.

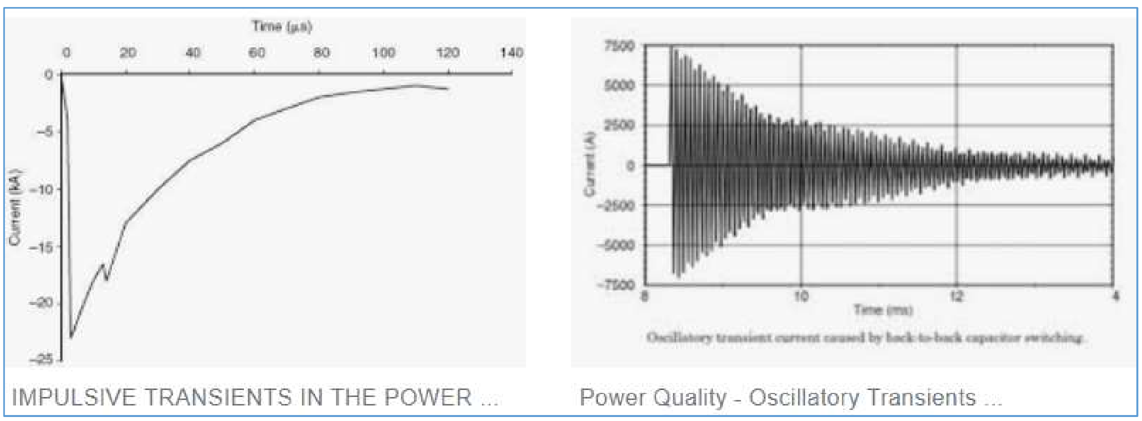


Figure 2-1 Comparison of Impulsive Transients and Oscillatory Transients

Transients can be categorized at three frequency ranges:

High-frequency - Oscillatory transient with predominate frequency component higher than 500 kHz in period of microseconds. These frequency range are normally results of the local system reacted to an impulsive transient.

Medium-frequency – Oscillatory transient with predominate frequency component between 5 to 500 kHz in period of tens of microseconds.

Low-frequency - Oscillatory transient with predominate frequency component lower than 5 kHz in period of 0.3 to 50 microseconds. This category of phenomena is often caused by the capacitor bank and energization.

Transients is also possible to be categorized according to their mode, common mode and normal mode. Normal mode is referring to line to neutral. It is also referred as differential-mode or transverse-mode noise. Larger load such as big motor or capacitor bank doing switching operation will create normal mode noise.Common mode is referring to a transient appears in between line or neutral to ground Common mode is usually generated by lightning, the circuit breakers switching operation and poor earthing. Surge protectors will result in common-mode noise because the energy from the normal-mode noise is diverted into neutral wire. Figure 2-2 shows an overview of normal mode and common mode noise.

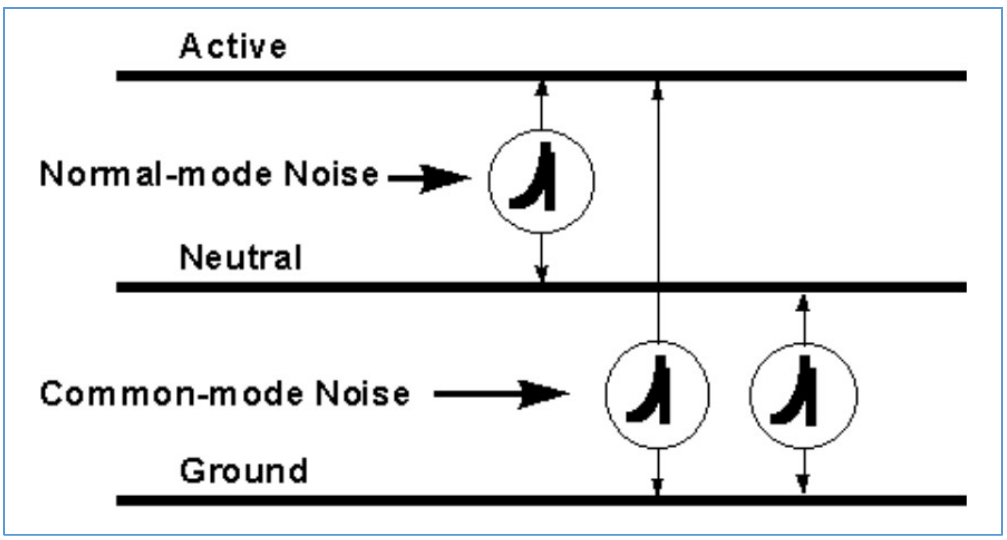


Figure 2-2 Normal-mode Noise and Common-mode Noise

The voltage tension created by over voltage has very high chance to damage the lines and equipment’s connected to the system.

There are three main factors for transient overvoltages occur on utility systems:

1. Capacitor switching
2. Ferroresonance
3. Lightning

2.2 Capacitor switching

Capacitor switching is a very common switching activity happen on utility systems. Most of utility loads are inductive and they consume lagging reactive power, hence capacitors are a countermeasure to deal with the losses caused by the reactive power on utility system. In other word, capacitor is used to produce leading reactive power to compensate lagging reactive power. However, use of capacitors will produce oscillatory transients when there is any switching process, this is one of the disadvantage that we want to minimize. Figure 2-3 shows the one line diagram of a typical utility feeder capacitor switching condition, Figure 2-4 shows the output of transient voltage is observed at the monitor location when the switch is closed.

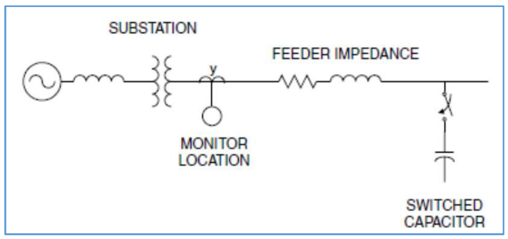


Figure 2-3 One line diagram for capacitor switching

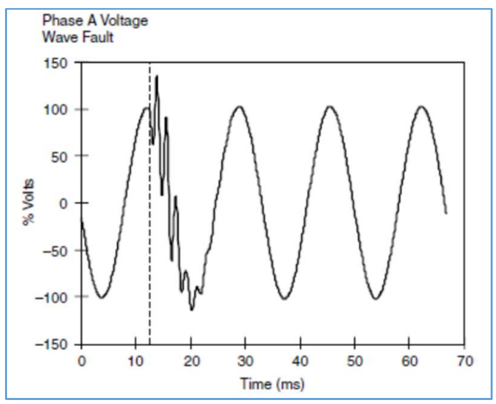


Figure 2-4 Typical utility capacitor-switching transient reaching 1.34 p.u. votlage.

When switching grounded-wye transformer banks may produce abnormal transient voltage in the local earthing system because of the current surge that accompanies the energization. Figure 2-5 shows transient current which is nearly 4 times of the load current flowing in the feeder during capacitor switching event.

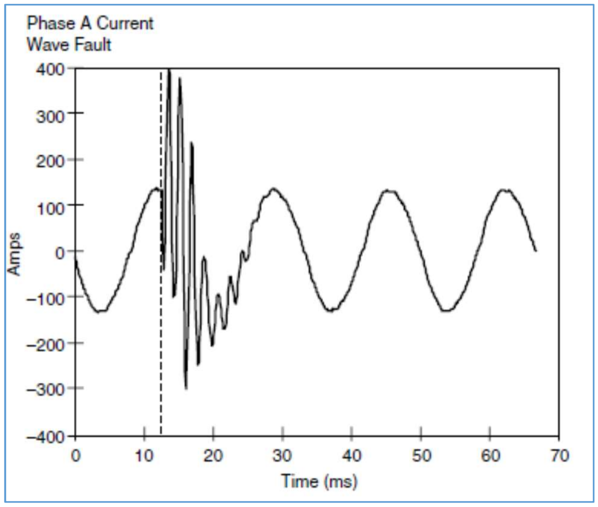


Figure 2-5 Feeder current associated with capacitor-switching event.

There are several type of capacitor switching transients:

- Isolated capacitor switching transient,
- Back to back capacitor switching transient,
- Magnification of capacitor switching transient and
- Capacitor switch restrike transient

2.2.1 Isolated Capacitor Switching Transient

Isolated capacitor switching transient is defined as energizing an isolated single or three-phase capacitor bank. When multiple three phase capacitor bank are located nearby, transient generated by energizing one bank and other remain offline is still considered as isolated capacitor switching energizing. Below Figure 2-6 shows the one line diagram of isolated capacitor bank switching and its equivalent circuit in time-domain and s-domain.

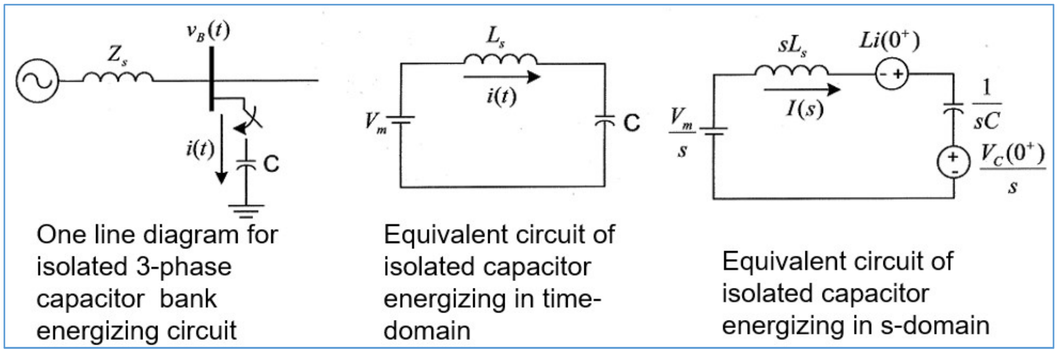


Figure 2-6 Equivalent Circuits of Isolated Capacitor Switching

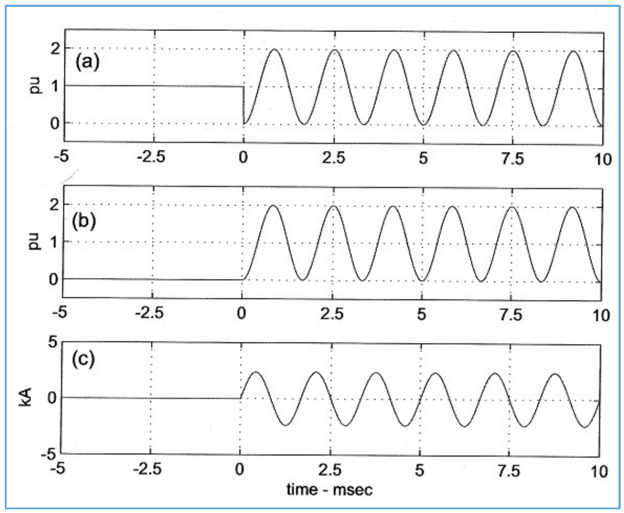


Figure 2-7 Voltage and current waveforms during isolated capacitor switching transient

Voltage and current waveforms during isolated capacitor switching transient based on assumption are show in Figure 2-7 (a) Voltage at the substation bus, (b) Voltage at the capacitor terminals and (c) Current flowing into the bank.

2.2.2 Back to Back Capacitor Switching

Back-to-back capacitor switching is defined as energizing a capacitor bank while one or more nearby capacitor banks are already energized.

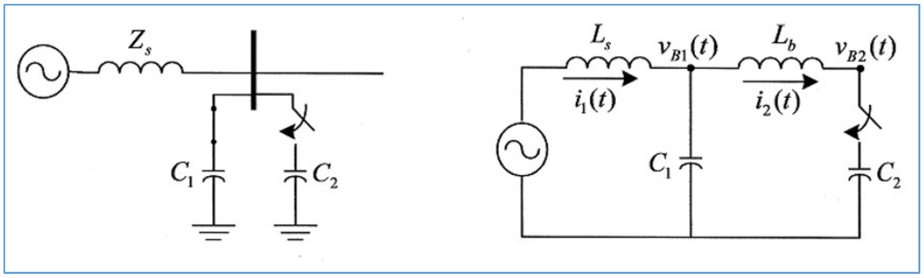


Figure 2-8 Equivalent Circuits of Back to Back Capacitor Switching

Figure 2-8 shows the typical back to back capacitor switching equivalent circuit. Capacitor C_2 is energized while a nearby capacitor C_1 is already in service. Figure 2-9 to Figure 2-12 show the voltage and current transient waveform behaviour during back to back capacitor switching. Figure 2-9 and Figure 2-10 are the voltage level measured at capacitor terminal during back to back energizing. Figure 2-11 and Figure 2-12 show inrush current value flowing into C1 and C2 respectively.

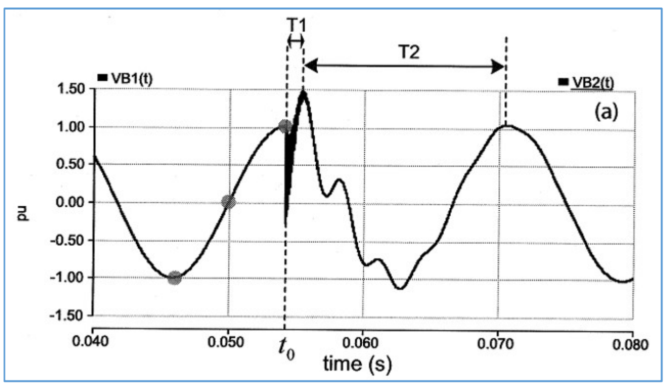


Figure 2-9 Transient overvoltage during a back-to-back energizing measured at capacitor terminals

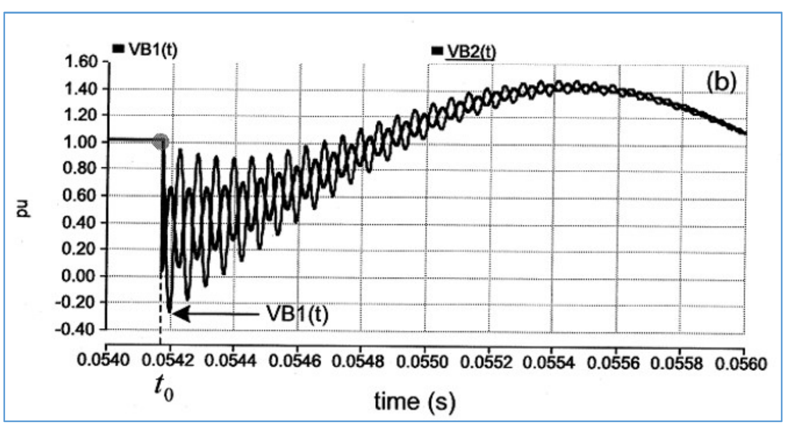


Figure 2-10 Zoom of waveforms during T1 period. Capacitor C2 is larger than capacitor C1.

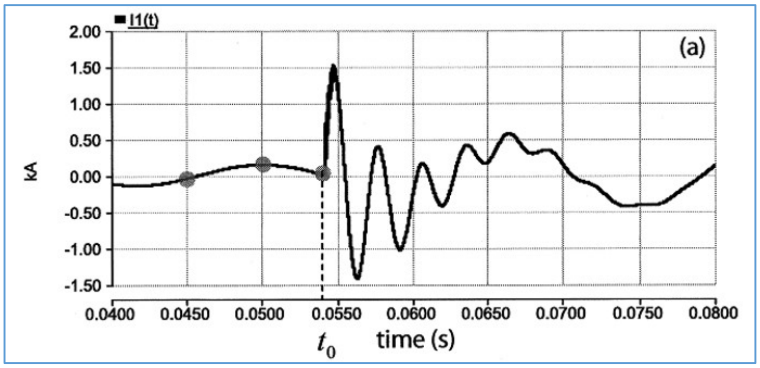


Figure 2-11 The inrush current during a back-to-back capacitor energizing. (a) Current $i_1(t)$ *into* C1 and C2

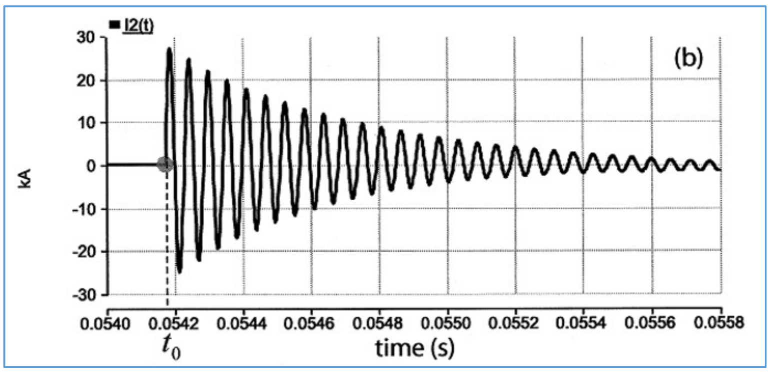


Figure 2-12 The inrush current during a back-to-back capacitor energizing. (b) Current into C2

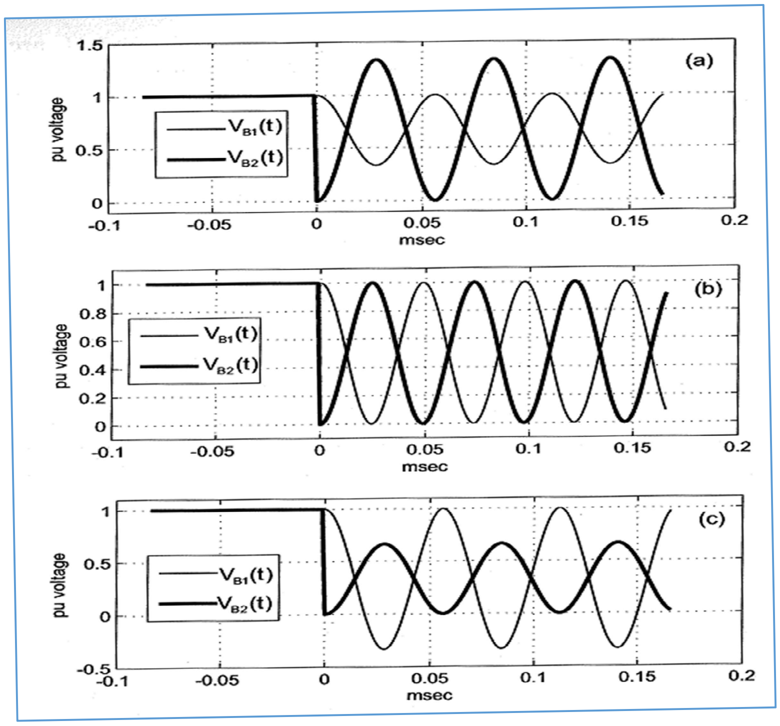


Figure 2-13 Overvoltage Surges of Back to Back Capacitor Switching of C1 vs C2

Figure 2-13 shows comparison of voltage waveforms behaviour between different value of C_1 and C_2 are used.

V_{B1} and V_{B2} are voltages (per unitized to V_m) across capacitors C_1 and C_2 immediately after switching instant t = 0. Whereas waveform of graph (a), (b) and (c) indicate capacitance value ratio of capacitor C_1 and C_2.

(a) $C_1 = 2\ C_2$ (C_1 is larger than C_2)

(b) $C_1 = C_2$

(c) $C_1 = ½\ C_2$ (C_1 is smaller than C_2)

From above waveforms graphs, we observe that waveform (a) has larger transient overvoltage (> 1 p.u.) at C_2, waveform (b) has unity transient overvoltage at C_2 and waveform (c) has smaller transient voltage (< 1 p.u.) at C_2. It is obvious that when a larger C_2 is energized while a smaller C1 is already in service, it will produce a lower transient overvoltage.

2.2.3 Magnification of Capacitor-Switching Transients

A drawback of integrate capacitor bank at the customer location may raise the impact of utility capacitor switching transient on end-user equipment. As mentioned in previous chapter (see Figure 2-4), typically transient overvoltage magnitude between 1.3 to 1.4 p.u occurs at the primary distribution system. However this transient at the end-user bus can be magnified by load side capacitors and cause the transient overvoltage value reach at 3.0 to 4.0 p.u. on the LV bus. In this situation, all end user equipment are exposed under the risk of damaging. Figure 2-14 shows the one line diagram of the distribution of capacitor bank whereas Figure 2-15 shows the switching transient behaviour at capacitor terminal. This magnification on low-voltage bus can occur at a wide range of transformer and capacitor sizes.

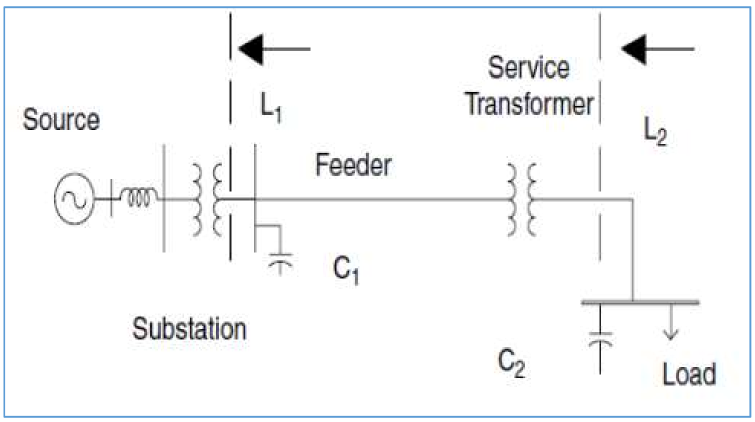


Figure 2-14 Voltage magnification at customer capacitor due to energizing capacitor on utility system

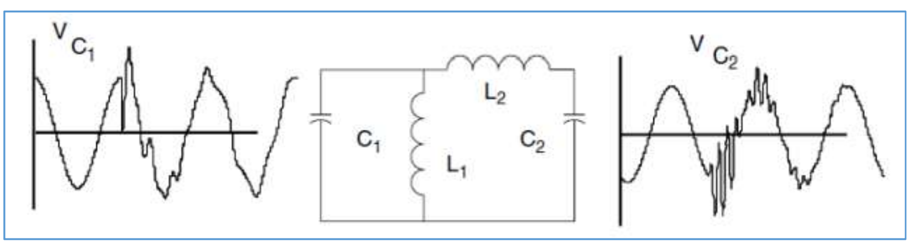


Figure 2-15 Equivalent Circuit

2.2.4 Capacitor Switch Restrike Transients

De-energizing capacitor process normally does not cause any transient oscillation. However if there is contamination or insulation failure, it will cause contactor opening failure because an arc will be established between contacts and capacitor will be restrikes or reignites. The process is called reignition when the arc is re-established within half of a cycle of current interruption. Whereas if the arc re-established after the half cycle, the process is called restrike. The event can be repeated multiple times during contact opening process. (Math H.J. Bollen, 2006). Figure 2-16 shows the typical capacitor de-energizing circuit.

At the moment of restrike, the system voltage will oscillate at the natural frequency which is formed by capacitor capacitance and system inductance. This result the voltage polarity experience the instant changes from positive to negative or vice versa.

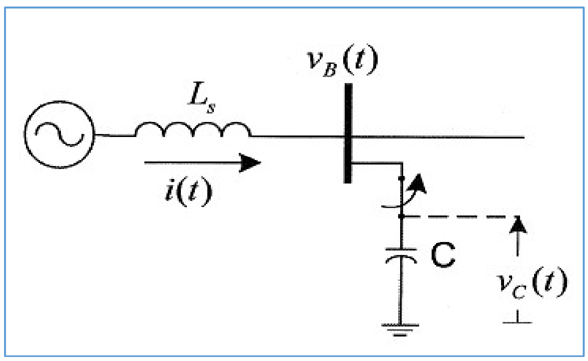


Figure 2-16 One line diagram for a capacitor de-energizing

Figure 2-17 indicates multiple restrikes are possible. After the first restrike, the voltage trapped in the capacitor is very high, it can reach $3V_m$. The second restrike can occur when the potential difference between contact is the largest, where the $V_B(t)$ is at its negative peak ($-V_m$).

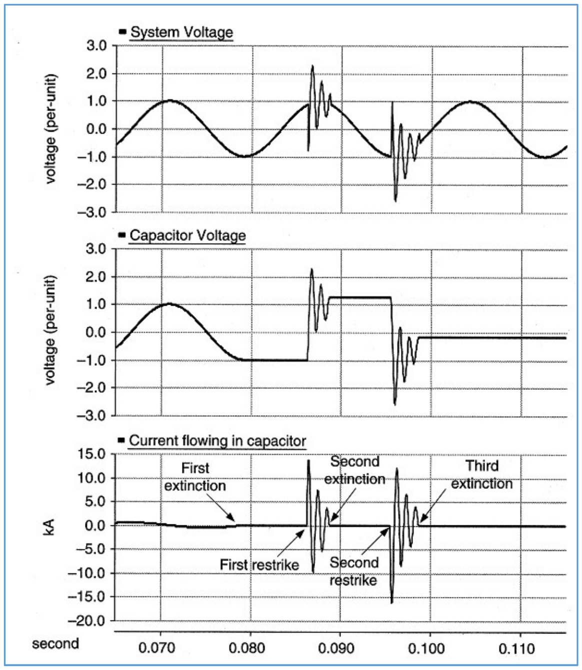


Figure 2-17 System and capacitor voltages along with capacitor current during a successive restrike while de-energizing the capacitor

2.3 Ferroresonance

Ferroresonance is a special resonance between nonlinear magnetizing reactance of a transformer and a capacitance. The capacitance can be the form of capacitor bank of underground cable, they can cause a large overvoltage for long duration. Ferroresonance can result in serious damage to power system equipment. (Bollen, 1999)

When magnetizing reactance of a transformer is arranged in series with capacitor bank, there will be three common event happen and result in ferroresonance:

- Manual switching of an unloaded, cable-fed, 3-phase transformer where only one phase is closed.
- Manual switching of an unloaded, cable-fed, 3-phase transformer where one of the phases is open.
- One of two riser-pole fuses may blow leaving a transformer with one or two phases open.

Figure 2-18 shows the common event of ferroresonance happen in transformer and Figure 2-19 to Figure 2-20 are example of unstable and stable of ferroresonance voltage level after initial transient

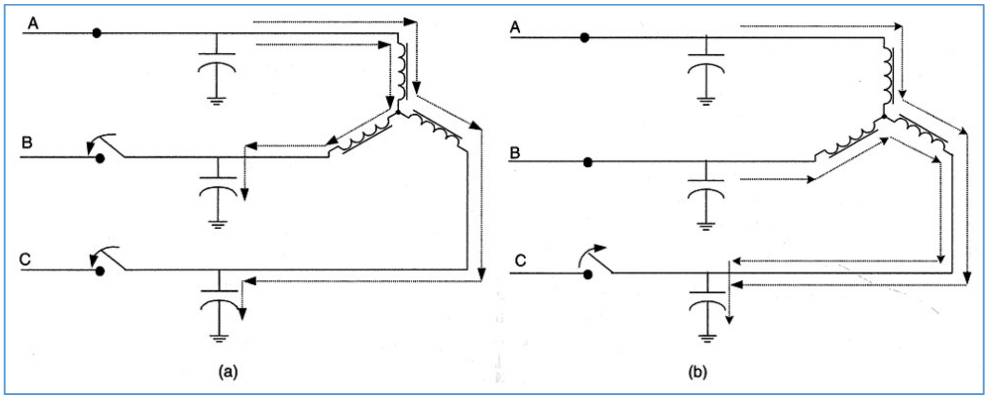


Figure 2-18 Common system conditions where ferroresonance may occur

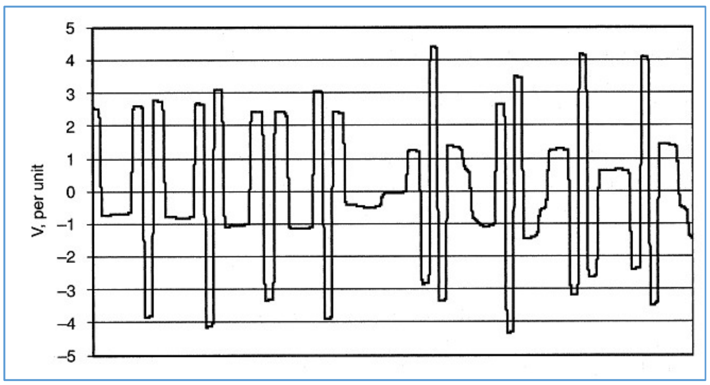


Figure 2-19 Example of unstable, chaotic ferroresonance voltages.

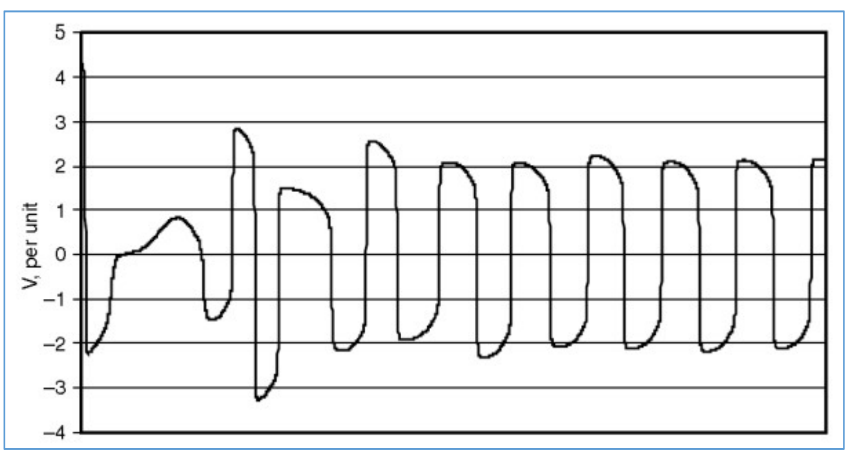


Figure 2-20 Example of ferroresonance voltages at stable operating condition

System conditions that help to raise up the possibility of ferroresonance include:

- Higher distribution voltage levels, most notably 25- and 35- kV class systems
- Switching of lightly loaded and unloaded transformers
- Ungrounded transformer primary connections
- Very lengthy underground cable circuits
- Cable damage and manual switching during construction of underground cable systems
- Weak systems, i.e., low short-circuit currents
- Low-loss transformers
- Three-phase systems with single-phase switching devices.

Common sign of ferroresonance are: audible noise, overheating, high overvoltages and surge arrester failure and flicker.

2.4 Lightning

Lightning is a natural causes for overvoltages other than capacitor switching. It is a natural phenomenon of charge accumulated in the clouds due to thunder storm and discharges into a neighbouring cloud or to the ground. Lightning stroke can be categorized into three modes (Rashid, 2017):

(a) Lightning direct strike on live phase wire (direct flashover),

(b) Lightning direct strike on shield wire or tower structure, and

(c) Lightning indirect strike.

In event of (a), negative charges are discharged from thundercloud to the transmission line. This event result in the voltage increase on one phase or more phase wires. The stroke current (in the travelling form) travel in two directions and raise the voltage of the transmission line. If this event was not protected properly, then the overvoltage may surpass the line-to-ground insulation level and cause insulation failure.

In the event of (b), when lightning strikes a tower, the huge impulse current may flow into shield wires and to the earth (via tower structure) providing the footing resistance is small. Otherwise the lightning current will increase the voltage of the tower to high value with respect to ground and this will result in a flashover from tower to one or more phase conductors.

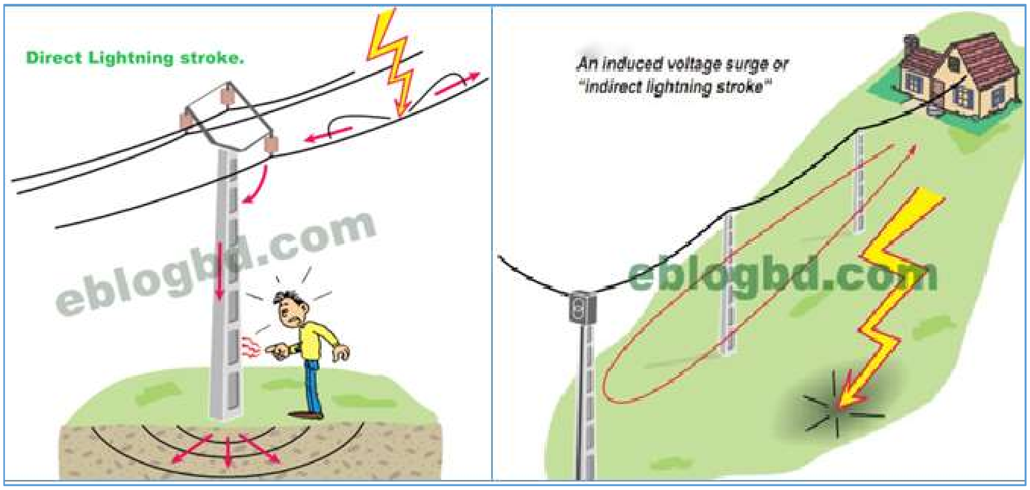


Figure 2-21 Illustration of direct and indirect lightning strokes [Source: www.eblogbd.com]

In the event of (c), when a lightning strike to the ground where the striking point is near to the transmission line, a "virtual wire" can be considered connecting both thundercloud and earth point.Surge current (lightning current) is flowing through on the "virtual wire". In this instant, transmission line and ground will behave as huge capacitor charged and this induced charge will cause overvoltage occur on the transmission line. Direct and indirect lightning stroke are illustrated in Figure 2-21.

2.4.1 Lightning Protection Standard

Malaysia is a tropical rainforest country and this climate characteristic make it has numbers of lightning incident over a year. Lightning protection standard BS EN/IEC 62305 is an important guidance to follow for building and utility grid system in Malaysia. BS EN/IEC 62305 classify lightning sources, damages and losses into S1 to S4, D1 to D3, and L1 to L4 respectively. An ideal lightning protection for a structure is to enclose it within an earthed metallic shield however this practice is impossible due to the high cost consideration. Hence lightning protection level (LPL) is established to divide the protection level in several categories. LPL has four levels and each level has their own maximum and minimum values of lightning current level. The lightning current maximum value is used for reference of designing or selecting proper surge protective devices (SPDs). In addition, lightning protection zones (LPZ) concept is described and it is particularly for the protection against Lightning Electromagnetic Impulse

(LEMP). In general the LPZ can be classified by LPZ1, LPZ 2…etc. The higher number of the zone, the better protection of sensitive electronic equipment against electromagnetic effect. The detail of illustration and explanation of above standards are described in appendix of BE EN/IEC 62305.

2.5 Prevention and protection of capacitor switching transients

As we discussed in previous section capacitor switching transients bring power quality issue to distribution system. They can be prevented and protected by different methods.

Synchronous closing control is a prevention method by switching capacitor contact at the instant of system voltage matches the capacitor voltage during the change of positive to negative cycle of the phase voltage. This method prevent the rapid change of voltage when capacitors are energized. (Alexander, 1985). Figure 2-22 shows the different of overvoltage surges output with and without synchronous closing control method in system. Microprocessor are required to process and provide closing signal in order to forecasting the control switches.

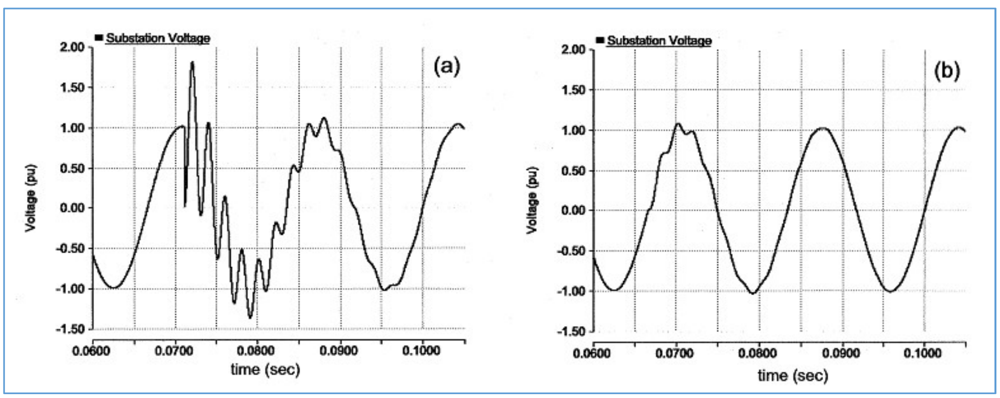


Figure 2-22 Comparison of Overvoltage Surges without Synchronous Closing Control (a) and with Synchronous Closing Control (b)

As for capacitor switch restrike transient, a periodic maintenance is required to ensure the contact is cleaned from the contamination and no insulation failure. Synchronous closing breaker with pre-insertion resistors is a protection method from switching transients. The switching transient will be damped to a negligible level by resistors, but this will bring up another disadvantage which is significant power loss.

2.6 Prevention and protection of lightning surge

Shielding phase wire is a prevention method from lightning surge. It can be done by installing an earthed neutral wire over the live phase wire. This can block most of the event of lightning stroke to the phase wire, however it will not certainly prevent line flashovers due to the potential of backflashovers. The occurrence of backflashovers can be minimized by keeping the tower footing resistance as low as possible. So that the flashover will not occur due to extremely high voltage on top of the pole. Figure 2-23 illustrates the shielding concept.

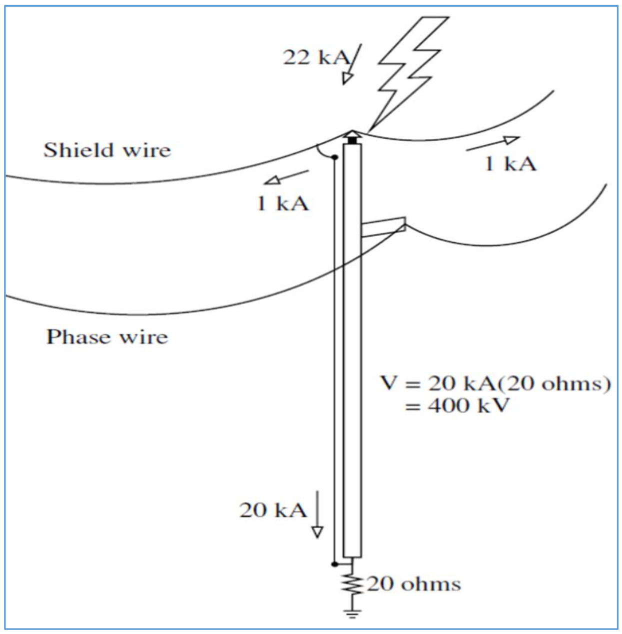


Figure 2-23 Shield Wire on top of Phase Wire

Six basic of lightning surge protection for load equipment are proposed. (Roger C. Dugan, 2012)

(1) Voltage across sensitive insulation is limited
(2) Surge current is shunt away from the load
(3) Surge current is stopped from entering the load
(4) Equipotential bonding grounds at equipment
(5) Prevent or decrease surge energy from flowing between grounds
(6) Limit and block overvoltage by using low-pass filter

Arrester and TVSS (transient voltage surge suppressors) are protection device to protect load equipment from damage of transient overvoltages. The working principle is to limit the maximum overvoltage surge.

2.7 Surge protection device (SPD)

Surge protection device (SPD) is a general term used for surge arrester. It is a protective device designed and installed in between a conductor of an electrical system and ground purpose to limit the magnitude of transient overvoltages on equipment. It is normally installed in different systems such as power distribution panels, process control systems, communications systems, and other heavy-duty industrial systems.

Surge arrester can be classified into two protection technologies, surge suppressor and surge diverter. Figure 2-24 and Figure 2-25 show the simple circuit concept of the two protection technologies. Furthermore surge diverter can be classified into two different modes of operation, crowbar and clamping.

2.7.1 Surge Suppressor

Transient overvoltage is normally carry higher frequency (5 kHz to 500 kHz) than the normal power line frequency (50 or 60 Hz). Surge suppressor concept is to utilise the low pass filter series with the power line to attenuate the transient and hence stop the transient overvoltage surge propagation.

This low pass filter can be constructed by simple resistor and capacitor, however this simple configuration circuit has several major limitation.

1. High inrush current will be produced during switching.
2. High peak voltage will be produced when occurs resonance with inductive components
3. Create additional reactive load on power system voltage.

These limitations can be wiped out by adding a series resistor, providing this resistor has to be withstand high transient voltage.

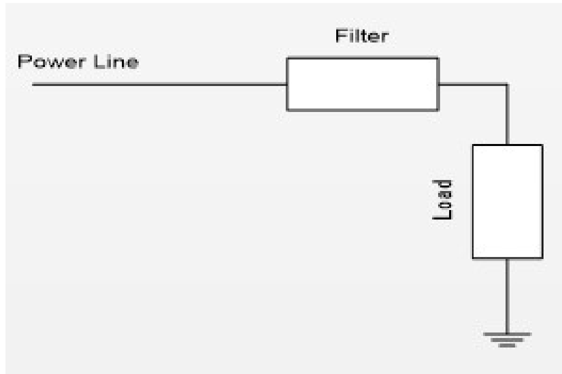


Figure 2-24 One line diagram of surge suppressor technology

2.7.2 Surge Diverter

The working principle of surge diverter utilise a shunt element with non-linear impedance characteristic to conduct the overvoltage surge to ground. The non-linear impedance material has the dielectric strength is inversely proportional to the voltage level. When high voltage is applied on the surge arrester, insulation breakdown happen and impedance in between conductor to ground will be very low. The voltage surge usually breaks down the insulation of the arrester momentarily, divert the voltage surge to propagate to ground and dissipate itself. The arrester insulation property will then be restored after the transient overvoltage surge drop below the insulation breakdown threshold level. With this characteristic surge arrester able to discharge the dangerous transient overvoltage before the surge damage the protected equipment.

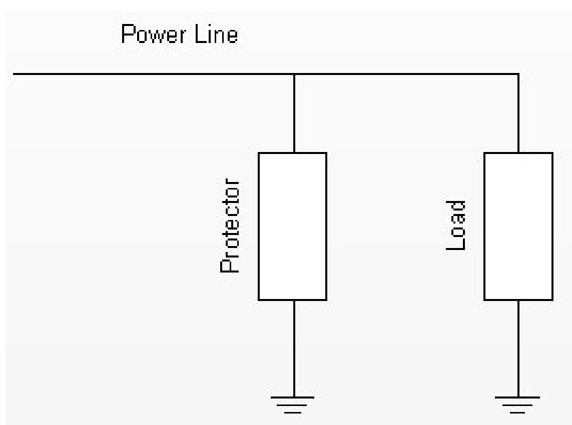


Figure 2-25 One line diagram of surge diverter technology

There are some criteria should be satisfied in order to work as a surge diverter.

1. Minimize the steady state leakage current with high impedance during normal operating voltage level. Ideally is infinite impedance.
2. Provide low impedance path to ground during surge.
3. Store or release the surge energy without damage to surge diverter.
4. Restore the impedance property after the surge drop below the shunt element insulation breakdown level.

Surge diverter can be categorized into crowbar and clamping.

Crowbar device: This device is normally a gas tube constructed with a gap injected with noble gas or air, normally known as Gas Discharge Tube (GDT). When there is a high overvoltage transients apply on the device, the avalanche breakdown of gas will happen inside the gas tube and gap arc will appear. Once the gap arc is formed, the impedance will drop steeply, power frequency current or "follow current" will flow through the gas tube and to ground.

The drawback of this crowbar device is power voltage drop dramatically to a very low or zero value for minimum duration of one-half cycle due to the major current flowing to ground. This will result some loads to switch from online to offline condition unnecessarily. In addition, crowbar device has slower response as it takes some time to create a low impedance arcing path during avalanche breakdown process. (Roger C. Dugan, 2012)

This is the reason why crowbars are not commonly used in power line circuit, instead it is widely used in communication field. Example of crowbar devices are air gap, carbon block, gas discharge tube (GDT) silicon control rectifier (SCR)

Clamping device: This device is constructed with non-linear resistors (varistors) and it conducts very low amount of current during normal operation. When there is a high voltage apply on it, then impedance will drop rapidly and they start conduct the surge current heavily to ground, and hence the voltage surge will be limited. When the surge current is beginning to conduct to ground, clamping device does not behave like the gap-type device, which is the voltage will not be reduced to below the conduction level. However, due to the existence of resistor, the power losses will always present (because of leakage current) during normal operation, and the large amount of heat dissipate during surge condition.

Example of clamping devices are Zener (avalanche diode) and Metal Oxide Varistor (MOV). GDT and MOV are the most widely used surge protection devices in industry. Figure 2-26 shows the example of crowbar device (GDT) and clamping device (MOV).

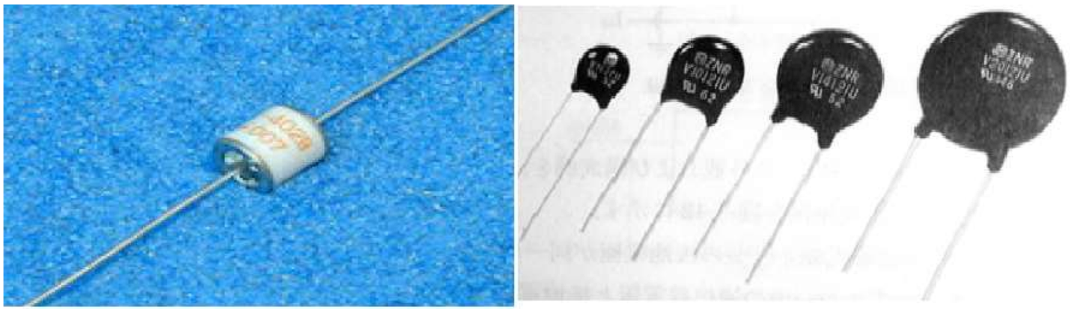


Figure 2-26 Gas Discharge Tube (GDT) and Metal Oxide Varistor (MOV) *(Hitoshi Kijima, 2012)*

2.7.2.1 Gas Discharge Tube (GDT)

Figure 2-27 illustrates GDT construction by two or more metal electrodes separated by a small gap. It is hermetically sealed enclosure by material of ceramic-to-metal or glass-to-metal cylinder.

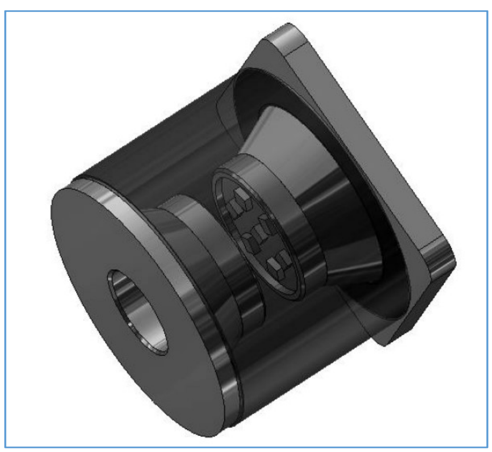


Figure 2-27 Inner view of a surface mount two-electrode GDT

A noble gas mixture is filled into the hermetically sealed cylinder. When there is high voltage (raise above the GDT tripping point) apply to the electrodes, the gas is ionized and cause spark-over (breakdown) occur in a glow discharge form, as a result arc appears and a low impedance route is built for the surge current conduction.

The construction of GDT make them to have extremely low capacitance (less than 2pF). This allows GDT is widely used in high frequency applications. There is a certain distance to place GDT away from the sensitive electronics, because GDT may produce high-frequency radiation and influence sensitive electronic when it operates. The distance is subject to the sensitivity of the electronic or how well the electronic is shielded. The alternative way to prevent the influence is to install the GDT in a shielded enclosure.

2.7.2.2 Metal Oxide Varistor (MOV)

Metal Oxide Varistor (MOV) are wired as surge arrester nowadays in high voltage system due to its voltage dependant resistance characteristic or also refer to its V-I characteristics. Figure 2-28 illustrates metal oxide discs are constructed inside a porcelain or polymer insulator and form a surge arrester. Numbers of discs are arranged in series is proportional to the voltage rating whereas the larger cross section of discs could raise the surge arrester energy rating. (Unahalekhaka, 2014)

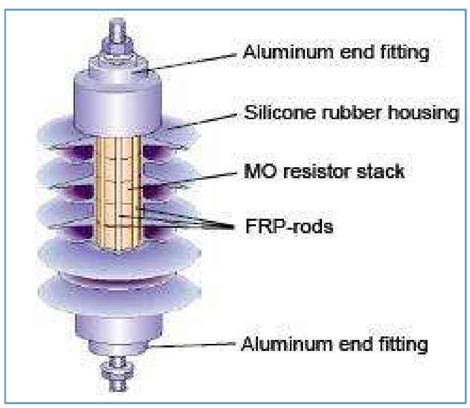


Figure 2-28 Construction of Metal Oxide Varistor (MOV) Surge Arrester

MOV is capable to sustain high levels of transient energy during surge diversion, this is because MOV experience sintering process during manufacturing and this make the structure to be crystalline microstructure. This structure allow MOV to be able to dissipate high transient energy. Figure 2-29 indicates typical V-I characteristic of MOV. When the MOV is under the condition of normal condition, the current flowing MOV is nearly to be zero. However when high voltage transients is applied across MOV, the impedance will drop dramatically and result in current raise steeply. After the overvoltage surge voltage level is fall under the protection voltage level, the impedance of MOV will restore and this will cause the MOV be open circuit to ground. Figure 3-30 show a clear picture of the output voltage characteristic after MOV is triggered. There is a drawback of MOV, a small amount of current will flowing through the varistor to ground under normal condition. Although this is a very small current, but it is still a power loss. Due to this reason, MOV is not suitable for protection in low power communication signal line.

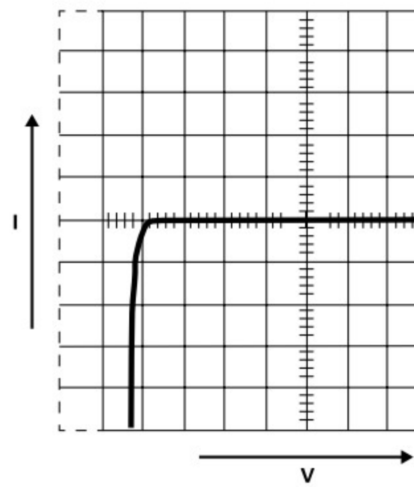


Figure 2-29 Typical Varistor V-I Characteristic

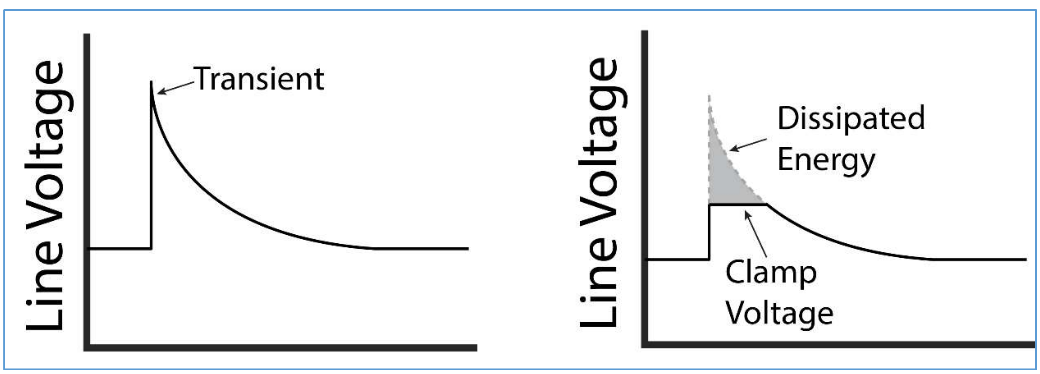


Figure 2-30 MOV clamping voltage characteristic

2.7.3 Characteristics of Power Electronic

Power electronic has been developed for decades and there are more and more advance technology are invented. These development widen the application of switching power electronic due to their improvement in power handling capability and switching frequency. Figure 2-31 show the power capability and switching frequency of different power electronics. It shows that thyristor has the highest power capability, whereas MOSFET has the highest switching frequency capability. This is also mean that MOSFET has fastest response time.

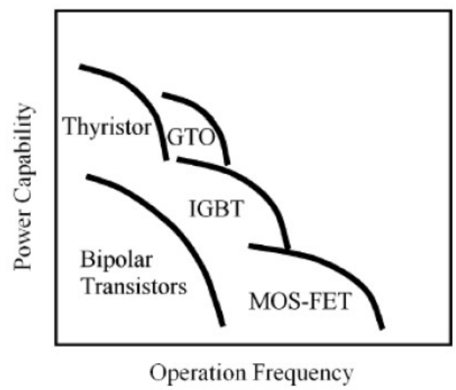


Figure 2-31 Power and frequency capabilities of different semiconductors

2.8 Standard Lightning Impulse

In last section we learnt transient overvoltages are caused by lightning and switching surges. These transient overvoltage are generally in the wave shape form of steep build-up of voltage. The wave shape can be characterized into two sections, front time (t_f) and tail time (t_t). See Figure 2-33 of the typical lightning impulse waveform. Front time is referring to the raise time duration of the lightning impulse waveform at 10% to 90% of its peak value. Whereas tail time is referring to the decay duration of the lightning impulse waveform to 50% of its peak value. There are research results showed that these waves have a rise time of 0.5 to 10 µs and decay time of 30 to 200 µs. The lightning impulse waveform is mostly unidirectional and cab be represented as double exponential waves. It can be defined by the following equation. (M S Naidu, 2009)

$$V = V_o [\exp(-\alpha t) - \exp(-\beta t)]$$

where α and β are constants of microsecond values. V_o represents a factor that depends on the peak value.

Referring to Figure 2-32, point A represents peak value (100%) of the impulse waveform. Point C to D represent 10% to 90% of the peak value and a straight line joining point C and D is extended to intercept with time axis at O_1 is refer as virtual origin. Front time is defined as 1.25 times the interval between corresponding time of point C and D which are t_1 and t_2 respectively. Point E is positioned at 50% of peak value and the corresponding time in time axis is t_4, hence, tail time is referring to O_1t_4. Sometime the point C can be not clear or missing due to the steeply shape waveform as it is very close to the magnitude axis, the corresponding time of t'_1 of point F (30% of peak value) can be taken for calculation. In this case, the front time can be defined as $1.67(O_1t_3 - O_1t'_1)$. The tolerance allowed for peak value, front time and tail time are ±3%, ±30% and ±20% respectively. (M S Naidu, 2009)

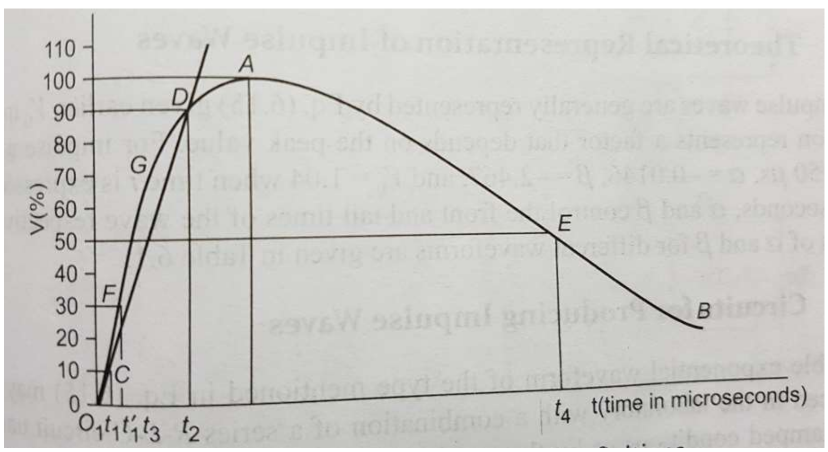


Figure 2-32 Impulse wave and its definitions

Front time, $t_f = 1.25\ (O_1t_2 - O_1t_1)$ [point C to D]

Front time, $t_f = 1.67(O_1t_3 - O_1t'_1)$ [point F to D]

Tail time, $t_t = O_1t_4$

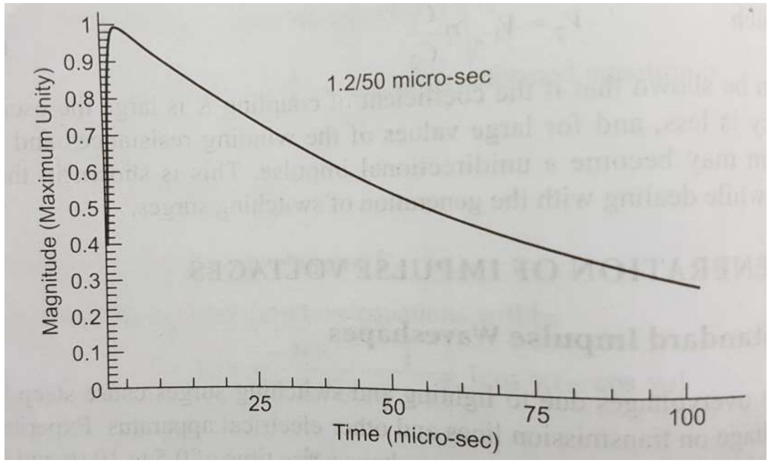
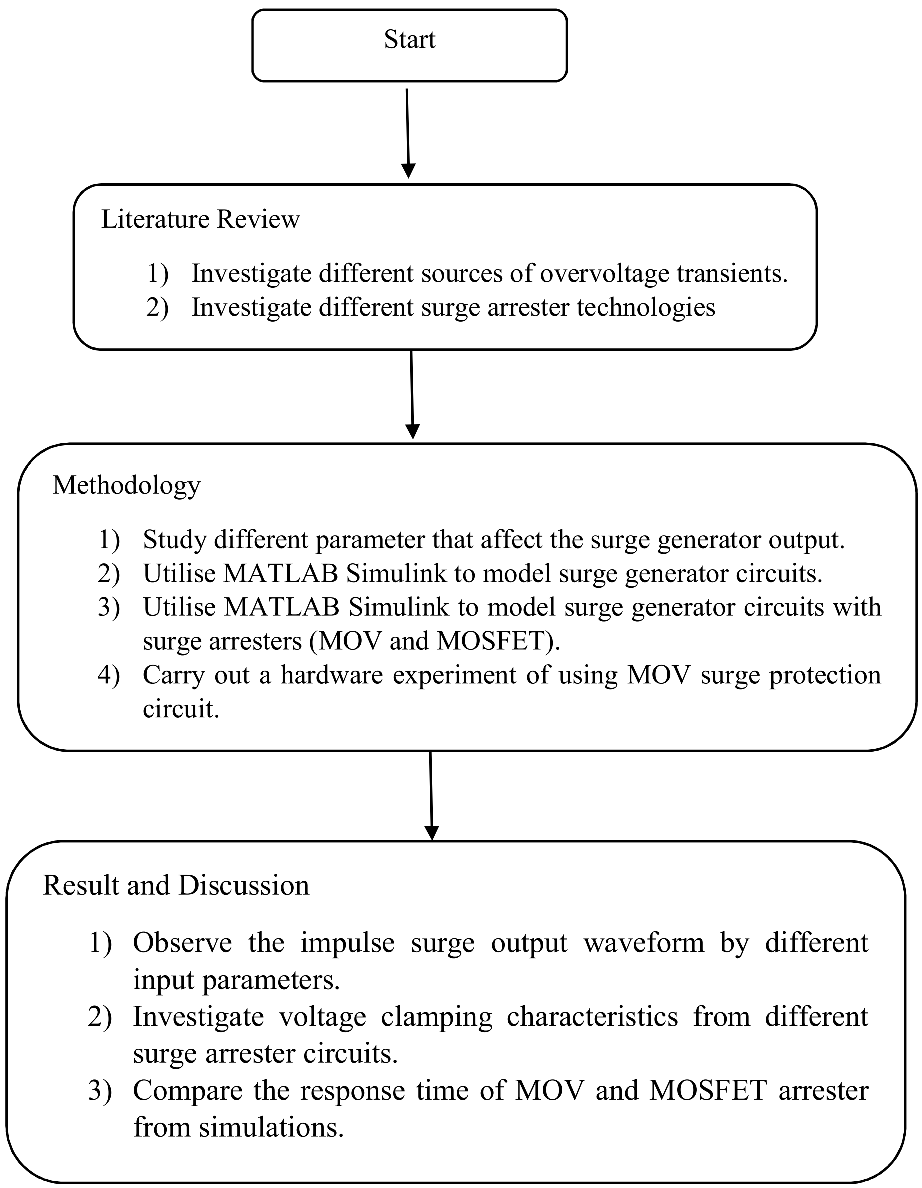


Figure 2-33 Typical 1.2/50 μs waveform

IEC 61000 standards show impulse voltage waveform should be in a shape with front time 1.2-250 μs and tail time 50-2500 μs. (Vivek Kumar Verma, 2014). Figure 2-33 indicates the typical lightning impulse waveform in 1.2/50 μs waveform and it is described in 1.2/50 μs with 1000kV which represents the impulse voltage wave has peak value of 1000kV with front time of 1.2 μs and tail time of 50 μs wave shape.

2.9 Project Flow

MATLAB Simulink is used to construct and verify the different type of lightning impulse surge generator circuits for 1.2/50 μs and 8/20 μs lightning impulse waveform. MOV and MOSFT are added into circuits to work as surge arrester and divert the surge to ground. The voltage clamping behaviour of the MOSFET and MOV are observed. Project flow is as below:



Conclusion

1) Conclude the result of research.
2) Suggest some further study and development of the research

2.10 Conclusion

In this chapter, internal and external factors that cause different type of overvoltage transients are mainly contributed by capacitor switching, ferroresonance and lightning. There are several protection devices such as conventional SPD (GDT, MOV) and electronic SPD are also discussed. However their performance of protection against lightning surge should be further studied. Lightning protection device performance of conventional and electronic is focused into this project due to the damaging caused by lightning is unpredictable and enormous.

3 METHODOLOGY

3.1 Introduction

In this chapter, different of impulse wave generator circuits are discussed and some calculation formula are derived in order to determine the capacitors and resistors component values.

3.2 Lightning Overvoltage Surge Circuits

As discussed previous section, we can express the lightning impulse waveform in double exponential waveform equation. Constructing a different combination of RLC or RC circuits in the laboratory may obtain the double exponential waveform equation.

Figure 3-1 shows four different circuits for producing impulse waves. Circuit (a) is a combination of series RLC circuit, and the effect of the inductance is to cause oscillations in the front and tail parts of an impulse waveform. Circuit (a) is only limited to model generator. By controlling of the R and L values simultaneously, the front and tail time of the wave can be adjusted according to desired shape. With reference to the book of High Voltage Engineering written by M.S. Naidu and V. Kamaraju, the knowledge of controlling of front time (β) can be determined by the selection of inductance value, tail time (α) can be determined by the selection of resistance value. The formulation of circuit (a) will not be discussed in detail because this circuit is not chosen for this simulation study. It is worth mentioning that simplicity is the advantage of this circuit. However the drawback is inflexible and independent in waveshape control. Besides, due to the test objects are mainly capacitive in nature, hence changing of test object will affect the basic circuit and result in the change of impulse waveshape. This is another advantage of this circuit. Circuit (b) to (d) are usually used for commercial generators. The working principle of impulse generator circuits are a pre-charged capacitor (C or C_1) discharge it instantly to the waveshaping circuit via closing the switch, S. The output voltage at C_2 is a discharged voltage $V_0(t)$ in double exponential waveshape.

Circuit (b) and (c) are commonly used circuits to produce the impulse wave. The benefits of these two circuits are the front and tail parts can be independently controlled by varying R_1 and R_2 separately. In addition, since the test objects are mainly capacitive in nature it is considered to form a part of C_2. (Mazen Abdel-Salam, 2000)

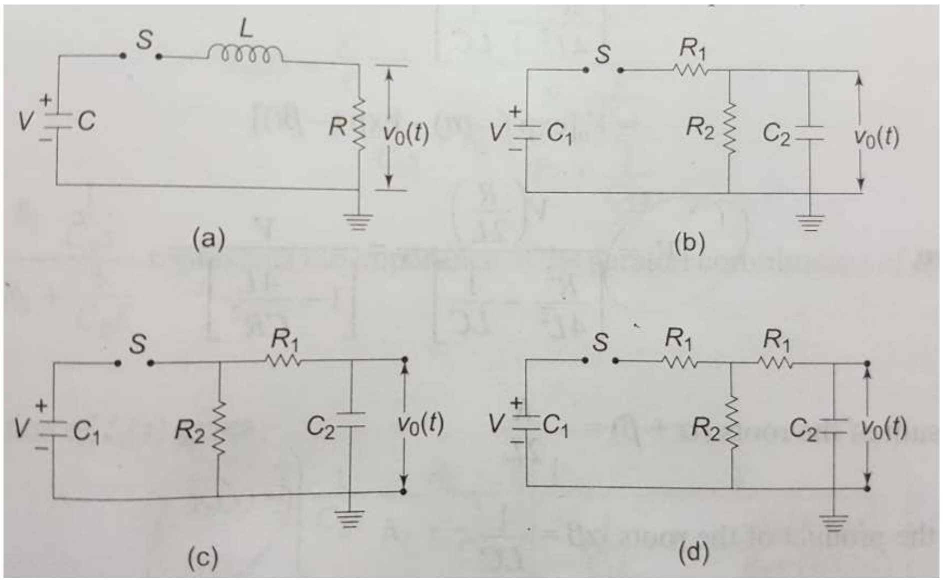


Figure 3-1 Circuits for producing impulse waves

Equivalent circuit (d) configuration is combination of circuit (b) and (c) with the resistance R_1 split into two portions and positioned at the left and right side of R_2. It gives the greater flexibility to the circuits.

3.3 Analysis of impulse generator circuit

In analysis of lightning overvoltage surges circuit (b), the current in generator circuit is I(t) at any time (t) after the gap sparks over.

By using Laplace transform, the impedance of circuit is

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

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

Current is

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

Substitution of Eq. 4.1 into I(s)

$$I(s) = \left(\frac{V_{in}}{s}\right)\left[\frac{C_1 s(R_2 C_2 s + 1)}{R_1 R_2 C_1 C_2 s^2 + (R_1 C_1 + R_2 C_2 + R_2 C_1)s + 1}\right] \tag{3.2}$$

Output voltage is

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

Substitution of Eq. 4.2 into *V*(s)

$$v(s) = \frac{V_{in} R_2 C_1}{R_1 R_2 C_1 C_2 s^2 + (R_1 C_1 + R_2 C_2 + R_2 C_1)s + 1} \tag{3.3}$$

The output voltage can be further simplified into

$$v(s) = \left[\frac{V_{in} R_2 C_1}{R_1 R_2 C_1 C_2}\right]\left[\frac{1}{s^2 + as + b}\right]$$

$$v(s) = \left[\frac{V_{in}}{R_1 C_2}\right]\left(\frac{1}{(s + \alpha - \beta)(s + \alpha + \beta)}\right) \tag{3.4}$$

where

$$a=\frac{1}{R_2C_2}+\frac{1}{R_1C_1}+\frac{1}{R_1C_2}, \qquad b=\frac{1}{\mathrm{R_1C_1R_2C_2}},$$

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

By using inverse Laplace transform, the output voltage is

$$V(t)=\left(\frac{V_{in}}{2\beta R_1C_2}\right)\left[e^{-(\alpha-\beta)t}-e^{-(\alpha+\beta)t}\right] \tag{3.5}$$

or

$$V(t)=\left[\frac{V_{in}}{2R_1C_2\beta}\right]\left\{e^{-\alpha_1 t_f}-e^{-\alpha_2 t_f}\right\} \tag{3.6}$$

Where

V_{in} is input voltage source, V(t) is output voltage magnitude at a specific time, t

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

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

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

Tail time, $t_t = Kt_f$, and

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

Similar analysis is carried out for lightning overvoltage surges circuit (c).

The output voltage is

$$v(t)=\left(\frac{V_0}{2\beta R_1C_2}\right)\left[e^{-(\alpha-\beta)t}-e^{-(\alpha+\beta)t}\right] \tag{3.7}$$

or

$$v(t)=\left[\frac{V_0}{2R_1C_2\beta}\right]\left\{e^{-\alpha_1 t_f}-e^{-\alpha_2 t_f}\right\} \qquad (3.8)$$

where

$$a=\frac{1}{R_1C_1}+\frac{1}{R_2C_1}+\frac{1}{R_1C_2}, \qquad b=\frac{1}{\mathrm{R_1C_1R_2C_2}},$$

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

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

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

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

Tail time, $t_t = K\ t_t$, and

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

Since Figure 3-1 circuit (b) and (c) are commonly used for lightning impulse generator, we should further consider which one is more suitable used for this study. As we can see in the both circuits, based on the voltage divider rule output voltage (V_o) is subjected to R_2 due to the parallel arrangement.

In circuit (b), R_2 is positioned at the load side of R_1 and this will reduce the output voltage because part of discharged voltage (from C_1) drop on R_1. Whereas in circuit (c), R_2 is positioned at the generator side of R_1 and this configuration do not cause voltage drop on R_1. As a result, maximum output voltage can be obtained, and hence circuit (c) is chosen to be modelled in MATLAB Simulink.

4 RESULT AND DISCUSSION

4.1 Introduction

This chapter content included the MATLAB model of surge generator circuits and compared the arrester performances of MOV and MOSFET. An impulse wave generator circuit model is generated by using MATLAB SIMULINK and the parameters are calculated in order to determine the desired impulse surge waveform.

4.2 Calculation of parameters used in impulse generator circuit

In order to get the desired peak impulse voltage level (6kV will be used), we first to assume the common capacitance value $C_1 = 0.125\mu F$ and $C_2 = 1nF$ are used into circuit.

Find $(\alpha - \beta)$:

$$\because t_t = K t_f, \qquad \text{and} \qquad \because K - 1 = \frac{0.7}{(\alpha - \beta)t_f}$$

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

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

$$\therefore (\alpha - \beta) = 14344.2623$$

Find R_2:

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

$$R_2 = \frac{1}{0.125\mu(14344.2623)}$$

$$\therefore R_2 = 557.714\ \Omega$$

Find $(\alpha + \beta)$:

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

$$1.2u = \left(\frac{1}{2\beta}\right)\ln\left[\frac{2\beta + 14344.2623}{14344.2623}\right]$$

$$\beta = 2428185.929$$

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

$$(\alpha + \beta) = 2(2428185.929) + 14344.2623$$

$$\therefore (\alpha + \beta) = 4870716.12$$

Find R_1:

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

$$R_1 = \frac{1}{0.125u(4870716.12)} + \frac{1}{1n(4870716.12)}$$

$$R_1 = 206.951\Omega$$

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

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

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

$$V_{in} = \left(\frac{6000(2 \times 2428185.929 \times 206.951 \times 10^{-9})}{e^{-(14344.2623)(1.2\times10^{-6})} - e^{-(4870716.12)(1.2\times10^{-6})}} \right)$$

$$V_{in} = \left(\frac{6000(2 \times 2428185.929 \times 206.951 \times 10^{-9})}{e^{-(14344.2623)(1.2\times10^{-6})} - e^{-(4870716.12)(1.2\times10^{-6})}} \right)$$

V_{in} = 6153 V

4.3 Simulation result

Impulse wave generator circuit is model in MATLAB Simulink as show in Figure 4-1. Different component parameter values are used and recorded in Table 1.

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

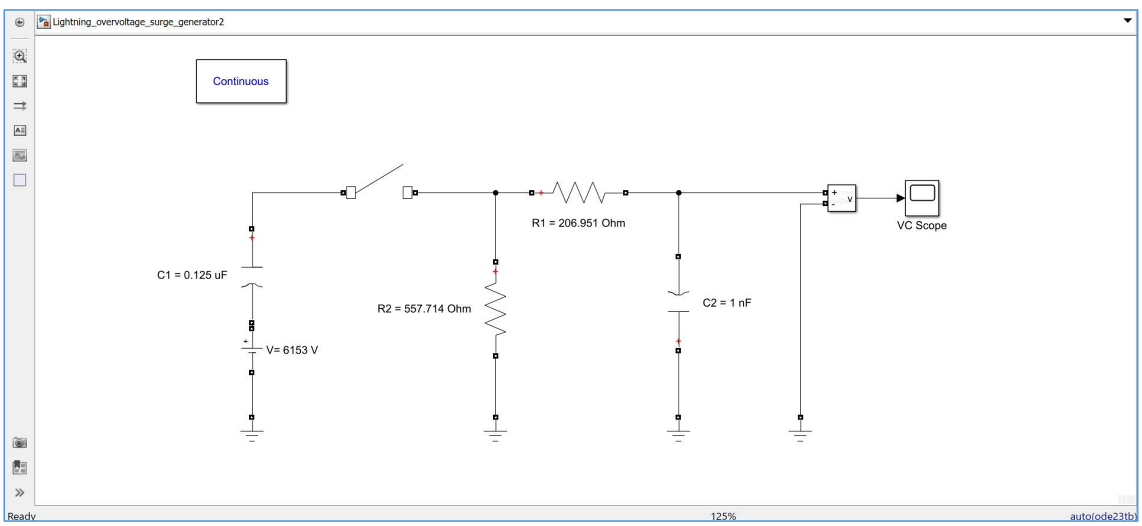


Figure 4-1 Standard Lightning Impulse Generator Circuit Model in MATLAB Simulink

By using this model, we verify the accuracy of the Equation.3.7 by changing the input voltage. Base on the Equation.3.7, the calculated input voltage (V_{in}) is 1025 V, 3077 V and 6153 V for output peak voltage 1 kV, 3 kV, and 6 kV respectively. After inject the different input voltage value, simulation results are show in Figure 4-2 and Figure 4-3 and Figure 4-4 for the desired peak output voltage at 1kV, 3kV and 6kV respectively.

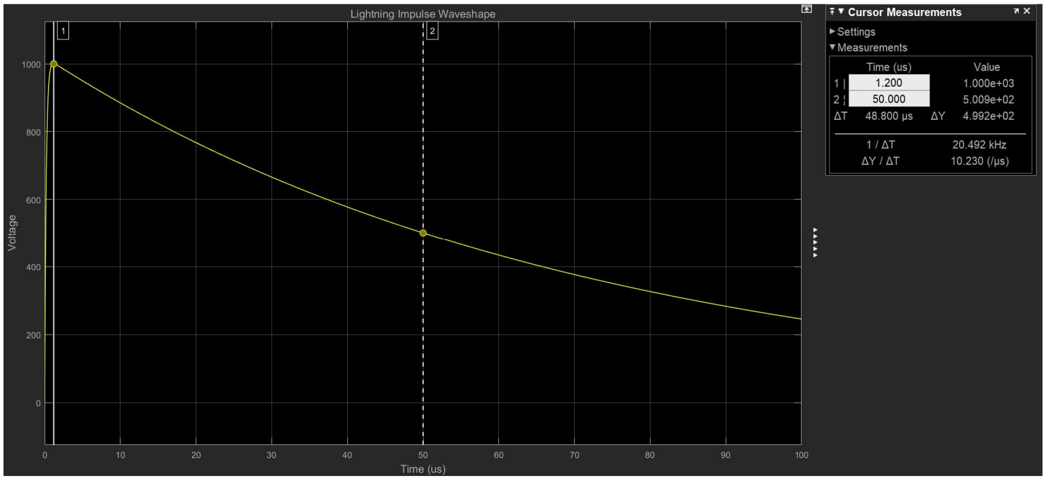


Figure 4-2 Standard Lightning Impulse Simulation Result (Peak voltage at 1kV)

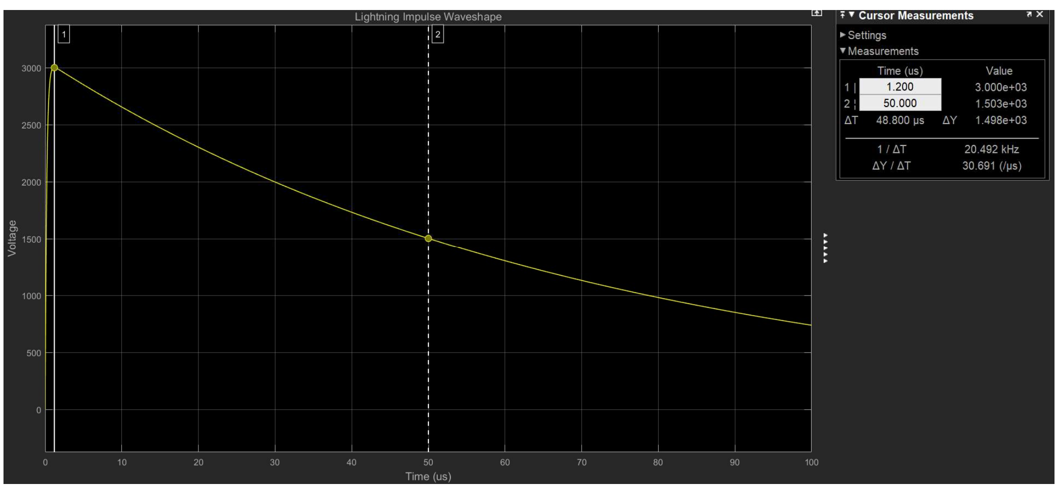


Figure 4-3 Standard Lightning Impulse Simulation Result (Peak voltage at 3kV)

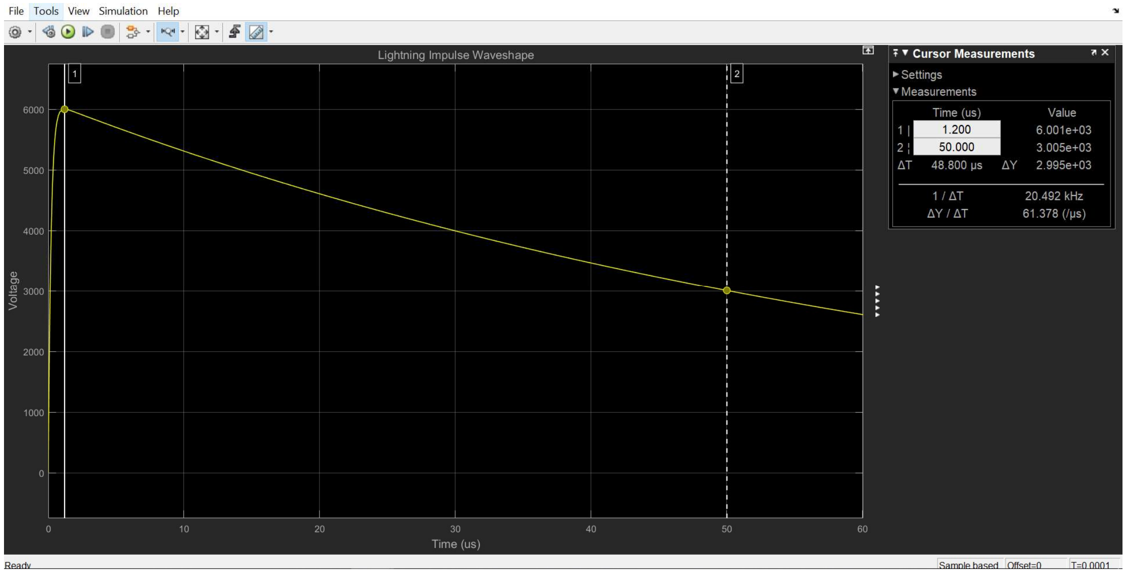


Figure 4-4 Standard Lightning Impulse Simulation Result (Peak voltage at 6 kV)

4.3.2 Generate 1.2/50 µs Lightning Impulse Generator Circuit Model with Different Capacitor and Resistor Rating

Figure 4-5 and Figure 4-6 are showing the change of different capacitors rating lead to the change of the resistors values in order to maintain the same lightning impulse waveshape of peak voltage 6 kV.

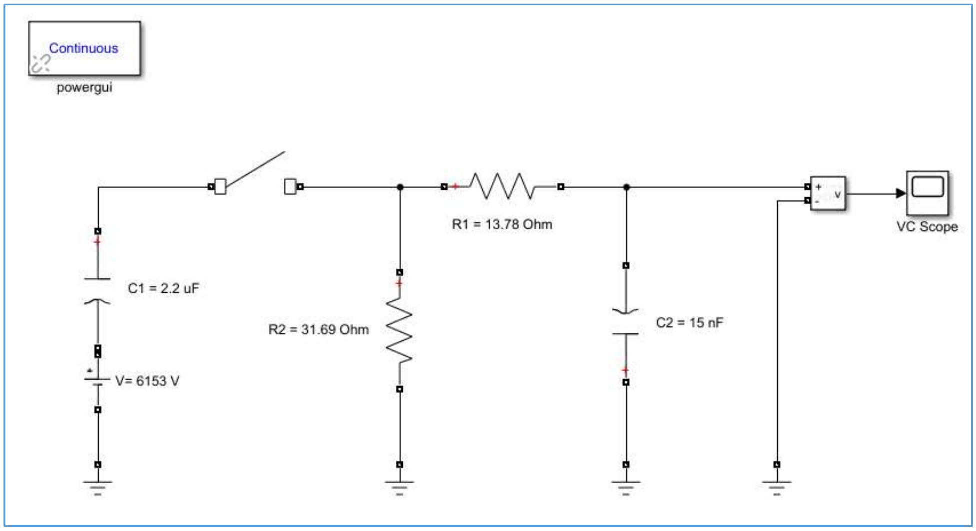


Figure 4-5 Standard Lightning Impulse Generator Circuit Model With Different Capacitors and Resistors Rating

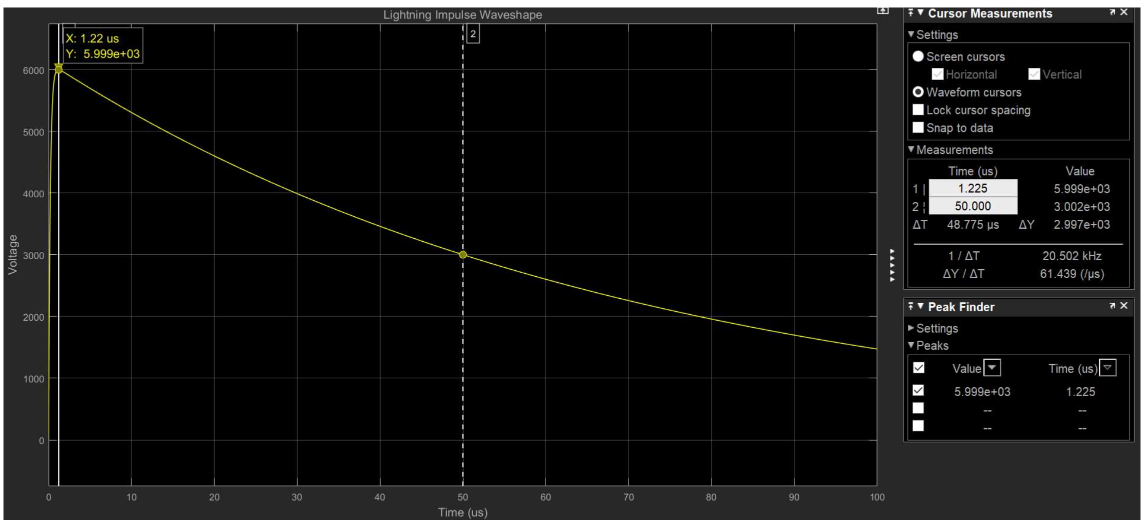


Figure 4-6 Lightning Impulse Circuit Simulation Result With Different Capacitors and Resistors Rating

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

An 8/20 µs impulse waveshape can be generated by repeating the calculation with desired t_f time (8 µs) and t_t (20 µs) and we obtained α, β, R_1 and R_2 values (value show in Table 1). Figure 4-7 shows the circuit model and Figure 4-8 is the simulation result of 8/20 µs impulse waveshape.

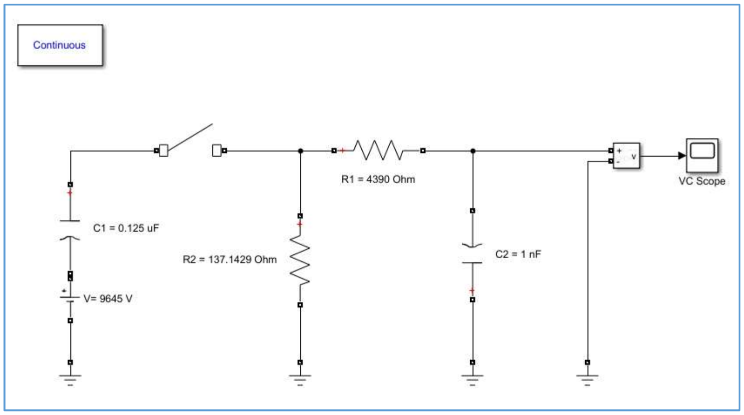


Figure 4-7 8/20 µs Impulse Generator Circuit Model in MATLAB Simulink

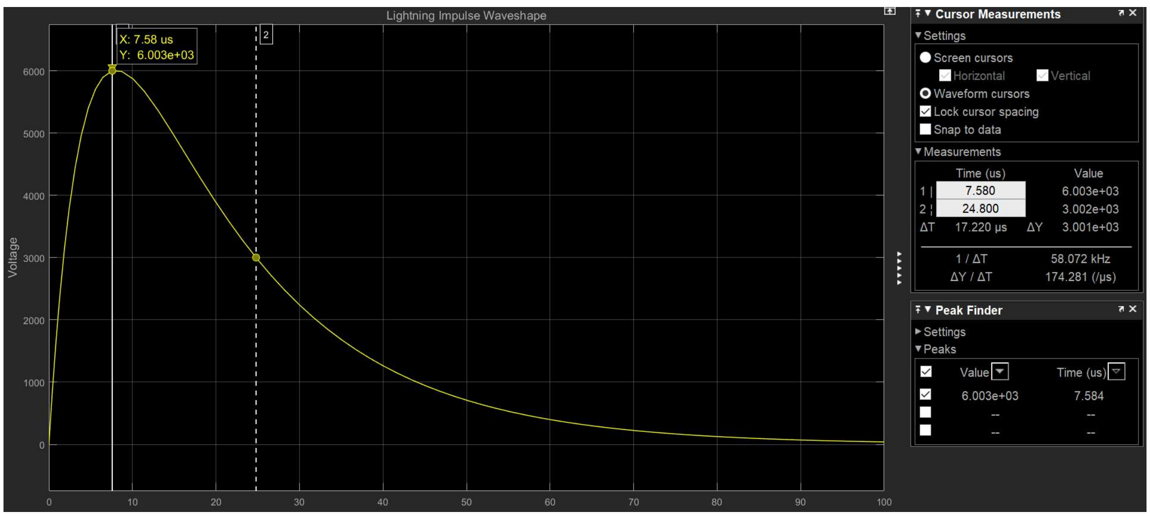


Figure 4-8 8/20 µs Impulse Generator Circuit Model Simulation Result

Simulation results shows the accurate impulse waveshape and peak voltage magnitude are obtained according to the calculations. These result proved the accuracy of the calculation and wave front time and wave tail time can be controlled by different value of α and β. Whereas the impulse peak voltage (output voltage) can be controlled by the input voltage source. Table 1 below is comparison of parameters are used to generate 1.2/50 µs and 8/20 µs impulse waveform.

Impulse standard of 6kV	**α-β**	**α+β**	**C1 (µF)**	**C2 (µF)**	**R1 (Ω)**	**R2 (Ω)**
1.2/50 µs	14344.26	4870716.12	0.125	0.001	206.95	557.71
1.2/50 µs	14344.26	4870716.12	2.2	15	13.78	31.69
8/20 µs	58333.33	229608.68	0.125	0.001	137.15	4390.08

Table 4-1 Comparison of Parameter are used for 1.2/50 µs and 8/20 µs impulse waveform

4.3.4 Standard Lightning Impulse Generator Circuit Model with MOV Protection

Now a surge arrester (MOV) is added into the circuit and observe the clamping characteristic. The circuit is show in Figure 4-9.

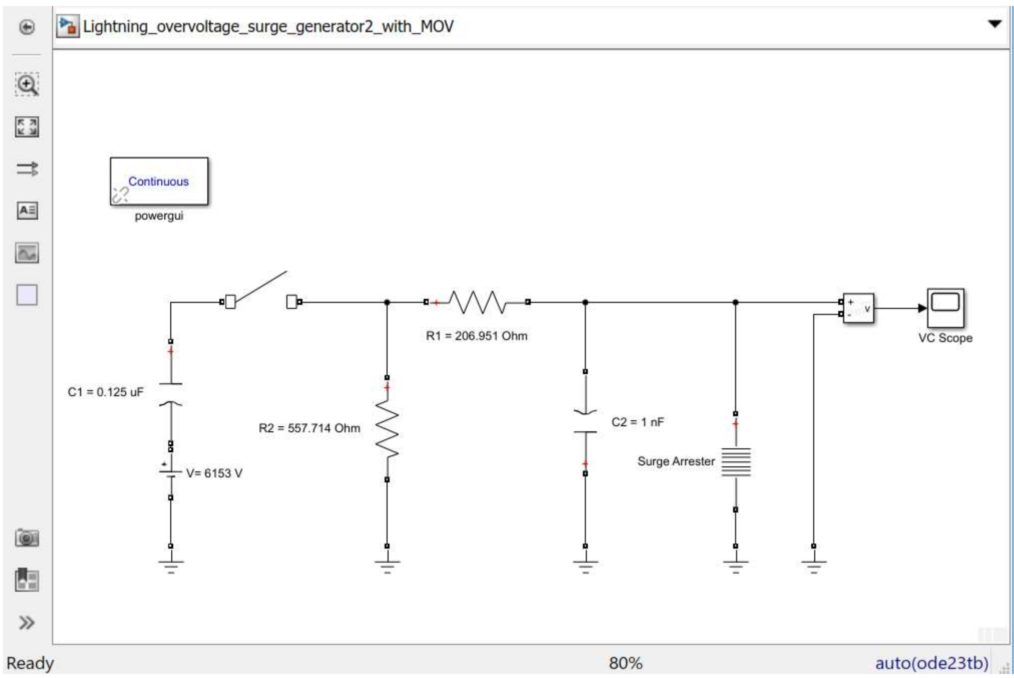


Figure 4-9 Standard Lightning Impulse Generator Circuit with MOV protection Model in MATLAB Simulink

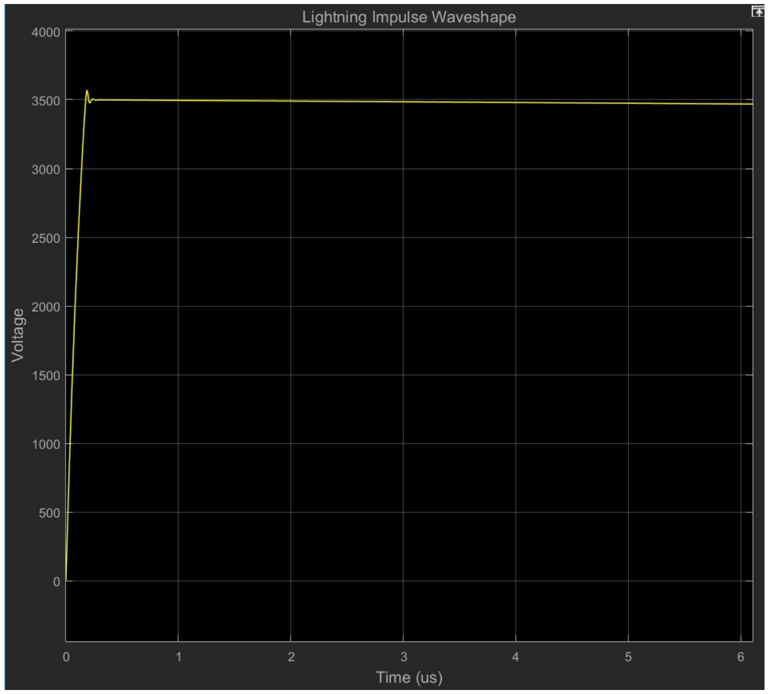


Figure 4-10 Overvoltage surge is clamp at 3.5 kV

The voltage protection level of the MOV (surge arrester block in Simulink) is selected to be 3.5 kV. The input lightning overvoltage surge has peak value of 6 kV as show in Figure 4-4. Whereas Figure 4-10 shows the result of peak voltage is clamp at 3.5kV, it indicates that the MOV clamp the surge voltage to the protection level as soon as it detects the surge exceeds 3.5 kV. Output voltage is maintained at 3.5 kV because MOV surge arrester restores its insulation level when the detected surge drop to below 3.5 kV. Figure 4-11 show an overview of comparison of the overvoltage surge and clamping voltage.

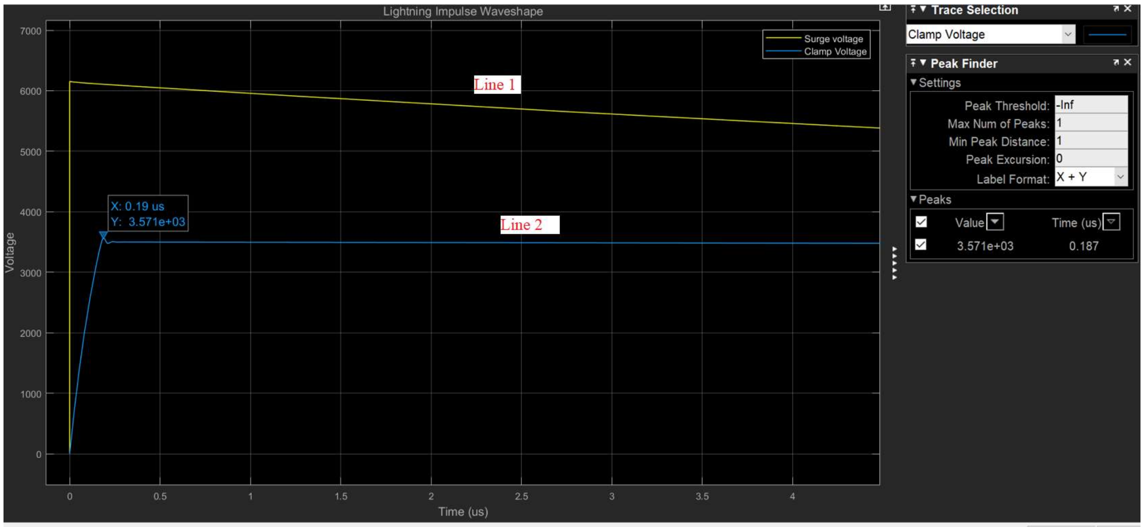


Figure 4-11 Comparison of the peak voltage surge and clamping voltage level

Line 1 indicate an input overvoltage surge. We can see the surge is not following the standard of 1.2/50 μs impulse waveshape. This is because 1.2/50 μs is an open circuit voltage waveform and if the surge arrester is triggered, the overvoltage surge is conducted to ground and there is no longer in “open circuit” form. Line 1 is actually a composite surge waveform which is combination of open circuit voltage waveform (1.2/50 μs) and short circuit current waveform (8/20 μs). Whereas line 2 is the clamping voltage level measured on MOV.

If the overvoltage surge peak magnitude and the surge arrester clamping voltage level has big different, there is an overshot oscillatory at the clamping voltage level and the oscillation is damped into very short time. See Figure 4-12, input overvoltage surge with 6 kV is clamped at 200V. The result shows there is an oscillatory transient at clamping voltage level, it is oscillating in between upper and lower voltage level of 200 V and stabilize at clamping level (200 V) in about 0.12 μs.

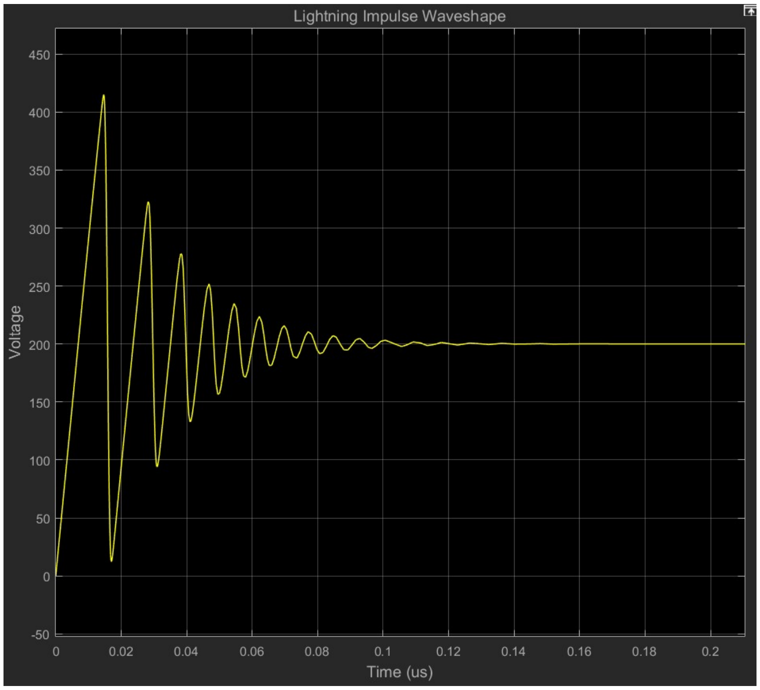


Figure 4-12 Overvoltage surge is clamp at 200V with oscillatory transient

4.3.5 Standard Lightning Impulse Generator Circuit Model with MOSFET Protection

A repeated simulation is setup by replacing conventional surge arrester (MOV) to power electronic which is also work as surge diverting function as well. In this case we use MOSFET as a switch to conduct the surge energy to ground, this surge diverting concept is similar with GDT. Circuit model are show in Figure 4-13, the signal generator is used to trigger the MOSFET into ON state. The signal generator is assumed as a surge detector and sending an ON signal to MOSFET after the surge reach to the triggering level (voltage protection level), and the measurement output port from MOSFET is connected to a scope in order to observe the voltage drop across MOSFET during ON state. Simulation result is show in Figure 4-14 and 3V voltage drop across the MOSFET is captured. The MOSFET voltage drop is small and subjected to the internal resistance. We can see from the result the voltage drop reach to peak (3 V) in 0.001 μs. We can consider this is the response time of MOSFET which is duration of forming a short circuit path for overvoltage surge to ground. Compare with the MOV clamping result (Figure 4-11), MOSFET response time (0.001 μs) is faster than MOV response time (0.19 μs).

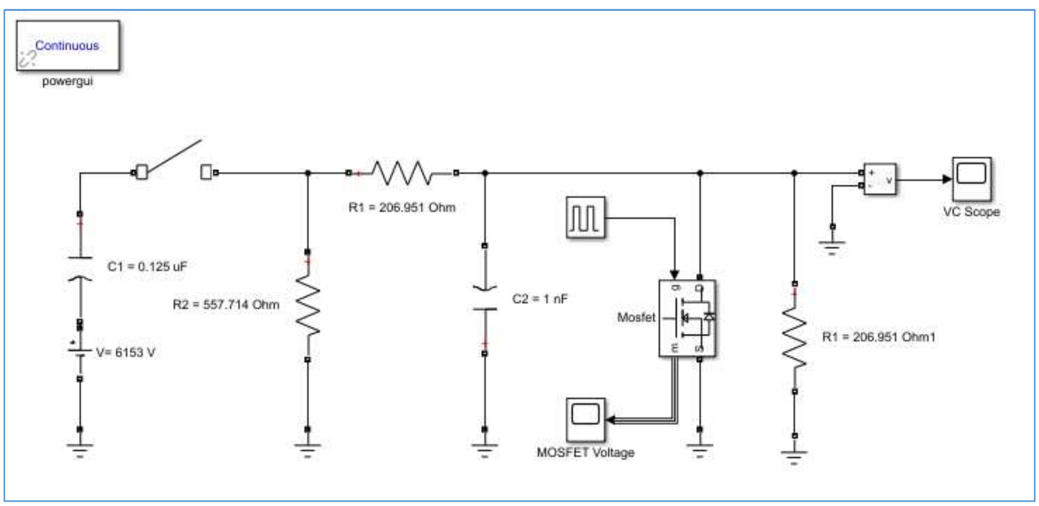


Figure 4-13 Standard Lightning Impulse Generator Circuit with MOSFET protection Model in MATLAB Simulink

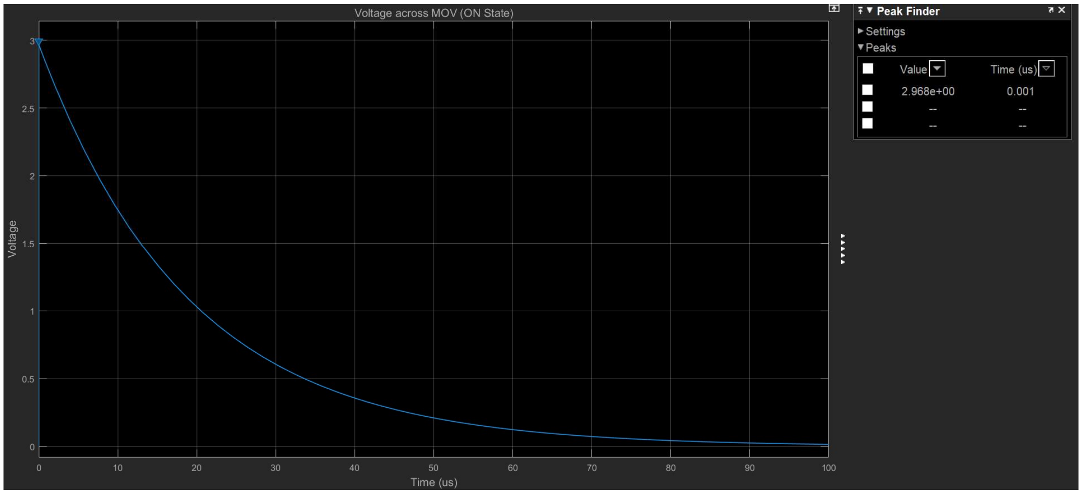


Figure 4-14 Voltage across on MOSFET when ON state

	Response time (µs)
Circuit with MOV	0.19
Circuit with MOSFET	0.001

Table 4-2 Comparison of MOV and MOSFET response time

4.4 Hardware Experiment Setup and Result

Figure 4-15 show a surge protection experiment is setup with a surge generator able to generate surge voltage level up to 6 kV and connecting with a test chamber, MOV with 200 V protection level is chosen. The voltage surge waveform is recorded as show in Figure 4-16, the oscilloscope shows the impulse voltage magnitude with 6000V.

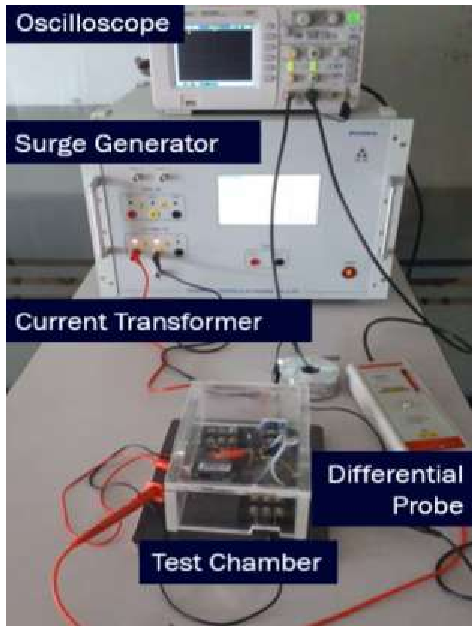


Figure 4-15 Surge protection experiment setup

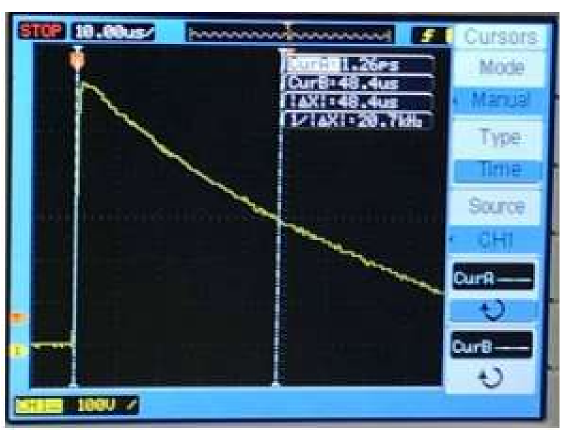


Figure 4-16 Impulse voltage surge waveform

Figure 4-17 MOV Clamping waveform

Figure 4-17 show current and voltage on MOV are captured. The current waveform indicates the current passing through the MOV to ground. Whereas voltage waveform indicates the voltage drop across on MOV when overvoltage surge is shunt to ground. We can see that current is rising rapidly when the clamping is started at 200 V. This is proving that the surge energy (current) is conducting to ground during the surge clamping duration.

5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In this report, different source of overvoltage transients are studied and can be classified into internal and external factors. Internal overvoltage transients are usually result from ferroresonance and capacitor switching. Capacitor switching transients can be further sorted into isolated capacitor switching, back to back capacitor switching, magnification of capacitor switching and capacitor switch restrike. Whereas for external surge is generally refer to lightning and it can be further divided into direct and indirect lightning. Direct lightning overvoltage transient is rarely happen compare to the indirect lightning overvoltage transient.

Surge protection technology can be generally divided into two groups, suppression and diversion. Suppression is referring to the technology of low pass filter as overvoltage transient are always in high frequency. Whereas diversion is a technology of shunting the surge energy to ground whenever the overvoltage transient is higher than the protection voltage level.

In addition, I have also studied lightning impulse wave generator circuit can be designed by MATLAB Simulink and the front time and tail time of the lightning impulse waveform can be controlled by α, β after different parameters of resistors and capacitors are used into the circuit. Conventional SPD (MOV) and power electronic SPD (MOSFET) are simulated and their results are investigate and compared. I noted that the MOSFET has faster response time than MOV. However MOSFET is having a surge diversion characteristic like GDT, which it shunts all the surge to ground instead of keeping it at the protection voltage level, this result in the output voltage level drop to zero. In the hardware experiment, only the MOV protection function has been studied by observing the surge clamping characteristic of MOV, current is shunt to ground when the surge clamping is started.

5.2 Recommendations

Conventional SPD (MOV) and power electronic SPD (MOSFET) are simulated into this project, and only MOV are used into actual hardware experiment. The further study in characteristic comparison of both conventional SPD (such as GDT and spark gap) and power electronic (such as IGBT, thyristor, Zener diode) can be conducted in more experiments. There are more comparisons study in term of response time in healthy and failed conditions, failure mode related to temperature and number of lightning strike could be further investigated. In addition, the capacitor rating used in simulation are for verifying the calculations, in actual practical prototype experiment we should take the capacitor rating into consideration because the impulse surge can harm the small rating component.

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7 APPENDICES

APPENDIX A: BS_EN_IEC_62305 Lightning Protection Standard

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 6651 ran in parallel, but as of August 2008, BS 6651 has been withdrawn and now BS EN/IEC 63205 is the recognised standard for lightning protection.

The BS EN/IEC 62305 standard reflects increased scientific understanding of lightning and its effects over the last twenty years, and takes stock of the growing impact of technology and electronic systems on our daily activities. More complex and exacting than its predecessor, BS EN/IEC 62305 includes four distinct parts - general principles, risk management, physical damage to structures and life hazard, and electronic systems protection.

These parts to the standard are introduced here. In 2010 these parts underwent periodic technical review, with updated parts 1, 3 and 4 released in 2011. Updated part 2 is currently under discussion and is expected to be published in late 2012.

Key to BS EN/IEC 62305 is that all considerations for lightning protection are driven by a comprehensive and complex risk assessment and that this assessment not only takes into account the structure to be protected, but also the services to which the structure is connected. In essence, structural lightning protection can no longer be considered in isolation, protection against transient overvoltages or electrical surges is integral to BS EN/IEC 62305.

Structure of BS EN/IEC 62305

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

Part 1: General principles

BS EN/IEC 62305-1 (part 1) is an introduction to the other parts of the standard and essentially describes how to design a Lightning Protection System (LPS) in accordance with the accompanying parts of the standard.

Part 2: Risk management

BS EN/IEC 62305-2 (part 2) risk management approach, does not concentrate so much on the purely physical damage to a structure caused by a lightning discharge, but more on the risk of loss of human life, loss of service to the public, loss of cultural heritage and economic 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.

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.

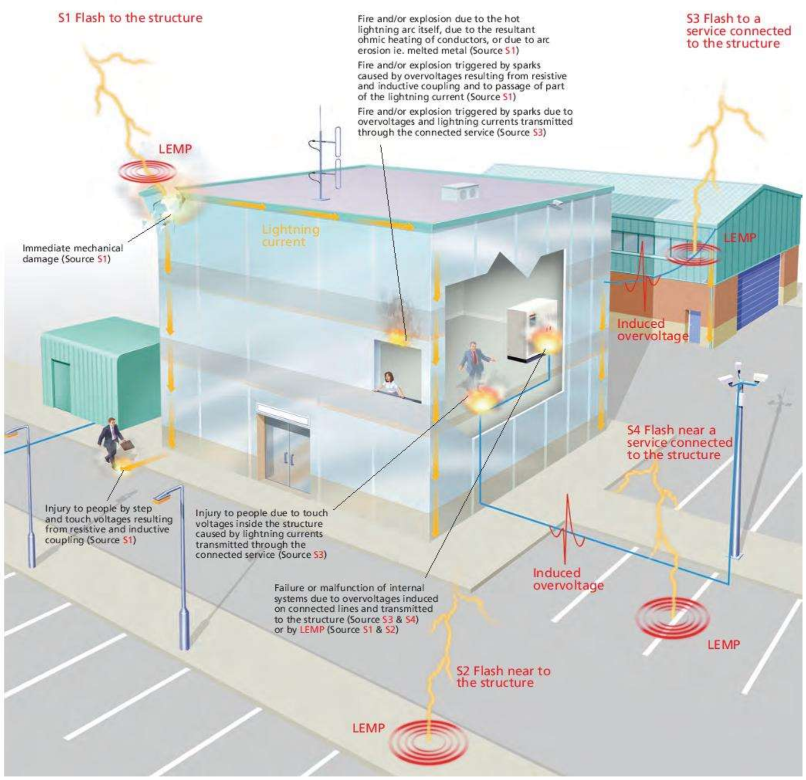


Figure 12: The types of damage and loss resulting from a lightning strike on or near a structure

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.

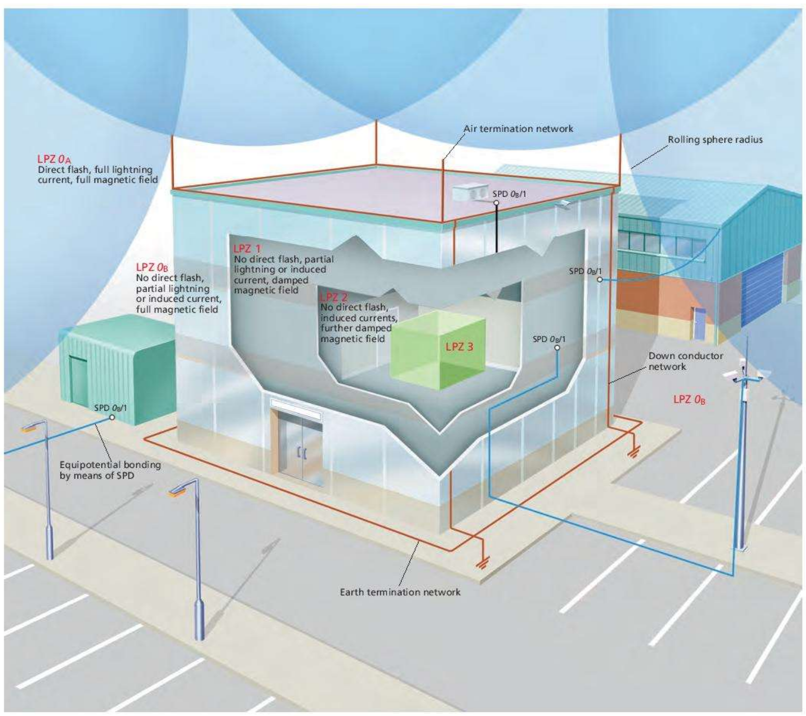


Figure 13: The LPZ concept

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**

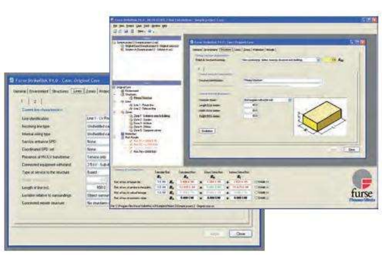
R_3 **risk of loss of cultural heritage**

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).



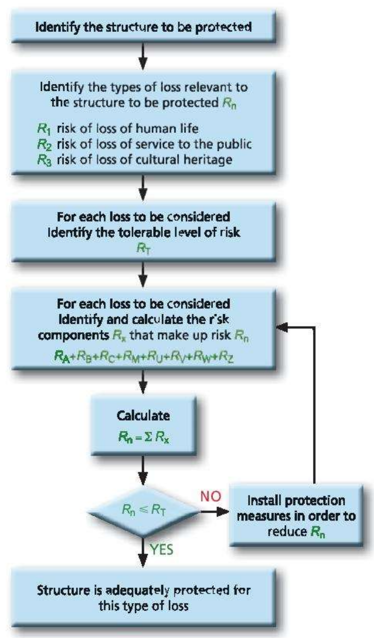


Figure 14: Procedure for deciding the need for protection (BS EN/IEC 62305-1 Figure 1)

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.

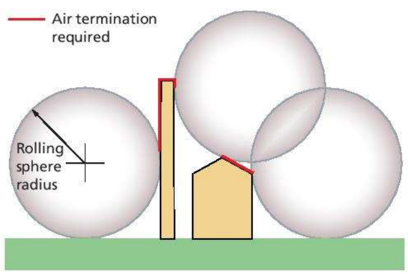


Figure 15: Application of the rolling sphere method

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).

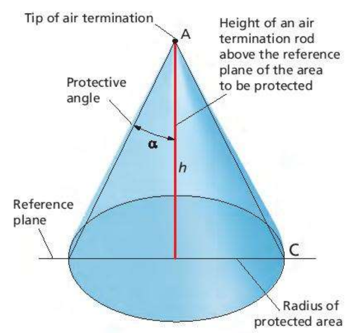
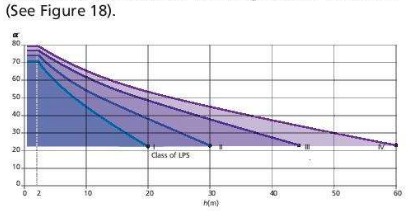


Figure 16: The protective angle method for a single air rod

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.

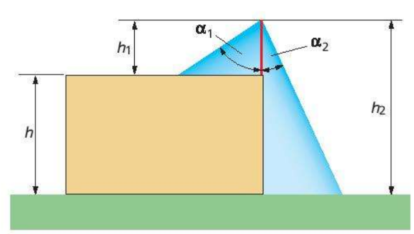


Figure 18: Effect of the height of the reference plane on the protection angle

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 (5.7º)
- 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.

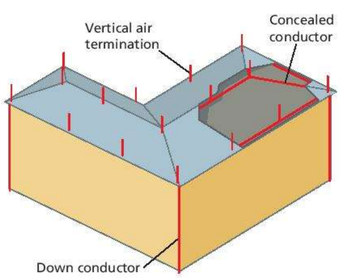


Figure 19: Concealed air termination network

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

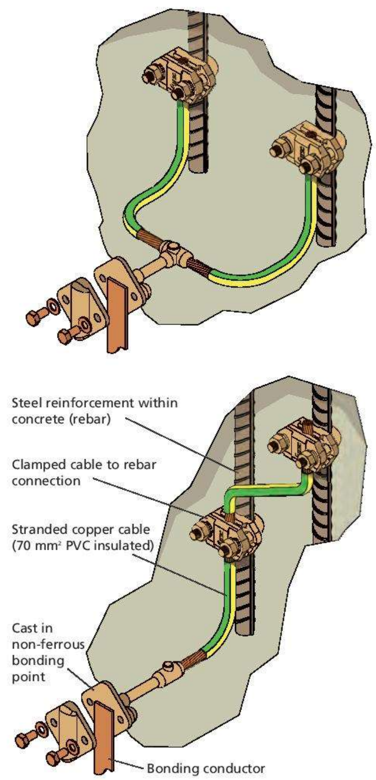


Figure 20: Typical methods of bonding to steel reinforcement within concrete

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.

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.

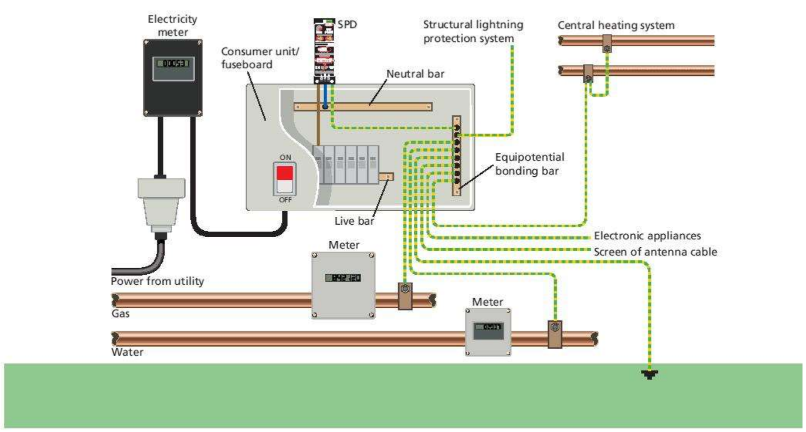


Figure 21: Example of main equipotential bonding

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.

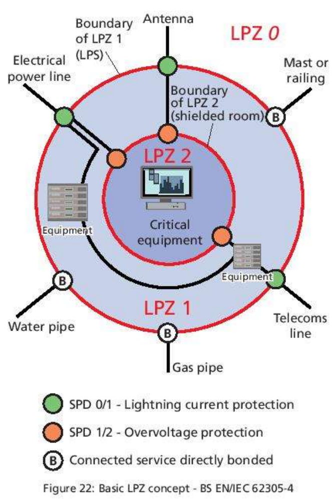


Figure 22: Basic LPZ concept - BS EN/IEC 62305-4

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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