In-Service Condition Monitoring of Polymer Housed Surge Arrester within EThekwini Electricity

By

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ABSTRACT

The primary objective of this research was to investigate the failures occurring in the family of surge arresters used within EThekwini Electricity, making use of different diagnostic methods, such as leakage current testing (LC), infrared scanning (IR), and partial discharge (PD) measurements. The different diagnostic tests were used to assess the degradation process of the polymer housed surge arresters and their failure.

The measurements were used for diagnosis of 120 kV/65 kA surge arresters of different brands. Tests were performed on surge arresters that were still in the system and these test results were compared with results from tests performed on failed units. Results obtained from the different tests were compared to the test results for different families or designs. An imperfect arrester will exhibit excessive heating when an electrical surge is discharged. The aforementioned tenets are the primary factors influencing degradation and causing failure of Metal Oxide Surge Arrester (MOSA) in a system.

These factors can decrease creepage and flashover distance on insulation, which could result in a substantial increase in resistive leakage current, (which is a few microamperes in ideal condition), overheating, and PD formation on the zinc oxide varistor element. Therefore, it is extremely important to assess the status of the surge arresters whilst they are in service, firstly so that they can be removed from the system before they fail and, and secondly, to verify their condition, and their ability to effectively protect the substation apparatus.

Using infrared inspection, valuable information of condition of surge arresters was obtained, heat inside the surge arresters was detected and this shows that IR analysis can therefore be considered as an additional method to assess the condition of polymer housed surge arresters. It was observed that partial discharge activity is an indication of degradation in arrester varistor. LC test, IR, and PD measurement were valuable in obtaining sufficient information for failure of surge arresters. In additional, during the visual internal inspection of arresters, evidence of punctures, treeing, tracking, and moisture masks were noted on ZnO blocks and seals. These results indicate that the moisture ingress through the sealing collar can cause unnecessary outages.

DECLARATION OF ORIGINAL AUTHORSHIP

I hereby declare that, this dissertation represents original work by the author and has not been submitted in any form at another university. Where use has been made of the work of others, it has been duly acknowledged in the text and included in the list of references.

Makhosonke Gumede

DEDICATION

This dissertation is dedicated to my parents Mr. Amon Mbuso Gumede and Mrs. Thembi Rejoice Ngidi. I thank them for their support and sacrifices through my years of study and ensuring that I reach my dream of pursuing a career in Electrical Engineering. In addition, I thank my friends for encouraging and supporting me to achieve my destiny.

.....God bless you all for your input!!!...

ACKNOWLEDGEMENTS

Firstly, the author would like to thank the Lord who provided the strength and confidence to initiate this research and the ability to complete it.

"Everything is possible for him who believes." Mark 9:23

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LIST OF ABBREVIATIONS

CM	Current measurement
CRT	Cathode Ray Tube
DUT	Durban University of Technology
EPDM	Ethylene Propylene Diene copolymer
EVA	Ethylene Vinyl Acetate
FRP	Fiber-glass Reinforced Plastic
HV	High Voltage
Hz	Hertz
Ic	Capacitive current
IEC	International Electrotechnical Commission
Ir	Resistive current
IR	Infrared
It	Total current
LC	Leakage Current
kA	Kiloampere
kHz	Kilohertz
kV	Kilovolt
mA	Milliampere
MCOV	Maximum Continuous Operating Voltage
MOSA	Metal Oxide Surge Arrester

MOV Metal Oxide Varistor

MV Medium Voltage

pC Pico Coulomb

PD Partial Discharge

pF Pico Farads

SiR Silicon Rubber

TF Transient filter

TOV Temporary Voltage

UV Ultra Violet

UKZN University of KwaZulu Natal

VDR Voltage Depended Resistor

VVR Voltage-Variable Resistor

ZnO Zinc Oxide

LIST OF SYMBOLS

α	Exponent defining the degree of nonlinearity.
°C	Degree Celsius
C_c	Cavity capacitance
ΔT	Temperature gradient
k	Scale factor
K	Discharge onset
kV/cm²	Kilovolt per centimeter square
δVa	Voltage drop across the terminal
q	Apparent charge
s	Distance, cm
Ua	Extinction voltage
Ue	Onset voltage
Vc	Voltage across the void capacitance
V_{ap}	Applied voltage to varistor
V_r	Rated voltage of the surge arrester (kV)
N_v	Number of varistors element inside the arrester

PUBLICATIONS

A. M. Gumede and G. Frederick d'Almaine 2013, "*In-service condition monitoring of surge arresters within eThekwini electricity*". Proceeding SAUPEC, South Africa, pp.62-63.

B. M. Gumede and G. Frederick d'Almaine "*Surge arrester faults and their causes at EThekwini electricity*". International Journal of Electrical Engineering, March 2014, Vol. 2, No.1, pp. 160.

CHAPTER 1: INTRODUCTION

Overvoltages in an electrical network are generally caused by lightning strikes, system faults, or switching operations. These overvoltages could reach dangerous amplitudes for electrical network apparatus. To protect the network equipment and to guarantee secure and reliable operation, surge arresters are installed in all types of electrical transmission and substation systems.

Presently, polymeric surge arresters are used all over the world because of their better performance in contaminated areas when compared to porcelain house arresters. Since polymeric surge arresters were introduced 1980's, many studies have been done to test their behaviour using different measurements.

Ageing of the polymer insulators is caused by environmental factors such as ultraviolet radiation, (UV), contaminations, moisture ingress, and electrical stress including leakage current, local discharge and corona discharge [38]. These phenomena may eventually cause failure of surge arresters in the system. Hence, it is important to monitor surge arresters while in service so as to increase life span [39].

1.1 Background

The advanced gapped silicon carbide arrester was the first effective overstress protection for high voltage power networks [1]. Silicon carbide surge arresters were developed in the 1930's to give full protection against overvoltage. Gapped silicon carbide arresters were used for both transmission and distribution systems

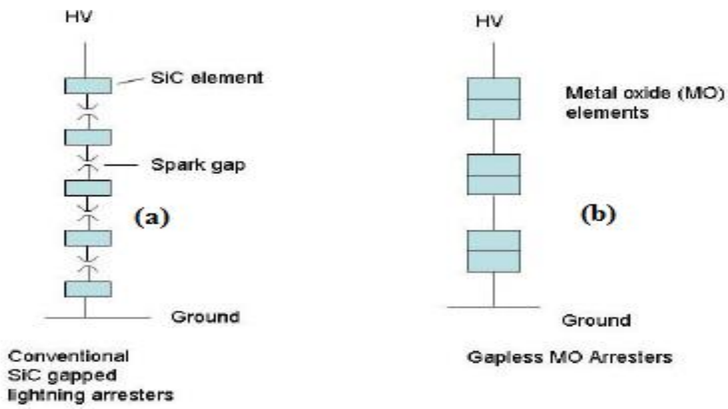


Figure 1.1: Gap and gapless surge arrester [1].

Hinrichsen stated that rapid improvements in technology allowed the introduction of polymer housed surge arresters in the mid-1980s in medium voltage (MV) electrical systems. These polymer housed surge arresters were superior to the previously used porcelain housed arrester designs, which often suffered from sealing deficiencies, extreme sensitivity to pollution and unsatisfactory overload performance [3], [4].

Amin et al assert that polymer (made of silicone rubber) has recently been the material of choice for high voltage insulation. Polymer exhibits higher performance in polluted areas compared to other materials such as ethylene propylene diene copolymer (EPDM), EPDM/SR blends and ethylene vinyl acetate (EVA) [40].

Furthermore, the polymer housed surge arrester has several advantages including a better short circuit capacity, increased personal safety, flexibility in erection, and a less brittle nature when compared to porcelain and silicon carbide surge arresters [41]. Another key point is their hydrophobicity, particularly those manufactured with silicone rubber (SiR) which helps to prevent the formation of water films on the insulator surface, even when that surface is polluted [40].

More than seven years of experience have shown that polymer housed surge arresters are less prone to moisture ingress than porcelain arresters, thus minimizing one of the most common causes of failure of surge arresters [41]. At the end of 1980’s, polymer surge arresters were available for system voltages up to 145 kV. Today's polymer housed surge arresters have been accepted for system voltages up to 550 kV [42].

1.2 Problem Statement

Polymer housed surge arresters are the preferable protective apparatus in electrical network against overvoltages caused by lightning and switching operation, when compared to porcelain arresters. Nonetheless, failures in polymeric housed surge arresters have recently increased [42]. This has resulted in a number of studies being done to establish the condition of surge arresters whilst in service, the object being to remove them from service before they fail.

Most polymer surge arresters failures today are caused by moisture ingress into the arrester sealing or housing. This could be caused by poor design on the insulation material, or bad sealing. It is well known that poor insulation in polluted areas can readily allow partial flashover of several units in the surge arrester [43].

Furthermore, possible thermal instability due to the effect of heavy external pollution can cause low strength on non-linear varistor during service conditions [3], [4]. The early metal oxide surge arresters exhibited increasing power loss with normal system conditions due to penetration of moisture into the metal oxide blocks, thereby promoting oxidation [44].

Because of these factors, the quality of the surge arrester sealing system is critical and accurate testing and measurements is required to diagnose sealing problems in a surge arrester [30], [45] so as to avert this type of failure.

1.2.1 The EThekwini Electricity Problem

It has been argued that a faulty surge arrester often shows no outside indication of damage. Unfortunately, such a statement is often correct; thus, it is extremely important to monitor the status of the arrester in-service before a judgment is made [46].

Recently, eThekwini Electricity has experienced a trend where a certain brand of surge arresters fails (see Figure 1.2) without any associated overvoltages in the electrical system. (Overvoltages caused by lightning strikes, switching operations, or system faults).

Figure 1.2: ZnO surge arresters with polymer housing that failed.

This causes unnecessary outages along the line. Figure 1.3 represents the number of surge arresters that failed in the system during the period 2000 to 2004. Since this has happened in the past and continues to happen, a decision was taken to perform an investigation to identify the causes of failure and find satisfactory solutions.

The main intentions of this dissertation are thus to investigate the failure of surge arresters so as to improve the arrester specification to avoid failure in the future, and to extend the lifetime of the polymer surge arrester.

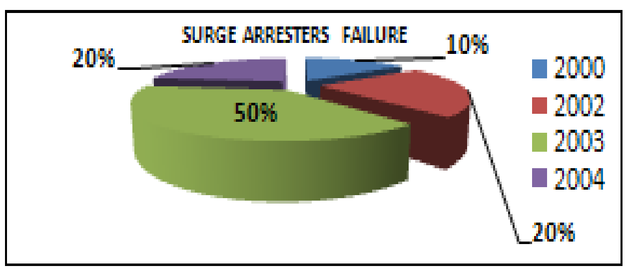


Figure 1.3: Surge arrester failure at eThekwini Electricity.

1.3 Research Questions

The aim of the research is to find solutions to the following questions:

- What are the factors affecting the surge arresters while in service operation?
- What causes a particular family of surge arresters to fail?
- How best to improve the surge arrester specification so as to avoid failure in the future, reduce outage time, and cost of replacement of failing surge arresters?

By investigating the above delineate questions will help the organisation to identify the failing problem of the family types of surge arrester.

1.4 Research Objectives

The main objective of this dissertation is to establish test measurements to check the condition of polymer housed surge arresters whilst in service. This will help to remove the irregular arresters from the system before they fail so as to reduce outages at eThekwini electricity.

Thus, the main purposes of this research are to

- Improve the surge arrester specification so as to avoid failure in the future,
- Reduce outage time and,
- Reduce cost of replacement of failing surge arresters.

1.5 Hypotheses

Surge arrester failure can be measured and predicted by means of partial discharge and leakage current testing, and infrared scanning. Such predictions and measurements can be confirmed by visual inspection.

1.6 Structure of Dissertation

This dissertation is structured in the following method:

1.6.1 Chapter 1: Introduction

This chapter discusses the main focus and rationale of this research and includes the objective, problem statement, background and history, and methodology.

1.6.2 Chapter 2: Literature Review

This chapter reviews literature relevant to this research, and describes factors affecting the polymer housed arrester that may cause the arrester to fail in an electrical network, including diagrams and images. Operation, characteristics and various factors that cause arrester degradation while in service are briefly explained in this chapter.

1.6.3 Chapter 3: Design and Research Methodology

This chapter explains the method and techniques used for the data acquisition process of this dissertation.

1.6.4 Chapter 4: Results and Discussion

This chapter presents and discusses the findings of this dissertation, namely, identifying the factors that cause arrester degradation while in service.

1.6.5 Chapter 5: Conclusion and Recommendations

This chapter summarises the findings of this research, and presents recommendations and projected areas for further research.

- **Reference**

The literature resources that have been referred and cited in the thesis are listed in this section.

- **Appendices**

Specifications of the test equipment used in the research and the papers presented at conferences are presented in this subdivision.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

EThekwini electricity, based in Durban, South Africa, utilizes polymeric housed surge arresters in outdoor high voltage substations, to restrict the voltage level in apparatus such as circuit breakers and transformers to below the withstand voltage level during overvoltages caused by lightning strikes, switching and circuit breaking. These types of arresters are used worldwide because of their superior performance.

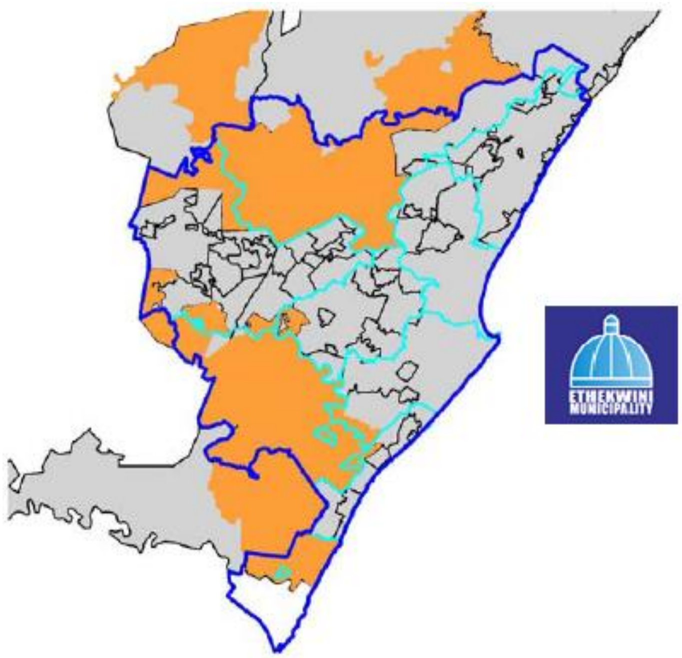


Figure 2.1: Map showing location of eThekwini Electricity [2].

Their advantage over porcelain or ceramic surge arresters is that they perform well in polluted areas, [42]. Apart from electrical stresses caused by AC voltage impulses or switching operations, the degradation of polymeric housed surge arresters can also be influenced by other environmental factors, such as moisture ingress into the sealing or housing and salt contamination [47]. All of the above factors could lead to a permanent failure on the varistor blocks of surge arresters and could cause power failure [42].

Neto et al stated that the failure of these family types' arresters has recently increased. As a consequence, power companies have been more concerned with the operation of their arresters. They have been researching and improving techniques for their monitoring and maintenance, with the aim of removing them from service before they fail [48].

2.2 Polymer Housed Surge Arresters

In order to provide a clear description of the structure being investigated in this research, a description of polymer housed arrester is given, covering the characteristics of the arrester, physical structure, and principle operations.

2.3 Description of Polymer Housed Arresters

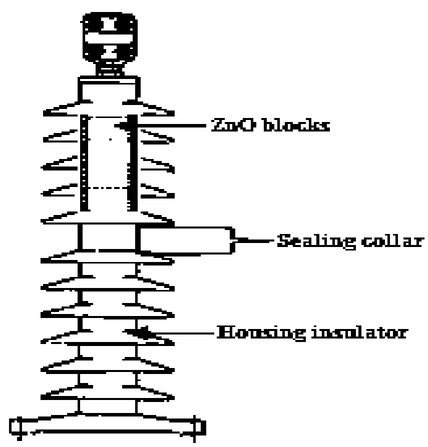


Figure 2.2: Cross-sectional drawing view of a polymer housed surge arrester.

The insulated housing is directly molded on to zinc oxide (ZnO) varistor blocks and fiberglass reinforced plastic (FRP) to ensure total enclosure of all components, and high mechanical strength of the entire structure of the surge arrester [35].

The surge arrester housings have traditionally been made of polymeric insulating material for both distribution systems and medium voltage systems, and recently even for transmission substations system voltages (see Figure 2.2).

The heart of an arrester comprises individual ZnO resistor blocks stacked on top of each other to provide the desired nonlinear voltage-current, or V-I characteristics [16].

According to [35] ZnO varistor blocks are semiconductors that are highly sensitive to voltage. Hence, any degradation in the varistor blocks can lead to arrester failure in service. To avoid this problem, selecting good monitoring techniques can help to minimize these failures.

2.3.1 Characteristics of Polymer Housed Material

The polymeric housing material is made of silicone rubber (SiR), which provides high hydrophobicity, which is the ability to prevent wetting of the insulator surface. As may be seen in Figure 2.3, moisture on the surface on the SiR forms globules. This in turn prevents continuous leakage current paths from developing [35]. It is resistant to UV radiation and has been shown to be the best insulator when compared porcelain [42].

Hydrophobicity results in efficient suppression of leakage currents caused by external pollution, and reduced electrical discharge on the surface of surge arresters. As a result of this, flashover and surface discharge is less than that of porcelain insulators. The leakage is on the surface of silicone rubber is slight small (0.001 mA) compared to porcelain is between 0.1 mA and 1 mA(see Figure 2.3) [4].

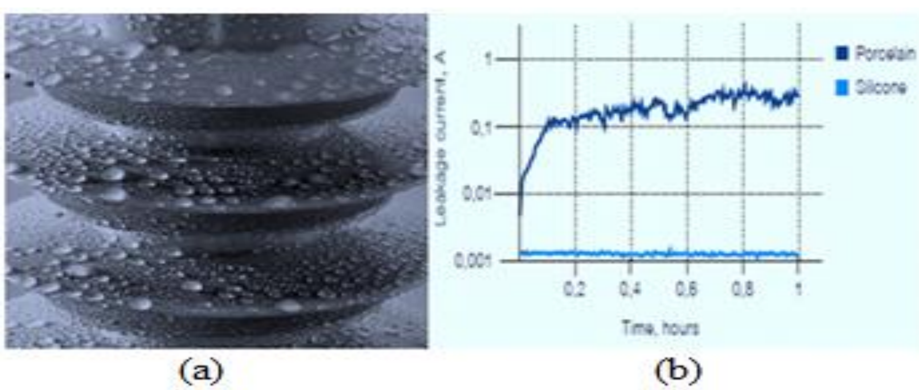


Figure 2.3: Leakage current on the hydrophobic material [3], [4].

Hydrophobicity can be described using the contact angle on the material surface (ɵ) that the liquid drop makes when it comes into the contact with a solid surface [33]. This angle is a measure of the surface wettability (see Figure 2.4) [3], [4]. The wettable material allows water to trace a large surface area and make a contact angle of less than 90°. The angle also gives information about surface energies, and surface roughness [42].

As seen from Figure 2.5, the experimental relationship between conductivity and flashover gradient for hydrophobic and hydrophilic polymer surfaces are presented. The excellent hydrophobic flashover gradient (Ea) is not below 1.5 kV/ cm between rain conductivity of 100 and 100k (uS/cm) [33], [5].

The smaller the contact angle, the more wettable on the surface and vice versa. The insulation surfaces are assumed to be hydrophilic when the contact angle is less than 35° for contact angles greater than 90°, as the surface deteriorates and contaminant deposition on the specimen surface may cause a reduction in hydrophobicity of the insulation material of a surge arrester [40].

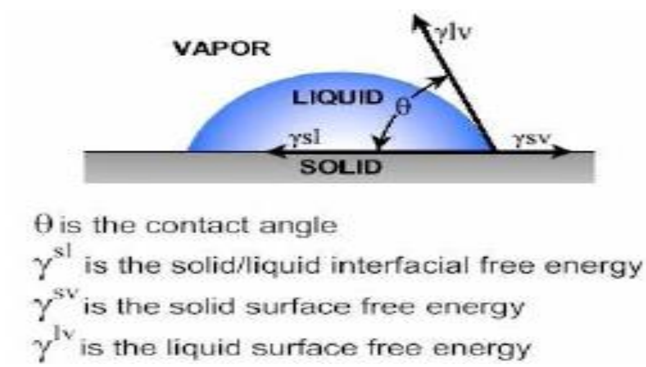


Figure 2.4: The shape of a liquid droplet on a hydrophobic surface [5].

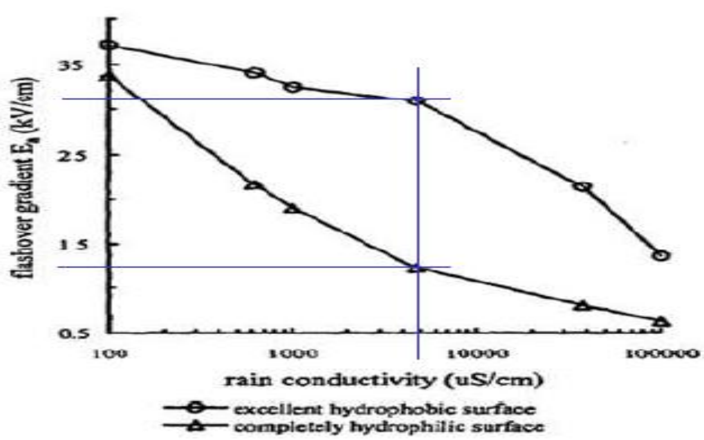


Figure 2.5: Relationship between conductivity and flashover gradient for hydrophobic and hydrophilic polymer surfaces [5].

2.3.2 Zinc Oxide Varistor (ZnO)

The heart of an arrester comprises individual ZnO resistor blocks stacked on top of each other, to provide the desired nonlinear voltage-current or V-I characteristics, and to present a robust relationship with temperature. The secret of the arresters' success in diverting lightning or high electrical surges is the ZnO varistor; this is the heart of an arrester. ZnO varistor blocks are semiconductors that are highly sensitive to voltage; hence, any degradation in the varistor blocks can lead to arrester failure in service [17].

Selecting a good monitoring technique can assist to reduce these failures. The non-linear conductivity of zinc oxide ceramics has been the basis of their development as varistor products for surge arresting and overvoltage application in power system [49].

Zinc oxide varistor elements are manufactured using materials that are composed of a specially formulated compound of zinc oxide and small amounts of other selected metal oxides [5] (see Figure 2.6). The ZnO varistors are bipolar ceramic semiconductor devices that operate as nonlinear resistors when the voltage exceeds the maximum continuous operating voltage (MCOV) [1], [3], [4], [21].

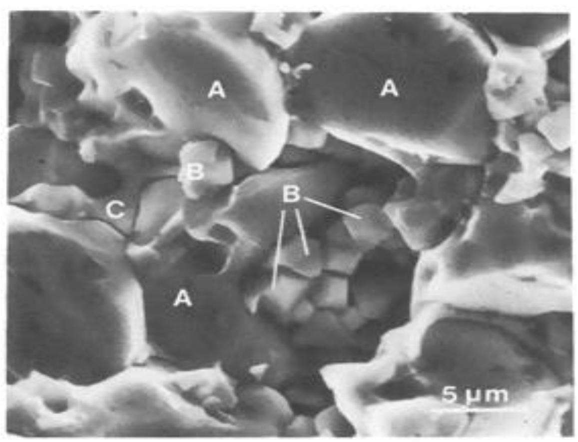


Figure 2.6: ZnO varistor microstructure [6].

The term varistor is a generic name for voltage-variable resistor (VVR), meaning resistance of the ZnO varistors decreases as voltage magnitude increases [22]. ZnO varistors acts as an open circuit during normal operating voltages, and conduct current during voltage transients or an elevation in voltage above the rated MCOV [1].

Contemporary ZnO varistors are developed using zinc oxide due to their nonlinear characteristics, and the fact that their range of voltage and current is far superior to silicon carbide varistors. Thus, the characteristic feature of zinc oxide visitors is the exponential variation of current over a narrow range of applied voltage [49]. Within the useful varistor voltage range, the voltage-current relationship is approximated by the equation (1.1).

$$I = AV^{\alpha} \qquad \ldots (1.1)$$

Where,

I = current in amperes,

V = voltage in volts,

A = a material constant, and

α = exponent defining the degree of nonlinearity.

2.4 Principle of Operation of Surge Arrester

The primary requirement of a surge arrester is to protect the electrical apparatus under all circumstances, for instance overvoltage, lightning etc. Aiming to minimize the residual voltage (the symbol: Ures according to IEC standard 60099-4) (frequently also called discharge voltage) that will normally leads to the reduction in the capability of the surge arrester to withstand power frequency produced by overvoltage [50].

Polymer housed surge arresters should constitute a reliable part of the system [43], [51]. They are designed to withstand the overvoltages and the resulting currents through them with a sufficiently high reliability, taking into account pollution and other site matters during service [35]. IEC standard 60071-1 states that, the electrical system can be overstress by different types of voltages such as; temporary overvoltage, slow-front overvoltage, and fast-front overvoltages [52].

In normal service the Silicon carbide surge arrester (SiC) almost behaves like an insulator [35]: it does not allow the current to pass through it, during high voltage frequency such as switching overvoltages, and lightning overvoltages) [53]. Overvoltages can be caused by lightning strokes , switching and circuit breaking or certain load flow conditions [54].

The resulting voltage across the terminal of the surge arrester will remain low to protect the associated device from the effects of overvoltages [35]. Characteristic curve of Gapless surge arrester varistor is shown on Figure 2.8.

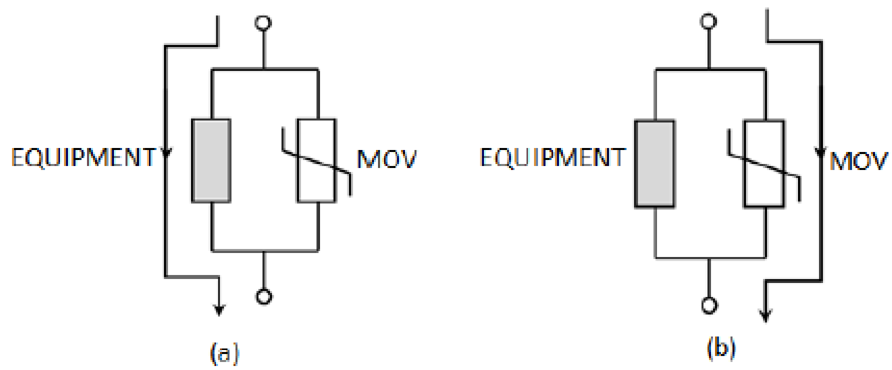


Figure 2.7: Varistor operations (a) Under normal operating voltage and (b) Under overvoltage conditions [7].

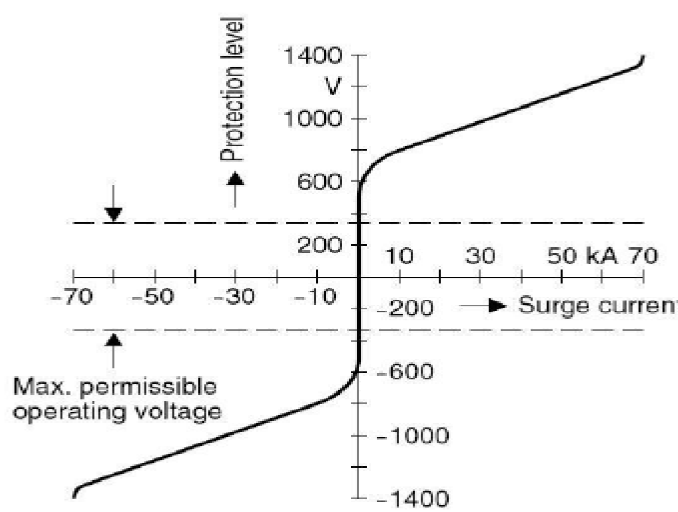


Figure 2.8: V-I Characteristic Curve of Gapless surge arrester varistor on a Linear Scale [7].

Surge arresters are part of the protection system of power substations which are connected in parallel with electrical apparatus such transformer etc.[6] as shown on Figure 2.7, their function being to divert the fraction of the charge which is introduced to the outdoor substations as a result of a direct lightning stroke[35], [55] (see Figure 2.9), aiming to minimize the voltage that passes through it, and ensuring that high voltage does not enter the electrical system and cause damage to the electrical apparatus as shown in Figure 2.10.

Their responses are to absorb part of the surge energy, converting it to thermal energy. A defective arrester may not be able to perform these functions satisfactorily when an electrical surge occurs.

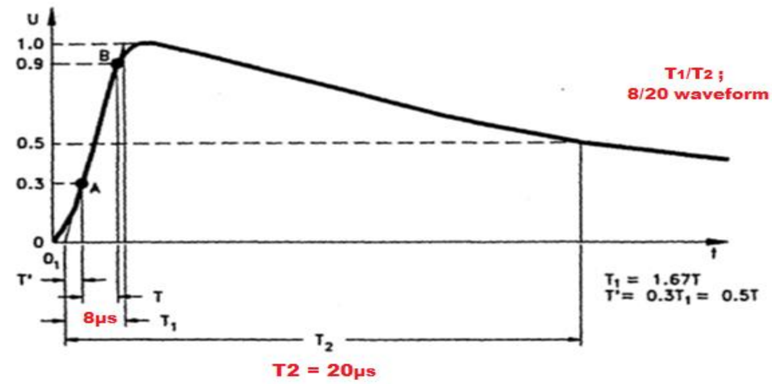


Figure 2.9: IEC standard waveform of the lightning strike [8].

Figure 2.10: Failure power transformer due to overvoltage [8].

2.5 Failures in Polymer Housed Arresters

2.5.1 Introduction

A number of studies have been done to establish the condition of surge arresters while in service. The aim is to remove them from service before they fail [30, 35], [50]. Various scenarios of the ageing process of polymeric arrester have been established, and several factors that contribute to the ageing process have been identified [38], [56].

These factors are mainly: moisture, humidity, mechanical breach of housing, thermal stresses, and pollution level. Currently, most researchers agree on the parameters affecting the ageing of this family of arresters [57].

In this research, leakage current (LC) measurement is utilized to gain valuable information about the degradation of the ZnO surge arrester, with partial discharge (PD) measurement revealed internal moisture in arrester. The thermovision technique is also applied to arresters to visualize the hot spot inside varistor blocks.

2.6 Factors Affecting the Performance of the Polymer Housed Arrester

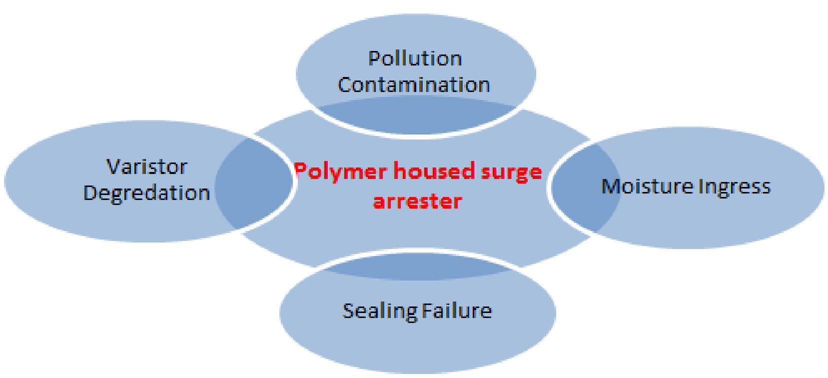


Figure 2.11: Factors affecting the performance of polymer housed arrester [9], [10].

Moisture ingress into an arrester has been found to be a problem in the arrester [58]. Moisture ingress presents a gradual increase in the resistive component of the current loss that contributes to thermal instability in the arrester, finally resulting incomplete fault. It is known that most surge arrester failures [51] occur because of moisture ingress into the porcelain housing. Moisture ingress, exacerbated by pollution, plays an important role in the degradation of a surge arrester [42].

Moisture ingress in high voltage apparatus is the most important source of degradation[59], [60]. Therefore, the diagnostic method used for surge arresters should be sensitive to possible internal moisture content [61], [62].

As shown on Figure 2.12, in the last century, moisture ingress was responsible for 80 % of outages in arresters. The same problem is being experienced today (see Fig 2.12) [26]. Moisture ingress may result in moisture condensation, changes in the protection level, and the energy dissipation capability [61]. Frequently, aging of the surge arrester may present a gradual rise in the resistive component of the current loss that contributes to thermal instability, finally resulting incomplete fault [63].

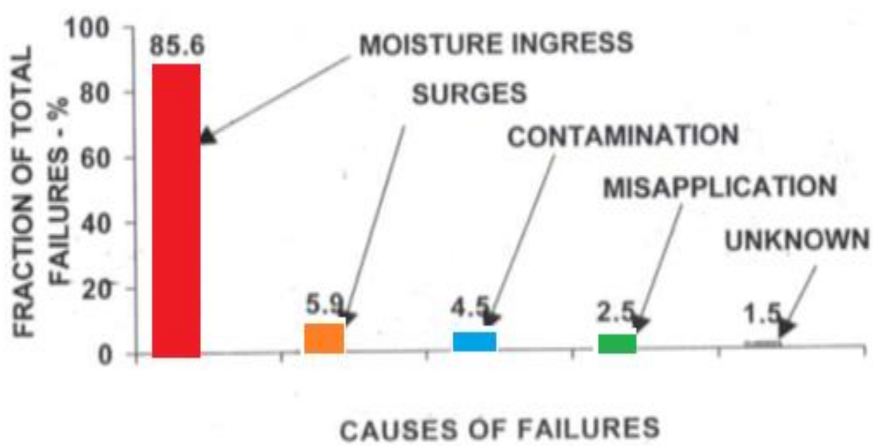


Figure 2.12: Total failure of surge arresters in percentage [8].

The moisture absorption in an arrester could result in slightly increased current leakage [64], which is typically in the range of mA [65], [13]. Hence, this can lead to overheating of the zinc-oxide (ZnO) varistor elements, causing the thermal runaway ZnO varistor that might cause arrester to bursts [48].

An arrester with some kind of failure is not able to operate appropriately during an electrical surge or overvoltages. As a consequence, the aforementioned allows moisture ingress into arrester housing or sealing [22].

This could result in partial discharges and significantly increased resistive current leakage and its harmonic components in varistor blocks [13], [66]. Moisture ingress presents an excessive heating problem that can lead to thermal runaway and degradation of the ZnO varistor element. To evade these problems, power companies have demonstrated an increased concern with the operation of their arresters, searching and improving methods for their monitoring of ZnO surge arresters [1], [17, 67].

2.6.1 Effect of Moisture Ingress

The pollution exhibited by moisture ingress could induce surface discharges which could damage the ZnO varistor of the arrester [38]. When the polymers are electrically stressed, partial discharge can form in regions of high electrical stress within the insulator as shown in Figure 2.13. [68].

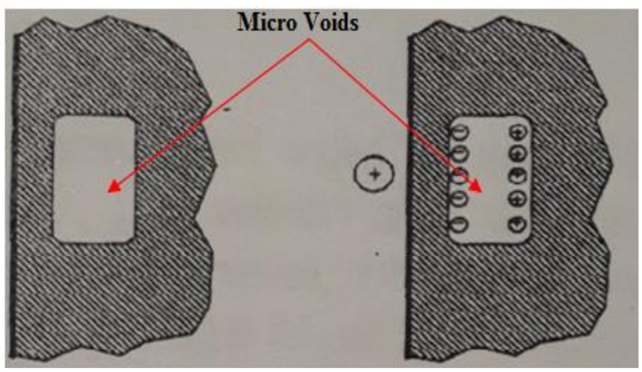


Figure 2.13: Micro Voids on the insulator [11].

PD is a significant degradation mechanism in polymers that can lead to premature failure of high voltage equipment [68]. Thus, the damage could be detected by measuring the partial discharge magnitude.

The most important quantities to be determined within an electrical PD test are apparent charge; the inception and extinction voltage

Partial discharge into the polymeric surge arresters can cause the arrester to suffer from environmental and aging stresses while in service, this can cause their performance to deteriorate [1], [69].

PD has been the most common cause of degradation [26], [68]. This can possibly cause the internal partial discharge on the surface area of ZnO varistor elements [26] as shown in Figure 2.14. Therefore, there is a need to monitor the condition of such insulators closely. Any damage needs early detection to avoid further degradation to complete breakdown.

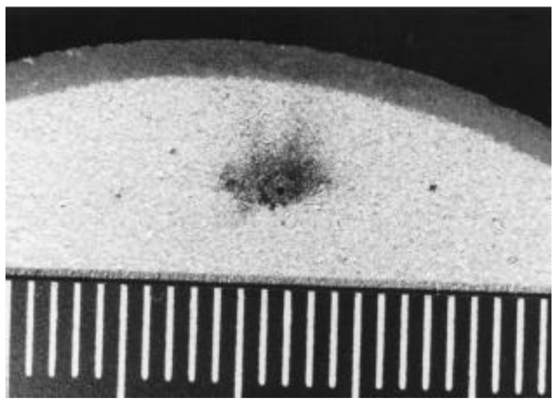


Figure 2.14: Puncture on surface of zinc oxide varistor element [12].

2.6.1 Impact of Moisture in ZnO Arrester

The looseness of the insulation from the end sealing (as signified in Figure 2.15) for a surge arrester in-service can result in increased humidity inside. This will result in surge arrester failure [20]. Humidity has been shown to increase up to 40-50 %. However, at very high humidity levels (about 95 %); there is the possibility of condensation and temperature changes [26].

The moisture layer on the internal wall of the housing or on the varistor column can initiate internal flashover. Conversely, moisture absorption into the sealing can also lead to electrical discharge activity, such as tracking, cracking and water trees marks; trees are the source of aging [28], [26].

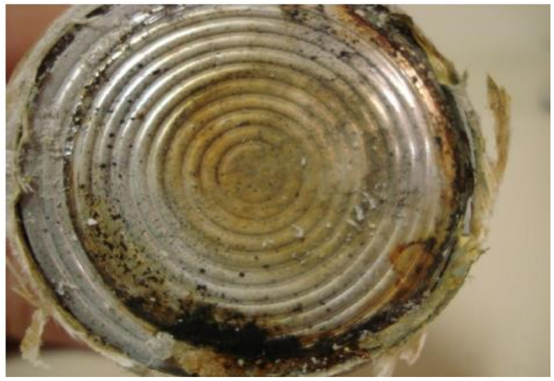


Figure 2.14 (a): Moisture ingress on the sealing interior [13].

Figure 2.14 (b): Moisture ingress on the sealing interior [Ami & Salam].

2.7 Sealing Failure

Nowadays, most transmission surge arresters are polymer housed. Although arrester failure due to moisture ingress is greatly reduced by the use of polymer housing designs, sealing testing of these arrester types and diagnosis methods related to it are especially relevant [58], [44].

A defective arrester may not be able to work satisfactorily when an electrical surge occurs. Hence, it could allow moisture to penetrate to surge arrester housing or sealing [62], (see Figures 2.14 (a) - (b)). A consequence of this effect is the reduction of the level of security in the performance of the apparatus [50], [70].

Owing to continuous leakage of gases, the system protection against explosion becomes inefficient, and no longer capable of performing in conditions of extreme heat [23].

Confirmed effective and proper tests for this family of arresters must be developed. For proper design, a thorough knowledge of arrester behaviour during different moisture diffusion processes is required [40].

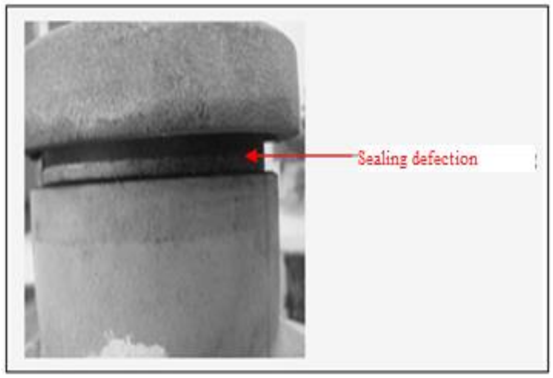


Figure 2.15 (a): Upper sealing defect [14].

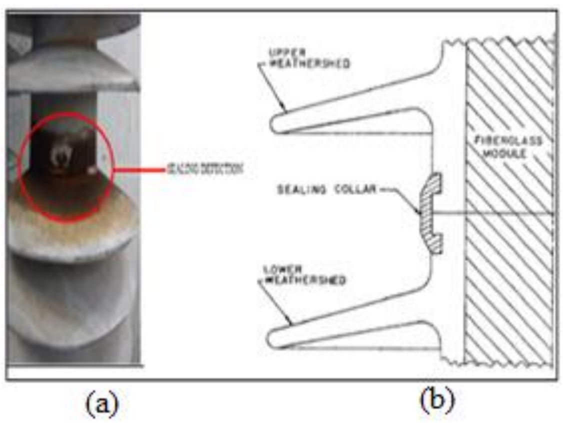


Figure 2.15 (b): Sealing collar defective [14], [15].

2.8 Degradation

The ZnO varistor degradation is used to describe the electrical condition of a varistor relative to its past or future state when under the influence of external stresses. Electrical stresses, including leakage current and dry-band discharges are directly responsible for tracking and erosion in an arrester [17].

Figure 2.16 presents the influence of the dry band position on the measured peak amplitudes of the internal A.C current of arrester.

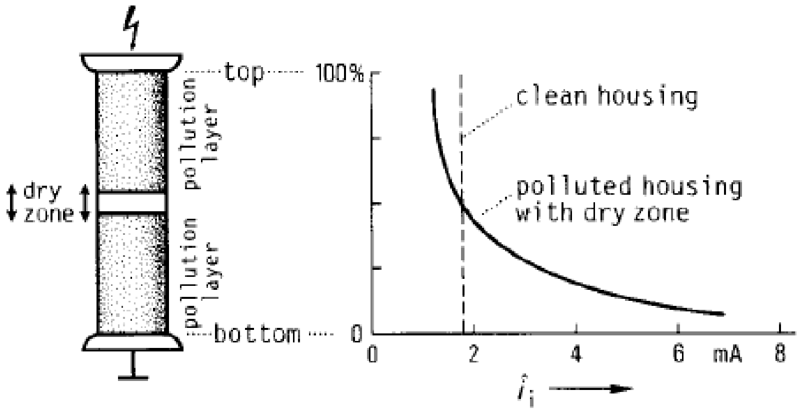


Figure 2.16: Effect of the dry band position on the on the measured peak amplitudes of the internal A.C [16].

The formation of sparking discharge is closely related to the varying trends of the total leakage current and creates high temperature spots, leading to bond separation and other chemical changes on the surface insulation (see Figure 2.17).

In this situation, temperature measurement with infrared scanning has very frequently used multipurpose maintenance techniques. The thermo vision technique is detects increased block temperatures on the housing surface of the arrester that can cause the arrester to fail [1], [17].

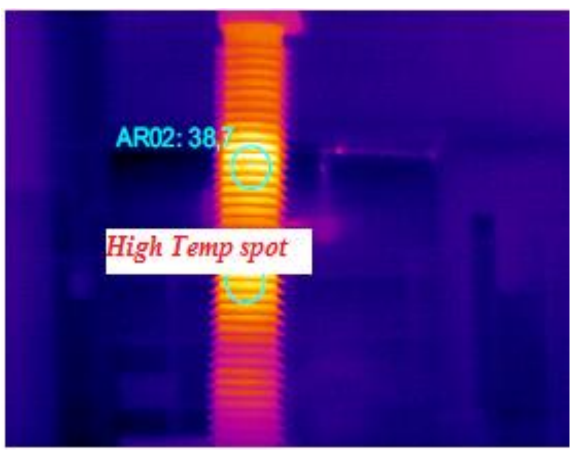


Figure 2.17: High temperature [17].

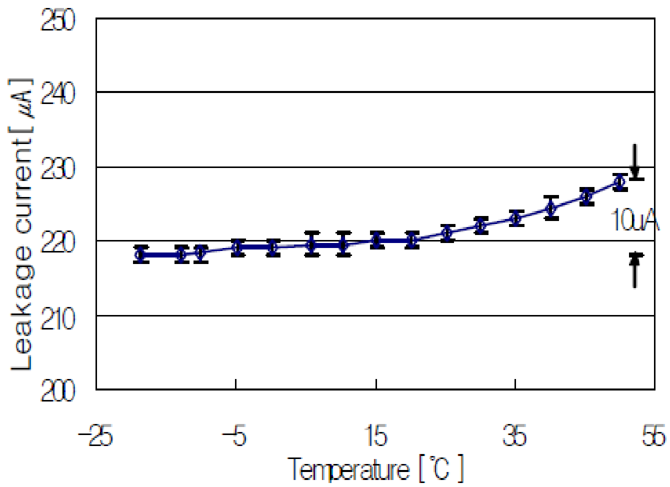


Figure 2.18: Represents LC variation as a function of ambient temperature [17].

The amount of degradation is a good indication of varistor reliability and is usually used to foresee the life span of a ZnO varistor [41], [22]. The process of degradation causes the gradual increase of leakage current with time on the arrester and thermal increase in zinc element varistor [40].

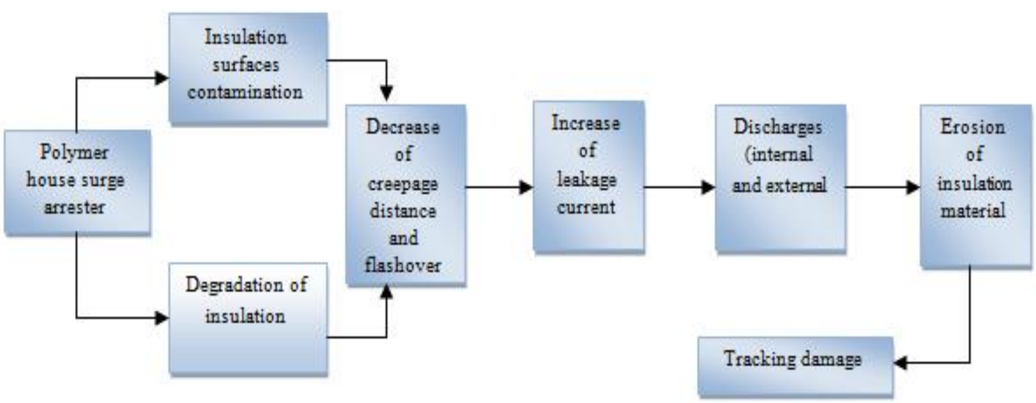


Figure 2.19: Degradation process of polymer housed surge arrester from tracking [7].

The formation of sparking discharge is closely related to the varying trends of the total leakage current, and creates high temperature spots, leading to bond separation and other chemical changes on the surface insulation [1]. This process can lead to failure of the varistor elements. ZnO varistor degradation is used to describe the electrical condition of a varistor relative to its past or future state, when under the influence of external stresses.

The surge arresters convert part of the energy present in the electric surge to thermal energy, and dissipate it to the environment [1]. However, they are subjected to a series of influences that can degrade their components, decreasing their performance and lifespan [48], [71].

The varistor degradation can be the result of natural ageing, premature ageing, or breaking [48], [72]. However, in many cases, when a varistor failure diagnosis is done, vestiges of some factors that may have caused its failure are found. Premature degradation of varistors is a factor that can contribute to the occurrence of thermal runaway [1].

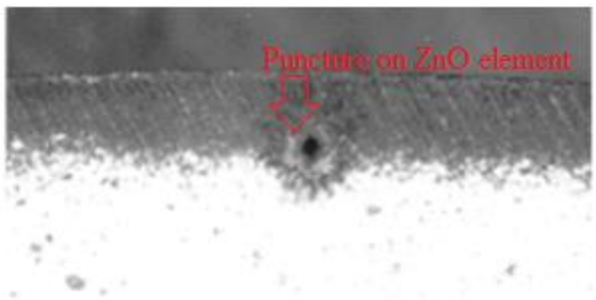


Figure 2.20: Damage to the disc created by lightning [47].

2.8.1 ZnO Varistor Due to Thermal Runaway

The consequence of increased leakage current is that energy absorption capability decreases, which in turn may lead to thermal runaway and cause failure of surge arrester in service [1]. The zinc oxide varistors fail in different in two ways:

- As a result of cracking from excessive thermally–induced mechanical stress in the bulk, or
- As a result of a melting puncture at the edge of the electrode.

In addition, partial discharge (PD) has been reported as the source of fail in surge arrester [26]. ZnO varistor blocks have been characterized as the heart of arrester, since they serve as surge absorbers, aiming to protect the system. The zinc oxide varistors have a large, but imperfect, capacity to absorb energy, and as a result, they are subject to an occasional failure (see Figure 2.21). This has been reported by many researchers [44], [73].

Significant ZnO varistor failure mechanisms include: electrical puncture as shown in Figure 2.20, thermal cracking, and thermal runaway (Figure 2.21), all resulting from excessive heating; in particular, from non-uniform heating.

Non-uniform heating occurs in MOV's as a result of electrical properties that originate in the varistor fabrication process[49]. Figure 2.22 present comparison the relationship between power loss and temperature on the ZnO varistor under different condition.

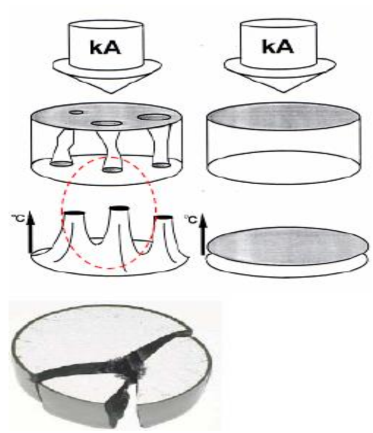


Figure 2.21: Thermal cracking on ZnO varistor [8].

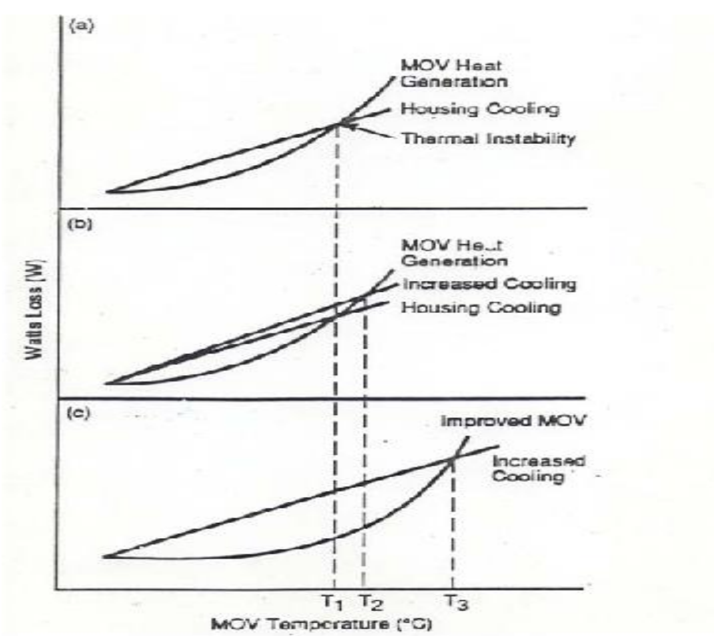


Figure 2.22: Graph illustrates the performance of ZnO varistor [8].

2.9 External pollution

Contamination is a common problem, not only in surge arresters, but also in higher voltage apparatus that serve as protection devices for outdoor substations. Depending on the region where the equipment is located, this problem can be accentuated by high air humidity or salinity [1], [3].

Typical environmental conditions such as (a) dust and salted road contamination, (b) industrial emissions, (c), salted air from oceans (d) and fire are shown in Figure 2.23 affect the performance of outdoor polymeric surge arresters in some areas [18], [66].

External pollution can cause serious problems for surge arresters in service. Pollution decreases the creepage distance for the current conduction, making possible the occurrence of discharges on the surface area of polymeric surge arresters [42], [48].

Figure 2.23: Enviromental conditions [18],[44].

Figure 2.24: Surface contamination [19].

2.10 Failure Modes of Surge Arrester

Due to various factors affecting the arrester in service, a surge arrester failure may appear in different ways [23]:

The arrester with polymer housing may burn open the external insulation; such failed arresters are shown in Figure 2.25.

Figure 2.25: Polymeric surge arrester that failed during in service condition [19].

Polymer housed surge arresters are exposed to various stresses, such as temporary overvoltages (TOV), switching overvoltages, and lightning overvoltages. Thus, due to different factors affecting them, their failure may appear in different ways [62]:

- Damage of sealing due to thermal heating produced inside varistor (see Figure 2.28).

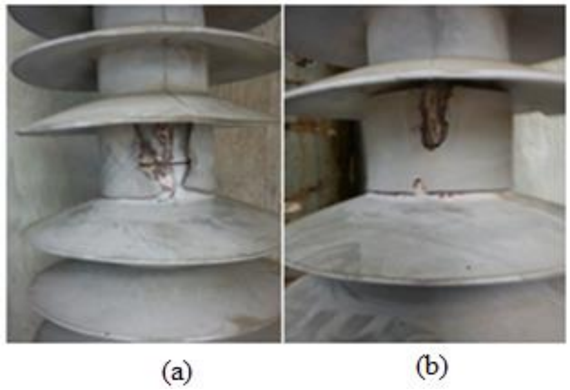


Figure 2.26: Defective sealing increase high rate of moisture ingress [45].

- Localized losses and discharges caused by poor inter-disc contact.

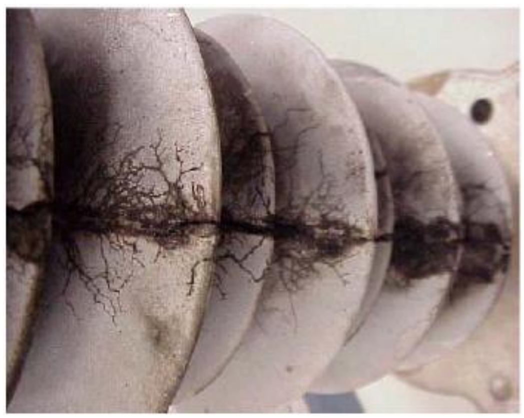


Figure 2.27: Deterioration on insulation housing [1].

- Mechanical fractures in ZnO varistor due to thermal runaway after a high current surge (see Figure 2.28).

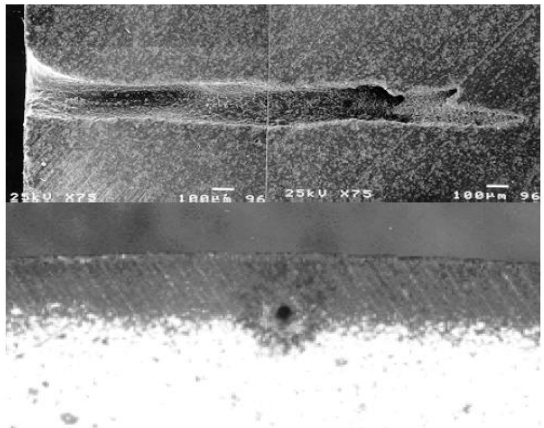


Figure 2.28: Mechanical cracks in varistor elements [20, 21].

- Damage due to surge current concentration at the edge of the electrode resulting in failure (see Figure 2.29).

Figure 2.29: Damage to the ZnO disc created by lightning [22].

- Resultant damage to the disc created by previous multiple-stroke lightning surges.

CHAPTER 3: DIAGNOSIS MEASUREMENTS

There are no simple, practical field tests that will determine the complete protective characteristics of surge arresters. However, the condition of the metal oxide surge arresters is measured by performing tests such as partial discharge (PD), radio interference detection, leakage current measurement and infrared scanning (IR) [48], [13].

Polymer materials can more easily exaggerate the appearance of ageing due to partial discharge and leakage currents on the surface. However, if these problems are not detected, they can cause the strength and frequency of the partial discharge to increase. In additional, leakage currents may lead to catastrophic failure of the metal oxide arrester on the system. These phenomena are dangerous and can cause a total failure of the metal oxide arrester [74].

These tests can be performed with apparatus usually available, and will give sufficient information to determine whether the arrester can be relied upon to perform under normal conditions, as well as units whose insulating qualities have deteriorated [62].

Mostly, the majority of the diagnostic methods mentioned above are performed while the surge arrester is in-service. The following tests selected for this investigation were chosen after review of appropriate literature studies.

- Leakage current test (offline)
- Partial discharge test
- Infrared scanning

The testing will not only cover the surge arrester condition, but it will also cover their major active parts, for instance, zinc oxide varistor (ZnO) and insulation of the arresters.

3.1 Partial Discharge (PD)

Partial Discharges are: "*Localized electrical discharges that only partially bridge the insulation between conductors and which can or cannot occur adjacent to a conductor. Partial discharges are in general a consequence of local electrical stress concentrations in the insulation or on the surface of the insulation. Generally, such discharges appear as pulses having duration of much less than 1 μs*"[75].

In the last century, when HV was first introduced, partial discharge was recognized as the result of its ageing process. The degree of degradation is measured through partial discharges [76], [77], [78].

It was observed that 'partial discharge' action is both an indication of degradation in the insulation systems of power apparatus - irrespective of the network stress - and a stress mechanism in itself [79]. Such problems cause the strength of partial discharge to increase, and may eventually lead to failure of the apparatus in the system [40], [80].

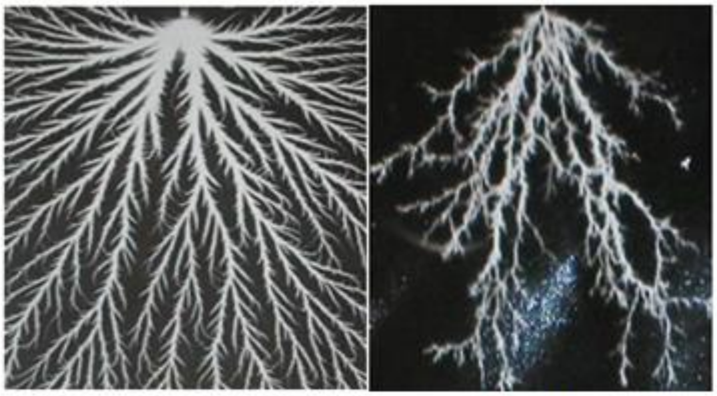
The thermal stress created by a partial discharge may be adequate to cause damage to polymeric materials. A partial discharge generally causes progressive deterioration of insulating materials, eventually leading to electrical breakdown [40].

3.1.1 Partial Discharge Occurrence

During the life of polymer housed arresters, the internal components are continually exposed to stress that can lead to PD. This PD is of the major causes of failure of surge arresters of high voltage [81].

PD's are mostly caused by a local field enhancement, due to imperfections in the insulation, such as gas filled inclusions or voids (see Figure 3.2(a)) and cracks. PD's dissipate energy, generally in the form of heat. Heat energy dissipation may cause thermal degradation of the insulation, although the level is generally low [82].

PD causes progressive deterioration of insulating materials, ultimately leading to electrical breakdown. The cumulative effect of partial discharges within solid dielectrics is the formation of numerous, branching, partially conducting discharge channels, and a process called treeing [50], as shown in Figure 3.1. Electrical treeing is a significant degradation mechanism in polymers that can lead to premature failure of high voltage equipment [83]. Lahti reported that rendering to the PD analysis the discharges most probably occurred in voids or cavities in the moist interface between polymeric arrester housing and inner parts [62].



(a) (b)

Figure 3.1: Treeing [23].

As seen, Figure 3.2(a) represents a discharge in a void internal to a potted assembly. Voids are present in solid potted assemblies; the key to mitigating partial discharges in the voids is to reduce the number of voids, and reduce their size based on the voltage potential across the void [17].

Further most arresters with internal air volume will experience partial discharge during rain, fog, and sometimes snowy conditions. The occurrence of these is an acceptable condition in most arrester designs [84].

3.1.1.1 Internal Partial Discharge

Where cavities are present in the solid dielectric of insulation systems, the field strength is greater inside than in the surrounding medium. When the voltage across the cavity exceeds the ignition voltage, a partial discharge breakdown will result. Usually, a pulse-shaped discharge occurs in the cavity, when alternating voltage of sufficient amplitude is applied [17].

Over a long period of time, internal partial discharges can cause surrounding dielectric deterioration under certain circumstances; erosion can even cause complete breakdown and destruction [30]. Figure 3.2.shows the proposed equivalent circuit for pulse shaped partial discharge (see Figure 3.3) [24].

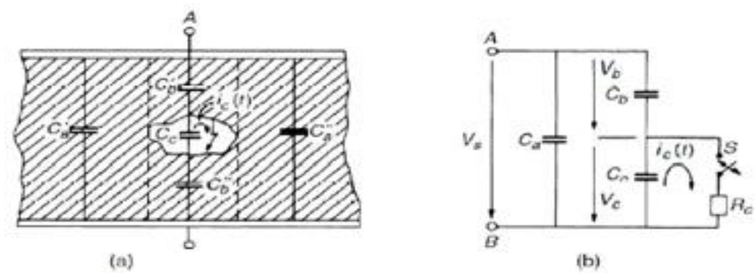


Figure 3.2 (a): Scheme of an insulation system comprising a cavity and (b) Equivalent circuit [24].

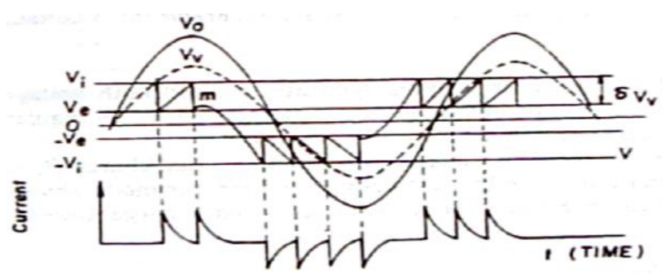


Figure 3.3: Voltage waves in the equivalent circuit for pulse-shaped internal partial discharges [25].

$$\delta V_a = \frac{C_b}{C_a + C_b} \delta V_c \quad \dots (2.2)$$

Where,

Vc = voltage across the void capacitance

C_c = cavity capacitance

δVa = voltage drop across the terminal

3.1.1.2 Partial Discharge Induced Degradation

Repetitive discharge events cause permanent mechanical deterioration of the insulation material. More specifically, this damage is caused by the energy dissipated by high energy electrons or ions, ultraviolet light from the discharges, and cracking [85], [5]. Usually, such discharges appear as pulses of duration of much less than 1μs (IEC standard 60270). Thus, it necessary to perform PD measurement to check surge arresters insulation integrity while are in-service [41].

The deterioration of ZnO varistor elements under partial discharge conditions in air may be caused by both the erosion of the side surface of the ZnO varistor, and the action of some generated gases [4]. The deterioration may accelerate aging under service conditions, and may eventually give rise to the ignition of partial discharge. The term 'partial discharge' includes a wide group of discharge phenomena:

Occurring in voids or cavities within solid or liquid dielectrics (Figure 3.2), internal discharges in surge arresters are usually initiated by non-uniform pollution on the housing, or, in unusual cases, by high humidity and condensation. Most internal discharge that occurs within insulation material is caused by age and poor material design. External discharges (surface discharges) appear at the boundary of different insulation materials [67], [26]. The tracking occurs across the surface of the insulation, creating erosion of the insulation material.

Figure 3.4: Internal partial discharge [26].

- Water trees

When polymer surge arresters are stressed, micro-voids can form at regions of high electrical stress within the insulator. Partial discharge activity can then take place, leading to the formation and growth of a fractal structure within the insulation, which exhibits a treelike shape - called electrical trees. The water trees lead to electrical trees, which produce partial discharge, and ultimately, failure [17]. This can accelerate the degradation of the surge arrester. Moreover, the moisture ingress results in thermal overheating in the zinc oxide varistor elements [17].

- Tracking

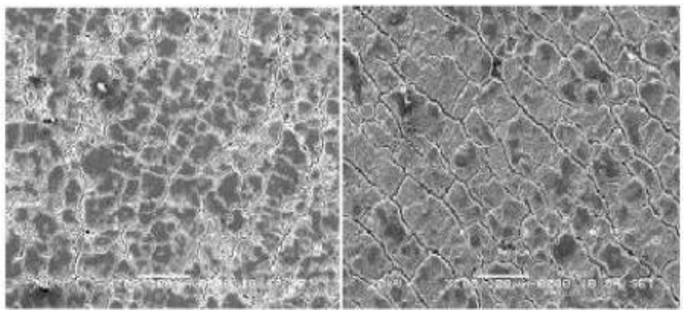


Figure 3.5: Surface tracking on the surge arrester [22].

Tracking originates from electrical surface discharge activity (see Figure 3.5), due to the flowing of leakage current on the insulator surface, under wet contaminated conditions[45], [86], [87]. Additionally, the leakage current can result in non-uniform heating of electrolytes that eventually causes dry-bands to be formed in narrow sections where the leakage current density is highest [88].

3.1.1.3 Diagnosing the PD on Insulation

In the last 25 years, a large amount of research has been performed on the dielectric materials, to study their fortitude under electrical, mechanical, thermal, and other stresses [89]. When dealing with partial discharge, at least three stages of information handling are needed to collect sufficient data for an evaluation [27]. These stages are presented in Figure 3.6 below [27].

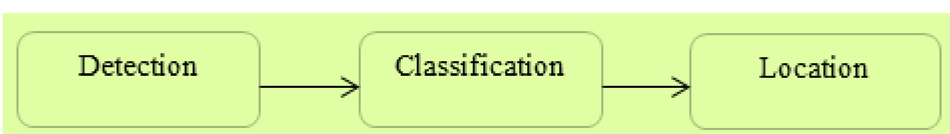


Figure 3.6: Three stages of information handling are needed to collect sufficient data for an evaluation [27].

3.1.1.4 Detection

Detection of PD is performed with a classical discharge detector, having a bandwidth of 250 kHz. Detectors are commercially available or can easily be built, and can be found among the standard equipment of HV laboratories. Electrical detection shows the presence magnitude of the PD under observation.

3.1.1.5 Classification

Classification of PD aims to recognise the defect causing the discharges, such as internal or surface discharges, corona, treeing, etc. This information is vital for estimating the harmfulness of the discharge.

3.1.1.6 Location

Locating the position of the discharge in a dielectric construction, ideally, reveals the type of material or the interface between materials and the local field strength where the discharge takes place. Several important terms regarding partial discharge are as follows (see Table 3.1):

Table: 3.1 Important terms regarding partial discharge [27].

Parameters	Values
Operating voltage	The voltage at which the insulation system or finished product is normally operated.
Inception voltage	The voltage at which the partial discharge begin to occur.
Extinction voltage	The voltage at which the partial discharges end.
Picocoulomb (pC)	A measure of electric charge. An ampere is one coulomb/second. Picocoulomb is 10^{-12} coulombs, a very small amount of charge
Ellipse	A common pattern to show partial discharge superimposed on a phase representation of a voltage waveform

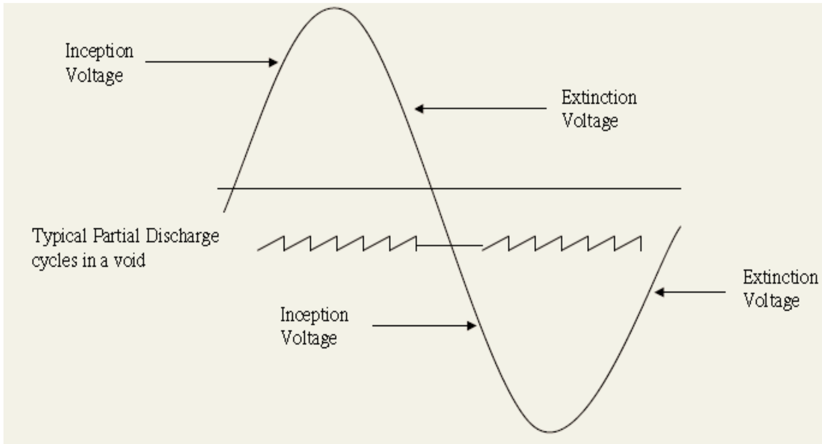


Figure 3.7: Inception and extinction of partial discharge with AC voltage testing [28].

3.1.1.7 Classification of PD Measuring Devices for Measurement of Charge

Nazemi reported that there are different types of PD charge measuring devices composed according to the classification in Figure 3.8, where the given bandwidths are approximate benchmarks according to the application range and the measurement conditions, the different

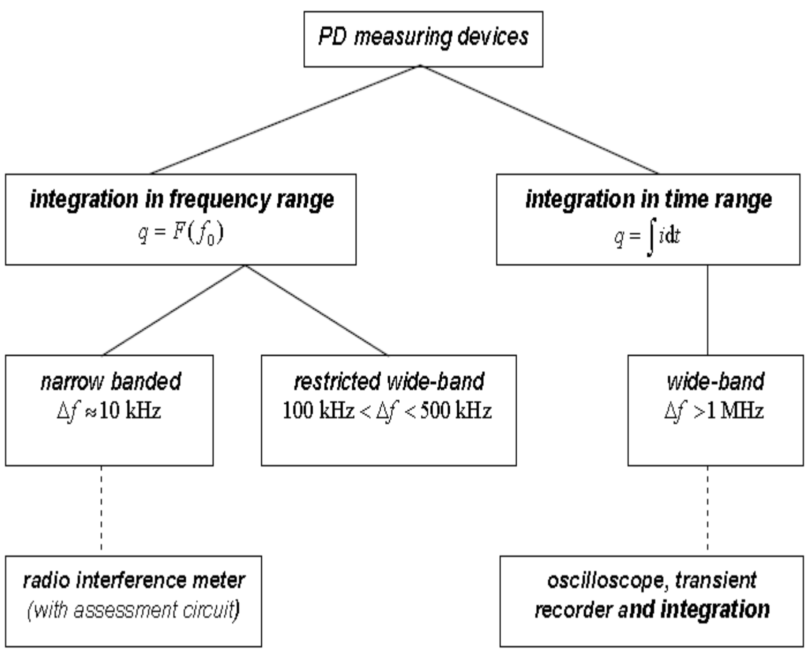


Figure 3.8: Three stages of information handling are needed to collect sufficient data for an evaluation [Nazemi].

devices, which are available on the market, possess additional components in many cases, e.g. oscillographic demonstrations of PD pulses over an elliptic base line. Displays on the oscilloscope for some typical discharges are shown in Figure 3.9. Together with corresponding waveforms arising out of external discharges as well as from contact noise [Nazemi].

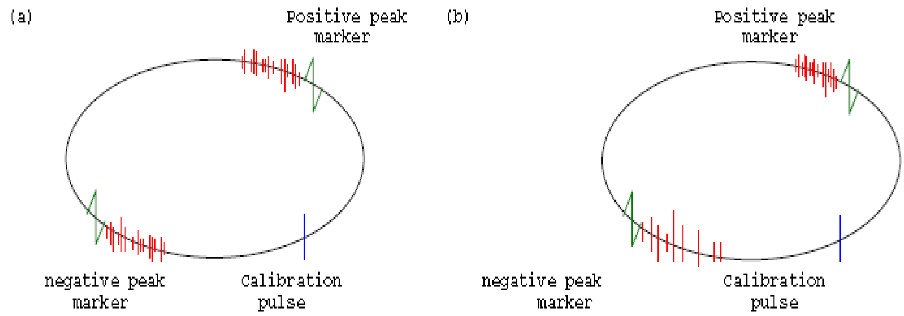


Figure 3.9: The common design to show partial discharge superimposed on a phase representation of a voltage waveform [29].

3.2 Leakage Current Test

Nowadays, the leakage current measurements are the common utilized diagnostic method for assessing the condition of ZnO surge arresters [90]. A variety of different online and offline techniques for measurements of leakage current are in use. The resistive leakage current is the most important factor in arrester diagnostics, but the total leakage current and third harmonic component flowing through an arrester are widely employed as an ageing indicator [48].

Consequently, by obtaining leakage current measurements the insulation performance of the polymeric housed can be obtained, as the leakage current changes according to contamination surface [40]. The current designs with polymer housed surge arrester for high voltage have only been tested according to the existing IEC standard, IEC 99-4 of 1991, which only covers arresters with porcelain housing surge arrester [82]. These standards do not address tests for polymer housed surge arresters.

Insulation deterioration caused by moisture ingress, and wet surface contamination, are the main factors in degradation and cause of failure of ZnO arrester [48]. As already indicated the insulation deterioration increases leakage currents and eventually causes damage to the zinc blocks. Thus, it is extremely important to measure the condition of the surge arresters while is in service. This can limit unnecessary long outages and time consuming maintenance.

3.2.1 Properties of the Leakage Current

During normal service, the surge arrester carries a continuous small leakage current flowing through the surface, typically in a range of 0.2-3mA [23]. The total current flowing through the arrester is composed of resistive leakage current [23].

The resistive leakage current is produced through changes of the Schottky barrier, which is formed between the ZnO grains, and increases with arrester deterioration or aging (which is caused by environmental factors such as UV, contaminants, and humidity) [67]. However, the increase in the resistive leakage current will cause an increase in the power losses and hence increased temperature in the ZnO-block [40].

The leakage current is directly proportional to hydrophobicity loss, especially for composite insulation. The more the loss of hydrophobicity or reduction of silicon insulation, the more the leakage current increases [40]. These leakage currents can cause damage to the stability of the arrester, particularly in the low conduction zone where the V-I characteristic of a ZnO (see Figure 3.10) varistor is very sensitive to temperature [42].

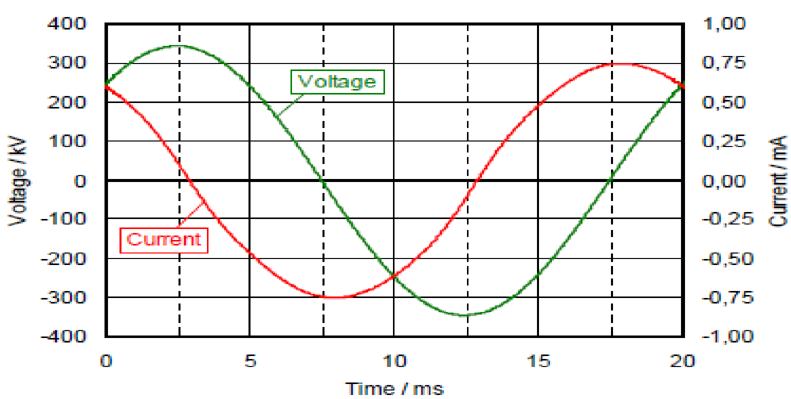


Figure 3.10: Typical V/I characteristic for a MOSA [30].

The A.C. leakage current flowing through the surge arrester consists of a large capacitive current (Ic) and a small resistive component (Ir) [39], [30]. This can be seen in Figure 3.12, which shows a typical laboratory measurement of leakage current of a single non-linear ZnO varistor, when energized at a voltage equivalent to continuous operation for a complete surge arrester [31].

The capacitive current depends on the number of varistor columns that are in parallel. Figure 3.11 shows the waveform of the leakage current components when a rated operating voltage is applied to a surge arrester.

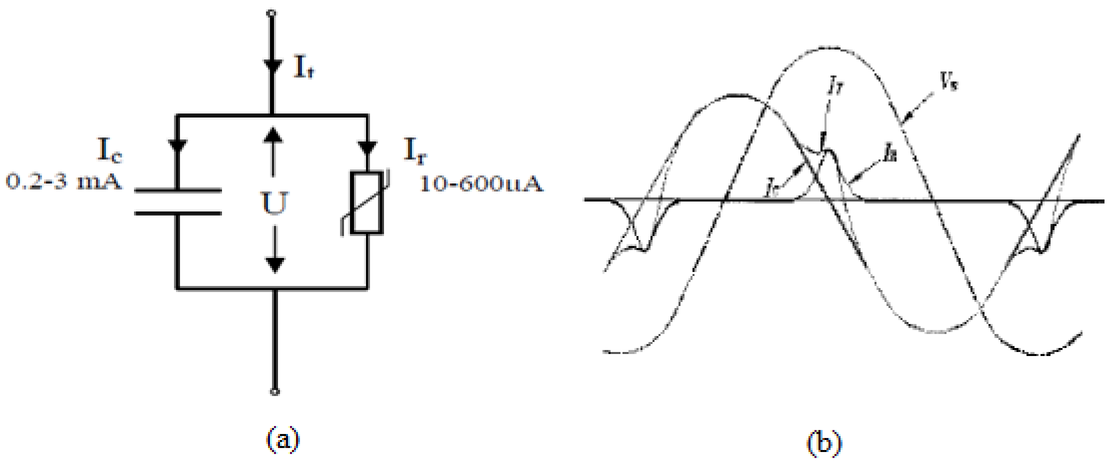


Figure 3.11: Electric equivalent circuit for a MOSA and waveform of the leakage current components [31], [32].

The phasor sum of leakage current component Ir and Ic are equal to total leakage current (It = I_L). The resistive leakage current component itself varies with the degradation of the surge arrester [39]. Additionally, capacitive current does not vary with the degradation of the surge arrester. Figure 2.40 shows all currents are time dependent; It, Ic and Ir can therefore be written as [4], [32], [91]:

$I_{(L)} = It(t) = Ir(t) + Ic(t)$ ... (3.4)

All currents are time dependent, so I_L, I_C and Ir can be written as:

$I_L(t) = I_R(t) + Ic(t)$ … (3.5)

The resistive current component can be obtained by subtracting the capacitive current component from the total leakage current as shown below:

$I_R (t) = I_L (t) - I_c (t)$ ... (3.6)

The subtraction in (2) can be applied as described below.

Equation (1) can be written as:

$I_L (t) = (I_r) + I_c \cos\omega t$ ... (3.7)

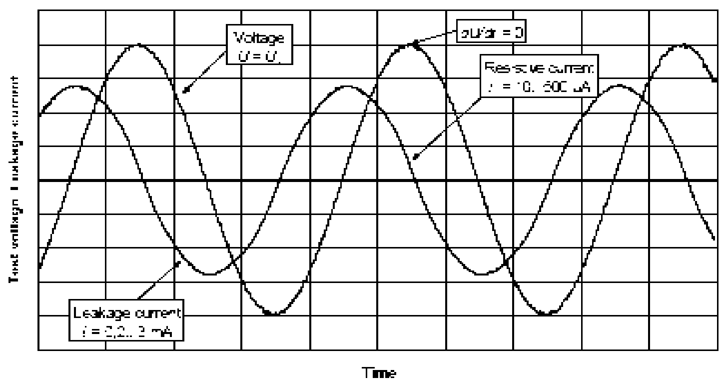


Figure 3.12: Typical leakage current of a non-linear metal-oxide resistor in laboratory conditions [31].

3.2.1.1 Leakage Current as a Source of Heat

MOSA's are known to exhibit an increase in resistive leakage current in relation with the arrester operating time [23]. As is well known, the increase of resistive and capacitive current will cause an increase in power losses (I^2R), and therefore an increase in ambient temperature. An increase in temperature may bring the surge arrester to a temperature which exhibits an inadequate safety margin for thermal stability [82]. This depends on the overall surge arrester design [67].

Heat dissipation is reduced at the centre of a column [35]. Many researchers have reported that an increase of the resistive current can be considered as an indicator of the arrester condition, and with continued operation, in time, can cause failures or permanent degradation [33], [34]. Therefore, performing LC measurement can give valuable data about the degradation of the ZnO surge arresters [92].

The resistive leakage current is the most important factor in arrester diagnostics, but the total leakage current and third harmonic component flowing through an arrester are widely employed as an ageing indicator [23], [93]. Therefore, the goal of leakage current measurements is to determine the performance of the insulator, as the leakage current change variously according to surface contamination [82].

3.2.1.2 Effect of Leakage Current

In high current conditions, the zinc oxide junctions of the varistor begin to degrade, resulting in a lower measured MCOV or turn-on voltage. As the degradation continues, the varistor's MCOV continues to drop until it conducts continuously, shorting or fragmenting within several seconds [49]. One of the key parameters related to measuring degradation of a varistor is leakage current.

Leakage current (LC) in the pre-breakdown region of a varistor is important for two reasons [49]:

- Leakage determines the amount of power loss an MOV is expected to generate upon application of a nominal steady-state operating voltage and,
- It determines the magnitude of the steady-state operating voltage that the MOV can accept without generating an excessive amount of heat.

3.2.1.3 LC Measurements

IEC standard 99-5 stated that the leakage current measurement can be divided into two groups [20]. The first one is online measurement, where the surge arrester is connected to the electrical system and energized with the source voltage during normal operation, and offline measurements - this requires disconnecting the surge arrester from the power system and energizing it with a separate source on site.

3.3 Harmonics

A surge arrester is a non- linear device, and consequently, gives rise to harmonics. Since the capacitive current follows the supply voltage, there will be no harmonics present in the capacitive current for a voltage having a pure sine wave. The harmonic content depends on the magnitude of the resistive current and the degree of non-linearity, which is a function of voltage and temperature[3]. The resistive current, however, contains harmonics (Figure 3.13.).

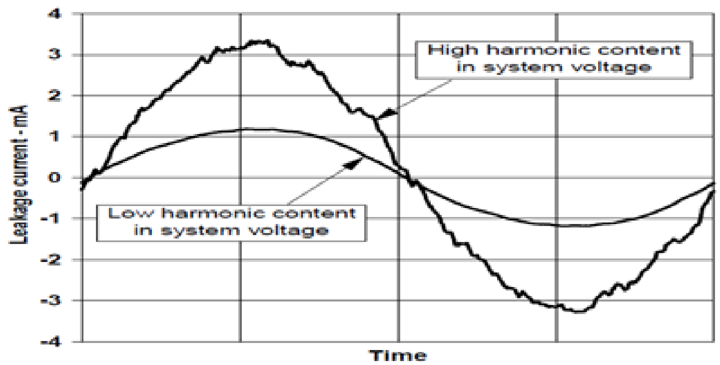


Figure 3.13: Leakage currents of arresters in service conditions [33].

Harmonics can be a source of errors in the varistor conduction current. Changes in harmonics in the supply voltage cause changes in current peak value [33]. The presence of harmonics in the operating voltage can generate a third harmonic capacitive component, in addition to the third harmonic resistive component. The content of the resistive component is typically 10 to 40 % [33].

In some cases, moisture ingress causes changes in the ZnO varistor current, and thus changes in the content of the third harmonics. This demonstrates that the moisture penetration through the end arrester (toward the center) increases third harmonics. Hinrichsen states that the third harmonic component flowing through an arrester is widely employed as an ageing indicator [30].

3.4 Thermal Measurement

Besides adverse climatic conditions that accelerate the surge arrester aging, in normal operating conditions they are subjected to constant voltage, resulting in temperature rises, due to energy loss on a resistive current by a cyclic process [13], [94]. Furthermore, defective housing has been reported as a source of failure [20] (see Figure 2.15(b)).

The increase in temperature brings the arrester to a temperature which exhibits an inadequate thermal stability safety margin. The exact values of this safety margin depend on the overall surge arrester design [95]. Without a thermal energy dissipation capability, the surge arrester would continually heat up until it reached self-destruction (called thermal runaway).

The thermal energy absorption capability of the arrester is defined as the maximum level of energy injected into the surge arrester at which it can still cool down to its under normal operating temperature [20], [34]. Figure 3.14 illustrates that the power loss from continuously applied power voltage is temperature dependent increases as the temperature increases [34]. The surge arrester's design allows for dissipation of a certain limited amount of heat energy into the surrounding environment.

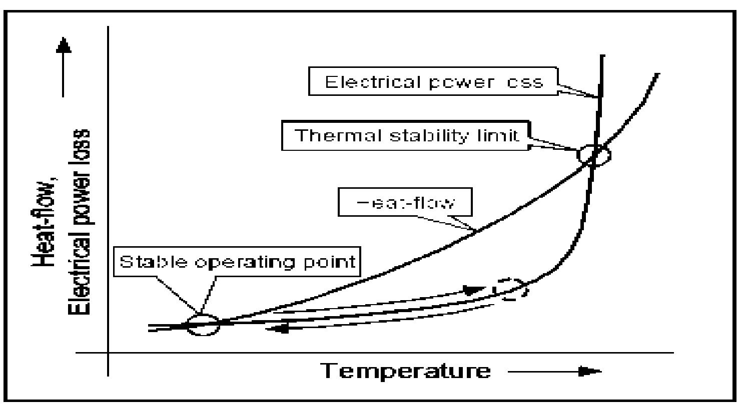


Fig. 3.14: Description of thermal stability [34], [35].

It has been proved that the defective surge arrester loses its characteristic as an insulator under power frequency conditions, and it then allows the high amount of leakage currents to flow through it. As a consequence, it will present with excessive heating which can lead to thermal runaway.

Thermographic inspection is a widely used method to monitor surge arresters, preventing their failure [5]. Thermal inspections are the most dominant techniques for monitoring and predictive maintenance of ZnO arresters.

The proposed direct measurements of the MOSA temperature, give an accurate indication of the condition of the arrester, but require that the arrester be equipped with special transducers at the time of manufacturing. Therefore, this method is used only in special arrester applications. Alternatively, measurement of the arrester temperature can be carried out by means of thermal imaging methods.

The infrared thermo camera should be able to detect an abnormally high temperature when compared to a healthy surge arrester. A study done by Strimiska of Sumter Electric Cooperative, Florida in 1995 revealed that moisture ingress reduced the resistance of surge arresters, allowing current to flow through them resulting in heating of the surge arresters [46].

CHAPTER 4: DESIGN AND RESEARCH METHODOLOGY

4.1 Introduction

To obtain relevant failure information concerning surge arresters, different techniques were performed on different families of arresters. This research was carried out in three stages: analysis, visual inspection, and experimental tests. Analysis refers to the survey of literature studies that are related to the subject. Various topologies were evaluated. The flowchart diagram below in Figure 4.1 gives a full description and understanding of the data acquisition process of research.

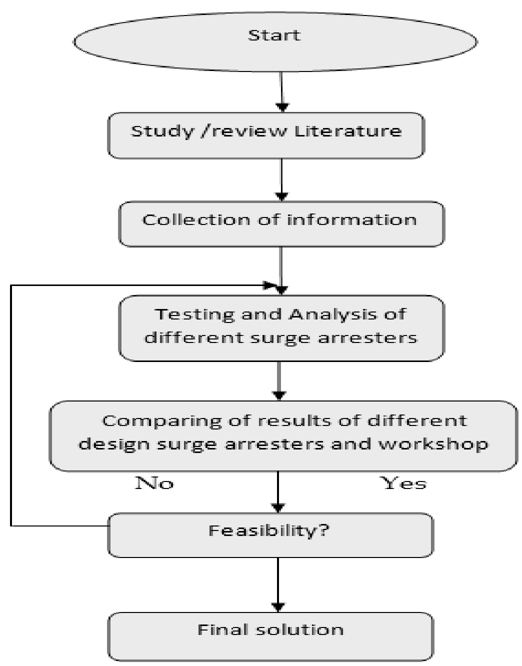


Figure 4.1: Data acquisition flowchart.

To achieve accurate information regarding arrester fault detection and diagnosis, it is extremely important to select a set of inputs whose data is capable of allowing fault identification in the surge arrester.

In light of this, the research methodology applied for evaluating the failure of family surge arresters was established in accordance with the proposed International Electrotechnical

Commission (IEC) standard, using leakage current and partial discharge measurements for revealing internal moisture levels in polymer housed surge arresters.

Thermovision technique was also used as an extra tool for a data acquisition. The advantage of this tool (Infrared scanning) is that it is a non-destructive technique used diversely in maintenance, and does not require disconnection of the apparatus.

4.2 Research Design and Methodology

To achieve good results for fault detection and diagnosis, it was imperative to select a set of inputs whose information could be used for fault identification in the surge arrester. The tests identified were applied for evaluating the failure of polymeric surge arrester of 275/132kV of different substations of eThekwini electricity.

The tests selected for this research were chosen after review of appropriate literature studies. The tests did not only cover the surge arrester condition, but also examined their major active parts, for instance, zinc oxide varistor (ZnO) and insulation of the arresters.

The following tests made up the methodology for this research:

- Laboratory test (PD),
- On site measurements (LCM and IR) and
- Visual inspection

The PD, LCM, IR analysis, as well as visual inspection, were performed to acquire the surge arrester condition. The intention was to determine whether the arresters can be relied upon to perform under normal conditions, and to identify those which have deteriorated.

4.3 Surge Arrester Evaluation

The above-mentioned tests were performed in different places: Within the HV laboratory, on-site measurement in different substation of 132kV/275kV within eThekwini municipality, and the visual inspection was conducted in the electrical workshop. The first step of the research was to analyse the characteristics of the surge arrester in service, considering their manufacturer, rated voltage and housing material. Figure 4.2 presents the diagnostic flow chart utilised for data acquisition.

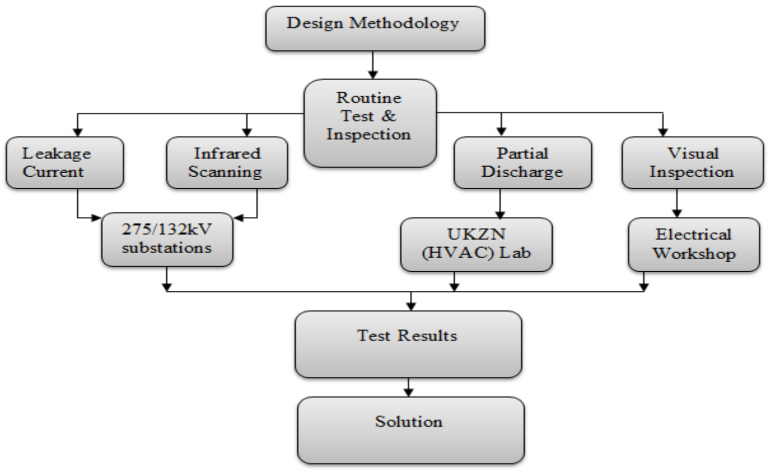


Figure 4.2: Surge Arresters Diagnostic Flowchart.

Figure 4.3: EThekwini Substation with polymer housed surge arresters.

4.4 Surge Arrester Characteristics

A test was conducted on families of station class surge arresters. Gapless polymer housed ZnO surge arresters have superior electrical performance because their energy absorption capabilities are greater, the discharge voltage (protection levels) are lower, and the pressure relief greater. The surge arresters were from three different manufacturers in the United States of America. The properties of arresters that were tested are listed in Table 4.1.

Table 4.1: Surge Arrester Types Tested

Arrester Manufacture	Housing Material	Uc [kV]	Molded housing	Number of sheds
A	Polymer	98	X	24
B	Polymer	98	X	24
C	Polymer	98	X	24

Uc Max. Continuous operating voltage (IEC 60099-4) *

The arresters were close or wrap design. This type of design utilised a fiberglass cloth impregnated with resin, which is wrapped around a stack of a metal oxide varistor blocks, including the end fittings. These are made of polymer which is directly molded onto the wrap.

4.5 Partial Discharge Analysis Performed in the Laboratory

PD measurements on zinc oxide varistor elements were performed in the HVAC Laboratory at University of KwaZulu Natal (UKZN) situated on the Howard College Campus. The tests were carried out using an AC voltage power transformer 220V/66kV and a coupling capacitor device of 200kV and 0.001µF. The plate-plate (Rogowski profile) was used to connect the ZnO varistor across the coupling device and resistor of 20MΩ.

The oscilloscope output results (pulses) were fed into a wide band amplifier and pulse display. The most important partial discharge measurements were to determine the onset voltage (Ue) and the extinction voltage (Ua). The laboratory tests were performed using the conventional apparent charge measurement of IEC 60270 standard. IEC 60099-4 states that PD level limit is 10pC.

4.6 Partial Discharge Test Circuit

The circuit in Figure 4.4 was designed to have a specific resonance frequency in the range of 50 kHz to 100 kHz. The pulses were fed into a wide band amplifier, and the output pulses were displayed on a Cathode Ray Tube (CRT) screen, superimposed on the supply sine wave, in order to detect the points on the wave where the discharges occur, relative to the zero crossings. The positive and negative half waves are often displayed as an ellipse.

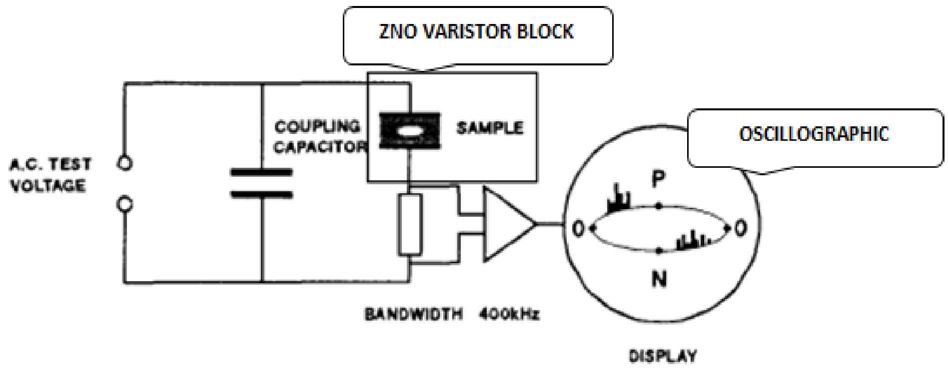


Figure 4.4: Test circuit for partial discharge measurement [27].

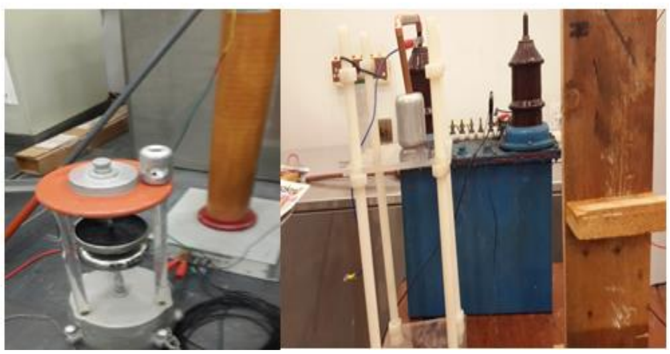


Figure 4.5: HV Final circuit diagram for partial discharge (PD).

Table 4.2: Circuit components of PD measuring circuit.

Components	Values
Transformer	240/66kV
Coupling capacitor	200kV, 1nF
Resistor	10kΩ
Plate electrodes	
Transient amplifier	
Oscilloscope	

The peak voltmeter (SM) measured the voltage on the secondary winding and was connected in series with measuring capacitor (CM) 1nF, 200V.

The interference voltage measuring device (STM) was connected to the coupling one- pole (AV) on the earth lead of the test object. The various interference voltage pulses were taken from the intermediate frequency amplifier.

When an increase of the signal occurred, it was possible for a convenient oscillographic indication of the onset of the pulse to be obtained. The pulse was superimposed on an alternating voltage in phase with the test voltage, so that their phase relation with respect to the test voltage was shown on the cathode-ray oscilloscope.

4.6.1 Main Test Object

The test object used to test varistor element is demonstrated in the circuit diagram below (see Figure 4.6). The plate electrode was connected in parallel with 1nF, 200kV coupling capacitor. Before setup, the plates were polished to prevent the generation of apparent partial discharge during the measurements.

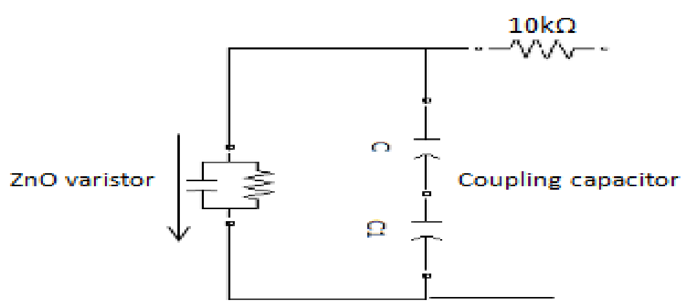


Figure 4.6: Test circuit diagram for PD.

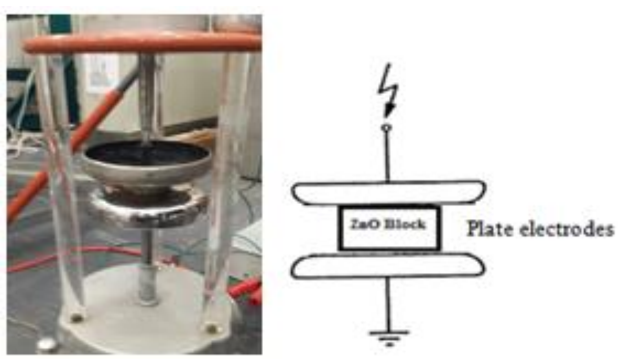


Figure 4.7: Plate electrodes used to measure PD on ZnO varistor.

4.6.1.1 Test Transformer

Figure 4.8: Typical designs of AC test transformer.

The typical configuration of the transformer is single-stage. The testing power transformer rating is coupled to 220V, with the maximum voltage at the secondary side being 66kV with apparent power of 5kVA. The secondary side of the transformer was set in order to supply the maximum continuous operating voltage (MCOV) at the ZnO varistor of the arrester.

4.6.1.2 Partial Discharge Meter (DXX-7000®)

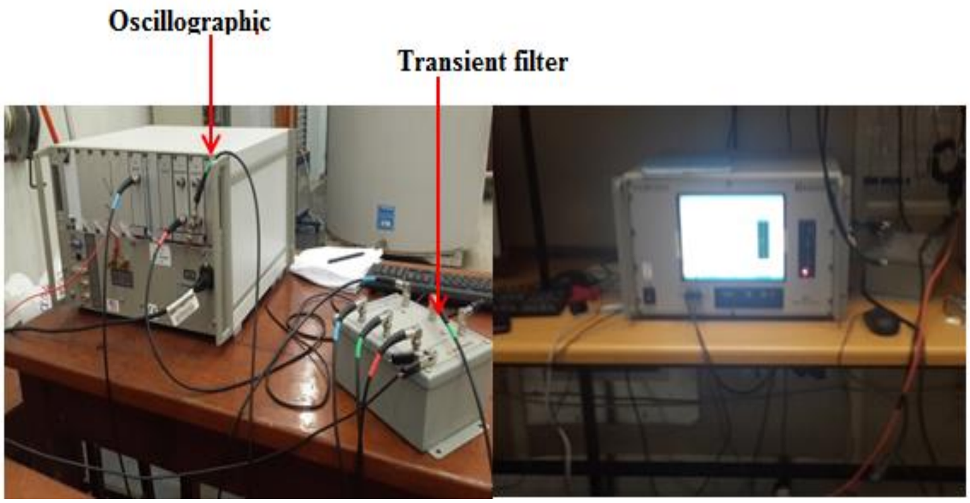


Figure 4.9: Partial discharge meter.

The measured PD intensity is displayed either in pC or in µV in accordance with IEC 60 270 / IS 6209. According to IEC 60 270, the measured quality must be multiplied by a correction factor, which considers the circuit characteristics of the complete test arrangement. With the built-in correction circuit, it is possible to incorporate the factor into the display.

The DXX-7000® system was used to read true charge in pC over all ranges of the system. The actual partial discharge intensity was read directly without calculations. At switch position, the correction factor was displayed directly. The PC pulses were tapped from the analogue output terminal and displayed on the built-in oscilloscope. The specifications of the DXX-7000® are shown in Appendix A.

4.6.1.3 Transient Filter

Figure 4.10: Transient filter.

The transient amplifier was connected in parallel with DXX-7000®. The use of the TF was necessary to give protection, when the intermittent pulse of interference occurred during measurements.

4.6.1.4 Coupling Capacitor

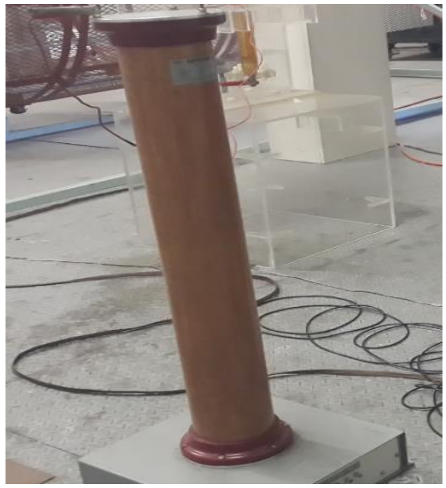


Figure 4.11: Coupling capacity.

The Hipotronics HV PD calibration coupling capacitor of 1nF was used to calibrate partial discharge test circuits. The couplings capacitors are discharge free capacitors.

4.6.1.5 Resistor

Figure 4.12: 10kΩ resistor.

4.6.1.6 Calibration of Partial Discharge Supply

In order to attain valid measurements, the DXX-7000® was calibrated before testing. The calibration of a measuring system in the complete test circuit was made to determine the scale factor *k* for the measurement of the apparent charge *q*. The Table 4.3 show the parameters and their values that were calibrated.

Table 4.3: Circuit parameter of PD measuring circuit

Parameters	Values
PD Range	5-10pC
Sensitivity	3pC
PD Bandwidth	50-100 kHz

The lower and upper limit frequencies $f_1$and f_2 are the frequencies at which the transfer impedance Z (*f*) has fallen by 6 dB from the peak pass band value. Midband frequency *fm* and bandwidth Δ*f*: for all kinds of measuring systems, the midband frequency is defined by equation (4.1 and 4.2):

$$f\text{m} = \frac{f1+f2}{2} \qquad \dots (4.1)$$

and the bandwidth by:

$$\Delta f = f2 - f1 \qquad \dots (4.2)$$

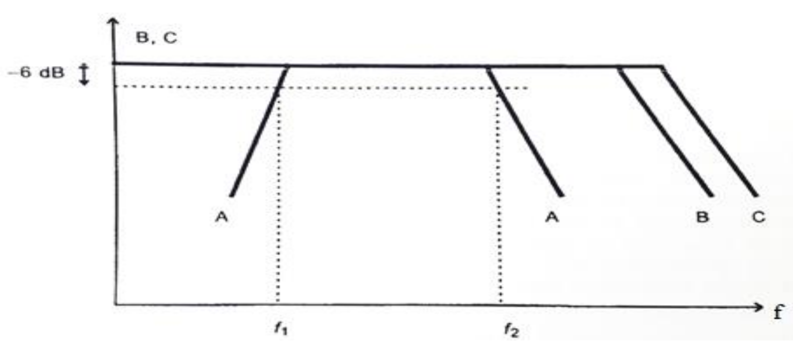


Figure 4.13: Relationship between amplitude and frequency to minimize integration errors for a wide-band system [*IEC 2238/2000].

Table 4.4: Circuit parameter of PD measuring circuit

Parameter	Description
A	Bandpass of the measuring system
B	Amplitude frequency spectrum of the PD pulse
C	Amplitude frequency spectrum of calibration pulse
f1	Lower limit frequency
f2	Upper limit frequency

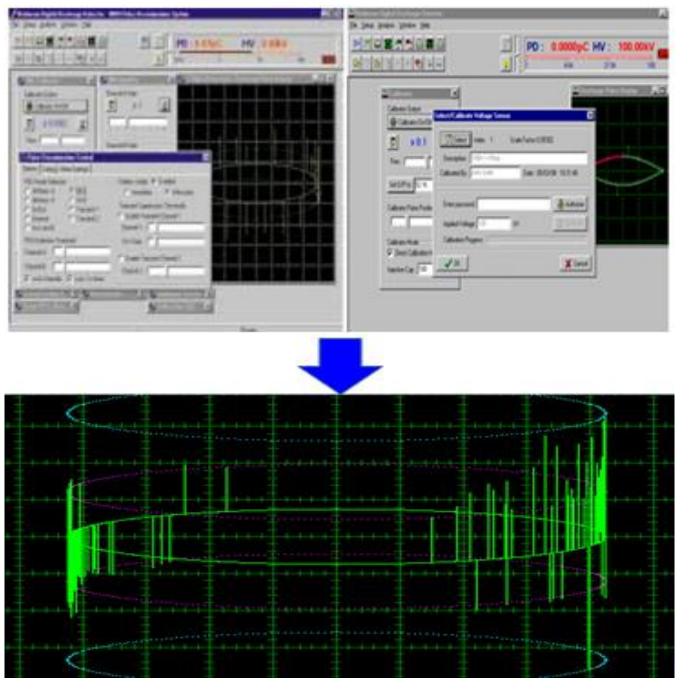


Figure 4.14: The main detector calibration window.

4.6.1.7 Partial Discharge Measurement

During test measurement, a 220V/ 66kV transformer was connected as a test object, with high voltage terminals fitted with screening electrodes to avoid external partial discharges. The earthing connection of the test object was again made via coupling capacitor, and the interference voltage measuring device was connected.

4.7 Infrared Analysis (Data Acquisition)

The infrared scanning test was implemented on the surge arresters on-site to check the buildup of heat due to internal moisture or block failure.

This procedure also helped to identify any hot spots inside the surge arrester. MOSA operation in polluted areas may be subjected to environmental stress, which can cause increased risk of varistor temperature increase. For the most part, the measurable increase in the varistor temperature is caused by animation from the uneven surface distribution, created by the wet pollution layer.

Infrared thermography was selected as the tool for data collection on the surge arresters via thermography. The methodology was applied on 120 kV/ 65 kA surge arresters on transmission substations of eThekwini electricity, for polymeric encapsulation. As soon as all data was collected, digital image processing methods were applied (see Figure 4.15). This process enabled the extraction of some thermographic variables from the thermogram (e.g. Maximum and minimum temperatures). Analysis was done by means of temperature gradient criteria.

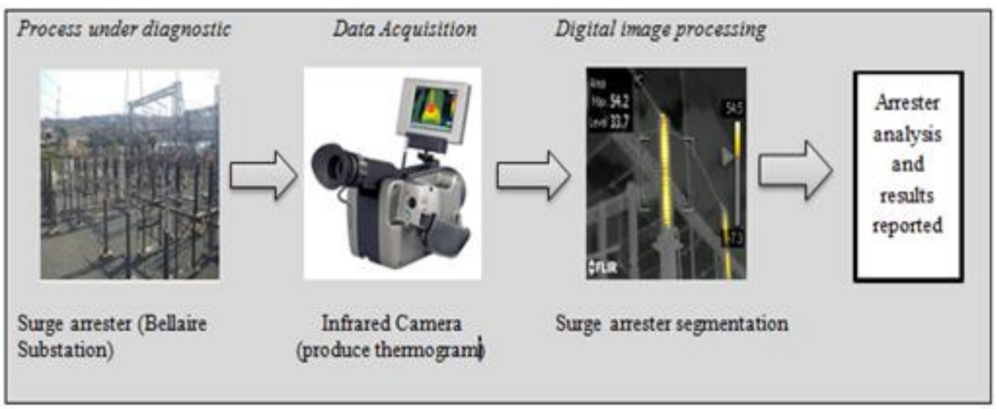


Figure 4.15: Methodology as applied.

The use of infrared thermography is a very convenient approach, since the measurement device operates with no physical contact with the test equipment. Additionally, the operating process is not disrupted, since the equipment being tested continues operating normally while measurement is taken.

The infrared scanning was conducted on 120kV / 65 kA polymer housed surge arresters. The main purpose of thermographs was to identify fault vicinity on surge arresters.

4.7.1 IR Data Acquisition Process

The IR inspections were conducted at the 275 kV and 132 kV major substations of the eThekwini Municipality. The IR analysis was conducted while the surge arresters were energized and under full load.

The infrared scanning was carried out by an infrared trained professional that is authorized to work in a dangerous area, and is familiar with the electric power system. It was vital to select a set of inputs that would provide information capable of detecting faults on the apparatus. Consequently, implementing IR scanning as a tool for data collection for this research was helpful in determining the condition of the surge arresters in service.

For accurate results, the themogram was performed when the wind velocity was below 5 ms^{-1} and when it was not raining. The infrared (IR) analysis was conducted while the arresters were energized and under full load. The recommended emissivity value of polymeric surge arresters is 0, 75 [76]. The emissivity of the material ε is the relative ability of its surface to emit energy by radiation.

4.7.1.1 IR Measurement Procedure

The thermograms were taken in six positions, named here as 01 to 06, with equally spaced angles (60 °, around the surge arrester) as presented in Figure 4.16 and a digital thermography was also taken at each position.

Due to obstacles and other difficulties, it is considered a good idea to arrange the positions of the six angles, at least three positions spaced at angles of 120 ° [76]. During infrared inspection, the professional operator adjusted and corrected the focus, with consideration given to the relative humidity, ambient temperature and object distance, to make sure that the influences of different heat sources were avoided.

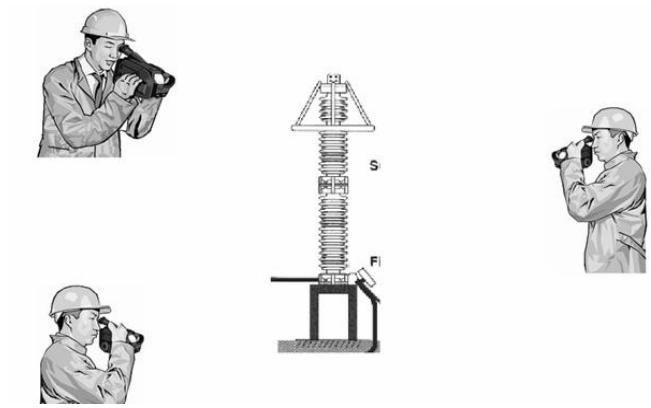


Figure 4.16: Attaining thermographic images in three positions [13].

Table 4.5: Infrared scanning parameter settings [13].

PARAMETERS	VALUES
Field of view/min focus distance	24°x18°/0.3m
Spatial resolution (IFOV)	1.mrad
Thermal sensitivity at 50/60Hz	0.08°C at 30°C
Electronic zoom function	2,4,8 interpolating
Focus	Automatic or manual
Digital image enhancement	Normal and enhanced
Detector type	Focal plane array (FPA)
Spectral range	7.5 to 13µma

4.7.1.2 IR Results Analysis

Once data was collected, the digital image processing methods were applied. This process has enabled the extraction of some thermographic variables from the thermogram (e.g. Maximum and minimum temperatures in the surge ZnO Varistors element).

4.8 Leakage Current Test

Offline leakage current measurement was performed with a Doble mobile AC or DC test instrument and it schematic circuit (see Figure 4.17 and 4.18). For safety reasons, the offline leakage current measurement was mainly used. This required the surge arrester to be disconnected from the electrical system.

The main disadvantages of the offline leakage current method are the cost of the required equipment, and the need for disconnecting the surge arrester from the power system.

For practical and safety reasons, the leakage current was normally accessed only at the earth end of the surge arrester. The purpose was to allow measurements of the LC that flows in the earth connection. The arrester must be equipped with a base, insulated from the pedestal.

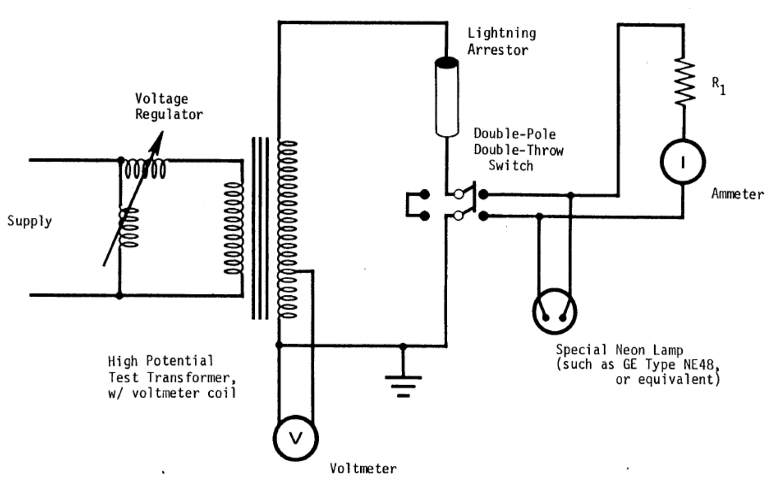


Figure 4.17: Circuit diagram of LCM [36].

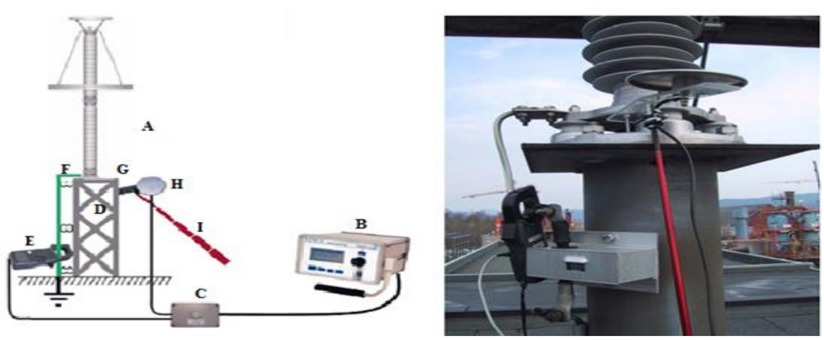


Figure 4.18: Offline LCM on surge arrester [13].

Table 4.6: Circuit components of LC measuring circuit [23].

Components	Description
A	Polymer housed surge arrester
B	LCM unit
C	Current probe with built in temperature sensor
D	Arrester pedestal
E	Clip-on current transformer
F	Surge arrester earth wire
G	Insulated base / insulator
H	Field prope / capacitive antenna
I	Telescopic

4.8.1 Leakage Current Measurement Interpretation of Results

The aim of the leakage current measurement method was to give some indication of dust, dirt, and moisture on the inside surface of the surge arrester. When performing tests, the external surface was clean and dry to ensure high accuracy of the results [36].

To standardize leakage current measurement, ABB has developed leakage current values for field tests as shown in Figure 4.19 [36].

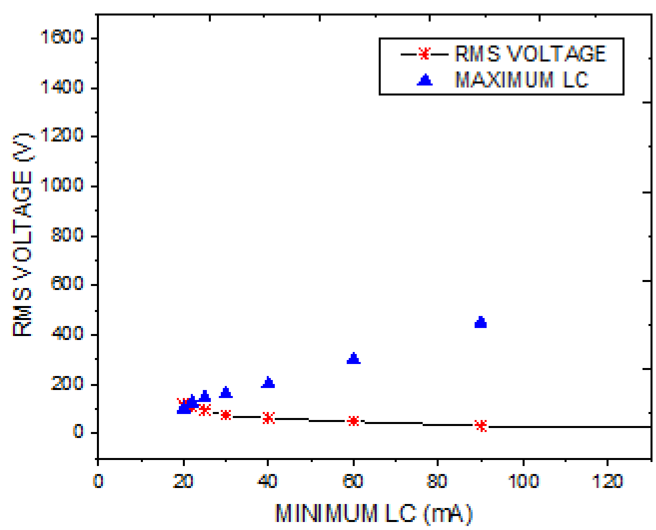


Figure 4.19: LCM severity level [36].

4.9 Site Inspection of the Polymer Housed Arresters

The condition valuation methodology consisted of analysis using individual score sheets to calculate a condition indicator score of the surge arrester. Developing an on-site inspection sheet can assist to record the information of surge arresters in service, as well as identify and monitor degraded arresters in-service.

This helps the organisation to remove faulty arresters in the system before it fails. By following this process, unnecessary outages can also be limited. The sheet should also include dates of inspections, and all details of person assigned to do work on the arrester.

4.10 Failure Analysis of Polymer Housed Surge Arrester

Since the outcomes of this study are dependent upon the standards used to assess satisfactory surge arrester behaviour, the surge arresters were considered "failed" if their measured behaviour did not match the following standards:

- Satisfying the performance levels guaranteed in manufacturers' data.
- Meet the required performance measures outlined in the pertinent industry standards (see Figure 4.20).

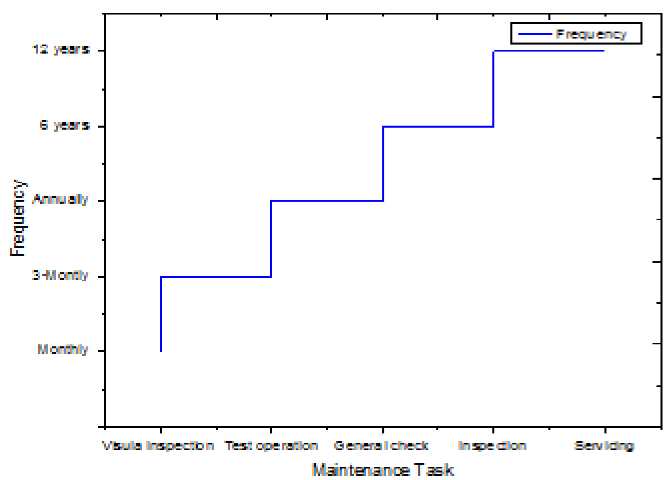


Figure 4.20: Example of time-based maintenance of electrical equipment [37].

4.11 Summary

The purpose of this chapter was to describe the research methodology of this study, describe the procedure used in designing the test instruments for data requisition, and provide a full explanation of diagnostic measurement selected for this research. Conducting the PD, IR and LC measurement, in conjunction with visual inspection of the internal parts of the surge arrester, was helpful in this study as important results were attained.

CHAPTER 5: RESULTS AND ANALYSIS

5.1 Introduction

Currently eThekwini Electricity uses different brands of surge arresters in substations for protection purpose on their system. The names of the companies have been omitted to maintain confidentiality and instead they have been labelled as follows:

- Surge arresters of manufacturer A
- Surge arresters of manufacturer B
- Surge arresters of manufacturer C

Therefore, the data acquisition process will focus on the above mentioned brands.

5.1.1 INFRARED THERMOGRAPY RESULTS

The infrared scanning test was implemented on the surge arresters on-site to check the accumulation of heat due to internal moisture or block failure. This procedure also assisted in recognizing hot spots inside the surge arrester. Through this investigation, eThekwini Electricity has discovered that the polymer housed surge arresters show abnormal heating patterns inside the metal oxide varistors during service conditions.

During field analysis, results indicating failing arresters on the system were obtained. Infrared images of surge arresters indicated significant heating within the devices. Results showing the thermal image and temperature profile of surge arresters are shown in Figures 6.1 (a) -(c). Note that the yellow in the centre of the image is a hot spot. This indicates that instant de-energization and replacement must be undertaken before their failure.

5.1.1.1 Inspection in Substation A

Figures 6.1 to 6.3 show the Thermo-grams for substation A. Two arresters showed a high temperature. These are polymer encapsulated, installed at major substation A. This brand of surge arresters has affected the reliability of the eThekwini transmission system.

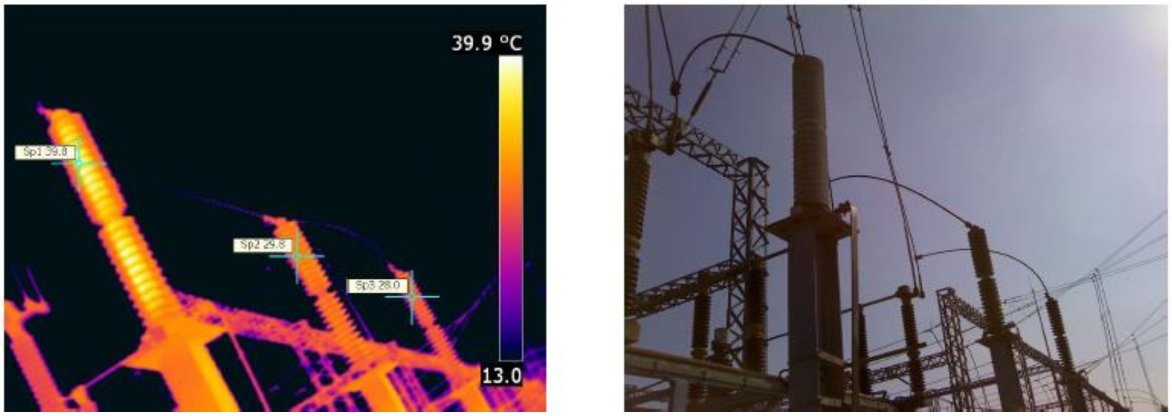


Figure 6.1: Thermo-grams for substation A; 2 arresters were showing a high amount of heat.

All the arresters of manufacturer A on Figure 6.1 were to be replaced because, these surge arrester were showing a high temperature inside the varistor.

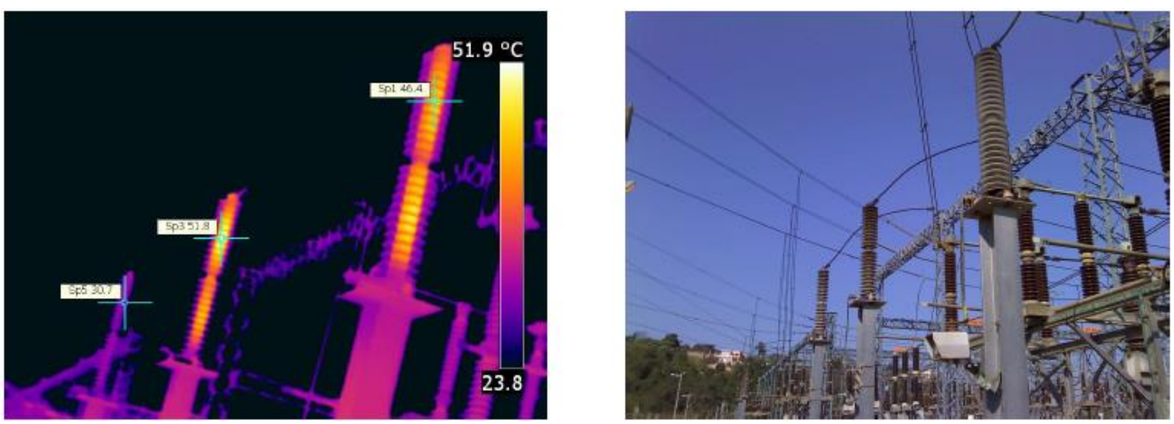


Figure 6.2: Thermo-grams for substation A indicated the high amount of temperature inside the arrester.

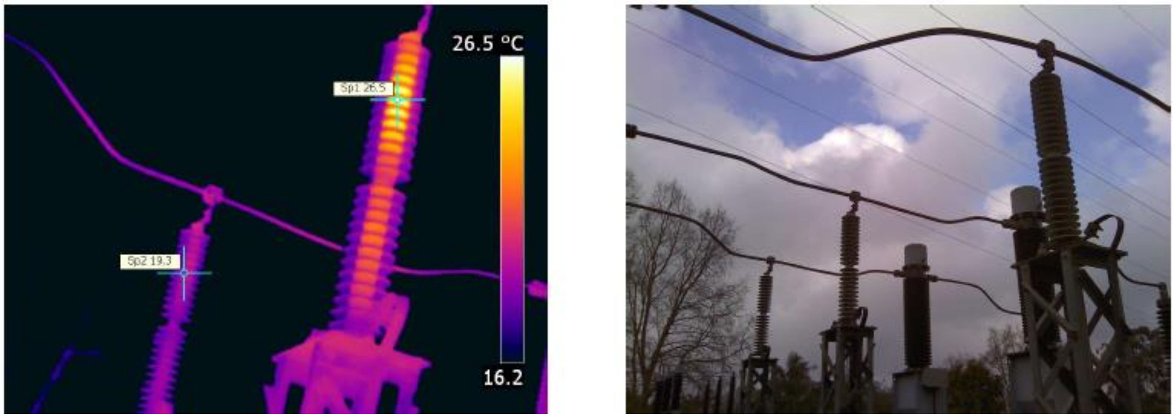


Figure 6.3: Thermo-grams for substation A indicated the amount of heat inside the arrester.

Table: 6.1. ΔT (°C) for surge arrester at substations A, for phase R, W and B

ΔT(°C)			
Surge Arrester Phase (R,W,B)			
	R	W	B
Sample 1	48.5	35.8	44.2
Sample 2	45.5	43.6	52.2
Sample 3	30.3	41.2	40.7
Sample 4	29.9	22.1	27.1

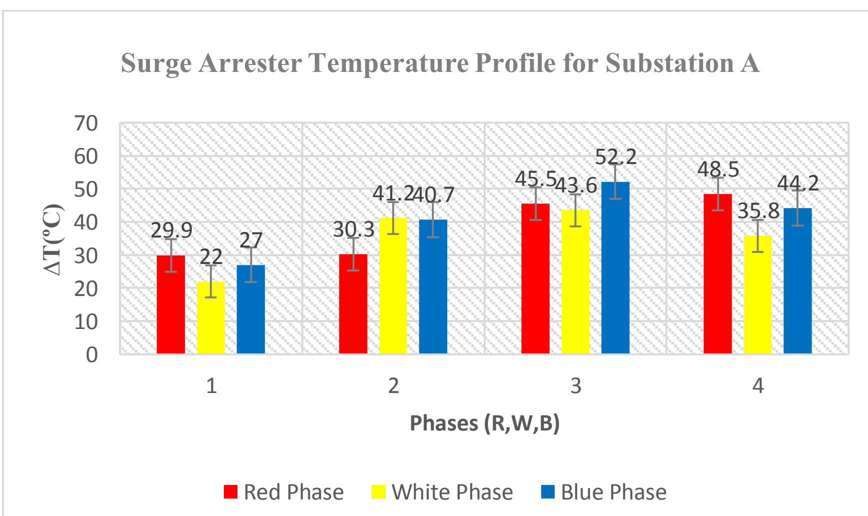


Figure 6.4: Temperature profile along the arrester of substation A.

5.1.1.2 Inspection in Substation B

The following results were collected from ZnO surge arresters, polymer encapsulated, installed at major substation B, located on line 1. The inspections were undertaken on the 132 kV systems.

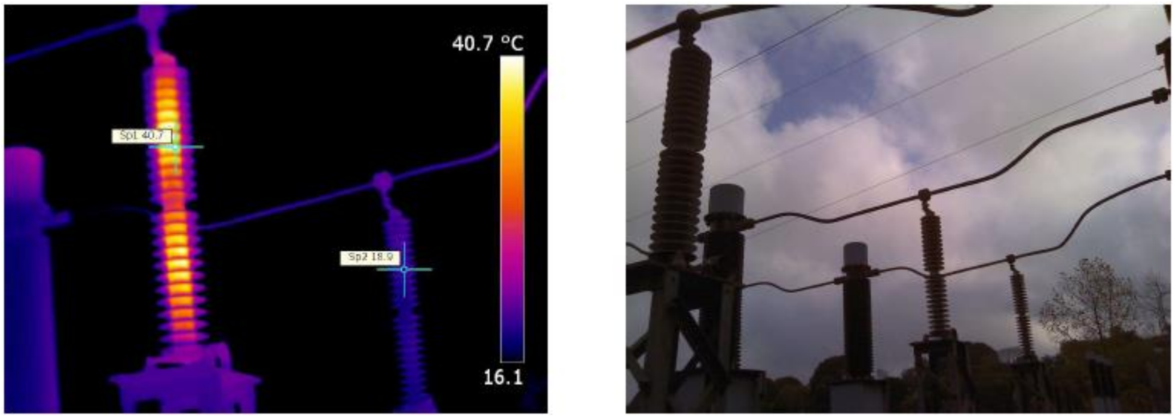


Figure 4.5: The thermal heating problem with these arresters could have affected the reliability of the substation B line 2.

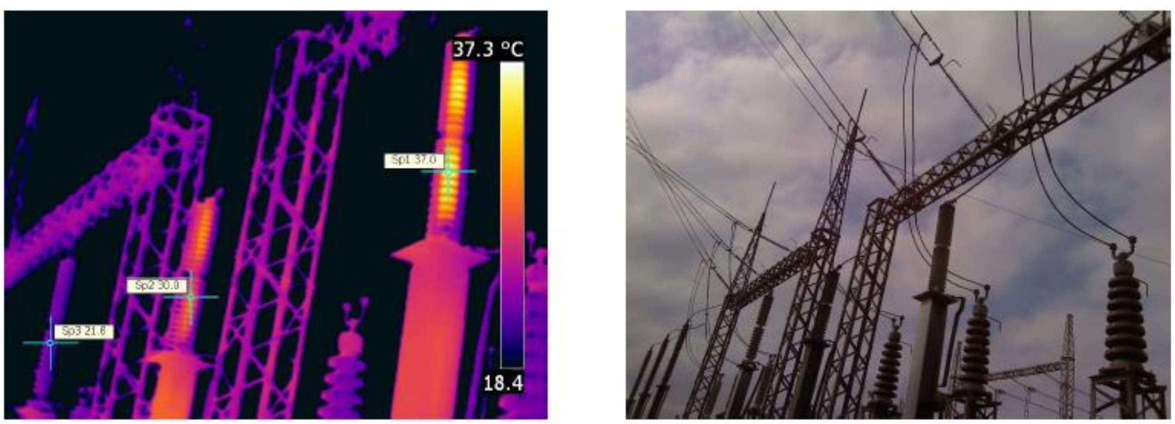


Figure 6.6: Thermo-grams for substation B showing the amount of heating inside arrester (132 kV surge arresters blue phase).

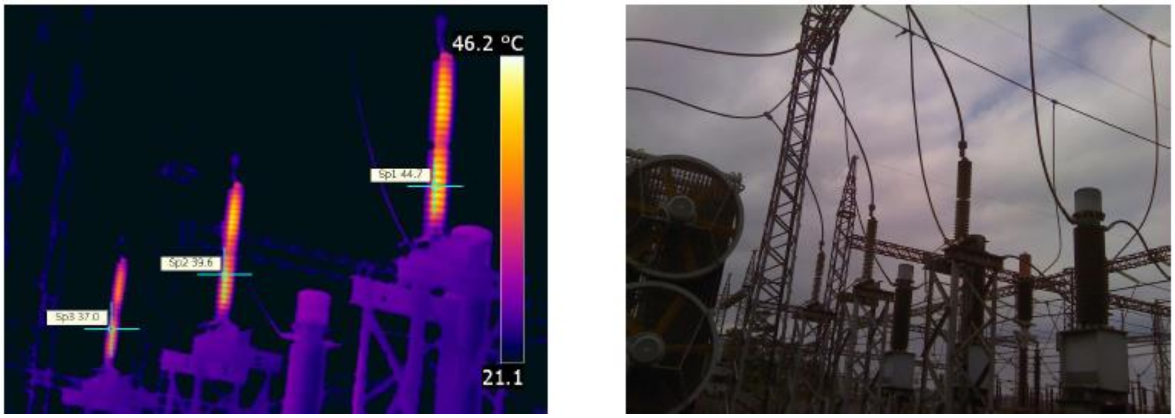


Figure 6.7: Thermo-grams for substation B showing the amount of heat inside arrester.

All the arresters in Figure 6.7 gave a high temperature profile inside the arrester. Because of this they were scheduled for replacement within five days to prevent failure.

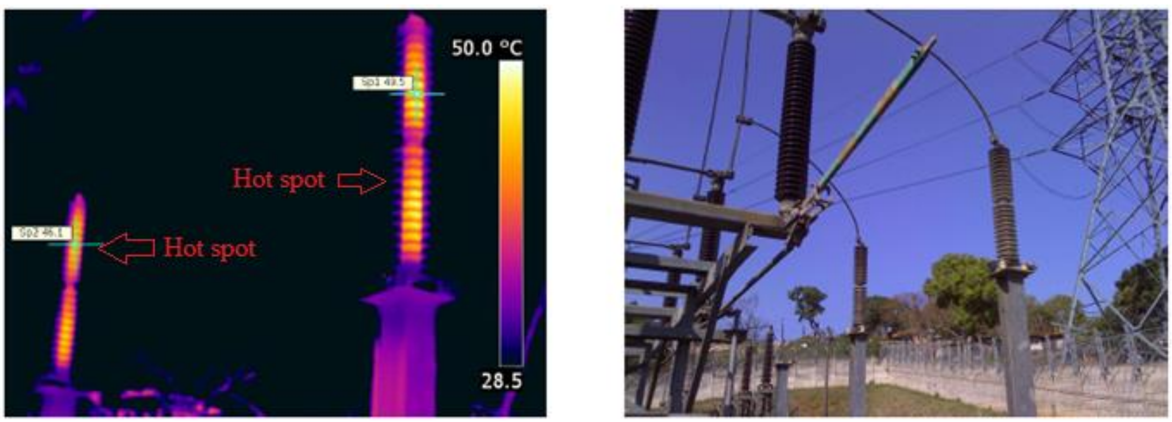


Figure 6.8: Thermo-grams for substation B showing the amount of heating inside arrester.

All the arresters on Figure 6.8 were to be replaced on the substation because they were showing hot spots. The temperature was 45º C on both of them. The problem with these arresters could have affected the reliability of the substation B line 2.

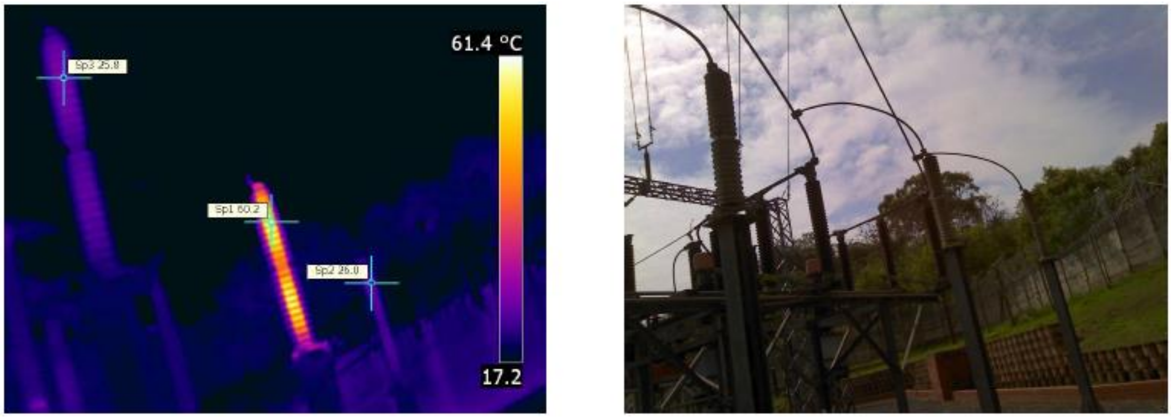


Figure 6.9: Thermo-grams for substation B showing the amount of heating inside arrester.

In Figure 6.9, the surge arrester in the white phase was showing a higher temperature than the ones on the red and blue phases. It was recommended for replacement before failure.

Table: 6.2. ΔT (°C) for surge arrester at substations B, for phase R, W and B

	ΔT(°C)		
	Surge Arrester Phase (R,W,B)		
	R	W	B
Sample 1	40.7	18.9	
Sample 2	37.0	39.6	44.6
Sample 3	46.1	40.5	
Sample 4	25.8	60.2	26.0

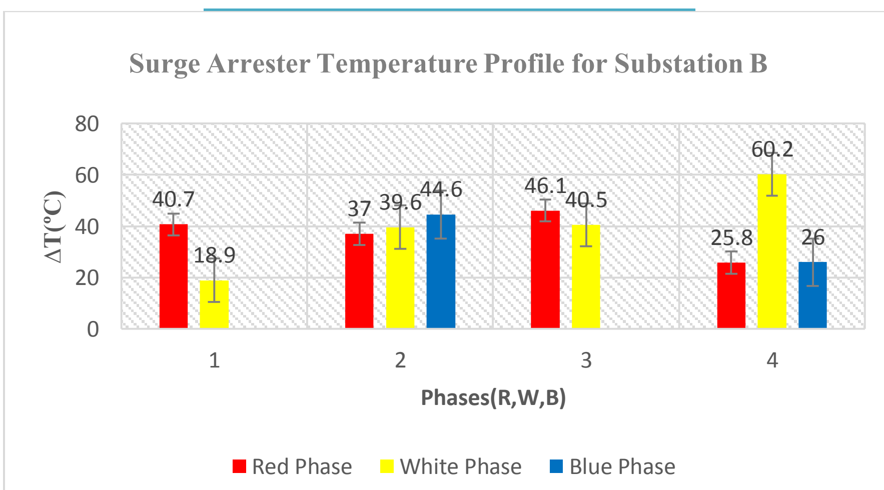


Figure 6.10: Temperature profile along the arrester of substation B.

During infrared inspection six surge arresters of manufacturer A in substation B were hot. The conditions of these arresters were bad and replacement was recommended.

5.1.1.3 Inspection in Substation C

The following results were collected from ZnO surge arresters, polymer encapsulated, installed at major substation C.

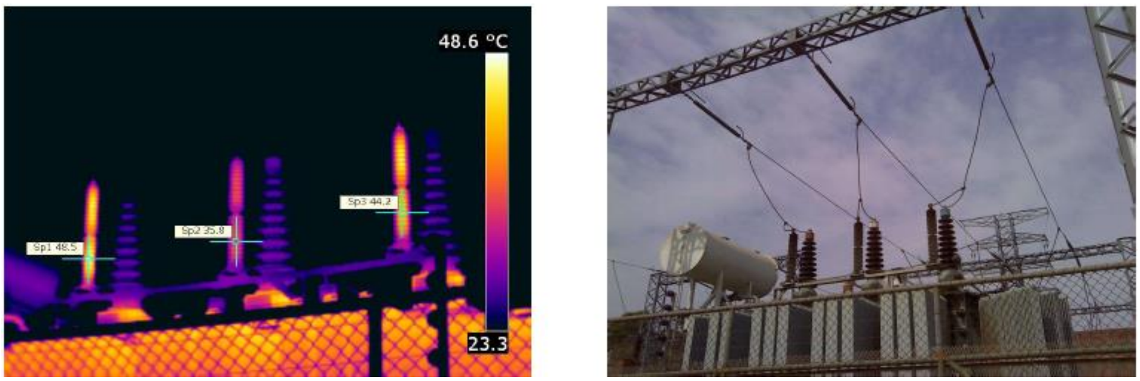


Figure 6.11: Thermo-grams for substation C showing the amount of heat inside arrester.

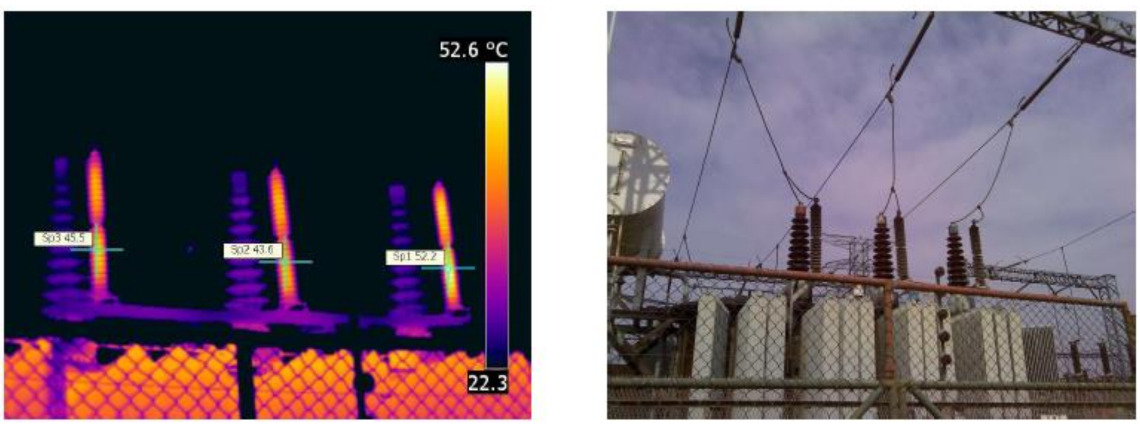


Figure 6.12: Thermo-grams for substation C showing the amount of heat inside arrester (transformer 1-132 kV Surge Arresters).

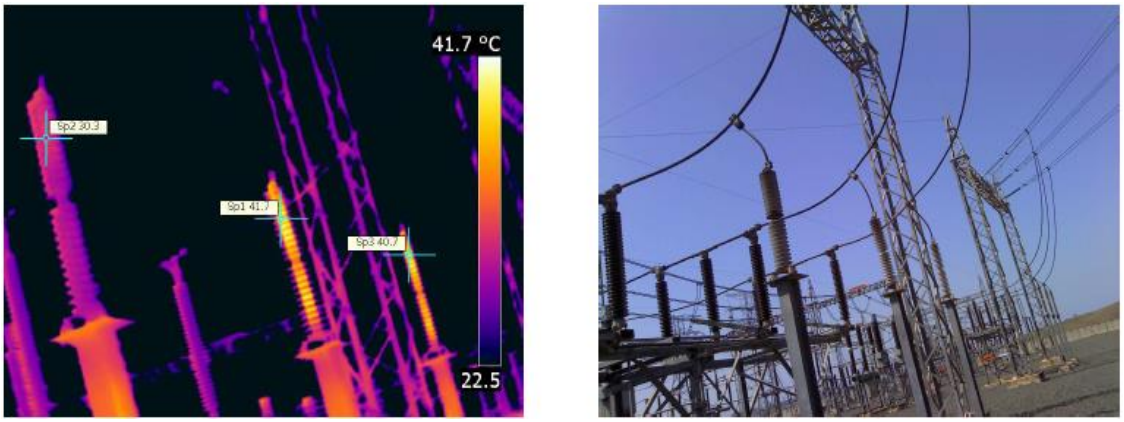


Figure 6.13: Thermo-grams for substation C showing the amount of heat inside arrester.

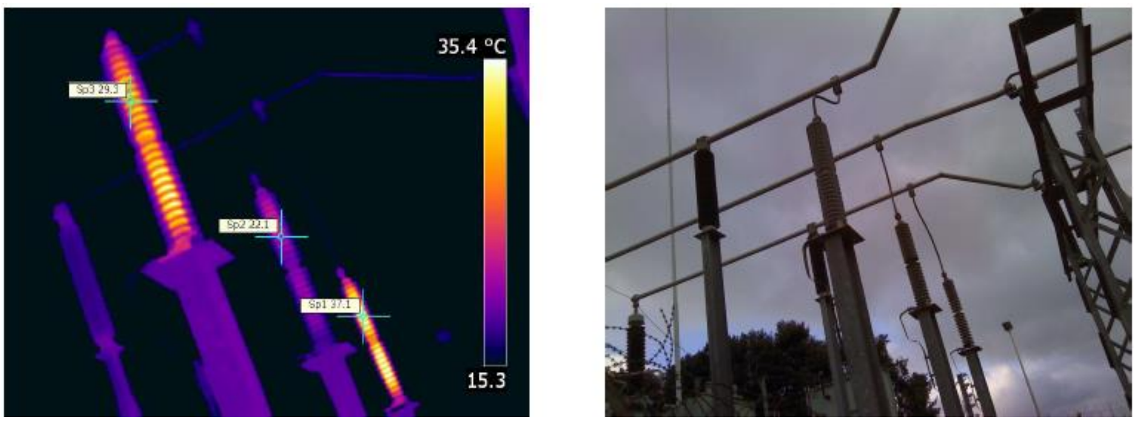


Figure 6.14: Thermo-grams for substation C showing the amount of heating inside arrester.

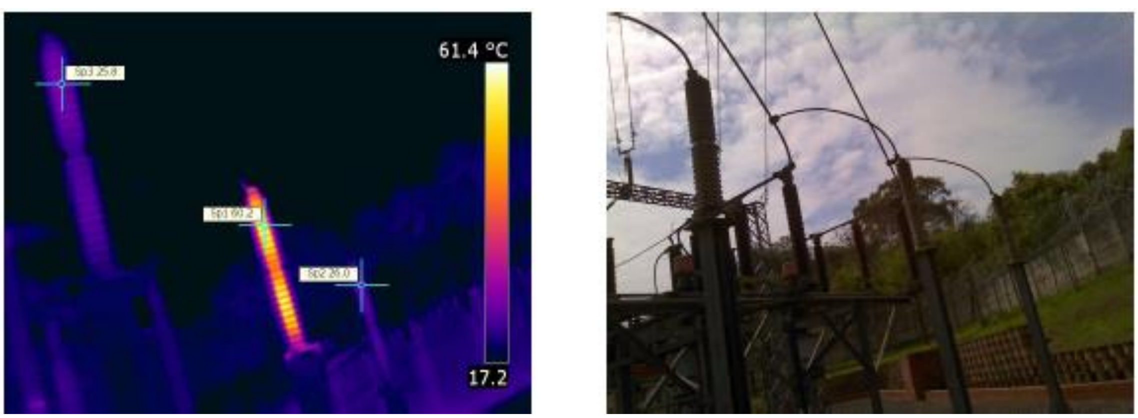


Figure 6.15: Thermo-grams for substation C showing the amount of heating inside arrester.

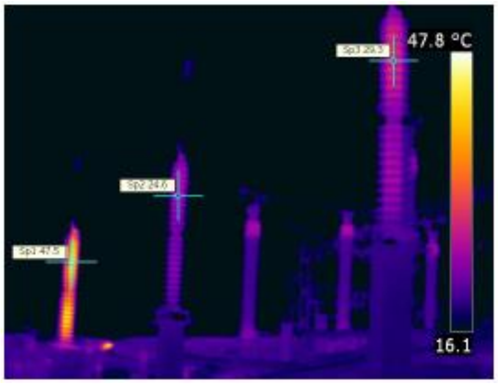


Figure 6.16: Thermo-grams for substation C showing the amount of heating inside arrester.

The arrester indicated in Figure 6.16 on red phase had a light spot when it was compared to blue and white phases. These arresters were to be replaced before failure.

Table: 6.3. ΔT (°C) for surge arrester at substations C, for phase (R, W and B).

ΔT(°C)			
Surge Arrester Phase (R,W,B)			
	R	W	B
Sample 1	23.8	29.6	28.0
Sample 2	30.7	51.8	46.4
Sample 3	19.3	26.5	
Sample 4	47.5	24.6	23.5

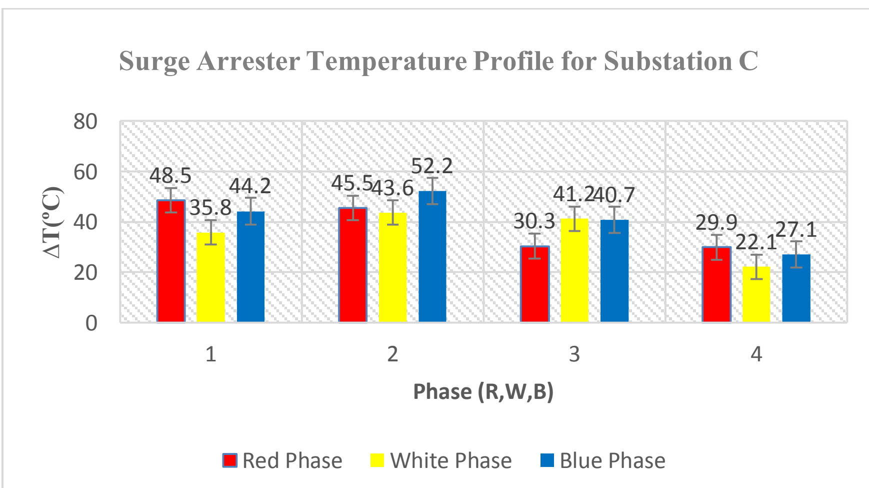


Figure 6.17: Temperature profile along the arrester of substation C.

On substation C, eight surge arresters showed high temperature inside the ZnO varistor blocks.

5.1.1.4 Summary of IR scanning results

It is recommended that faulty surge arresters be replaced before catastrophic failure. Mostly, the measurable increase in the varistor temperature is caused by uneven surface distribution created by the wet pollution layer and moisture ingress. During site inspection evidence of dust pollution was noted on the surface of arresters. The increase in the varistor temperature causes the degradation or failure of the arrester.

Miller et al reported that early MOSA's exhibited increasing power loss under normal system conditions owing to penetration of moisture into the metal oxide blocks, thereby promoting oxidation [9]. It was noted that after the infrared inspection had been carried out at the substations, the suspect surge arresters began failing within a month.

5.2 LEAKAGE CURRENT TEST RESULTS

The following results, illustrated in the figure below, represent the offline leakage currents and power loss that was measured on-site. The information includes the location (Red, White and Blue phases). Rated voltage of arrester is 98 kV; the measurement value of leakage currents is indicated in milliamperes. The results obtained on site are presented below (see Figure 7.1-7.4)

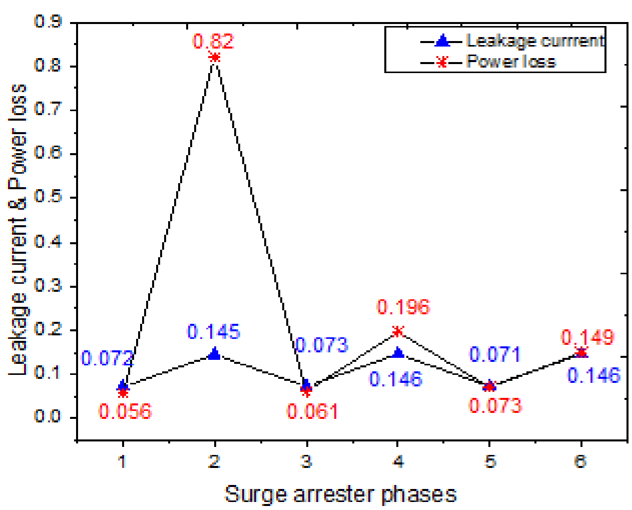


Figure 7.1: Graph showing power loss and leakage current on surge arrester phases on (Substation A).

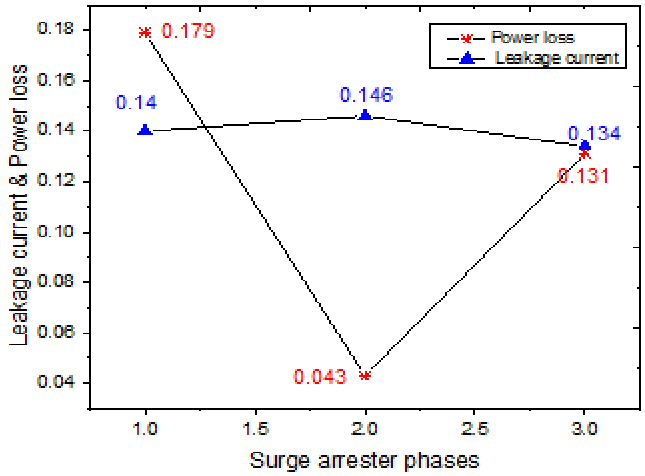


Figure 7.2: Graph showing power loss and leakage current on surge arrester phases (Substation B).

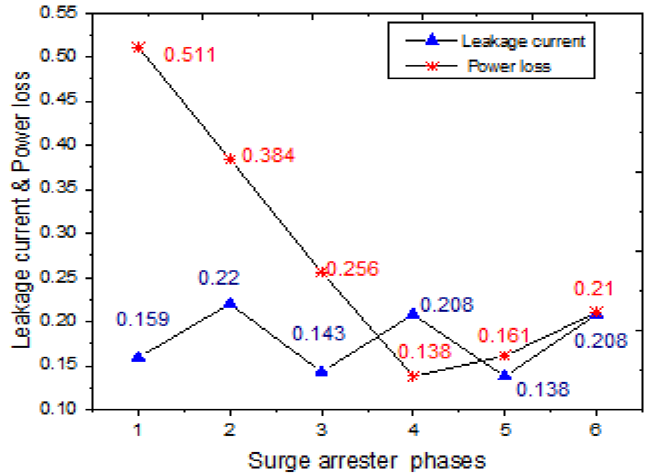


Figure 7.3: Graph showing power loss and leakage current on surge arrester phases (Substation C).

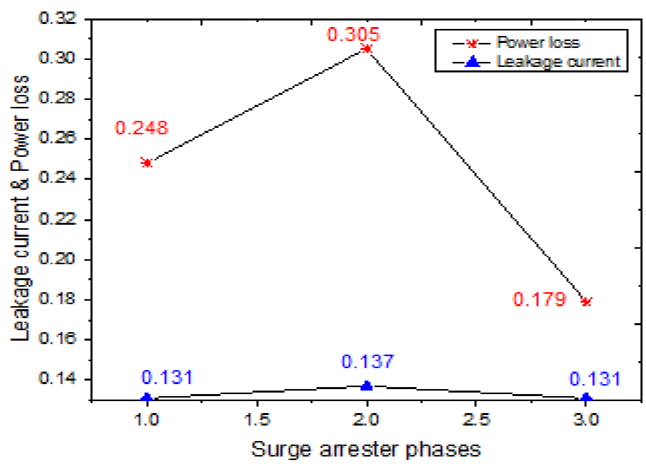


Figure 7.4: Graph showing power loss and leakage current on surge arrester phases (Substation C).

Figure 7.1 to 7.4 illustrate the measurement of leakage current and power loss in surge arresters. During measurement, we found that the leakage current is directly proportional to the power loss.

5.2.1 Summary of leakage current results

According to IEC, the resistive leakage current of the arrester should not exceed 700µA [23]. According to the results attained, we can conclude by saying that the conditions of these surge arresters were good. It is recommended that if the insulated base and insulation of the arrester earth wire are checked and found satisfactory and there is no indication of heat due to transients, then the arrester should be replaced as soon as possible [23].

5.3 PARTIAL DISCHARGE DIAGNOSIS

To verify results achieved during measurement, the surface of the varistor was polished before initiating measurements, and several breakdowns (overvoltages) initiated to remove any dust particles. The voltage applied to the varistor block for partial discharge measurements was calculated by counting number of blocks in the arrester and dividing by it rated voltage (see Figure 8.1).

Figure 8.1: Varistor blocks that were tested.

The voltage applied during the partial discharge measurement was calculated as shown below on equation (4.1).

$$Vap = \frac{Vr}{Vp} \qquad \ldots.(4.1)$$

V_{ap} applied voltage to varistor

V_r rated voltage of the surge arrester (kV)

N_v number of varistors element inside the arrester

$$Vap = \frac{Vr}{Vp} = \frac{120}{37} = 3.25\ kV$$

Throughout PD measurement when the voltage of 3.25 kV was applied to the varistors, unsatisfactory results were obtained (as presented on Figure 8.2.) because the varistors were conducting. Due to this the voltage was adjusted to 2.5 kV. By utilising the PD technique, the varistor elements tested were suspected of PD activity according to the attained waveforms.

5.3.1 Partial Discharge Test Results in the Laboratory

Figures 8.2(a)-(o) show the comparison of PD results of different varistor elements of arrester from top to bottom. The test results were taken at UKZN high voltage laboratory. The tested varistor elements have a diameter of 6 cm and height of 2.5 cm.

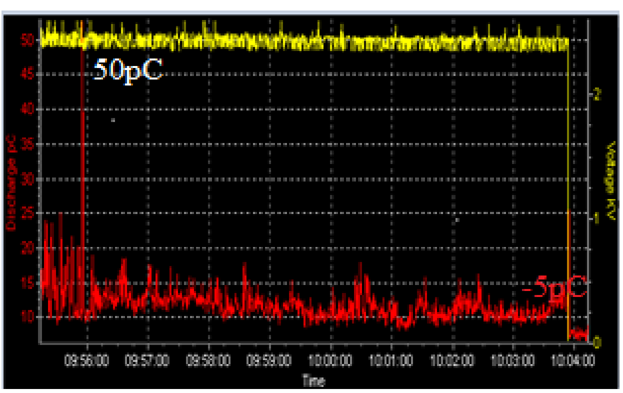


Figure 8.2(a): PD measurements (time versus apparent charge).

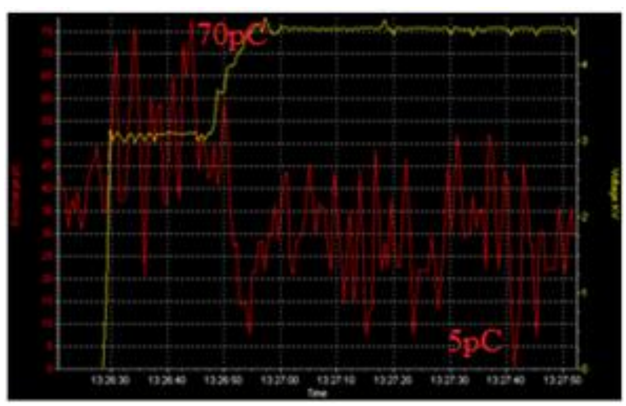


Figure 8.2 (c): PD measurements (time versus apparent charge).

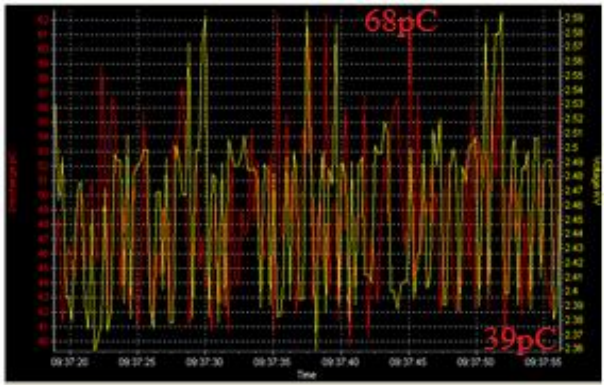


Figure 8.2(d): PD measurements (time versus apparent charge). Wrong place!

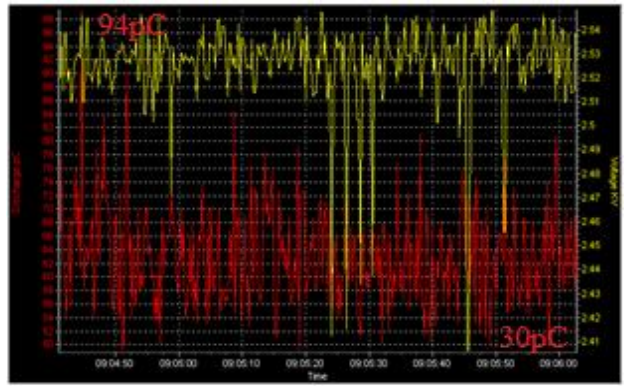


Figure 8.2 (e): PD measurements (time versus apparent charge).

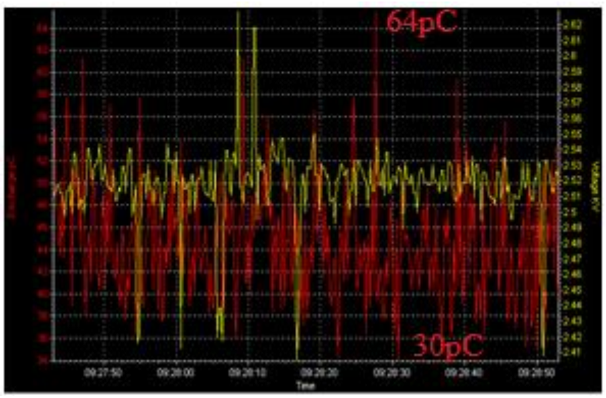


Figure 8.2 (f): PD measurements (time versus apparent charge).

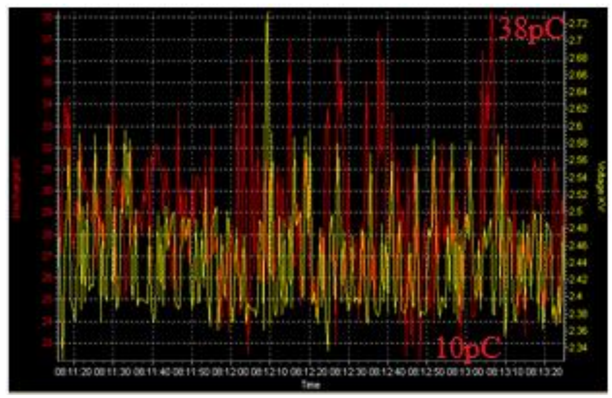


Figure 8.2 (g): PD measurements (time versus apparent charge).

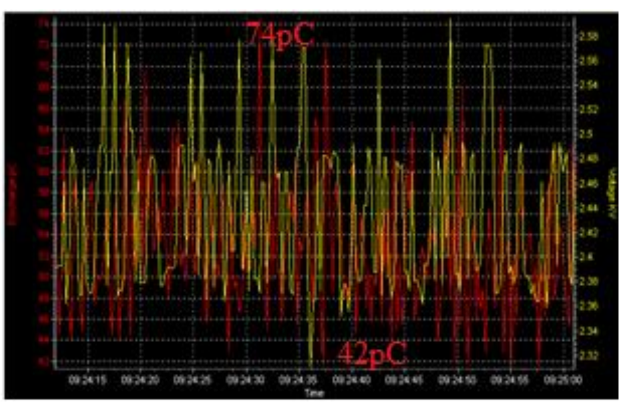


Figure 8.2 (h): PD measurements (time versus apparent charge).

Figure 8.2 (i): PD measurements (time versus apparent charge).

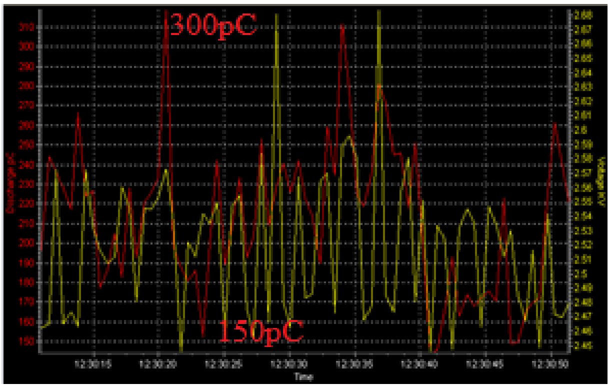


Figure 8.2 (j): PD measurements (time versus apparent charge).

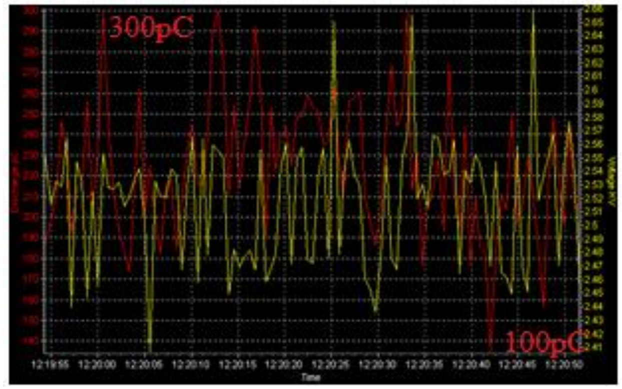


Figure 8.2 (k): PD measurements (time versus apparent charge).

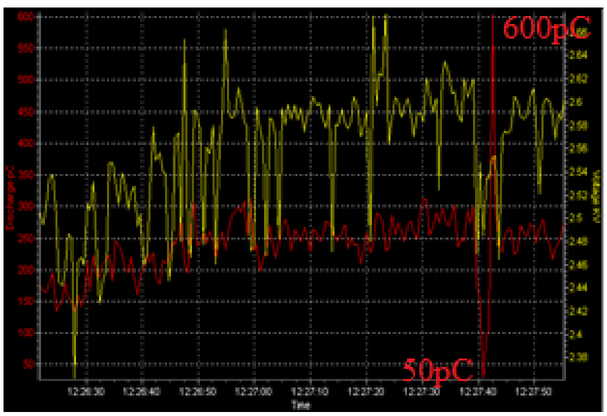


Figure 8.2 (l): PD measurements (time versus apparent charge).

Figure 8.2 (m): PD measurements (time versus apparent charge).

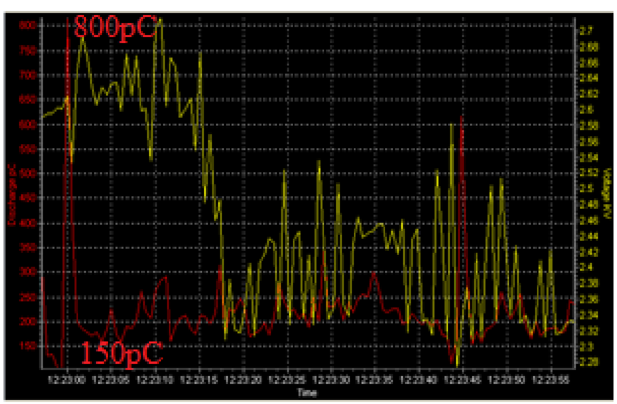


Figure 8.2 (n): PD measurements (time versus apparent charge).

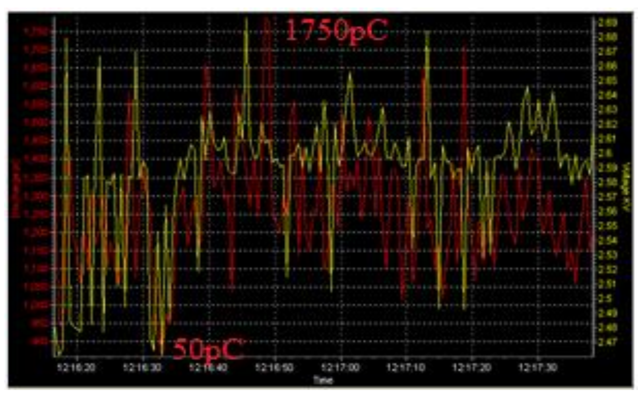


Figure 8.2 (o): PD measurements (time versus apparent charge).

When an impulses voltage of 2.5 kV was applied to the ZnO varistor blocks, the discharge voltage and partial discharge were measured with respect to time. The fundamental behaviour of ZnO varistors were expressed by the voltage, time and partial discharge.

Using this technique good results were attained. Thirty two varistor blocks each containing sixteen elements where tested, and sixteen were considered suspect of partial discharge activity considering the obtained output waveforms. The varistor closest to the sealing collar in the arrester showed the highest value of PD (see Table 8.1).

Throughout analysis on the PD waveform pulse results, it was noted that the applied operating voltage greatly affected PD pulses; the voltage decreasing as the discharge increased. The Table 4.4 compares the results of PD apparent measurement at laboratory.

Table: 8.1. Comparison of partial discharge results at laboratory.

Sample	Maximum value of apparent charge (pC) obtained at Lab	Maximum value of apparent charge (pC) obtained at Lab
1	**50**	**-5**
2	**68**	**39**
3	**70**	**5**
4	**64**	**30**
5	**74**	**-42**
6	**90**	**53**
7	**94**	**30**
8	**300**	**150**
9	**38**	**10**
10	**600**	**50**
11	**800**	**150**
12	**2300**	**50**
13	**300**	**100**
14	**1750**	**50**

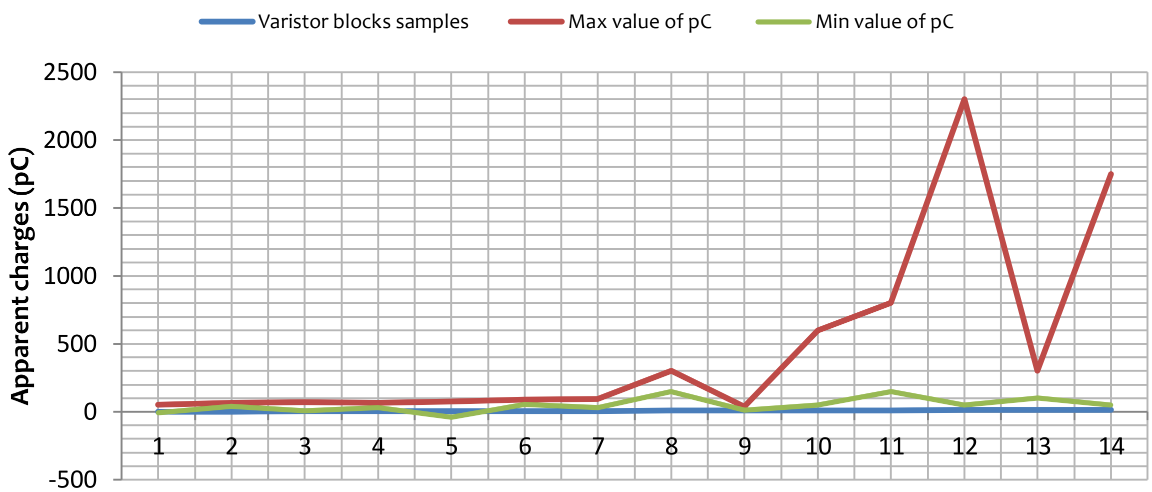


Figure 8.3: Comparison of partial discharge samples experimental results at laboratory.

Graph on Figure 8.3 above present the comparison of partial discharge samples experimental results that were performed in the laboratory, the result obtained indicated a high amount of apparent charge especially from samples ten to fourteen. We can conclude that partial discharge is the source of degradation in this family of ZnO arrester.

5.4 SURGE ARRESTER VISUAL ANALYSIS RESULTS

The results obtained during the visual inspection of the surge arresters of manufacturer A, (see Figure 9.1 show the samples that were taken during analysis). The moisture ingress through the sealing collar causes serious problems such as surface discharges.

These factors can eventually end with a full breakdown over the insulation system. Water treeing inside the sealing collar was noted as were cracks on the ZnO blocks closest to the sealing, punctures on the ZnO varistor elements and cracks, this indicates that that the failing started here.

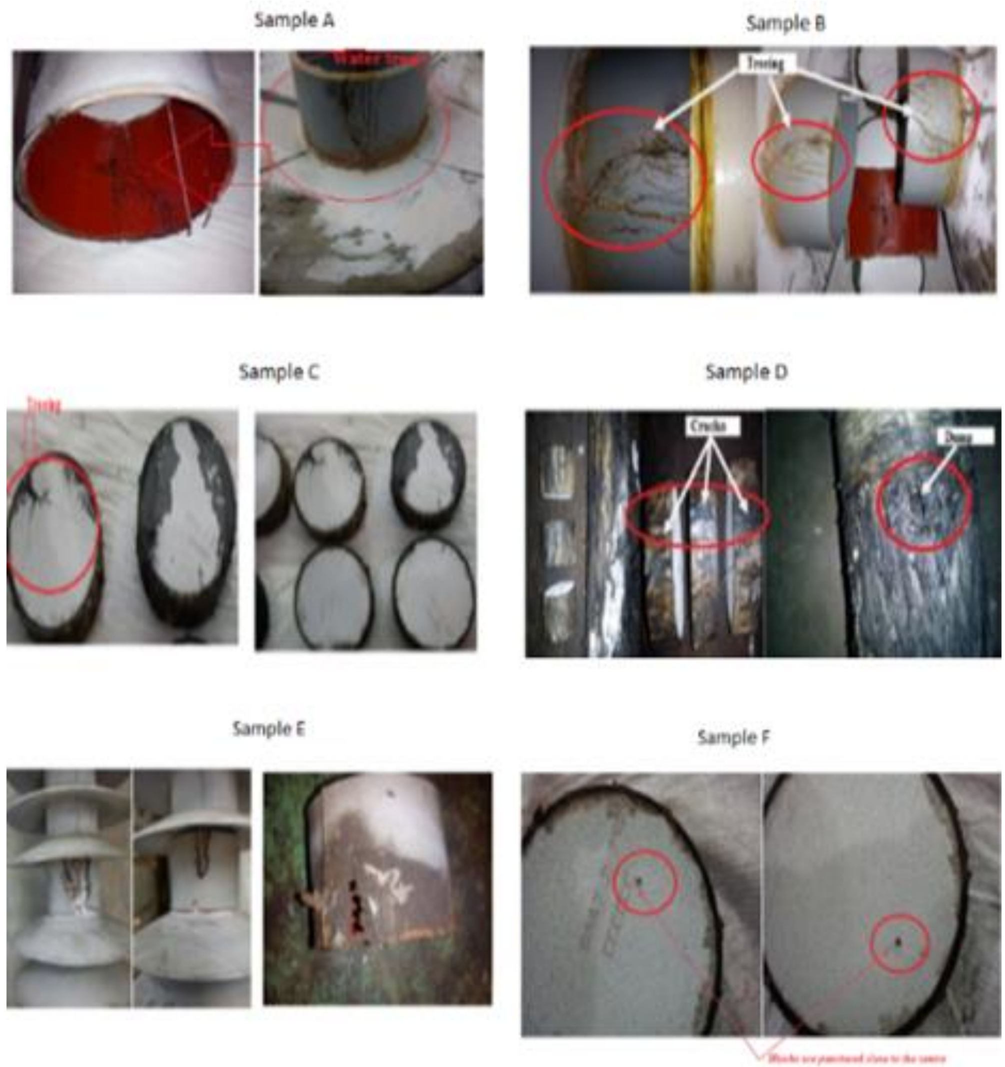


Figure 9.1: Surge arrester samples results that were taken during visual analysis.

The graph below on Figure 9.2 indicates the samples taken from the failed surge arresters of manufacturer "A" during visual inspection. After opening the arresters, when the samples were analysed, it was observed that most arresters were degrading in the middle ZnO varistor blocks and their sealing collar was damaged, this was allowing the moisture to enter the arrester.

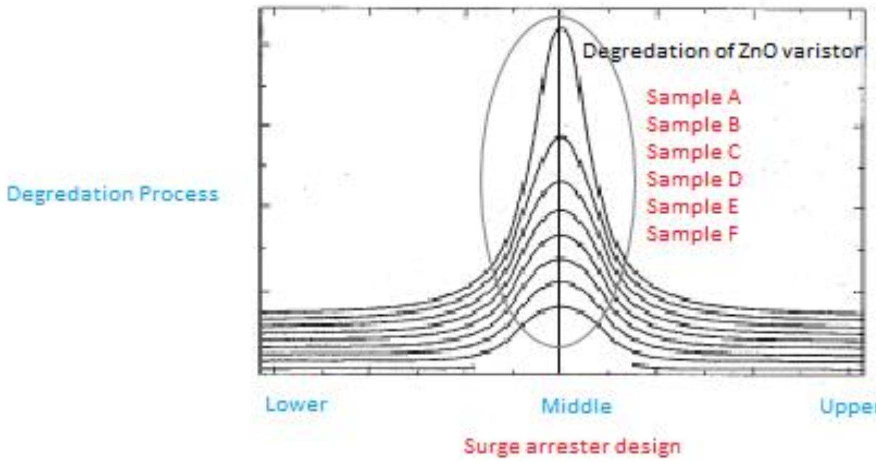


Figure 9.2: Graph present result taken during visual inspection.

5.4.1 Summary of PD results

It was concluded the arrester failure was caused by moisture ingress in the arrester. Moisture was the main root cause of failing of polymer housed surge arresters. This kind of problem has been reported before by many researchers on gapped arrester (silicon carbide) [1]. With a view to preventing such failures, surge arresters used on the network should not have a sealing collar; but should have continuous insulation from top to bottom.

CHAPTER 6: CONCLUSION AND RECOMMENDATION

6.1 Conclusion

This research focused on investigating the family of surge arresters that are failing on the 132 kV and 275 kV systems of eThekwini Electricity. The tests were conducted on faulted arresters and compared with arresters still in service.

During the field trial evaluation in eThekwini Electricity substations, different tests were undertaken both in the field and in the workshop and lab and pertinent results have been achieved. The following tests were performed. The offline leakage current test was performed in arresters in accordance with recommendations from IEC standards; the aim was to check the insulation integrity of arresters. Infrared scanning was utilised to detect the hot spot inside the arresters under in-service condition. To attain additional information concerning the status of the surge arresters, PD experimental test was performed.

Surge arresters that were measured, were generally found to be in an unsatisfactory state compared to the healthy surge arresters. They indicated high temperature inside the ZnO varistor elements. The following conclusions were drawn for this dissertation during the above mentioned tests:

During infrared analysis the arresters that were measured were abnormally hot inside the ZnO varistor when compared to healthy ones. Photos that were taken during arrester analysis were clear indicators of defective surge arresters. Moreover, surge arrester “A” had a light spot in the midpoint of insulation, demonstrating the point of origin of heat, indicating that the sealing collar between the last upper shed and first of lower shed (middle) was defective (Figure 2.26(a)) and (b)). It was suspected that defects in the sealing collar permits moisture ingress in the arrester, causing the heat inside varistor blocks to increase.

Good results were obtained during leakage current measurements. The leakage current was directly proportional to the power loss. The increase in the resistive leakage current along the surface insulation has an effect in failure of arresters. The results obtained demonstrate clearly that the leakage current is directly proportional to the power loss.

PD measurement: Use of these tests was valuable in obtaining sufficient information for failure of surge arresters. The situation was observed that PD action is an indication of degradation in MOSA supported by the results that were obtained during experiment at the laboratory. Electrical treeing is a significant degradation mechanism in polymers that can lead to premature failure of high voltage equipment.

During the visual inspection in the electrical workshop, it was noted that with some of the arresters of manufacture 'A', sealing was defective. This allowed the moisture to enter the zinc oxide varistor (ZnO). Evidence of treeing, punctures, cracks and moisture masks (Figure 9.1) were noted on the varistor elements. To address this issue, the design 'A' must should improve the joint sealing integrity through construction with a continuous rubber from top to bottom, so as to increase the lifespan of the arrester.

It was concluded that moisture ingress can cause serious problem on surge arresters in service. Moisture ingress appears to be the main cause of surge arrester failure within the system. This has been found during tests mentioned above. Surge arresters with sealing collar they allows the moisture ingress through the seal when aging takes place. During visual inspection evidence of gel leaks and puncturing were obtained.

Failure of the surge arrester in service causes unnecessary outages on the network.

The evidence acquired in this research will assist to improve the surge arrester specification so as to avoid failure in the future and will also benefit with replacing them before they fail on the system.

6.2 Recommendations

As a consequence of the result statements above, recommendations for the eThekwini electricity are that they should change their supplier and tender specifications should be upgraded, surge arresters to be used on the network must not have a sealing collar; but must be continuously insulated from top to bottom.

To prevent failure on the network the infrared analyses is recommended. The results obtained during field inspection should be compared for surge arresters of the same model and brand for all phases in the electrical network. When performing an arrester inspection the inspector needs to identify whether the surge arrester status is normal or abnormal. It is recommended that the inspector required writes a technical report for diagnosis.

Due to the results obtained during infrared inspection, it is recommended that the infrared inspection be performed monthly. If the temperature of the arrester is above 45°C when compared to other arresters, it is recommended that those be removed before they fail and bring down the system.

With a view to preventing such failures, proper inspection and maintenance policies must be issued, (the visual checks on site must be done). Developing an inspection sheet (Appendix C) can assist to record the information of surge arrester in service. This will help the electricity organization to remove thermal abnormal arresters before they fail. The proposed inspection sheet can help to record the information of arresters while in-service and this could help the inspector to compare the bad arresters with the good arresters. The sheet should comprise the date of inspection, all details of person assign to a job.

The information and results presented on this dissertation are recommended for utilization by power companies to for the monitoring of their surge arresters on the electrical networks. Leakage current, Infrared scanning and in additionally partial discharge test are the good recommended tools to be used for the in-service monitoring of arresters. Using the described tests could help power companies to avoid the unnecessary outages on the system.

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Appendix - A

Specification of partial discharge tool

PD Measurement System

PD measurement range	0-99999pC in standard notation, higher readings in scientific notation
PD measurement resolution	9 bits plus sign
PD phase resolution	0.35 degrees

Partial Discharge Site Locator (Optional)

Time resolution	12.5ns (80mHz sampling rate)
Capture memory depth	256 cycles, 256+ samples
Amplitude capture accuracy	Better than 1%
Amplifier ranges	12 switched 5dB ranges
Amplifier frequency range	100kHz to 5MHz

Voltage Measurement System

Voltage measurement range	0-99999KV. Peak Scaled RMS and True RMS measurement modes
Voltage measurement resolution	11 bits plus sign
Voltage measurement accuracy	better than 0.5% at I/P socket
Voltage frequency sync range	5Hz to 500Hz
Voltage measurement input	10VPk input, transient protected, high impedance. Can be used with capacitive divider, resistive divider or voltmeter resistor. The system can support up to 16 different voltage sensor calibrations to allow it to be moved around to different test installations.

Internal Calibrator System

Calibrator Output	set directly in pC; output displays in PC
Calibrator maximum output	10V step (1000pC into 100pF)
Calibrator output range	1mV to 10V in 13 ranges (0.1pC to 1000pC into 100pF)
Calibrator fine adjustment	0 to range voltage in 256 steps
Calibrator output rise time	less than 25nS into 100pF; slower into higher cap.
Calibrator operating modes	direct and indirect (transfer) modes supported

Amplifier Systems

PD amplifier ranges	6 switched 20dB ranges	
PD amplifier fine adjustment	10:1 in 200 steps	
PD amplifier gain linearity	<1% over whole range	
PD amplifier frequency range	20khz to 500KHz	
PD amplifier filter settings	Low Pass:	20kHz, 30kHz, 50kHz, 60kHz, 80kHz
	High Pass:	100kHz, 200kHz, 300kHz, 400kHz, 500KHz

Data Processing System

Windows 98 SE™ - based operating system, with Hipotronics DDX-7000 Program
Intel Pentium III™ (or equivalent) Processor, 1.1GHz (or faster)
16MB of RAM
1.44MB floppy disk drive; 30GB (or larger) hard disk drive; 52x CD/RW drive
SVGA (800 x 600) active matrix thin film LCD monitor
USB keyboard and mouse
Parallel printer port; one uncommitted serial port (COM2); 10/100 BASE–T LAN; USB2.0

Physical Characteristics

Power Supply	115V or 230V AC, ± 10%, 50Hz or 60Hz, <250VA
Operating temperature range	10°C to 35°C
Operating humidity range	35% to 80% non-condensing
System approvals	CE mark
DDX Detector-7000 Size	17.5"W x 10.5"H x 18"D, 40 lbs. (445mm x 270mm x 460mm, 18 kg) 6U, 19" standard case
DDX Detector 8003 Size	17.5"W x 10.5"H x 18"D, 50 lbs. (445mm x 270mm x 460mm, 23 kg) 6U, 19" standard case

Appendix-B

Infrared analysis of results

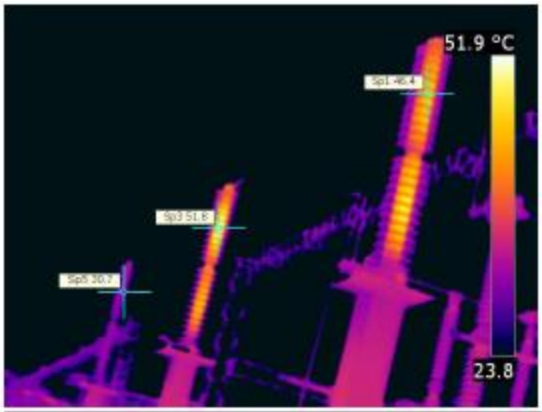

Image and Object Parameters		Text Comments	
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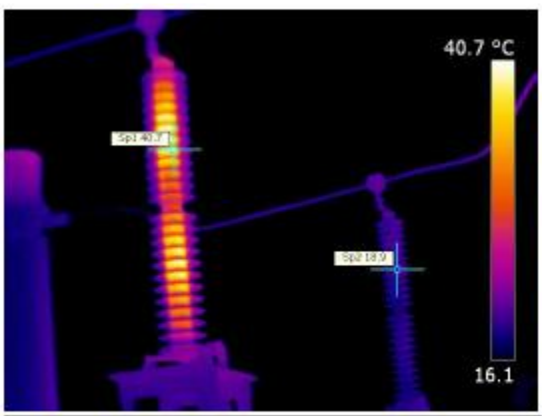

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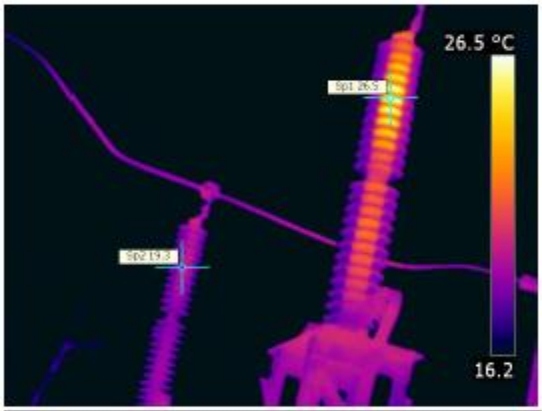

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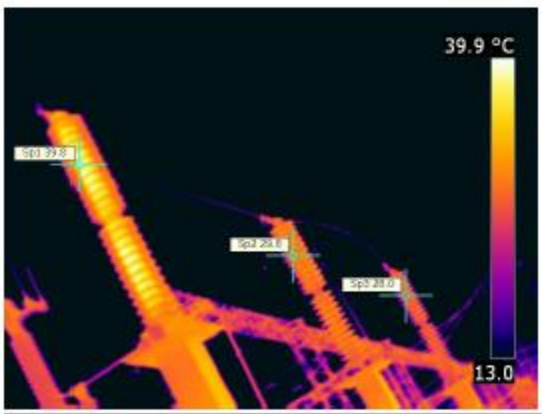

Image and Object Parameters		Text Comments	
Camera Model	FLIR T425	Priority 3: Replace all 3 within 30 days	Delta T = Sp1-Sp3 = 11.8 Degrees Celsius

Appendix-C

Inspection sheet for polymer surge arrester

POLYMER SURGE ARRESTER FIELD INSPECTION SHEET

Date: ____________________ Location:____

Manufacture: _____________ Year Manufactured:____________ Quality:__________

Arrester Identifier:_________ Phase:_________________ Surge Arrester Types:_____

Type of Surge Arrester		
Serial Number		
Number of Sheds		
Length in cm		
Insulation Types		
If create Damage		
Create Approved for Release to Site		
Various Tests Techniques of Surge Arrester		
	Good	***Bad***
Partial discharge		
Infrared Analysis		
Leakage Current		
Site Visual inspection		

*Comments if any damage is noted: ____

Inspected by: ________________________________ Signature:________________________

Appendix-D

INSERVICE CONDITION MONITORING OF SURGE ARRESTERS WITHIN ETHEKWINI ELECTRICITY

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Abstract: It is extremely important to measure the condition of the surge arresters while they are in service so that they can be removed from service before they fail.This paper presents systems for the monitoring of polymer housed surge arresters within eThekwini Electricity using various diagnostic methods. The systems measure the resistive leakage current that continuously flows through the ZnO varistor during normal service operation and temperature via infrared thermo vision for fault prediction purposes. The measurements are applied for diagnosis of 120kV/65kA surge arresters of different makes on 132kV and 275kV substations. Leakage current measurement and infrared analysis were valuable in obtaining sufficient information for failure of arresters. The thermal heat was detected inside an arrester and normal leakage current measurements. Tests were performed on surge arresters that are still in the system and test results were compared to the results from the tests performed on failed units. Results obtained from different tests, (tests mentioned above) were compared to the test results from different families or designs.

Keywords: Polymer housed surge arrester, infrared scanning, and leakage current measurements.

1. INTRODUCTION

Overvoltages in an electrical network may occur due to lightning strikes, system faults or switching operations. These overvoltages could reach dangerous amplitudes for electrical network apparatus. To protect the network equipment and to guarantee security and reliable operation, surge arresters are applied to all types of electrical transmission and substation systems.

Generally, surge arresters are constructed using nonlinear resistive elements covered by polymer insulators. Ageing of the polymer insulators is caused by environment factors such as UV, contaminations, moisture ingress and electrical stress including leakage current, local discharge and corona discharge [1]. These phenomena may eventually cause failure on surge arresters in the system. Hence, it is important to monitor the surge arrester while in service so as to increase it life span.

According to IEC standard 60071-2 surge arresters are very important devices placed within an electrical power system to ensure appropriate insulation coordination and to protect valuable equipment such as power transformers, circuit breakers etc. against lightning, transient voltage and switching surges. It has been reported that polymer housing material used for outdoor insulation is subjected to a number of degradation influences during service. These include tracking and erosion due to dry band arcing and possible material degradation from the environment such as ultraviolet rays, hydrolysis, fungi, and chemical attack by alkalis, acids and hydrocarbon liquids and vapors[2],[3],[4].

EThekwini Electricity has experienced a trend where a certain family of surge arresters fails without any anomalies on the electrical system (such as lightning strikes, switching operations or system faults). Fig .1 represents a number of surge arresters that failed on the system from year -2000 to 2004. Since this has happened in the past and continues to happen, a decision was taken to perform an investigation to identify the causes of failure and find optimal solutions.

The main intentions of this paper are to investigate the failure of surge arresters by performing various tests such as leakage current measurements (offline) and infra-red scanning (online) to identify the fault proximity; improve the surge arrester specification to avoid failure in the future and extending the life time of the polymer housing surge arrester.

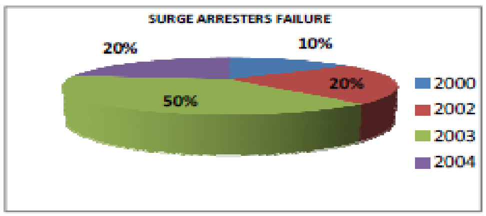

Figure 1: Surge arrester failure at eThekwini Electricity

2. BACKGROUND

The most advanced gapped silicon carbide arrester was the first really effective overvoltage protection for high voltage power networks. Gapped Silicon carbide surge arresters were developed in the 1930's to give good protection against overvoltages. These silicon carbide arresters were used on both transmission and distribution systems.

As the technology advanced rapidly, polymer housed surge arresters were introduced for the first time in the mid-1980s in MV electrical systems and proved to be a solution to the problems which could not be solved, for instance poor performance of several porcelain housed arrester designs which often suffered from sealing deficiencies, extreme sensitivity to pollution and unsatisfying overload performance [4]. Polymer housings (silicon rubber) has been the material of choice for high voltage insulation because of better behavior in polluted areas.

The silicon rubber is the only material offering hydrophobicity compared to other materials [5].The polymer housed surge arrester has several other advantages including a better short circuit capability, increased personnel safety, flexibility in erection and a less brittle nature compared to porcelain and silicon carbide surge arresters. Over seven years of experience with polymer housed surge arresters have proved that as they are less prone to moisture ingress than porcelain arresters, they therefore minimize one of the most common causes of failure of surge arresters [6].

At the end of 1980s polymer surge arresters were available up to 145kV system voltage and today polymer housed surge arresters have been accepted up to 550 kV system voltages. They appeared on the market around 1990s, being niche products at this time. The actual share of polymer housed HV arresters is now estimated to be 25% to 30% and is rising [10], [4].

3. IN-SERVICE DEGRADATION OF ZNO SURGE ARRESTERS

The electrical stresses, counting leakage current and dry-band discharges, are directly responsible for tracking and erosion. Formation of sparking discharge is closely related to the variation trends of the total leakage current and creates high temperature spots that lead to bond scissions and other chemical changes on the surface insulation [1].

The ZnO varistor degradation is used to describe the electrical condition of a varistor relative to its past or future state when under the influence of external stresses [7], [8].

The amount of degradation is a good quality indication of varistor reliability and is usually used for foreseeing the life span of ZnO varistor [8]. The process of degradation causes the gradual increase of current with time on arrester.

It has been recognized that partial discharge is a dangerous ageing process first noticed in the last century when HV technology was introduced for the generation and transmission of electrical power [9].

It must be appreciated that, besides electrical stress caused by voltage or impulse currents, the following factors can accelerate the degradation process:

• Sealing defects leading to ingress of moisture as show on figure 2

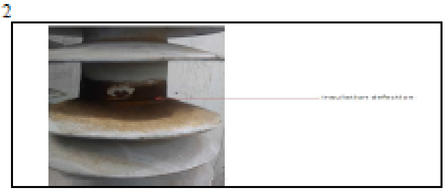

Figure 2: Slip of polymer housing

The Humidity increases up to the level of 40-50%. However, at very high humidity levels, about 95%, there is the possibility of condensation at temperature changes. The moisture layer on the internal wall of the housing or on the varistor column can initiate the internal flashover [7].

- Long term ageing during normal service voltage
- Discharges due to surface contamination

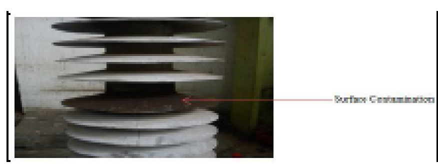

Figure 3: Surface contamination

- Internal partial discharge on the internal components of the surge arrester (varistor), as shown in figure 4 below.

Figure 4: Internal partial discharge [20]

- Design and physical arrangements of ZnO surge arresters.
- Overloading due to temporary and transient overvoltages.

4. FAILURE OF SURGE ARRESTERS

Polymer housed surge arresters are exposed to different types of stresses such TOV, switching overvoltages and lightning overvoltages. Moisture ingress may also cause accelerated ageing at the normal operating voltage. The surface deterioration and contaminant deposition on the specimen surface may cause a reduction in hydrophobicity of insulation material of a surge arrester. These stresses may cause the instantaneous overloading that will result in puncture, cracking or flashover of ZnO block varistors.

Hence, the failure of the surge arrester may appear in different ways:

- The arrester with a polymer housing may burn open the external insulation; such failed arresters are shown in Figure 5.
- The aged or overloaded arresters may show reduced protection against overvoltages, e.g. during transient overvoltage's, for instance due to-high energy temporary overvoltages, the arrester can fail before it actually has suppressed the overvoltages.
- An arrester can cause an earth fault due to internal flashover, partial discharge (which can be caused by external pollution or birds, monkeys etc.) and temporal overvoltage (TOV) which can occur in electrical networks etc.

The arrester failures may cause severe damage to the neighboring apparatus and be a safety risk for the maintenance staff.

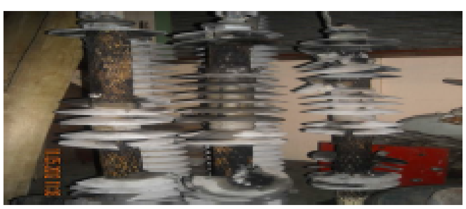

Figure 5: Metal Oxide surge arresters with polymer housing that failed during normal service operation.

5. TEST SELECTION

There are no simple, practical field tests that will determine the complete protective characteristics of surge arresters [12], but the condition of the metal oxide surge arresters are measured by performing different tests, such as partial discharge (P.D) [13], radio interference detection [3], leakage current measurement and infrared scanning (I.R). Polymer materials can have more easily show exaggerated ageing due to partial discharge and leakage currents on the surface. However, if these problems are not detected they can causes the strength and frequency of the partial discharge to increases [11] and also leakage currents and may lead to catastrophic failure of the metal oxide arrester on system. These phenomenon are dangerous and can cause a total outage of the metal oxide arrester [14].

These tests can be performed with apparatus usually available, which will give sufficient information to determine whether the arrester can be relied upon to perform under normal conditions. By performing these measurements the information will be obtained and these tests will indicate units whose insulating qualities have deteriorated [12]. The following tests selected on this investigation were chosen after review of appropriate literature studies.

- Leakage current test (offline)
- Infrared scanning

The testing will not only cover the surge arrester condition but it will also cover their major active parts, for instance zinc oxide varistor (ZnO) and insulation of arresters.

5.1 Infrared thermography

A defective surge arrester loses it characteristic as an insulator under power frequency condition. It will allow the leakage currents to flow through it. This can cause the temperature to increase inside the ZnO varistor which might cause the arrester to fail. However, to detect and diagnose a fault, it is vital to select a set of inputs whose information is reliable.

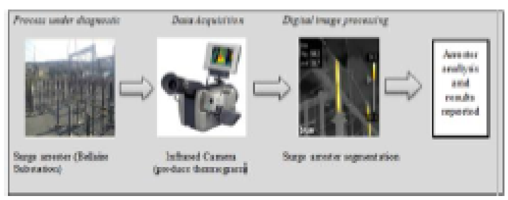

Figure 6: Methodology applies

Consequently, implementing the infrared thermograph as a tool for a data collection on this investigation will be helpful in obtaining the condition of surge arresters. Therefore, the methodology is applied for review on 120kV/65kA surge arresters on transmission substations of eThekwini electricity.

It is recognized that if there is a temperature difference between two points, there will also be heat transfer between those two points. Therefore, heat can be transferred in number different methods such as conduction, convection, evaporation or condensation and radiation. Here the focus is more on moisture condensation.

A Thermogram is a digital photo, taken by a device that is able to capture for example a lightning rod and codify its temperature using colors levels. As soon as all data is collected, it is necessary to apply digital image processing methods. This process enables the extraction of some thermographic variables from the thermogram (e.g. maximum and minimum temperatures). These variables are used by the diagnosis tool developed. The analyses are developed by considering some areas of the surge arrester thermograms by means of temperature gradient criteria.

5.2 Leakage current test

The current flowing from the hot conductor to ground over the outside surface of a device is called leakage current. But in case of the surge arrester insulation, it is the current flowing over the surface of the surge arrester insulation Fig.9 [12]. *"If no ground exists, the current flowing from a conductive portion of a device to a portion that is intended to be non-conductive under normal conditions"* [19].

During normal service the surge arrester carries a continuous small leakage current flowing through the surface, typically in a range of 0.2-3mA [20]. The total current flowing through the arrester is composed of resistive leakage current. The resistive leakage current is produced due to the changes of the schottky barrier which is formed between the zinc oxide (ZnO) grains and increases with arrester deterioration or aging (which is caused by environmental factors such as UV, contaminants and humidity) [15],[16].

However, the increase in the resistive leakage current will cause an increase in the power losses and hence increased temperature in the ZnO-block. The leakage current is directly proportional to hydrophobicity loss, especially for composite insulation.

The more the loss of hydrophobicity or reduction of silicon insulation, the higher the leakage current [21]. These leakages current can cause damage to the stability of the arrester, particularly in the low conduction zone where the V-I characteristic of a ZnO varistor is very sensitive to temperature [8].

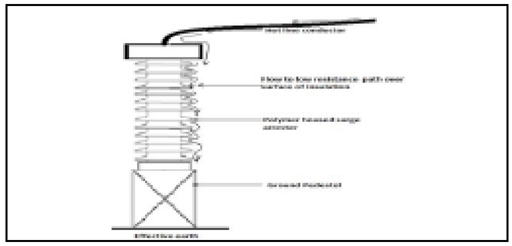

Figure 7: Leakage current flow to low resistance path over surface insulation.

The leakage current flowing through the surge arrester consists of a large capacitive current I_c and a small resistive component I_r. For a complete surge arrester, the capacitive current depends on the number of varistor columns that are in parallel. Fig.8. shows waveform of the leakage current components when a rated operating voltage is applied to a surge arrester.

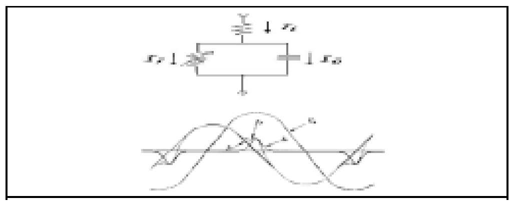

Figure 8: Equivalent circuit of surge arrester and waveform of the leakage current components [15]

Metal oxide surge arresters are known to exhibit an increase in resistive leakage current in relation with the arrester operating time [10]. As is well known, the increase of resistive and capacitive current will cause an increase in power losses (I^2R) and thereby an increase in ambient temperature. So an increase in temperature may bring a surge arrester to a temperature which exhibits an inadequate safety margin of thermal stability. This depends on the overall surge arrester design [16].

Heat dissipation is reduced at the centre of a column, as an arrester here is higher than those at the ends. Many researchers have reported that an increase of resistive current can be considered as an indicator of the arrester condition, and with the continued operation, in time it can cause failures or permanent degradation [10].

The resistive leakage current is the most important factor in arrester diagnostics, but the total leakage current and third harmonic component flowing through an arrester are widely employed as an ageing indicator [13], therefore the goal of leakage current measurements is to find the insulation performance of the insulator, as it has been reported by other researches, that the leakage current change according to contamination surface [17].

5.2.1 Offline leakage current measurement

Offline leakage current measurement can be performed with a mobile AC or DC test instrument. For safety reasons, the offline leakage current measurement is mainly to be used because it requires the surge arrester to be disconnected from the electrical system. The disadvantages of offline leakage current method are the cost of the required equipment and the need for disconnecting the surge arrester from the power system [13].

Measurements carried out online under normal service voltage are the most common method. For practical and safety reasons, the leakage current is normally accessed only at the earth end of the surge arrester. In order to allow measurements of the leakage current that flows in the earth connection, the arrester must be equipped with a base insulated from the pedestal.

6. SURGE ARRESTER EVALUATION

Recently, eThekwini Electricity uses different types of family brand of surge arresters in substation for protection purpose on the system. The following brands are:

- Surge arresters manufacture A
- Surge arresters manufacture B
- Surge arresters manufacture C

Therefore, the data acquisition process will focus on the above mentioned brands. Hence, the graph below illustrates the failure of different brands from year 2001to 2004.

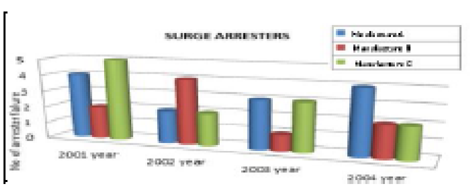

Figure 8: Graph showing failure of arrester from year 2001-2004

7. INFRARED THERMOGRAPHY RESULTS

The infrared (IR) analysis was conducted while the surge arresters were energized and under full load. Through the investigation eThekwini Electricity has discovered that thepolymer housed surge arresters are showing heating inside the metal oxide while in operational service.

The infrared (IR) analysis was conducted while the surge arresters was energized and under full load. Through the investigation eThekwini Electricity have discovered that the polymer housed surge arresters they showing the heating inside the metal oxide while in operation service. (Note that the yellow in center of the image is a hot spot). The measurements were completed on 3 different substations from October 2012 to November 2012.

7.1 Inspection in Substation A

The diagnoses were executed for ZnO surge arresters, station class surge arresters have superior electrical performance because their energy absorption capabilities are greater, and the discharge voltage (protection levels) is lower and the pressure relief is greater. They are polymeric encapsulated, installed at major substation A. This family type of surge arresters has affected the reliability of eThekwini transmission system.

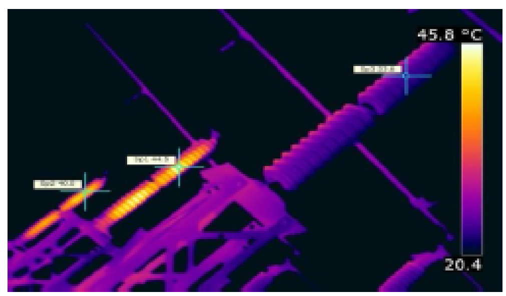

Figure 10: Thermo-grams for substation A, 2 arresters were showing high amount of heat

7.2 Inspection in Substation B

The following result were collected from ZnO surge arresters, polymeric encapsulated, installed at major substation B, located at line 1. The inspections were executed on 132 kV.

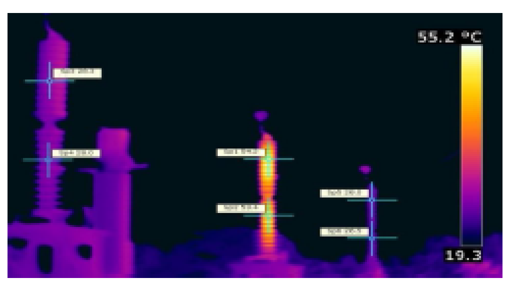

Figure 10: The thermal heating problem with these arresters could have affected the reliability of the substation B line 2

7.3 Inspection in Substation C

The following result were collected from ZnO surge arresters, polymeric encapsulated, installed at major substation C, located at line 2.

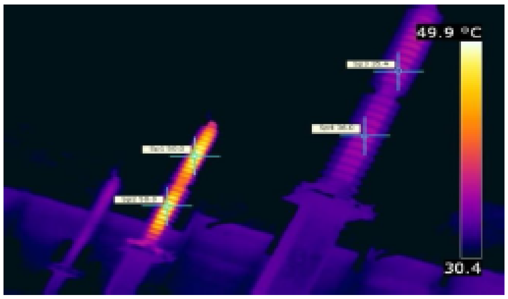

Figure 11: Thermo-grams for substation C was showing the high amount of heating inside arrester

8. FAILURE CRITERIA OF ARRESTER

Since the outcomes of this study are dependent upon the standards used to assess satisfactory surge arrester behavior, the surge arresters were considered "failed" if their measured behavior did not matched the following standards.

- Satisfying the performance levels guaranteed in manufacturers data.
- Meet the required performance measures outlined in the pertinent industry standards.

9. LEAKAGE CURRENT TEST RESULTS

The following results from the tables below represent the offline leakage currents that were measured. The information includes the type and brand, the serial number and location (Red, White and Blue phases).

The rated voltage of arrester is 98kV. The arrows indicate the measurements value of leakage currents in millampere.

Table 1: Resistive currents in milliampere for manufacture A

	Location	Serial Num	Rated kV	Test Modes	Test kV	mA
1	R-Ph	01C2018	98	GND RB	10	0.131
2	W-Ph	97F2822	98	GND RB	10	0.137
3	B-Ph	01C2015	98	GND RB	10	0.131

Table 2: Resistive currents in milliampere for manufacture B

	Locatio n	Serial Num	Rated kV	Test Modes	Test kV	mA
1	R-Ph	W53E550-02	98	GND RB	10	0.131
2	W-Ph	W53E550-03	98	GND RB	10	0.137
3	B-Ph	W53E550-01	98	GND RB	10	0.131

Table 3: Resistive currents in milliampere for manufacture C

	Location	Serial Num	Rated kV	Test Modes	Test kV	mA
1	R-Ph	W53E550-02	98	GND RB	10	0.149
2	W-Ph	W53E550-03	98	GND RB	10	0.146
3	B-Ph	W53E550-01	98	GND RB	10	0.149

10. CONCLUSION

The conclusion of this research was based on leakage current test and infrared scanning analysis of the family of surge arresters that are failing on the system. During the field trail evaluation in eThekwini Electricity substations, furthermore surge arresters that had been measured are proving to be in unsatisfactory condition. They were running abnormally hot inside the zinc oxide (ZnO) varistor. Moreover, surge arrester A were having a light spot in the midpoint of insulation, this demonstrates that the heat starts there because this type of brand on the middle of the surge the sealing collar between the last upper shed and first of lower shed (middle) was defected (figure 2).

Therefore, this gives rise to moisture ingress and this was causing the heating inside vairstor blocks to increase. On this issue, the design must improve the joint sealing integrity by construct with a continuous rubber from top to bottom so as to increase life span of arrester. The total leakage current measurement was also performed in arresters in accordance with the recommendation from IEC standard [22] to gain additional information concerning condition of arresters. The increase in the resistive leakage current on the surface insulation does not necessary mean that the arrester will fail. Hence, the evidence we acquired will help us to improve the surge arrester specification so as to avoid failure in the future and will also benefit us with replacing them before they fail on the system.

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Appendix-E

Surge Arrester Faults and their Causes at eThekwini Electricity

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Abstract— **Failures in polymeric housed surge arresters have recently increased. This has resulted in a number of studies being done in order to establish the condition of surge arresters whilst in service, the aim being to remove them from service before they failed. This paper utilizes a thermovision technique to predict potential faults allied to a visual inspection of arresters placed in eThekwini outdoor substations. Infrared analysis was valuable in obtaining sufficient information on arrester failures by detecting hotspots within the arresters while still connected to the system and comparing these test results with those performed on failed units. During the visual internal inspection of arresters evidence of punctures, treeing, tracking and moisture masks were noted on ZnO blocks and seals.**

Index Terms—**Polymer housed surge arrester, moisture ingress, infrared scanning and visual inspection**

I. Introduction

Polymeric housed surge arresters are widely applied to power transmission systems in order to protect the systems from overvoltages. Their advantage over porcelain or ceramic surge arrester is that they perform well in polluted with the polymeric silicone rubber arresters excelling [1]. Apart from electrical stresses caused by AC voltage impulses or switching operations, the degradation of polymeric housed surge arrester can also be influenced by other environmental factors, such as moisture ingress into the sealing or housing and salt contamination [1]-[6]. These factors could cause problems for the surge arrester in service. As a result, it is very important to measure the condition of arresters in service. Moisture ingress, exacerbated by pollution, plays an important role in the degradation of a surge arrester. It has been reported that moisture ingress in high voltage apparatus is the most important source of degradation [2], [5]. The moisture absorption in an arrester results in slightly increased leakage current, which is typically in the range of mA [7], [8]. Hence, this can lead to overheating of the zinc-oxide varistor (ZnO) elements causing the temperature of an arrester to increases until it bursts [9].

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Krystain Chrzan reported in the last century that moisture ingress was responsible for 80 per cent of outages in arresters [10]. The same problem is being experienced today (see Fig 1) [6].

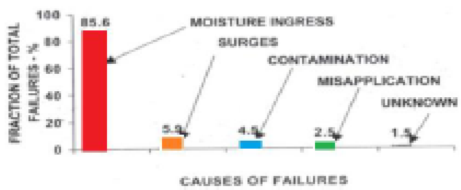


Figure 1. Total failure surge arresters in percentage [11].

As a result of this, it is imperative to do in service condition monitoring of surge arresters in order to check their condition before they fail. This paper presents various methods used to detect faults in surge arresters and their causes at eThekwini electricity.

The thermovision technique was utilized as a tool for data acquisition to detect thermal heat in the arrester and a visual inspection was also done at the electrical workshop to check the condition of the failed arresters. The measurements were applied for diagnosis of 120kV/65kA surge arresters of different makes. The author recommends infrared scanning as the preferred tool to be used for faults detection in arrester because of the validity of the results.

II. Description of Polymer Housed Arresters

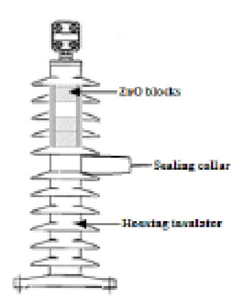


Figure 2. The cross-section drawing view of a polymer housed surge arrester

The insulated housing is directly molded on to ZnO varistor blocks and Fiber-glass reinforced plastic (FRP) to ensure total enclosure of all components and high mechanical strength of the entire structure of the surge arrester. The surge arresters housings have traditionally have been made of polymeric insulating material for arresters for both distribution systems and for medium voltage systems and recently even for power substations system voltages (see Fig. 2).

The heart of an arrester comprises individual ZnO resistor blocks stacked on top of each other to provide the desired nonlinear voltage-current or V-I characteristics and to present a strong relationship with temperature. The secret to the arresters success in diverting lightning or high electrical surges is the ZnO varistor; this is the heart of an arrester. ZnO varistor blocks are semiconductors that are highly sensitive to voltage. Hence, any degradation in the varistor blocks can lead to arrester failure in service. To avoid this problem, selecting a good monitoring techniques can help to minimize these failures.

III. Degradation of ZnO Surge Arresters

As discussed earlier, moisture or humidity inside surge arresters plays a significant role in the degradation process of varistor elements. This moisture increases thermal heating, leakage current [8] and causes discharges. These phenomena are directly responsible for tracking and erosion in a ZnO varistor block of an arrester (see Fig. 3).

Figure 3. Internal partial discharge [10].

The formation of sparking discharge is closely related to the variation trends of the total leakage current and creates high temperature spots leading to bond scissions and other chemical changes on the surface insulation [4]. Leading to permanent failure of the varistor elements. ZnO varistor degradation is used to describe the electrical condition of a varistor relative to its past or future state when under the influence of external stresses [10] and [12]. The amount of degradation is a good quality indication of varistor reliability and is usually used for foreseeing the life span of a ZnO varistor [10].

A. Sealing Defect

A defective arrester may not be able to work in a satisfactory way when an electrical surge occurs [9]. Hence, it could allow moisture to penetrate to a surge arrester housing or sealing (see Fig. 4 and Fig. 5). A consequence of this effect is the reduction of the level of security in the performance of the apparatus. As it has a continuous leakage of gases, the system of protection against explosion becomes inefficient, being no longer capable of performing on extreme heating [5].

Moisture can also penetrate into the interior through the housing material by diffusion [6]. Reference [13] also confirmed effective and proper tests for this family of arrester. For proper design, a thorough knowledge of arrester behavior during different moisture diffusion processes is required [6].

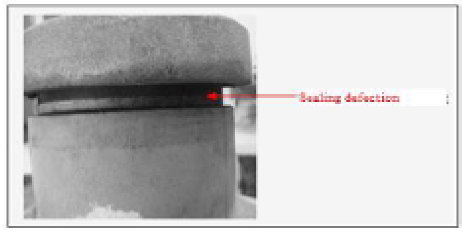


Figure 4. Upper sealing defection.

Figure 5. Sealing collar defective [14].

B. Moisture Ingress

Moisture ingress in high voltage apparatus is the primary source of degradation [2] and [5], because of this situation several studies and research have been done in order to improve sealing material of arresters [10]. Earlier publications have showed that multistress aging testing is an important design test to prevent polymer housed surge arresters having improper design of the insulation [15]. Moisture ingress may result in moisture condensation, changing the protection level and the energy dissipation capability. Frequently, the surge arrester aging may present a gradual rising in the resistive component of the current loss that contributes to thermal instability and finally leads to complete fault (see Fig. 6).

Figure 6. Moisture ingress on the sealing interior [16].

C. Influence of Moisture in ZnO Arrester

The looseness of the insulation from the end sealing as represented in Fig. 4 [2], where for a surge arrester in-service the humidity inside can increase due to deterioration of sealing. Humidity has been shown to increase up to 40-50%. However, at very high humidity levels, about 95%, there is the possibility of condensation at temperature changes [10].

The moisture layer on the internal wall of the housing or on the varistor column can initiate internal flashover [10]. Conversely, moisture absorption into the sealing can also leads to electrical discharge activity, such as tracking, cracking and water trees; trees are the source of aging [5].

IV. Failure Modes of ZnO Surge Arrester

The arrester with polymer housing may burn open the external insulation; such failed arresters are shown in Fig. 7.

Figure 7. Metal oxide surge arresters with polymer housing that failed during in service condition.

Various studies, as in [3] and [7] have been done and show that polymer housed surge arresters are exposed to various stresses such as temporary overvoltages (TOV), switching overvoltages and lightning overvoltages. Thus, due to different factors affecting them their failure may appear in different ways;

- Damage of sealing due to thermal heating produced inside varistor (see Fig. 8)

Figure 8. Defective sealing increase high rate of moisture ingress.

- Localized losses and discharges caused by poor inter-disc contact
- Housing deterioration or pollution changing the voltage distribution along the stack (see Fig. 9)

Figure 9. Deterioration on insulation housing [17].

- Mechanical fractures in ZnO varistor due to thermal runaway after a high current surge (see Fig. 10)

Figure 10. Mechanical cracks in varistor elements.

- Damage due to surge current concentration at the edge of the electrode resulting in failure
- Resultant damage to the disc created by previous multiple-stroke lightning surges.

V. Evaluation Methodology

To attain good results for fault detection and diagnosis, it is extremely important to select a set of inputs whose information is capable of allow the fault identification in the surge arrester. Hence, the research methodology applied for evaluating the failure of the family of surge arresters was established. Thermo vision technique was used as a tool for a data acquisition.

Infrared scanning was selected to be used on this study after review of the appropriate literature studies concerning failure of arresters in service condition. The use of infrared thermography is a very convenient approach since the measurement device operates with no physical contact with the tested equipment.

Fig. 11 presents the diagnostic flow chart utilized for data acquisition using thermovision in addition to visual inspection.

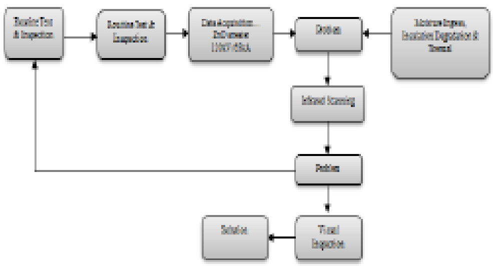


Figure 11. Evaluation flow chart.

The testing covered not only the surge arrester condition but also their major active parts, for instance zinc oxide varistor (ZnO) and insulation of arresters.

VI. TEST RESULTS

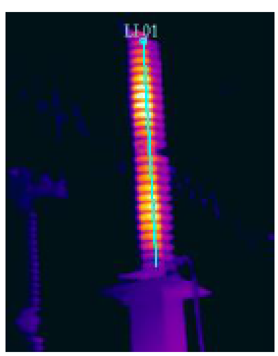
The infrared (IR) analysis was conducted while the surge arresters were energized and under full load. The surge arresters that were tested are of different manufactures (see Table I).

TABLE I. SURGE ARRESTER TYPES TESTED

Arrester manufacture	Housing material	Uc [kV]	Moulded housing	Number of sheds
A	polymer	98	X	24
B	polymer	98	X	24
C	polymer	98	X	24

Uc Max. Continuous operating voltage (IEC 60099-4)*

During the field trail analysis the results of failing arresters were obtained. Images of surge arresters showed the high rate of thermal heat. Results showed the thermal image and temperature profile of surge arresters tested, (see Fig. 12-Fig. 14). Note that the yellow in center of the image is a hot spot. This designates that instant de-energization and replacement must be undertaken before they failure.



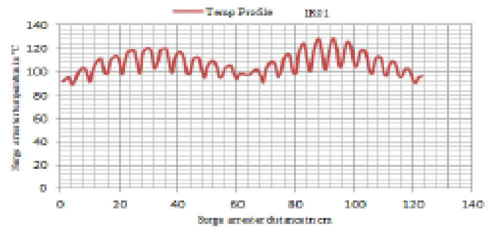
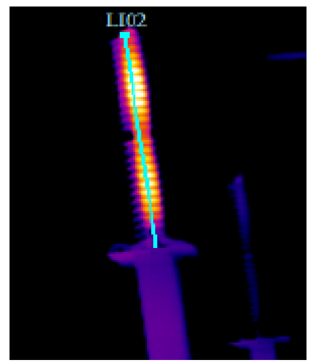


Figure 12. Thermal image of arrester and temperature profile along the arrester.



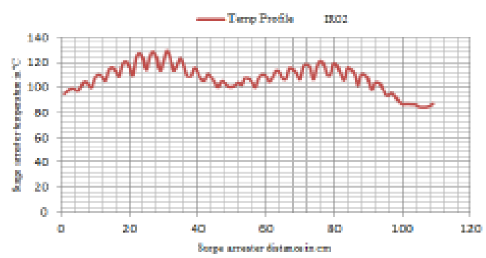
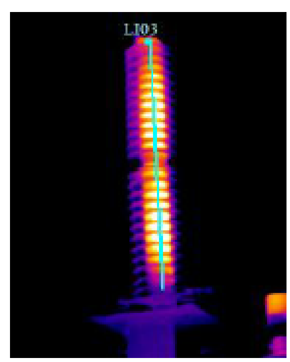


Figure 13. Thermal image of arrester and temperature profile along the arrester.



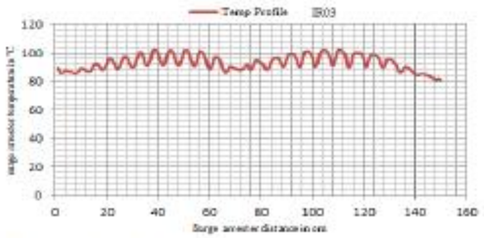


Figure 14. Thermal image of arrester and temperature profile along the arrester.

VII. Images Obtained During Visual Analysis

The results obtained during the visual inspection of the surge arresters of manufacturer A, (see Fig. 15-Fig. 18). The moisture ingress through the sealing collar causes serious problems such as surface discharges. These factors can eventually end with a full breakdown over the insulation system. Water treeing inside the sealing collar was noted as were cracks on the zinc oxide blocks closest to the sealing, this indicates that that the failing started here.

Figure 15. Treeing inside the sealing collar.

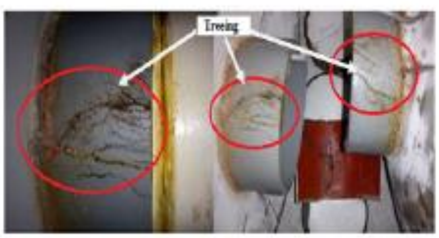


Figure 16. Water treeing on the sealing collar.

Figure 17. Cracks and damp on zinc oxide blocks.

Figure 18. Damp on zinc oxide varistors.

VIII. Conclusion

During thermovision analysis exciting results were obtained. The surge arresters that were measured in outdoors substations showed high thermal temperature inside the zinc oxide varistor. This proves that there was moisture ingress in the sealing collars of arresters whilst in service.

This determines that the heat was generated there because with this family of arresters the sealing of the surge arrester was defected, so it allowed humidity or moisture to penetrate. Throughout visual inspection on the arresters in the eThekwini electrical workshop, evidence of water trees, punctures on sealing collar was found. The images taken during arresters analysis clearly indicated failure of surge arresters caused by moisture ingress leading to degradation on varistor blocks.

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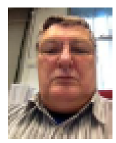

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