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Consideration of surge arresters for low voltage mains applications

Michalopoulos, Aristidis

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CONSIDERATION OF SURGE ARRESTERS FOR LOW VOLTAGE MAINS APPLICATIONS

Aristidis Michalopoulos

A project report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, October 2011

Declaration

I declare that this research report is my own, unaided work, except where otherwise acknowledged. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

Signed on this 12th day of October 2011

_____

Aristidis Michalopoulos

Abstract

The work presented in this report details the background to surge arresters and surge protective device components, viz., spark gaps, gas discharge tubes and metal oxide varistors. Current surge protective device technologies are detailed for several of the larger surge protective device manufacturers worldwide. Tests were performed using both 8/20 µs and 10/350 µs current impulses to verify the voltage and current response of gas discharge tubes with or without series MOVs and triggering circuits. Measurements obtained from the test setup were compared against each other, sharing a total impulse current of 35.8 kA peak using an 8/20 µs waveform and 10.2 kA peak using a 10/350 µs current impulse waveform. In the work presented, it is shown that series varistors dampened any voltage and current oscillatory behaviour superimposed from the current impulse generator due to their voltage clamping properties, which similarly do not allow any follow current to flow after a surge has subsided. No effect was seen by using a single varistor or a many parallel mounted varistors in series with a gas discharge tube. By using three electrode gas discharge tubes with a triggering circuit, the clamping voltage was reduced, as the gas tubes reacted faster than an equivalent circuit without a triggering module, which has the advantage of reducing the protection level for the protected equipment.

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This work is dedicated to my loving parents and sister for their support and patience throughout the years, and for always going out of their way to ensure my every success.

“ΕΝ ΟΙΔΑ, ΟΤΙ ΟΥΔΕΝ ΟΙΔΑ” – SOCRATES

“One thing I know, is that I know nothing”

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List of Abbreviations

AC	Alternating Current
GDT	Gas Discharge Tube
MOV	Metal Oxide Varistor
SAD	Silicone Avalanche Diode
SPD	Surge Protective Device
VPL	Voltage Protection Level

Chapter 1

1 Introduction

The notion of zoning seen in [1] and [2] provides an approach to protecting equipment against damage due to lightning induced surges entering a low voltage (LV) electrical system in a building. A number of lightning protection zones are created, where the first zone is outside the building and the last furthest inside the building. Surge protective devices (SPDs) are positioned at zone boundaries (LPZ 0 – LPZ3) so that surges due to lightning entering a building are progressively reduced as they pass further into the building, and each zone, where a portion of the surge current is diverted to ground via the SPD as it passes each zone. The most sensitive equipment, such as data cabinets and servers, are placed in the furthest protection zone inside the building. This concept of zoning as per [2] is illustrated in the figure below:

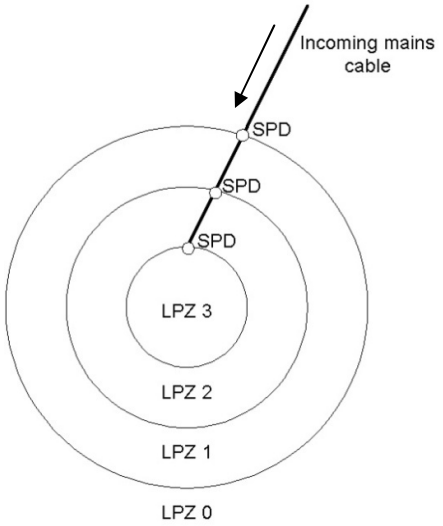


Figure 1: Lightning Protection Zones [2]

When the effects of direct lightning strikes are considered, the 10/350 µs current waveform (Class I) used [3]. Class II SPDs are tested with 8/20 µs

current impulses and Class III SPDs with combination 1.2/50 µs voltage impulse / 8/20 µs current impulse [4].

If a direct lightning strike is expected, and an external lightning protection system is installed, then a Class I SPD should be used at the first boundary and should be rated for the high energy associated with direct lightning strikes. The SPDs function is to divert most of the surge current to ground at the building entrance. This is then followed by a Class II SPD and thereafter a Class III SPD at the next respective zone boundaries towards the sensitive equipment that is being protected. It must be noted that if a direct lightning strike is not expected, then a Class I SPD is not required at the building entrance, and a Class II SPD should suffice [2].

Class I SPDs have traditionally employed mainly spark gaps due to the higher energy handling capability required by a Class I test. These devices usually have a pair of electrodes designed to break down at a certain voltage, and hence divert the surge currents such as those caused by direct lightning strikes to earth. As spark gaps are not enclosed, their response is dependent on environmental conditions and they unfavourably blow out hot plasma when they operate. A spark gap's response to an overvoltage is the creation of an electrical arc between its electrodes (short-circuit of one phase to earth). This means that the power supply is temporarily short circuited while the spark gap operates to take the surge to ground through this electrical arc. If this arc is not extinguished after the surge has been discharged, the electrical power supply will maintain this arc. This phenomenon is known as follow current and if not interrupted it can reach the prospective short-circuit current of the power supply, which would inevitably lead to operation of upstream overcurrent protection devices. Although spark gaps can conduct high currents, they do not have follow current interruption properties. In order to interrupt spark gap follow current, some Class I SPDs offer arc quenching properties (quenching spark gaps) that can interrupt follow current.

The high spark-over voltage of spark gaps results in an increased voltage protective level (highest voltage that the equipment will be subjected to).

There are various solutions available to decrease the spark-over voltage of spark gaps and one of these is to use a triggering circuit that initiates subsidiary discharges between the triggering and main electrodes in order to initiate the ignition of the main gap. The use of a triggering circuit allows the spark-over voltage to be reduced and hence for the residual voltage to be lower.

Metal oxide varistors (MOVs) are usually used mostly in lower surge energy applications and are relatively cost-effective clamping-type devices. Class I LV mains SPDs use triggered three electrode spark gaps, but the recent advent of MOVs has also produced Class I SPDs with MOVs rather than spark gaps [5]. Class II SPDs traditionally use MOVs, but some manufacturers have shown a combination of both of these components, where a spark gap is connected in series with a MOV [6]. Metal oxide varistors are known to quench power frequency follow current of spark gaps when placed in series with such devices, and they also ensure that the final clamping voltage is not below that of the mains supply voltage. Another configuration was seen in [7 and 8] where a spark gap and MOV were connected in parallel, but careful coordination was required between these two devices in order to use this combination successfully.

Gas discharge tubes (GDTs) are gas filled hermetically sealed spark gaps, which hence offer the same characteristics irrespective of environmental conditions, such as humidity and pressure. As GDTs are sealed they do not blow out hot plasma when they operate. Depending on the gasses that they are filled with, they have superior extinguishing properties when compared with spark gaps. GDTs are usually rated for smaller energy levels, i.e. for Class II and III applications.

Spark gaps with large enough ratings to withstand partial lightning currents are available, but can be bulky and complex. Therefore, using several smaller spark gaps in parallel, as per [9], could result in simpler and hence cheaper products. Due to the advantages that GDTs have compared to spark gaps, it would be favourable to replace spark gaps with GDTs. The problem with this

is that GDTs with high energy ratings are expensive and bulky and at present three electrode GDTs for Class I applications are not commercially available. [10 and 11] showed parallel connected GDT arrangements for both Class I and II applications.

It becomes important to understand the response behaviour of GDT with and without triggering circuits, as well as GDTs connected in series with MOVs, under both Class I and Class II tests, and this work focuses on these arrangements.

1.2 Research Objective

The reason for this research is firstly, to identify the various SPD technologies available for both Class I and II low voltage mains applications, as well as SPD components that make up SPDs, secondly, to setup and perform tests in order to identify the response characteristics of the GDTs with and without series connected MOVs and with and without triggering circuits and finally, to analyse the results in order to allow valuable comments to be made which can assist future SPD design.

1.3 Scope of the Report

Careful coordination is required between MOV and GDT in a parallel connected circuit in order to ensure that the GDT conducts before the MOV becomes overstressed. This becomes complex, and hence expensive to manufacture and it is simpler to rather connect a GDT in series with a MOV, hence this research focuses on this series configuration only. The scope of this report did not include for combination wave tests with 50 Hz mains and hence follow current investigations, as filters were not available for the 10/350 µs current impulse generator. As Class III applications are of the least exposure of the three classes, this report only focuses on Class I and II

applications. This work does not included for parallel connected GDTs and only focuses on single GDT operation.

1.4 Overview of the Report

This research report is structured in the following manner:

Chapter 2: This chapter is the literature survey that provides a brief outline of previous work and discusses sources of surges and impulse waveforms. Fundamental principles are then introduced such as gas discharge tube operation, voltage protection level and follow currents. The assumptions and limitations of existing surge arresters are also discussed.

Chapter 3: The testing procedure is detailed and the test results and findings of both 8/20 µs and 10/350 µs current impulse tests are presented and explained.

Chapter 4: The research report is concluded and areas of further research are identified.

Additional supporting material is provided in the appendices as follows:

Appendix A: Test result sheets.
Appendix B: Pictures taken during testing.
Appendix C: GDT Properties.

For convenience, each chapter and appendix begins with a summary of the main points covered in each chapter and ends with a brief introduction to the following chapter.

In the following chapter the literature survey is seen where the background to surge protective devices and gas discharge tubes is provided, as well as an overview of previous work in this field.

Chapter 2

2 Literature Survey

A brief outline of previous work is provided. Fundamental principles are introduced such as surges and sources of surges, followed by voltage protection level and follow currents. Surge protective devices are discussed as well as surge protective device components in order to understand the work that will be presented.

This chapter is the literature survey and introduces important concepts in order to understand the work that is being presented in this research report. It is important to understand what surges are, how they are created and why it is important to protect LV mains from surges. Surge protective devices are discussed followed by SPD coordination in order to understand SPD operation. Impulse waveforms, voltage protective level and follow current are presented in order to understand the limitations of SPDs and the testing impulse currents. Surge protective device components such as GDTs, MOVs, and triggered spark gaps are presented in this report as this work focuses on the testing of these components.

2.1 Surges

What was previously called transients, spikes, impulses and overvoltages are now formally known as surges, which is a sub-cycle voltage wave in electrical systems evidenced by sharp, brief disturbances in the input power voltage waveform, and often characterised by excessive voltage. The duration is less than a half-cycle of the normal voltage waveform and is generally less than a millisecond. This term is derived from the appearance of the abrupt disturbance of the normal voltage waveform and is often oscillatory-decaying.

2.1.1 Sources of Surges

Surges may be generated by lightning or by a sudden change of system conditions, or both. Surge types are normally classified as lightning generated and all others as switching generated. Surges due to switching phenomena, although are more common, are generally not as severe as lightning surges.

If the magnitude of overvoltage surpasses the maximum permissible levels, damage to equipment and undesirable system performance can be achieved. Surges therefore need to be reduced and protected against with SPDs to avoid these undesirable problems.

The frequent occurrence of abnormal applied voltage stresses from transient, short-circuit or sustained steady-state conditions results in premature insulation failure, where failure by short circuit results in the final stage.

Some examples of system generated and externally generated surges are listed below:

- Direct lightning strikes.
- High induced voltages associated with electromagnetic interference from indirect or adjacent lighting strikes.
- Capacitive or inductive switching of electrical loads.
- Electrostatic discharge.
- Power-frequency overvoltage.
- Transients or surges generated from heavy and light electrical machinery in general office or domestic environments, e.g. lifts, photocopy machines, etc.

The focus of this work will be on surges caused by lightning.

2.1.2 Risks Associated With Surges

The aim of limiting or mitigating surges is to prevent the following:

- Danger to human life.
- Capital investment loss in buildings and equipment.
- Environmental danger in critical buildings or environments associated with flammable or explosive materials.
- Loss of production and income, and inconvenience of system downtime.
- Loss of electronically stored data.
- Loss of irreplaceable cultural heritage.
- Loss of service to the public.

The above losses can be avoided by proper control of surges by making use of good earthing, lightning and surge protection systems. Depending on the environment or location, the expenditure required to secure this protection is good insurance and usually justifiable.

2.2 Surge Protective Devices

SPDs are used to limit and mitigate surges in LV electrical networks and equipment in order to limit the abovementioned risks. SPDs perform this function by diverting surge currents to ground, and hence away from the protected equipment, and by doing so they limit the voltage that the equipment is exposed to. SPDs only conduct under surge conditions within the surge protective device's ratings, and under normal operating conditions they do not influence the electrical system - although MOVs tend to exhibit a small leakage current as they are connected across a phase and neutral conductor. SPDs can consist of spark gaps, MOVs and silicone avalanche diodes, and there are two basic types of SPDs:

- Type I SPDs are current diverting (or switching type) devices.
- Type II SPDs are voltage clamping devices.

There is also a combination of the above two types of SPDs, that are called combination or mixed type of SPDs, that exhibit both voltage limiting and voltage switching characteristics in response to surges. Traditionally these devices make use of spark gaps and MOVs in parallel, but recent technology has also shown these devices connected in series [12].

2.2.1 Type I SPD

Type I SPDs are known as voltage switching SPDs as they have a high impedance when no surge is present, but their impedance can suddenly change to a low value in response to a surge. Components that have these characteristics are spark gaps and gas discharge tubes. Gas discharge tubes are hermetically sealed, gas filled spark gaps that offer the same performance irrespective of environmental conditions such as pressure and humidity, and which do not blow out hot plasma when they operate.

2.2.2 Type II SPD

Type II SPDs are also known as voltage limiting SPDs as they have a high impedance when no surge is present, but their impedance continually reduces in response to an increased surge current and voltage. Components with these characteristics are typically non-linear devices such as MOVs and silicone avalanche diodes (SADs).

2.3 Coordination of SPDs

2.3.1 Class I and II SPD Coordination

The combination of a Class I and II SPD in a single unit is done by placing a spark gap in parallel with a MOV, which results in a high energy rating while still clamping the transient voltage to a relatively low level. In this arrangement, the clamping voltage has a reduced duration as can be seen in [8]. However, in most cases it is required that Class I and II SPDs are kept separate.

Class I and II SPDs must be coordinated correctly, as MOVs in Class II SPDs have limited surge energy absorption capabilities. Switching type Class I SPDs must conduct most of the surge current, thereby preventing (and protecting) the Class II SPD from being overstressed.

This is usually achieved by ensuring that the Class I SPD starts conducting the surge before the Class II SPD is overstressed, even though the Class II SPD conducts a small portion of the current. The most common way of realizing this is by separating the SPDs with an appropriately-sized inductor, as shown in the figure below.

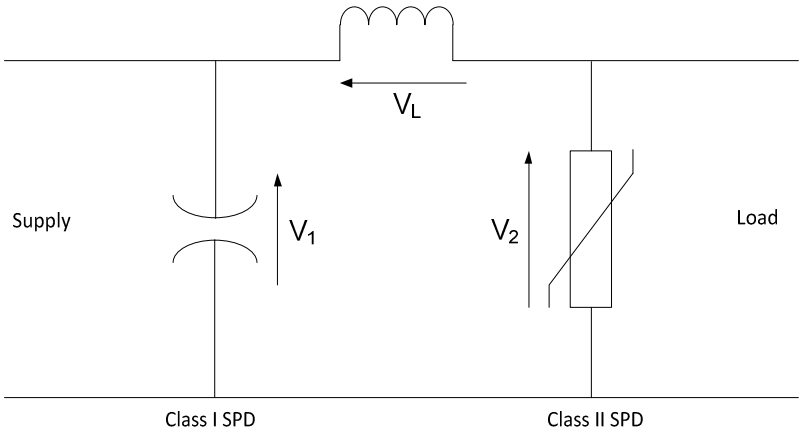


Figure 2: Coordination of Class I and II SPDs

The principle of operation is that V_2 and V_L rise fast enough, since V = L di/dt, so that V_1 rises fast enough for the Class I SPD to start conducting before the Class II SPD is damaged. The minimum required inductance is given by the SPD manufacturer. In many cases the cable between the SPDs is long enough for this inductance to be achieved; otherwise a discrete inductor must be added.

The function of the above impedance in between the Class I and Class II devices is to limit the current through the Class II MOV both before and after the Class I spark gap has operated.

It is possible to use MOVs in Class I devices, in such cases the inductor or impedance in between the Class I and Class II devices is required to limit the current to the Class II device.

As is detailed in Appendix C, gas discharge tubes do no operate instantaneously to surges as the air between its electrodes needs to ionise before arcing can occur between the main electrodes. This delay results in GDT operation of approximately 100 ns, as opposed to MOVs and SADs that operate in approximately 25 ns and near instantaneous (a few nanoseconds) respectively. MOVs are fast enough to handle transients with extremely steep current rises of up to 50 A / ns [13].

2.3.2 Class II and Class III SPD Coordination

It must be noted that if a Class III device cannot handle a Class II surge, then it needs to be coordinated with a Class II device to protect it [14]. The reason for this is that Class III devices cannot offer Class II protection and hence they could be damaged and result in a hazard. SADs have a smaller current handling capacity and a lower voltage clamping level, and they are mostly used in Class III devices to offer final equipment protection.

2.4 SPD Components

2.4.1 Spark Gaps

Spark gaps have traditionally been used successfully for Class I SPDs due to their high energy handling capabilities. These devices are usually a pair of electrodes designed to break down at a certain voltage and hence short-circuit the power supply. Spark gaps must respond quickly and spark over when surge voltages exceed the electric strength of a system's insulation. This discharge limits surge voltages to low levels and reduces the interference energy within a short period of time. As the high current arc is ignited, it prevents a further rise in surge voltage due to its constant low voltage which ideally is zero volts, but practically tends to that.

The operation of a spark gap can be compared to a voltage controlled switch, i.e. it only operates or "switches" after the voltage across its terminals surpasses a certain threshold. Spark gaps have conductance properties that change rapidly when breakdown occurs, from open-circuit to quasi-short circuit.

A disadvantage of spark gaps compared to clamping type SPDs, such as MOVs, is a higher spark-over voltage and hence clamping voltage. Therefore, some manufacturers have produced spark gaps that are triggered to flash over at a lower voltage, while the recent advent of MOVs with higher energy ratings has seen these devices used in Class I applications as well.

The electrical properties of an open gas-discharge path, depends on environmental parameters such as humidity, gas pressure, gas type and pollution. A disadvantage of conventional open-air spark gaps is that they have a high inception voltage, and they exhaust hot plasma under operation. Blowing out hot plasma is a disadvantage and such a solution would require a special housing with a pressure release system.

Gas discharge tubes, such as those used in the work presented here, overcome the disadvantages of air spark gaps by hermetic sealing. Gas filling enables spark discharge conditions to be controlled by shielding against environmental influence, as the breakdown voltage is related to gas pressure and electrode separation. The favourable advantage of hermetic sealing is that GDTs will offer a similar response at a certain temperature, as they are not affected by pressure or humidity. The rare gases neon and argon are predominantly used in gas discharge tubes and many manufacturers apply activating compounds on the effective electron surface of the electrodes. This reduces the work function of the electrons and aids in the stability of the ignition voltage [15]. Some manufacturers also attach an ignition aid to the internal cylindrical surface of the GDT insulator which ensures a faster response, as it speeds up the gas discharge by distorting the electric field [15]. Suitable material selection of the spark gap electrodes results in reduced spark gap ageing, for example, graphite does not create any metallic plasma and abrasion of electrodes compared to metallic electrodes.

GDTs show the specific behaviour that the ignition voltage increases with the steepness of the incoming voltage impulse, where conventional spark gaps only show this tendency at unpractical high steepness values.

Further operating properties of GDTs such as GDT operating domains, electrical breakdown in gasses and time lags in electrical breakdown are shown in Appendix C.

2.4.2 Metal Oxide Varistors

MOVs are bipolar, ceramic semiconductor devices designed to limit surges. The term varistor is a generic name for voltage variable resistor. The resistance of a MOV is nonlinear and decreases as voltage magnitude increases. The most common SPD technology used for many years is the MOV and is predominantly used for Class II applications. These are clamping

type of devices that limit the voltage to relatively low levels when diverting surge currents to ground. The distinguishing feature of a metal oxide varistor is its exponential variation of current over a narrow range of applied voltage. These devices have voltage clamping properties and clamp at a set voltage, by giving off excess voltage or surge energy as heat. When SPDs are functioning in the active region, they divert energy by conducting current to ground and absorbing energy by converting it into heat.

A common problem with MOVs is that there is a small magnitude of leakage current at all times. These devices are sensitive to high energy surges and they age quickly. Most manufacturers add thermal disconnection devices to MOV based SPDs to ensure that they do not ignite due to thermal runaway from 50 Hz mains overvoltage.

In parallel connected MOV circuits the surge current is distributed throughout each of the MOVs, which results in an improved circuit with a higher surge current capability.

2.4.3 Silicon Avalanche Diodes

SADs operate in a similar manner to MOVs, but instead of metal oxide, these type of surge suppressors use silicon based diodes, similar to zener diodes. SADs are inherently unidirectional; therefore two SAD devices in a back-to-back configuration are required to clamp alternating current (AC) voltages.

SADs have some characteristics that can be advantageous in comparison to MOVs. Most important, they have a sharper bend in the curve around the breakdown voltage, and as a result they tend to clamp closer to the normal peak voltage of the AC waveform.

The response time of SADs is faster than that of MOVs, but their energy ratings are much smaller, which may be important for surge suppression on electronic circuits with sensitive components and high-frequency signals. Their cost at present does not make them more advantageous for use in power systems, as transients are well within the range for MOVs to provide near instantaneous protection.

For most equipment connected to an AC power system, this is not a significant advantage as the surge withstand capability of the equipment is well above the protection levels of the MOVs. However, this advantage may be important when protecting data lines and other sensitive electronic equipment at the low voltage level, where the transient voltage magnitude may be more critical.

Silicon avalanche diodes are normally used in Class III SPDs, but they are also used in certain Class II applications as they clamp surges at lower levels than MOVs and also age slower [16]. The disadvantage of SADs is that they have low current handling capabilities and are also relatively expensive compared to MOVs. For fast rise times where the characteristics of the surge suppressor could be an issue the effect of voltage differences across short lead lengths (inductance) can be much more important than the response time of the actual surge protective device.

2.5 Impulse Waveforms

The most commonly used impulse current waveform for testing SPDs is the 8/20 µs waveform, and is specified in several IEC standards [1 and 4]. This waveform covers induced lightning and switching surges. However, when the effects of direct lightning strikes (Class I) are considered, the 10/350 µs waveform is used [3].

Class II SPDs are tested with 8/20 µs current impulses and Class III SPDs with a combination wave. The generator must be capable of delivering 8/20 µs current impulses in short circuit mode and 1.2/50 µs voltage impulses in open circuit mode. Details of this testing procedure are detailed in [17].

2.6 Voltage Protection Level

The voltage protection level is dependent on the residual or clamping level of the arrester. The VPL of an arrester is directly related to the reaction time of the arrester i.e., the faster the reaction time, the lower the VPL.

In many cases, the surge is lower in voltage than the VPL of the arrester or faster than the arrester's reaction time and the arrester does not detect the transient. This is common with switching type transients that account for 50 % of transients that are generated by inductive loads such as air-conditioner, lift motors and standby generators - all of which are commonplace in most modern day facilities. The specification shown in [18] clearly defines the level at which an arrester needs to operate in order to protect electrical systems.

A high voltage level for a long duration causes stress on the insulation of the system that is being protected. The residual voltage of a MOV stays constant at a high clamping voltage during the entire duration of the surge current. In a spark gap the residual voltage is at a high level until breakdown occurs after which it drops to a low voltage level.

Traditionally it has been seen using the following combination of surge arresters to reduce surge voltage levels:

- Class I spark gap based device at the building entrance
- Decoupling inductor for coordination between Class I and II SPDs.
- Class II MOV based device at the equipment being protected.

[8] indicates the impulse withstand categories for overvoltage limits and shows that the maximum allowed overvoltage, on a 230 V system, for a Class II and III device is 1.5 kV.

2.7 Follow Current

A gas discharge tube's response to an overvoltage is the creation of an electrical arc between its electrodes (short-circuit of one phase to earth). This means that the power supply is temporarily short circuited while the GDT operates to take the surge to ground through this electrical arc. After the surge has been discharged the electrical power supply continues to generate current which maintains the arc, which is known as the follow current. A favourable property that spark gaps have is that they are self-restoring as they return to their high impedance state after the surge has subsided, provided that there is no follow current.

This phenomenon is therefore an excessive current which may flow from the supply current source through the ignited spark gap, and occurs between the surge decay interval and the following zero crossing of the AC voltage. If not interrupted, the follow current reaches the prospective short-circuit current of the power supply (within a half-period, i.e. within 10 ms in case of 50 Hz). High temperatures and hence damage of equipment can occur if the arrester does not extinguish this follow current. An occurring follow current has to be extinguished at latest after the next natural AC zero crossing [19]. During this zero crossing the spark gap has to regain its electrical strengths between the main electrodes in a few microseconds. During this relatively long duration where the follow current flows, the energy dissipation inside of the spark gap is enormous. So it is an important to minimize either the follow current amplitude or the follow current duration. An optimal spark gap prevents any follow current after discharging the lightning current, but the occurrence of follow current also depends on the prospective short circuit current of the mains. Follow current has to be limited by using arc quenching spark gaps to

avoid the operation of the upstream protection, by drawing the prospective short-circuit power supply current.

The occurrence of follow current on spark gaps depends on the following:

- Prospective short circuit current of the low voltage system.
- Amplitude of the surge or overvoltage.
- Energy content of the surge or overvoltage.
- Synchronisation angle of surge on the power supply voltage.

If the time of influence of a surge is smaller than a given limit, or if the surge current remains smaller than a defined value, no follow current will occur. The power supply voltage drives follow current after the surge current has passed the gap. The gap has to extinguish the follow current, but the arcing voltage acts as a counter voltage and therefore the actual follow current in the gap is less than the prospective current. When the arcing voltage is equal to the actual value of the power supply voltage, the gap extinguishes and does not reignite. The reason for this is that a direct short circuit across the power supply will allow the prospective fault current of the supply transformer to flow. Thus the arc voltage must be higher than the mains supply voltage, in other words, current flows from a higher potential to a lower potential, hence if the voltage is kept at a high enough potential no current will flow.

MOVs do not allow follow current to flow and hence some manufacturers use MOVs to ensure that their devices do not let any follow current through, while others use arc quenching spark gaps.

It was seen in [20] that an SPD with a spark gap and MOV in parallel, predominantly only showed noticeable follow current at synchronisation angles of 240^{o} and 270^{o} (when incrementing the synchronisation angle in increments of 30^{o} over a full cycle of the mains AC voltage). This shows that as the peak values of follow current get smaller, the arcing voltage reaches the mains voltage faster.

Follow current quenching capabilities have been improved in spark gaps by using:

- Arc baffle plates.
- Quenching plates.
- Plastic material which releases quenching gas during heating up by an arc.
- Increasing the distance between the main electrodes to increase the arcing voltage.
- Building pressure during the discharge of surge current.
- Using an arc channel which is oriented transversally to the electric field.
- Triggering circuit on a 3-electrode spark gap.
- Using MOVs.

MOVs do not allow follow current to flow, as during the discharge of a surge current the voltage always remains above the instantaneous voltage of the power supply system. Follow current will always occur if the instantaneous value of the supply voltage is higher than the arcing voltage of a spark gap during the discharge of a surge. Hence, the residual voltage of an SPD needs to be higher than the instantaneous voltage of the power supply system.

2.8 Recent SPD Developments

Currently most Class I manufacturers use spark gaps with or without triggering circuits between phase and neutral and between neutral and earth conductors. Some manufacturers use MOVs for Class I protection, but these devices cannot protect sensitive electronic equipment effectively as the residual voltage is much higher than the permissible levels shown in [2]. Class II devices have shown MOVs connected between phase and neutral conductors and the use of either MOVs or spark gaps between the neutral and earth conductors depending on the mode of operation. Some devices use

spark gaps in series with MOVs throughout all phases, while others use only a spark gap between neutral and earth. Some manufacturers use spark gap technology for Class II protection as well. Various interconnections of the above can be done, depending on whether common mode or differential mode protection is required.

2.8.1 Spark Gap and MOVs in Series

As discussed, when spark gaps operate they cause a quasi-short circuit between phase and ground while mitigating a surge to ground. This means that the voltage collapses below the supply potential. A MOV does not allow this as it clamps the voltage to a set threshold. If these devices had to be placed in series, the overall characteristic of both these components would be that of the MOV. The advantage would be that once the surge had subsided the spark gap would return to its high impedance state and hence disconnect this device. This would protect the MOV as there would be no leakage current, MOV ageing and any unnecessary operation of these devices.

The advantage of placing a MOV and spark gap in series is therefore the following:

1. The spark gap protects the MOV as there is no constant leakage current or unnecessary operation.
2. No unnecessary voltage collapse below the supply potential.
3. No follow current is let through.
4. The spark gap disconnects once the surge has subsided.

Due to MOV clamping properties, a similar follow current quenching would be seen if a spark gap and MOV were placed in parallel.

2.8.2 Three Electrode Spark Gaps with Triggering Circuits

The high arcing and spark-over voltage of spark gaps results in an increased protection level. There are various solutions available to decrease the electrical strength of spark gaps and one of these is to use a triggering circuit to initiate smaller discharges between the triggering and earth electrodes in order to initiate the ignition of the main spark. The use of a triggering circuit allows for the spark-over voltage to be reduced and hence for the residual voltage to be lower. This allows the spark gap to mitigate smaller amplitude or faster impulse surges as well.

To extinguish follow current, the electrical arc voltage must be increased by various methods, i.e. by lengthening, cooling or multiplying of the arc. By using a triggered spark gap, the energy dissipation during the surge current will be higher, but in return the dominant energy from a power follow current is decreased rapidly. It was shown in [21] that short term trigger pulses, even if repetitive, are not able to initiate follow current through a triggered type of spark gap, due to their short time of interference. Circuits for triggering spark gaps usually contain a rather complex voltage detector and triggering pulse generator that is expensive.

In a coordinated Class I and II SPD configuration with a decoupling coil in between these two devices, the decoupling coil works well with fast rising surges as it allows the voltage to be high enough to allow breakdown of the Class I spark gap. For slow rising surges the voltage will be too low to allow the spark gap to ignite, which will result in the Class II MOV being overstressed and hence damaged. This phenomenon can be eliminated by using a 3-electrode spark gap with an electronic triggering circuit [22] that is voltage dependant rather than surge rise time dependant. This will allow the spark gap to reach low voltage protection levels even for high amplitude surges.

2.9 Concluding Comments

The background to this research was presented in this chapter by firstly introducing surges, sources of surges and risk associated with surges. Following this surge protective devices and coordination of SPDs was shown with a focus on SPD components such as GDTs and MOVs in order to understand SPD operation. Impulse waveforms, follow current and voltage protection level were discussed in order to understand SPD design objectives. Recent development of SPD technology was presented, including series connection of a spark gap with an MOV and triggering circuits in order to understand the testing that will be presented in the following chapter.

The following chapter indicates the tests that were performed including the testing objectives, test results and findings of the tests.

Chapter 3

3 Tests, Test Results and Findings

This chapter details the tests performed, followed by test results and test findings. A table summarising all the test results is shown, followed by the analysis of both the 8/20 µs and 10/350 µs impulse tests performed. The effects of MOVs and triggering circuits are looked at carefully.

The previous chapter presented the various SPD technologies available for both Class I and II low voltage mains applications, as well as SPD components that make up SPDs. A basic overview of voltage protection level, follow current and impulse waveforms were shown. The effects of a triggering circuit and a spark gap connected in series with a MOV were described in order to understand the testing performed in this research. This chapter details the tests performed in order to identify the response characteristics of GDTs with and without series connected MOVs and with and without triggering circuits. The test results are analysed in order to allow valuable comments to be made which can assist future SPD design.

The advantages of GDTs compared to spark gaps were described in the previous chapter and hence only GDTs were used in this work. In order to fully understand the response of GDTs, GDTs with series connected MOVs, and GDTs with triggering circuits, both 8/20 µs and 10/350 µs impulse current waveforms were used, as described in the previous chapter and [4, 23 and 24].

Through testing the response characteristics of the above components were attained in order to analyse the test results. It is important to identify the response of 2-electrode GDTs and compare it to 3-electrode GDTs. These tests allowed the effect of using parallel connected smaller MOVs rather than

a single larger MOV in series with the GDT to be shown. Further test showed the response of 3-electrode GDTs with and without a triggering circuit and with and without series connected MOVs.

3.1 Tests Performed

Voltage and current waveforms under both 8/20 µs and 10/350 µs impulse conditions were investigated for the following circuit arrangements:

- 2-Electrode GDT.
- 2-Electrode GDT with one series MOV.
- 2-Electrode GDT in series with many parallel connected MOVs.
- 3-Electrode GDTs without a triggering circuit.
- 3-Electrode GDTs with a triggering circuit.
- 3-Electrode GDT with a triggering circuit and series MOVs.

In order to be able to compare the effect adding MOVs or a triggering circuit to the GDTs, benchmark tests were performed with only a 2-electrode and 3-electrode GDT for both 8/20 µs and 10/350 µs impulse current waveform tests. The effects of using a 3-electrode GDT compared to a 2-electrode GDT were done, were 3-electrode GDTs were tested by leaving the triggering electrode of the GDT unconnected, earthed and connected to a triggering circuit.

The circuit diagram below shows a typical test setup circuit with a two electrode GDT with one series connected MOV. The MOV can either be a single MOV or replaced with parallel connected MOVs. The GDT can be of the two or three electrode type, where a triggering circuit can be used in conjunction with three electrode GDTs.

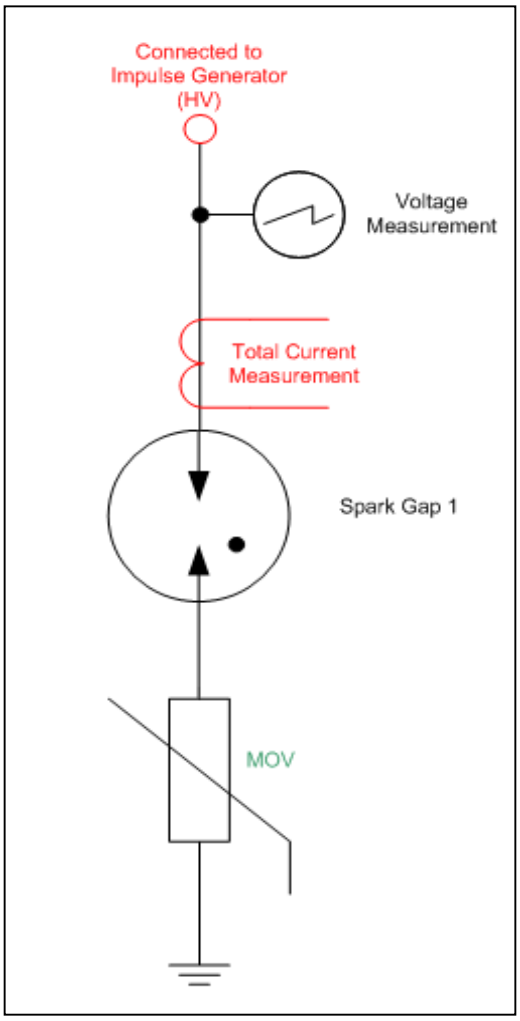


Figure 3: Circuit diagram of Test Setup

The measurements were done with an oscilloscope, were a voltage probe was used to measure voltage and a Pearson coil was used to measure the current waveforms.

3.2 Test Results

A summary of the abovementioned test results can be seen in the table below. Detailed test sheets of these tests are shown in Appendix A, and pictures taken of the test setup are shown in Appendix B.

Table 1: Summary of Test Results

Test	No of GDT Electrodes	No of 275 V MOVs in Parallel	Generator Charging Voltage [kV]	Peak Measured Voltage [kV]	8/20 µs Peak Current [kA]	10/350 µs Peak Current [kA]
1	2	None	20.00	13.00	33.4	N/A
2	2	1	18.00	13.40	27.8	
3	2	2	20.00	13.40	31.4	
4	2	4	20.00	14.90	28.4	
5	3 (Floating)	None	20.05	12.10	35.8	
6	3 (Earthed)	None	20.00	11.10	35.8	
7	3 (Triggering)	None	20.00	11.50	24.6	
8	2	None	7.06	1.30	N/A	7.08
9	2	1	7.00	1.80		6.84
10	2	2	7.00	1.60		6.70
11	2	4	10.00	1.80		10.10
12	3 (Triggering)	None	10.00	1.55		11.00
13	3 (Triggering)	4	10.00	2.10		10.20

The explanation of the test results are detailed in the section below for both the 8/20 µs and 10/350 µs impulse waveform tests.

3.3 Testing Using 8/20 µs Current Impulses

3.3.1 Effects of MOVs

As can be seen in the figure below, an oscillation superimposed by the impulse generator was seen on the measured voltage and current waveforms. It was seen that introducing a MOV in series with a GDT, resulted in dampening of this overshoot. This is due to the voltage clamping properties that MOVs possess, which are also responsible for eliminating follow current after a surge has subsided.

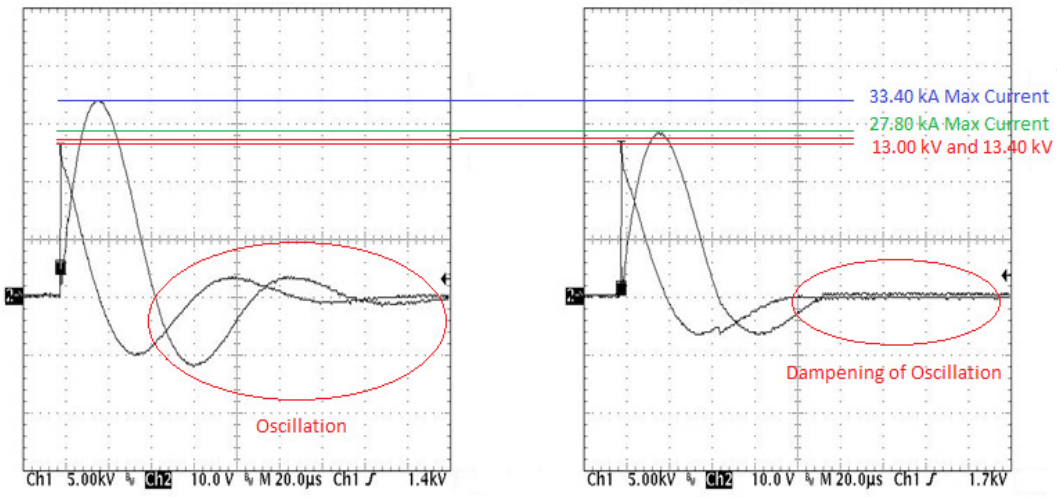


Figure 4: Waveforms of GDT only and GDT with single MOV

As can be seen in Appendix A, there was no noticeable difference in the voltage and current waveforms when using a single MOV or larger paralleled type of MOV in series with a GDT. The overall voltage was increased by 3 % while the current was decreased by 12 % by the introduction of MOVs. This could be attributed to the non-linear properties that MOVs possess, but also to the added impedance required to connect up the MOVs.

3.3.2 Using Three Electrode GDTs without Triggering Circuit

Test results captured on the oscilloscope were superimposed in the figure below. It can be seen that there is no noticeable effect on 3-electrode GDTs when the centre electrodes are earthed or left unconnected. The reason for this is that no current flows through the triggering electrode when it is not connected to a triggering circuit.

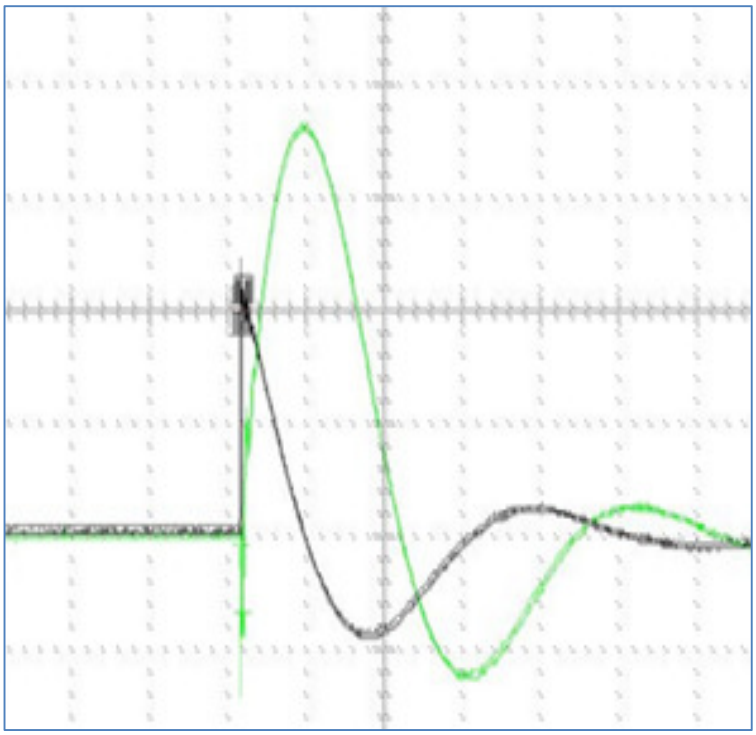


Figure 5: Waveforms of GDT with Earthed and Unconnected Triggering Terminals

3.3.3 Using Three Electrode GDTs with Triggering Circuit

When a triggering circuit was connected to the triggering electrodes, it resulted in an increase of approximately 40 % of the initial voltage compared to a similar test without a triggering circuit. This was a momentary spike, but

this phenomenon is due to the triggering circuit inductance coil which is dependent on the equation V = L $\frac{di}{dt}$. From this relationship, it can be seen that a high voltage will result from an 8/20 µs impulse current waveform as it has a fast rate of change. The faster the rate of change of current over time, the higher the output voltage will be.

As can be seen in the figure below, by excluding the initial spike seen in the voltage waveform, the overall voltage was reduced by approximately 8 %, which is due to the triggering circuit increasing the response time of the GDT. The overall current was also reduced by approximately 30 % and this is due to the impedance of the triggering circuit inductor coils.

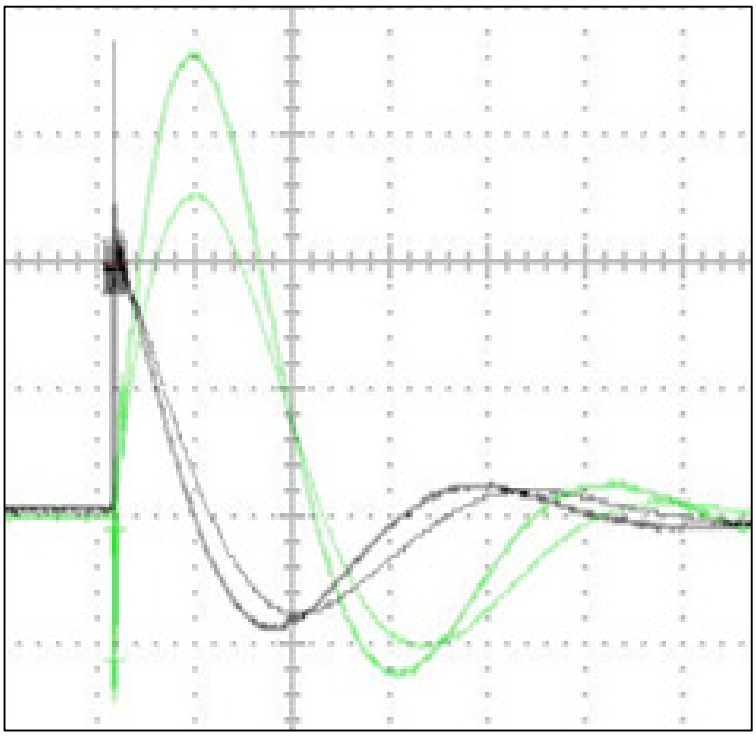


Figure 6: Waveforms of GDTs with and without a Triggering Circuit

It must be noted that the triggering circuit inductor designed for this work, was larger than actually required in order to ensure that the effects of the triggering circuit were evident. In practice this inductor coil needs to be correctly set to

ensure that triggering will occur. The design of this coil requires that the overall protection levels are taken into considerations, as per [2], to ensure that these are not exceeded. Insulation failure and damage to protected equipment could occur if the voltage protection level is exceeded.

Triggered spark gaps are not normally used in Class II applications, but rather in Class I application that are tested with 10/350 µs impulse current waveforms that have a slower rate of change compared to those of 8/20 µs Class II impulse current test. As will be seen in the 10/350 µs impulse current testing section, the overall voltages did not exceed those of similar tests and they were actually lower. The reason for this is that the triggering circuit allowed the GDT to respond faster.

3.4 Testing Using 10/350 µs Current Impulses

3.4.1 Effects of MOVs

As can be seen in the figure below, there was no noticeable difference in the voltage and current waveform when using a single MOV or a larger parallel type of MOV.

The overall voltage was increased while the current was decreased slightly by using MOVs. This can be attributed to the voltage drop across the MOVs and the additional inductance involved with connecting the MOVs.

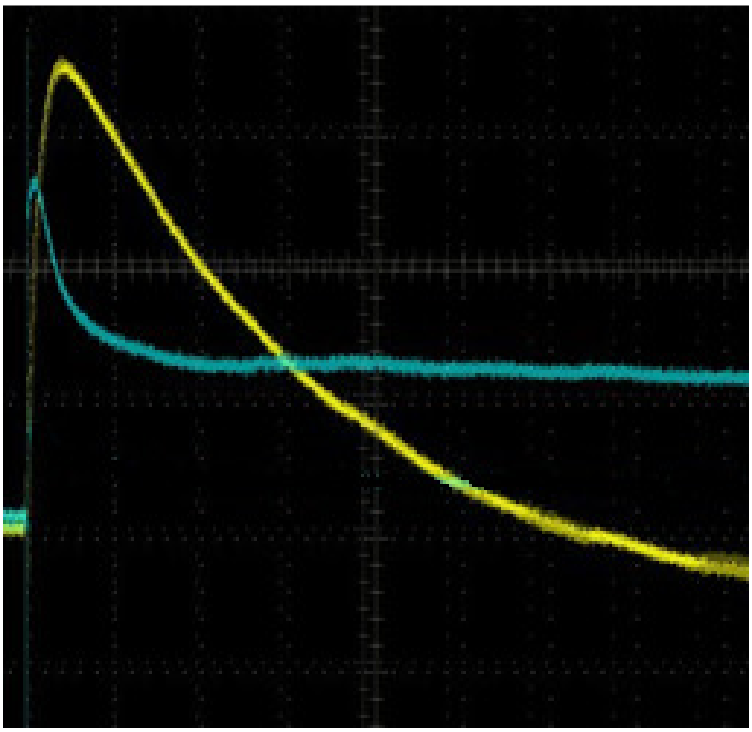


Figure 7: Waveforms of GDT in Series with Single and Parallel MOVs

3.4.2 Using Three Electrode GDTs with a Triggering Circuit

When a triggering circuit was connected to the GDT centre electrodes, it resulted in a decrease of up to 14 % on the overall voltage compared to a similar 2-electrode test without a triggering circuit. This is as a result of the triggering circuit allowing a smaller breakdown to occur, between the triggering electrode and earth electrode, as the voltage rises across the entire system. This smaller gap breakdown ionises the gas inside the gas discharge tube which allows it to respond faster to discharge the entire surge current.

As can be seen in the figure below, the overall current was also slightly reduced in comparison to a similar test without a triggering circuit. This could be due to the impedance of the triggering inductor coils.

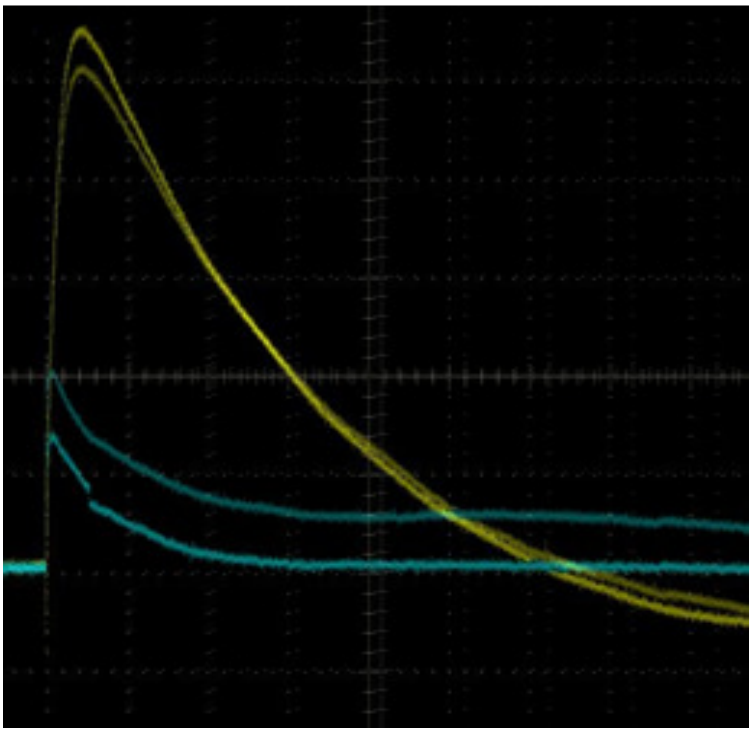


Figure 8: Waveforms of GDT with and without a Triggering Circuit

Again, it must be noted that the triggering circuit inductor designed for this work was larger than actually required to ensure that the effects of this triggering circuit were evident. In practice this inductor coil needs to be correctly sized to ensure that triggering will occur and that the overall protection levels, as detailed in [2], are not exceeded. Insulation failure and damage to protected equipment could occur if these values are exceeded.

3.5 Concluding Comments

This chapter detailed the tests setup and tests performed in order to identify the response characteristics of GDTs with and without series connected MOVs and triggering circuits. In order to fully understand the response of these configurations, both 8/20 µs and 10/350 µs impulse current waveforms were used. The test setup was illustrated and the test result were summarised. The test results were analysed and the following was found:

- MOVs dampened oscillations superimposed by the impulse generators. This would similarly eliminate any follow current under a 50 Hz mains test superimposed with 50 Hz mains.
- There was no noticeable difference in the voltage and current waveforms by using a single MOV or many parallel connected MOVs in series with a GDT. This means that future SPD design should use the cheaper and physically smaller MOV option.
- The additional impedance of the required cabling to connect the MOVs together with the effects of the MOVs resulted in a slight decrease in the voltage waveform and an increase in the current waveforms. It must be noted that connecting wiring in future SPD design would be as short as possible to save costs and space and any inductive effects.
- No effect was seen by replacing the 2-electrode GDTs with 3-electrode GDTs. There was also no effect seen by earthing or leaving the triggering electrode of a 3-electrode GDT floating when no triggering circuit was connected. This means that in future SPD design, the correct GDT must be used for each application, based on costs and size.
- A triggering circuit introduced an initial voltage spike due to the inductive properties of the triggering coil. This effect can be reduced by careful trigger coil design to suit the SPD application by taking space allowances and the overall voltage protection levels into consideration to avoid any insulation failure.
- A triggering circuit reduced the overall voltage as it increased the response time of the GDT. The current was also reduced due to the impedance of the triggering coils. Again, the triggering circuit needs to be carefully designed for each application.
- Triggering circuits are normally used in Class I applications that are tested with waveforms that have a slower rate of change compared to those of Class II. Careful coordination will be required in combined Class I and II devices with a triggering circuit.

In summary, it would be advantageous for future SPD design to make use of 3-electrode GDTs with series connected MOVs and a triggering circuit. The MOVs will eliminate any follow current and the triggering circuit will allow the GDT to operate faster. Careful triggering circuit design will be required in order to allow the GDT to operate effectively for both Class I and II applications. The entire circuit design must ensure that voltage protection levels are not exceeded to avoid insulation failure on the electrical system.

The next chapter will conclude this research report, followed by the test sheets, test photograph and GDT property appendices.

Chapter 4

4 Conclusion

This research report presented a background to the various SPD technologies available for both Class I and II low voltage mains applications, as well as the operation of SPD components. It was seen that most SPD manufacturers use spark gap technology for Class I arresters and some make use of a triggering circuit as well. With the advent of high energy MOVs some manufacturers only use MOVs for Class I protection. Most Class II arresters make use of MOVs, but spark gaps were also seen connected in series with MOVs in these devices.

Test results were presented under both 8/20 µs and 10/350 µs current impulse conditions. The response characteristics of both two electrode and three electrode GDTs were shown, with and without triggering circuits, as well as single or parallel connected MOVs in series with the GDTs.

The analysis of the test results allowed valuable comments to be made to assist future SPD design. It was shown that a triggering circuit reduced the overall voltage due to a faster response of the GDT. No noticeable effects were seen by adding series MOVs to the GDTs. Due to their properties, MOVs do not allow any power frequency follow current to flow as they clamp the voltage above the instantaneous voltage of the power supply system, where GDTs effectively short circuit the power supply system while discharging a surge.

4.1 Scope for Further Research

Combination wave tests with 50 Hz mains should be performed to view follow current quenching capabilities of series connected MOVs with GDTs and triggering circuits. Also, failure test of MOVs and GDT tests need to be performed to find the equivalent 10/350 µs impulse current ratings for 8/20 µs impulse current rated components. Ageing of these devices need to be identified to find how many impulses these components can withstand.

Triggering circuit design needs to be performed and tested to identify whether a SPD can successfully be used for both Class I and II application in a mixed Class I and II device.

Due to the high costs of higher rated GDTs and MOVs for Class I applications, investigations into a method of ensuring equal current sharing between parallel connected GDTs needs to be done, as this will reduce costs of SPDs as smaller and hence cheaper “off the shelf” components can be used to share a portion of the overall surge current.

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Appendix A

A Test Results

This appendix details the test results of both 8/20 µs and 10/350 µs impulse current tests performed. Details of each test indicate the average temperature at time of testing, the total measured impulse current as well as overall voltage and charging voltage of the impulse current generator.

A.1 Testing Using 8/20 µs Current Impulses

This section details testing performed on the 8/20 µs impulse generator. As detailed below tests were performed with 2-electrode and 3-electrode spark gaps, as well as with either single or parallel connected MOVs in series with the GDTs. Triggering circuits were also used as indicated below with some of the 3-electrode tests, while in other tests the triggering electrodes were either earthed or left unconnected. It must be noted that hermetically sealed GDTs were used, which are unaffected by atmospheric pressure and humidity, nevertheless, the humidity was measured and is indicated in the test sheets below.

A.1.1 Two Electrode GDT Test

Table A.1: Testing of Two Electrode GDT

Date Performed	13th May 2005	8/20 µs Waveform
Time Performed	14:41	2-Electrode GDT
Average Temperature	23 ℃	No MOVs
Average Humidity	24 %	V13-A500XN
Average Atmospheric Pressure	N/A	
Total Current [kA]	33.40	
Max Voltage [kV]	13.00	
Charging Voltage [kV]	20.00	

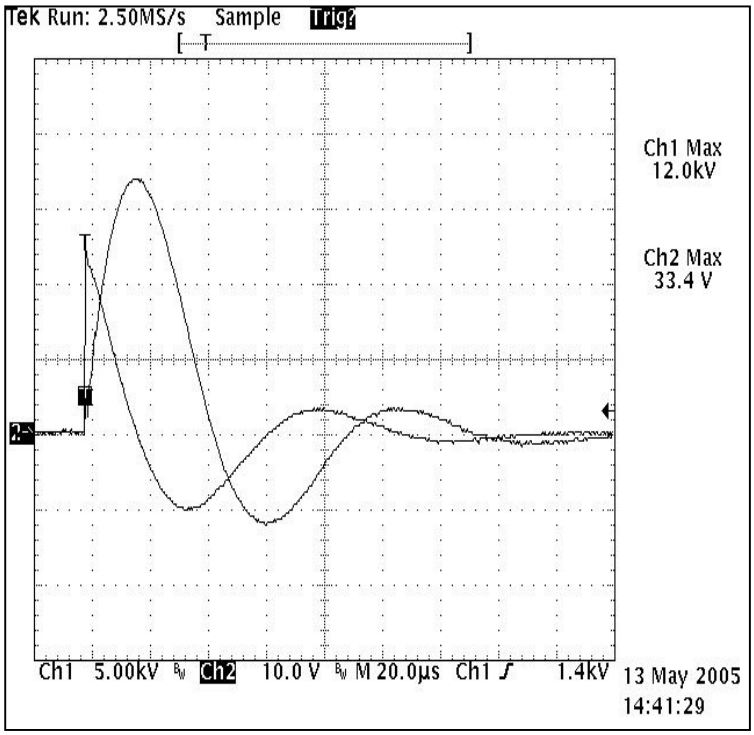


Figure A.1 Voltage and Current Waveforms of Two Electrode GDT

A.1.2 Two Electrode GDT in Series with One MOV

Table A.2: Testing of Two Electrode GDT with One Series MOV

Date Performed	13th May 2005	8/20 µs Waveform
Time Performed	15:26	2-Electrode GDT
Average Temperature	23 ℃	1 MOV
Average Humidity	24 %	V13-A500XN
Average Atmospheric Pressure	N/A	S20 K275 (0451)
Total Current [kA]	27.80	
Max Voltage [kV]	13.40	
Charging Voltage [kV]	18.00	

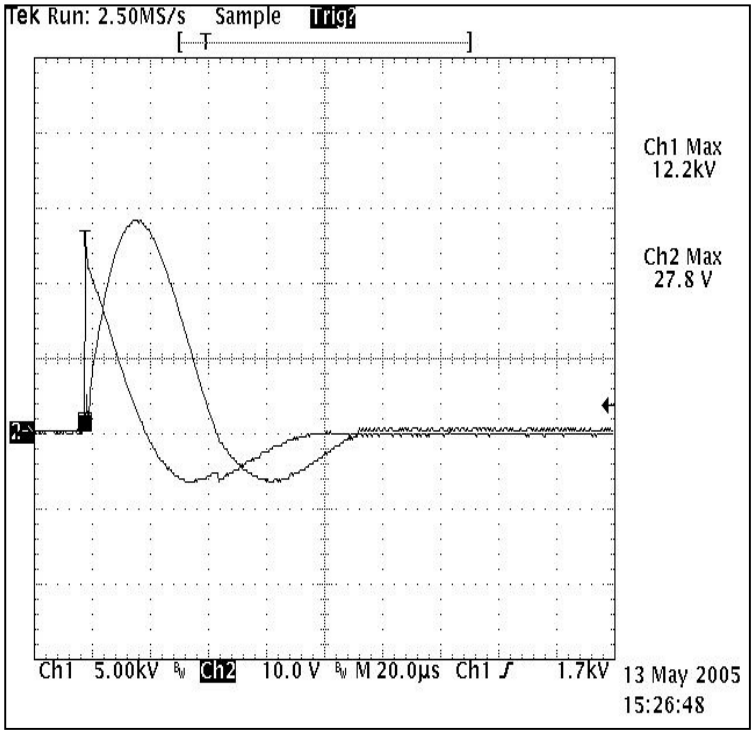


Figure A.2: Voltage and Current Waveforms of Two Electrode GDT with One Series MOV

A.1.3 Two Electrode GDT in Series with Two Parallel MOVs

Table A.3: Testing of Two Electrode GDT in Series with Two Parallel MOVs

Date Performed	13th May 2005	8/20 µs Waveform
Time Performed	15:26	2-Electrode GDT
Average Temperature	23 ℃	2 MOVs
Average Humidity	24 %	V13-A500XN
Average Atmospheric Pressure	N/A	S14 K275 (0502)
Total Current [kA]	31.40	
Max Voltage [kV]	13.40	
Charging Voltage [kV]	20.00	

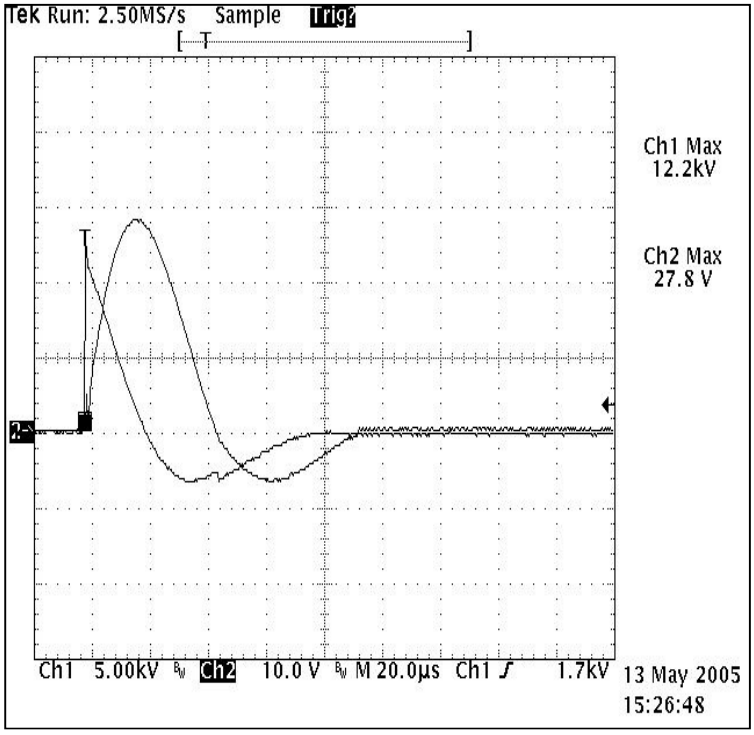


Figure A.3: Voltage and Current Waveforms of Two Electrode GDT in Series with Two Parallel MOVs

A.1.4 Two Electrode GDT in Series with Four Parallel MOVs

Table A.4: Testing of Two Electrode GDT in Series with Four Parallel MOVs

Date Performed	8th May 2005	8/20 µs Waveform
Time Performed	23:27	2-Electrode GDT
Average Temperature	23 ℃	4 MOVs
Average Humidity	47 %	V13-A500XN
Average Atmospheric Pressure	N/A	S20 K275 (0451)
Total Current [kA]	28.40	
Max Voltage [kV]	14.90	
Charging Voltage [kV]	20.00	

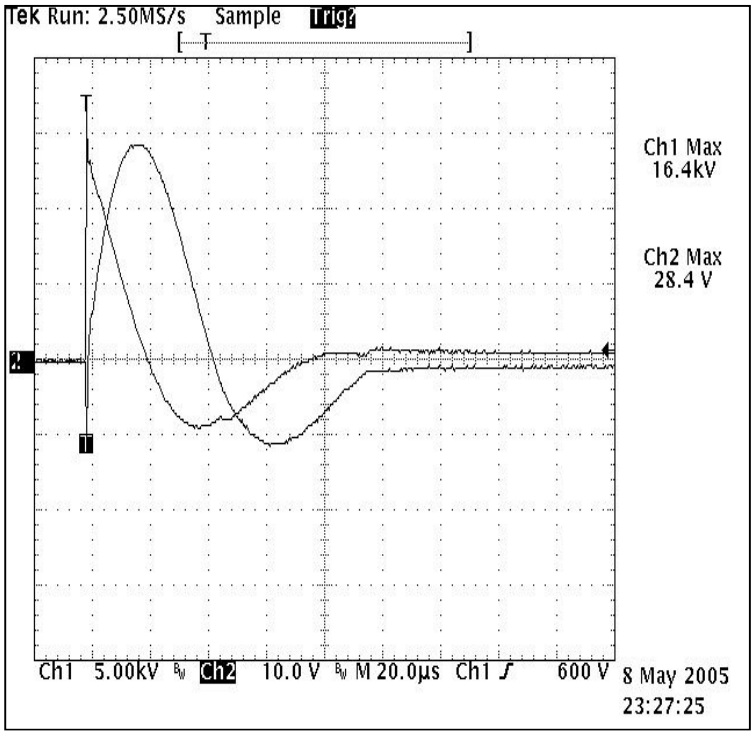


Figure A.4: Voltage and Current Waveforms of Two Electrode GDT in Series with Four Parallel MOVs

A.1.5 Three Electrode GDT with Floating Triggering Electrode

Table A.5: Testing of Three Electrode GDT with Floating Earth Electrode

Date Performed	23rd March 2005	8/20 µs Waveform
Time Performed	8:30	3-Electrode GDT
Average Temperature	21 ℃	No MOVs
Average Humidity	56 %	
Average Atmospheric Pressure	N/A	
Total Current [kA]	35.80	
Max Voltage [kV]	12.10	
Charging Voltage [kV]	20.05	

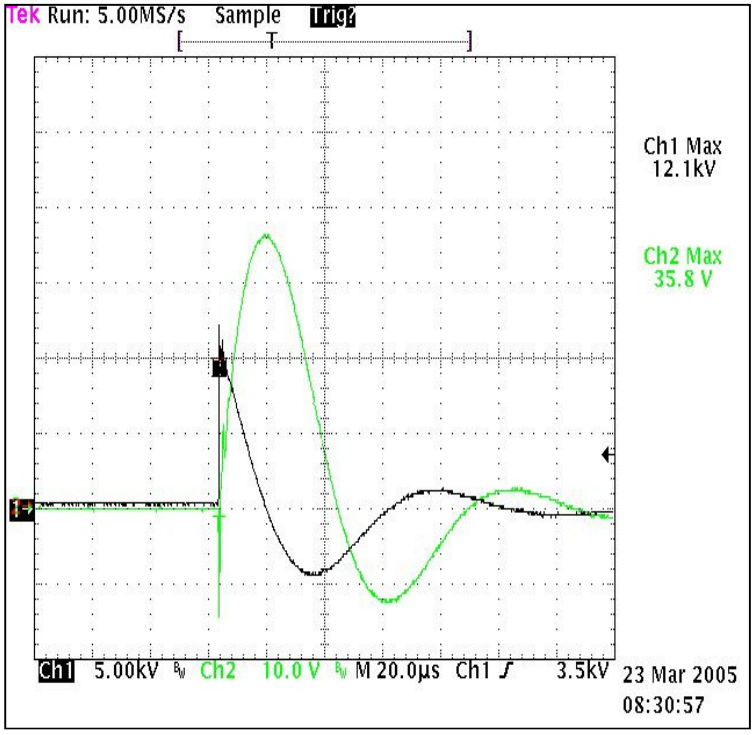


Figure A.5: Voltage and Current Waveforms of Three Electrode GDT with Floating Earth Electrode

A.1.6 Three Electrode GDT with Earthed Triggering Electrode

Table A.6: Testing of Three Electrode GDT with Earthed Earth Electrode

Date Performed	23rd March 2005	8/20 µs Waveform
Time Performed	13:12	3-Electrode GDT
Average Temperature	22 ℃	No MOVs
Average Humidity	50 %	
Average Atmospheric Pressure	N/A	
Total Current [kA]	35.80	
Max Voltage [kV]	11.10	
Charging Voltage [kV]	20.00	

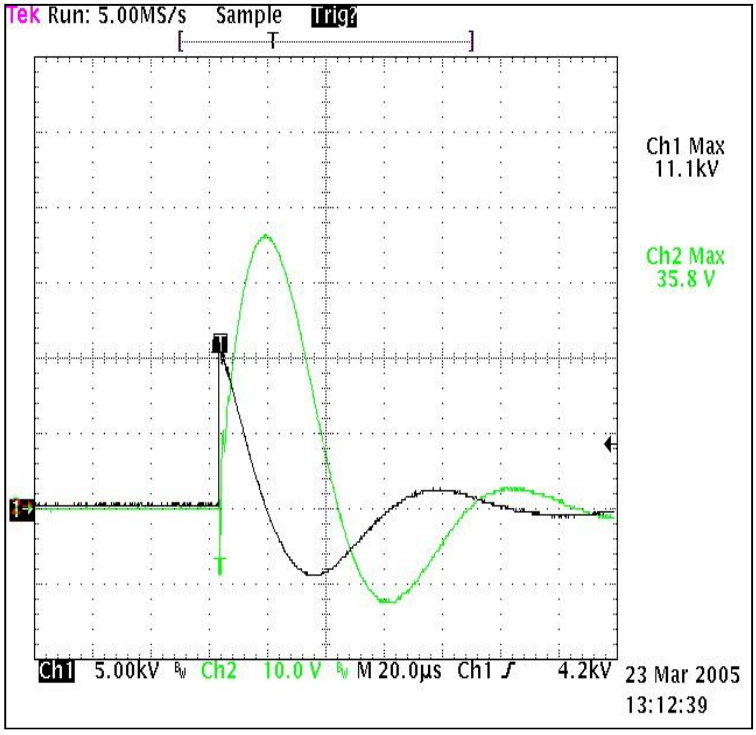


Figure A.6: Voltage and Current Waveforms of Three Electrode GDT with Earthed Earth Electrode

A.1.7 Three Electrode GDT with Triggering Circuit

Table A.7: Testing of Three Electrode GDT with Triggering Circuit

Date Performed	25th March 2005	8/20 µs Waveform
Time Performed	16:17	3-Electrode GDT
Average Temperature	23 ℃	No MOVs
Average Humidity	49 %	
Average Atmospheric Pressure	N/A	
Total Current [kA]	24.60	
Max Voltage [kV]	11.50	
Charging Voltage [kV]	20.00	

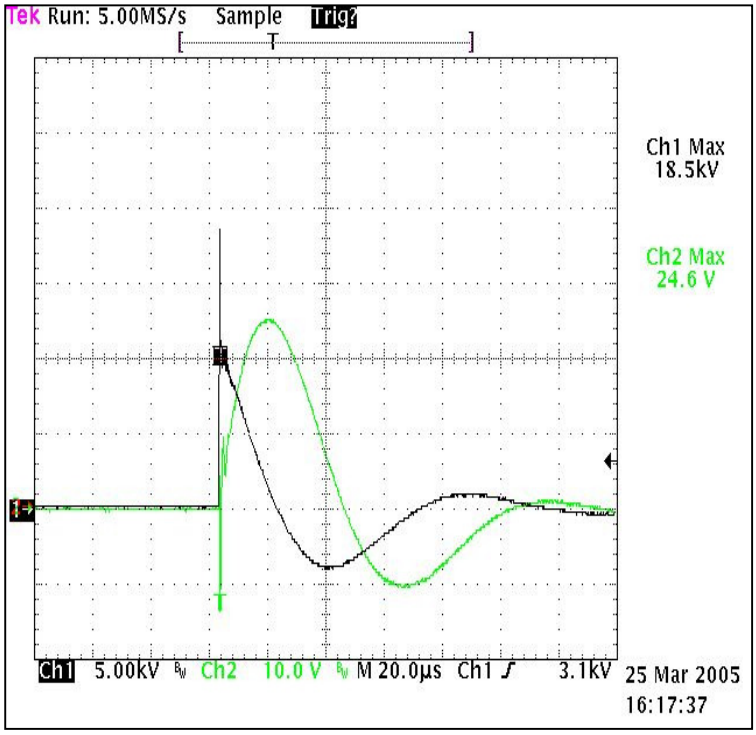


Figure A.7: Voltage and Current Waveforms of Three Electrode GDT with Triggering Circuit

A.2 Testing using 10/350 µs Current Impulses

This section details testing performed on the 10/350 µs impulse generator. As detailed below tests were performed with 2-electrode and 3-electrode GDTs, as well as with either single or parallel connected MOVs in series with the GDTs. Triggering circuits were also used as indicated below with some of the 3-electrode tests. It must be noted that hermetically sealed GDTs were used, which are unaffected by atmospheric pressure and humidity, nevertheless, the humidity was measured and is indicated in the test sheets below.

A.2.1 Two Electrode GDT Tests

Table A.8: Testing of Two Electrode GDT

Date Performed	6th June 2009	10/350 µs Waveform
Time Performed	16h46	2-Electrode GDT
Average Temperature	21 ℃	No MOVs
Average Humidity	14 %	
Average Atmospheric Pressure	N/A	
Total Current [kA]	7.08 kA	
Max Voltage [kV]	1.30 kV	
Charging Voltage [kV]	7.06 kV	

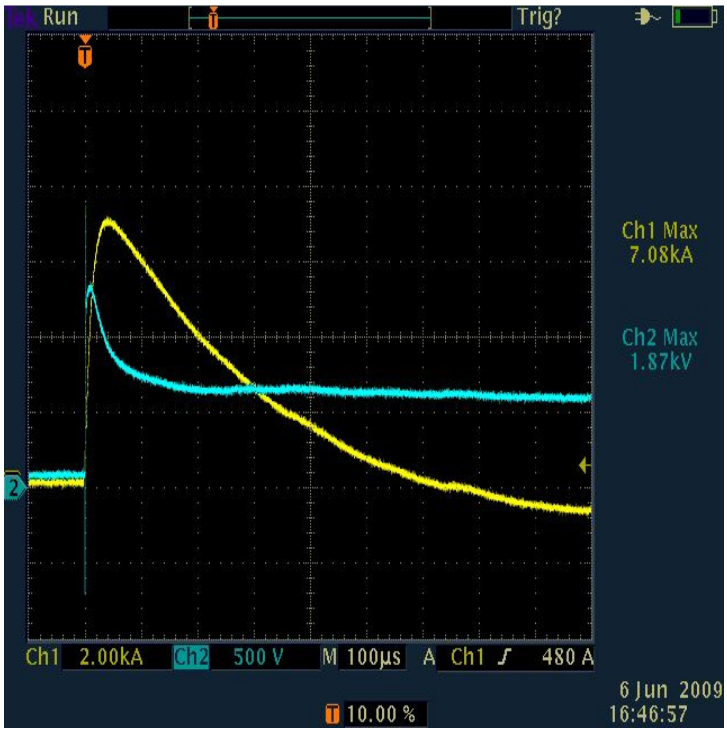


Figure A.8: Voltage and Current Waveforms of Two Electrode GDT

A.2.2 Two Electrode GDT in Series with One MOV

Table A.9: Testing of Two Electrode GDT in Series with One MOV

Date Performed	6th June 2009	10/350 µs Waveform
Time Performed	18h00	2-Electrode GDT
Average Temperature	21 ℃	1 MOV
Average Humidity	14 %	
Average Atmospheric Pressure	N/A	
Total Current [kA]	6.84 kA	
Max Voltage [kV]	1.80 kV	
Charging Voltage [kV]	7.00 kV	

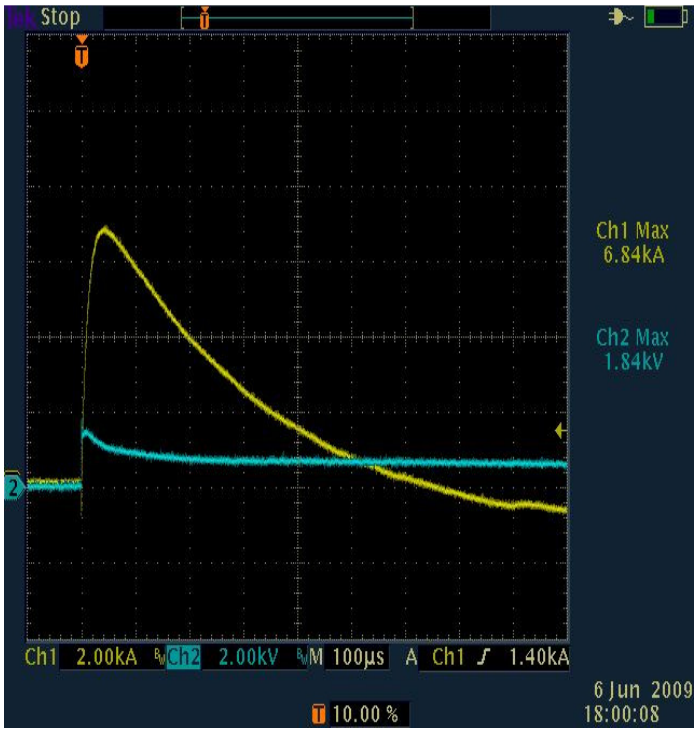


Figure A.9: Voltage and Current Waveforms of Two Electrode GDT in Series with One MOV

A.2.3 Two Electrode GDT in Series with Two Parallel MOVs

Table A.10: Testing of Two Electrode GDT in Series with Two Parallel MOVs

Date Performed	6th June 2009	10/350 µs Waveform
Time Performed	18h00	2-Electrode GDT
Average Temperature	21 ℃	2 MOVs
Average Humidity	14 %	
Average Atmospheric Pressure	N/A	
Total Current [kA]	6.70 kA	
Max Voltage [kV]	1.60 kV	
Charging Voltage [kV]	7.00 kV	

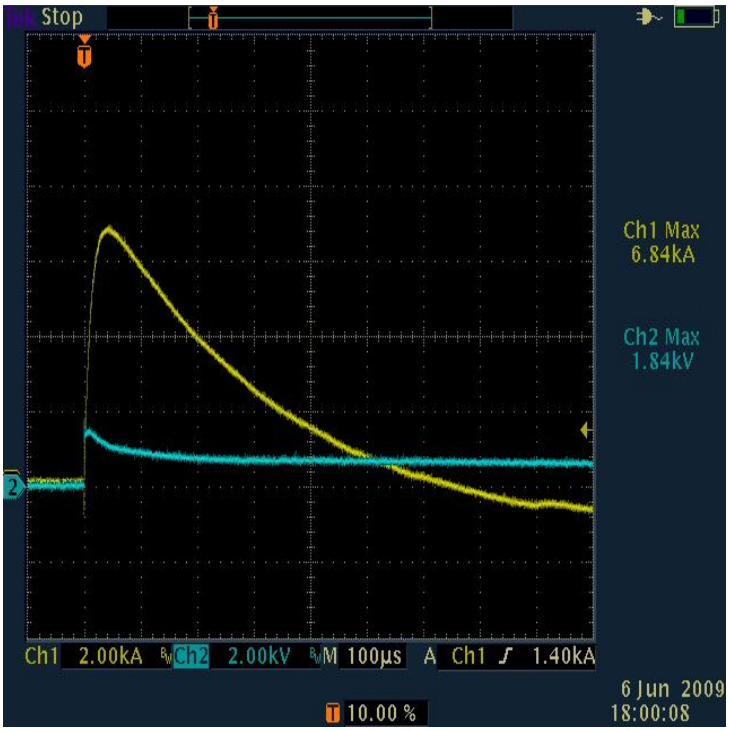


Figure A.10: Voltage and Current Waveforms of Two Electrode GDT in Series with Two Parallel MOVs

A.2.4 Two Electrode GDT in Series with Four Parallel MOVs

Table A.11: Testing of Two Electrode GDT in Series with Four Parallel MOVs

Date Performed	7th June 2009	10/350 µs Waveform
Time Performed	15h27	2-Electrode GDT
Average Temperature	21 ℃	4 MOVs
Average Humidity	14 %	
Average Atmospheric Pressure	N/A	
Total Current [kA]	10.10 kA	
Max Voltage [kV]	1.80 kV	
Charging Voltage [kV]	10.00 kV	

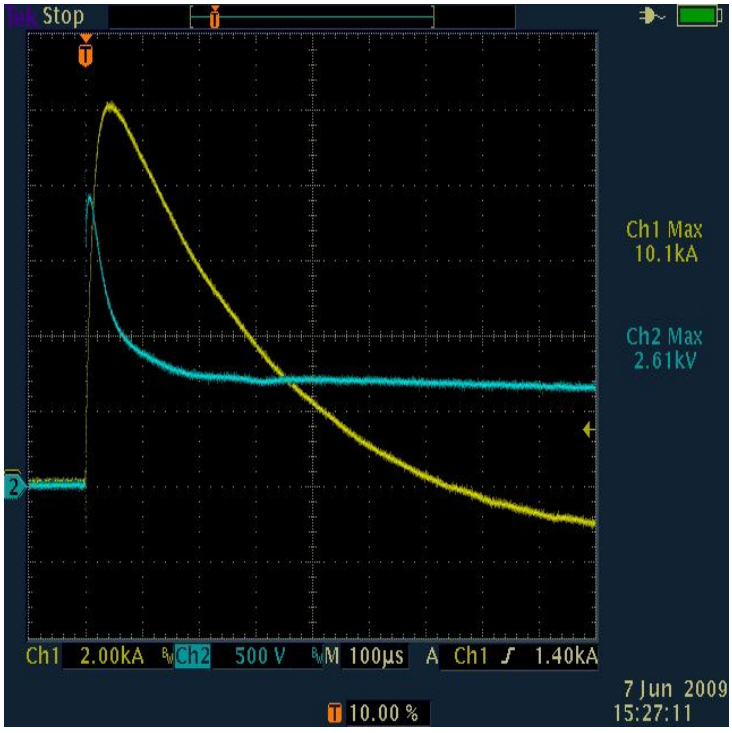


Figure A.11: Voltage and Current Waveforms of Two Electrode GDT in Series with Four Parallel MOVs

A.2.5 Three Electrode GDT with Triggering Circuit

Table A.12: Testing of Three Electrode GDT with Triggering Circuit

Date Performed	7th June 2009	10/350 µs Waveform
Time Performed	13h55	3-Electrode GDT
Average Temperature	21 ℃	Triggering Circuit
Average Humidity	14 %	No MOVs
Average Atmospheric Pressure	N/A	
Total Current [kA]	11.00 kA	
Max Voltage [kV]	1.55 kV	
Charging Voltage [kV]	10.00 kV	

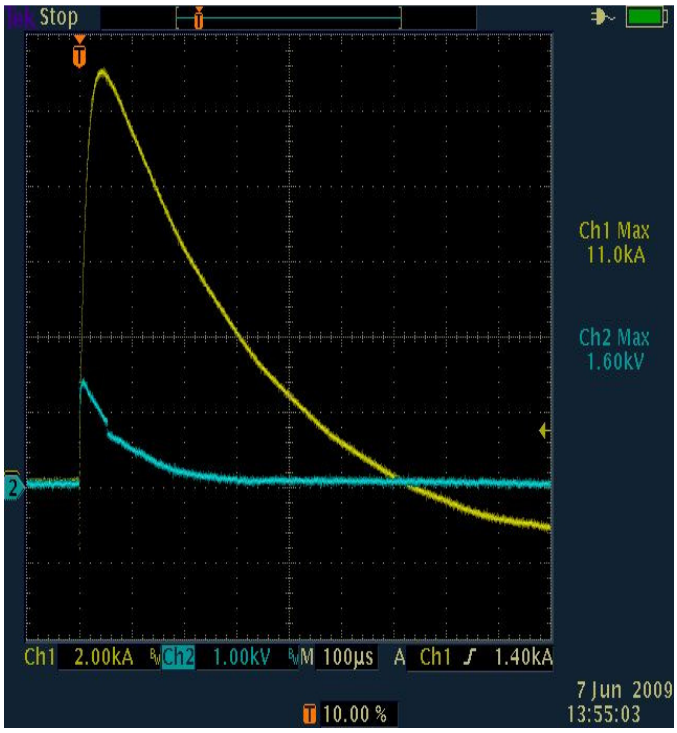


Figure A.12: Voltage and Current Waveforms of Three Electrode GDT with Triggering Circuit

A.2.6 Three Electrode GDT with Triggering Circuit and in Series with Four Parallel MOVs

Table A.13: Testing of Three Electrode GDT in Series with Four Parallel MOVs with a Triggering Circuit

Date Performed	7th June 2009	10/350 µs Waveform
Time Performed	13h17	3-Electrode GDT
Average Temperature	21 °C	Triggering Circuit
Average Humidity	14 %	4 MOVs
Average Atmospheric Pressure	N/A	
Total Current [kA]	10.20 kA	
Max Voltage [kV]	2.10 kV	
Charging Voltage [kV]	10.00 kV	

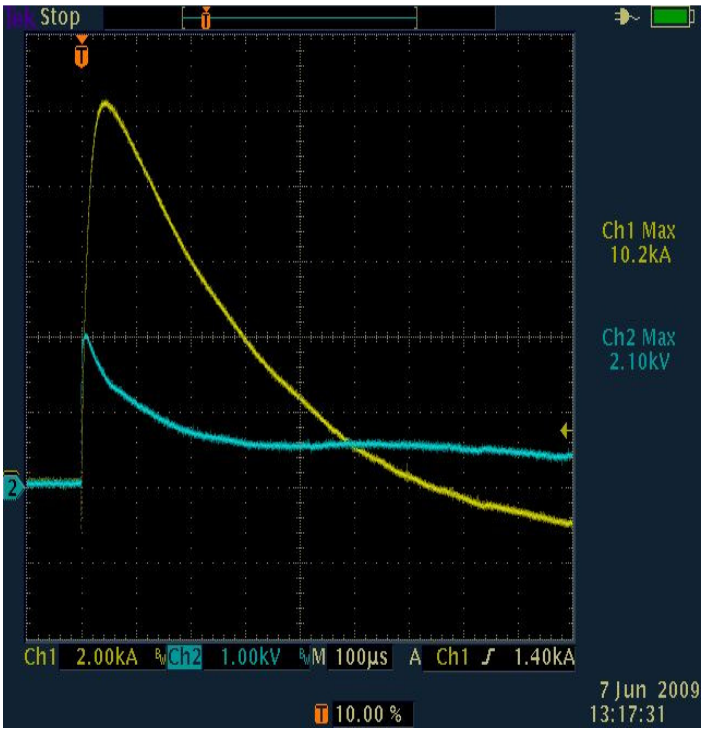


Figure A.13: Voltage and Current Waveforms of Three Electrode GDT in Series with Four Parallel MOVs with a Triggering Circuit

Appendix B

B Photographs of Test Setup

This appendix indicates photographs taken of the test setup in the High Voltage laboratory at the University of the Witwatersrand, School of Electrical and Information Engineering.



Figure B.1: Test Setup

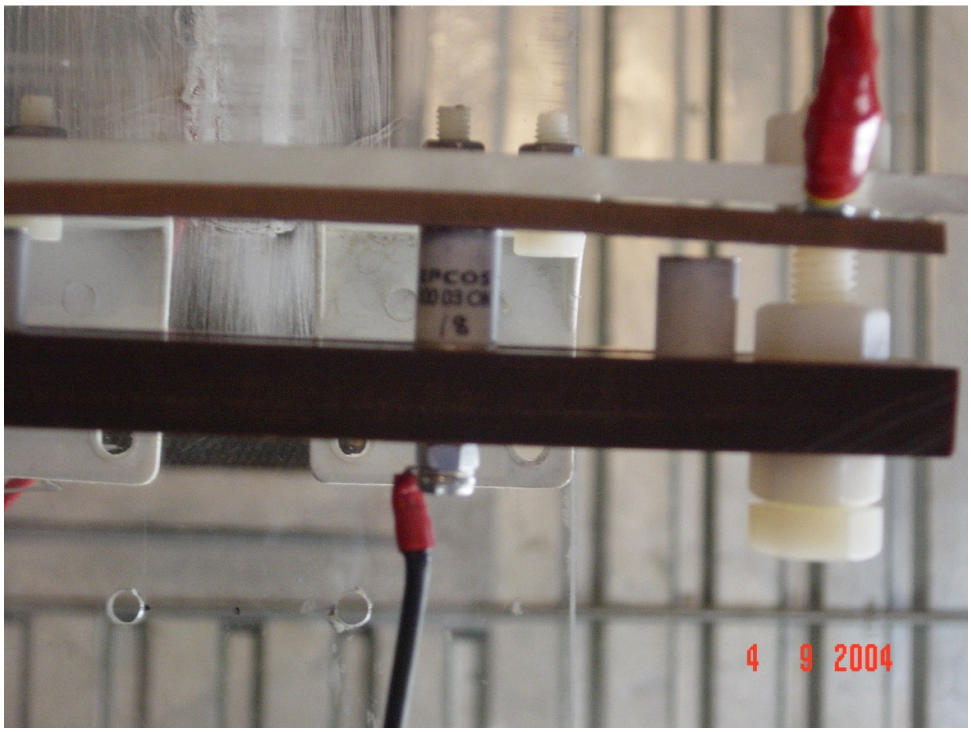


Figure B.2: Test Setup of GDT Mounting Mechanism

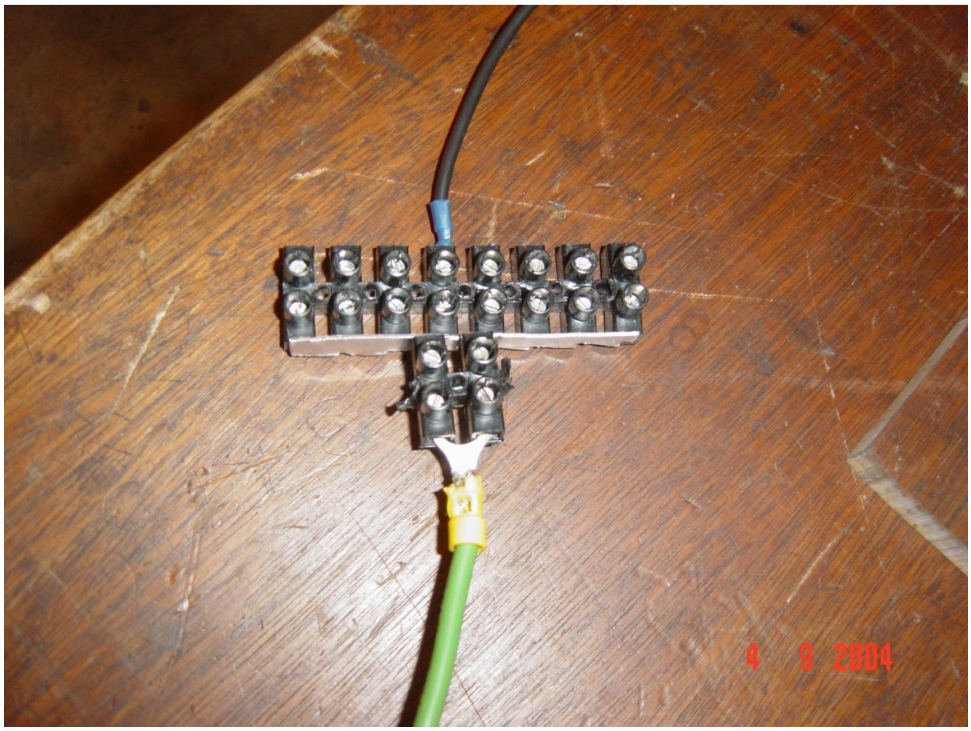


Figure B.3: Test Setup Connectors

Appendix C

C GDT Properties

This appendix details the properties of GDTs. The four operating domains of GDTs are described followed by electrical breakdown in gases, time lags in electrical breakdown and the ionisation mechanism.

C.1 GDT Operation

There are four operating domains in the behaviour of a GDT:

1. Non-operating range.
2. Glow range.
3. Arc range.
4. Extinction.

C.1.1 Non-operating range

This domain is characterised by an approximately infinite resistance. No current flows in the duration that the voltage rises to the spark-over voltage.

C.1.2 Glow Range

Once ignition has taken place the voltage drops to the glow voltage level in the glow-mode range. At breakdown the conductance suddenly increases.

C.1.3 Arc Range

As the current increases, transition to the arc mode occurs and the GDT shifts from the glow voltage to the arc voltage. It is in this arc mode that GDT are most effective, as the low arcing voltage values do not increase as high currents are discharged, i.e. the arc voltage stays constant as it is independent of the discharge current.

C.1.4 Extinction

As the overvoltage decreases to a value less than the glow voltage, the current through the GDT also decreases accordingly, until it drops below the minimum value necessary to maintain the arc mode, where the arc discharge suddenly extinguishes at the extinction voltage, and the GDT recovers its initial insulating properties.

C.2 Electrical Breakdown in Gases

Breakdown in gases is dependent on parameters such as temperature, pressure and electric field strength. By Paschen's Law, V = f (pd) it can be seen that the breakdown voltage V is dependent on the gap separation d, and the gas pressure p.

C.3 Time Lags in Electrical Breakdown

One of the most important parameters in electrical breakdown is time. If a step voltage is applied to a gap, then there will be a finite time before the gap actually breaks down. This time is made up of two components being the formative time lag and the statistical time lag.

The statistical time lag is the time taken for a free electron to become available and start the electron avalanche that will lead to electrical breakdown across a gap. As the name implies, this time lag is variable. The statistical time lag can be controlled (or eliminated) by providing the free electrons required, which can be done by ionisation.

Formative time lag is the time take for the electron avalanche to cross the gap, and is therefore relatively constant, but in general much faster than the statistical time lag.

C.4 Ionisation

The key process that allows electrical breakdown to occur is ionisation. Ionisation can happen in many different ways. Irrespective of the mechanism though, as the name implies, ionisation is the production of ions. Ions are produced when electrons are stripped from neutral atoms or molecules. The following four main mechanisms enable ionisation to take place:

1. Ionisation by collision.
2. Photoionisation.
3. Ionisation by metastable atoms.
4. Thermal Ionisation.

A low energy electron may, on collision with a neutral gas atom, excite it to a higher energy state. When the atom returns to its relaxed state, a photon is emitted. This photon may be able to ionise another atom whose ionisation energy is lower than the photon energy. The process can be symbolically written as $A + h\nu = A^* + e$, where A and A* represent the neutral and excited atoms of the gas respectively and $h\nu$ represents the photon energy. For photoionisation to occur, $h\nu$ must be greater than the atom ionisation energy. The photon energy is dependent on the photon wavelength, and the shorter the wavelength the higher the photon energy.