INVESTIGATION INTO CURRENT TRANSFORMER FAILURES WITHIN ESKOM DISTRIBUTION

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ABSTRACT

Conventional Current Transformers (CTs) provide the input signal required by protection relays, control equipment and energy metering in power networks. Catastrophic failures of CTs may lead to injury of personnel within the substation, interruption of power supply and damage to adjacent high voltage equipment.

One of the causes of CT failures is high values of insulation power factor. Research indicates that with increasing primary insulation power factor values, partial discharges develop between the paper insulation leading to its exponential decay with the end result of an ultimate CT failure. Reports in Eskom Distribution indicated that a number of CTs from one manufacturer were exceeding the specified insulation power factor value. This research was initiated to investigate the impact of high power factor on the premature failure of CTs. This study serves to analyse the significance of power factor on paper-oil insulation within a hair-pin type CT.

The internal primary insulation of a hair-pin type CT used in Eskom Distribution is reviewed in terms of its design, construction and relevant tests. Sample CTs rated at 132kV and manufactured in the year 2007 to 2009 from the specific manufacturer were selected for insulation power factor testing. The Doble M4100 diagnostic test system was used to perform the testing that also assisted in providing a comparison between the units with high insulation power factor values and that which were within the specified limits.

The results show that the high values of insulation power factor give a direct indication of the dielectric losses (I^2R) within that CT, which inadvertently indicates the shortened serviceable life of that CT. High moisture content within the primary insulation, low quality insulating oil and inadequate quality assurance were identified as some of the contributory factors in the CTs non compliance. The effects of high values of insulation power factor are the primary factor for continuous on-line condition monitoring techniques that enable data trending and provide for early warning of an imminent CT failure. The testing of the sample CTs provided a more dynamic approach for recommendations to prevent the installation of such units into the power network.

LIST OF ABBREVIATIONS

CT	Current Transformer
ED	Eskom Distribution
CIGRE	Conference Internationale des Grandes Réseaux Electriques
HV	High Voltage
IEC	International Electrotechnical Commission
NRS	National User Specification
kV	kilovolt
NCR	Non-Conformance Report
m	Metre
NERSA	National Energy Regulator of South Africa
DGA	Dissolved Gas Analysis
ppm	Parts per million
pC	Pico Coulomb
DDF	Dielectric Dissipation Factor
Hz	Hertz
ALF	Accuracy Limit Factor
pF	Pico Farad
rms	Root Mean Square
BIL	Basic Insulation Level
DAT	Design Acceptance Test
FAT	Factory Acceptance Test
SAT	Site Acceptance Test
MV	Medium Voltage
KPI	Key Performance Index
NEPS	Network Equipment Performance Management System
SAIFI	System Average Interruption Frequency Index
SAIDI	System Average Interruption Duration Index
CAIDI	Customer Average Interruption Duration Index
MVA	Mega volt Ampere
kWh	Kilowatt-hour
SLA	Service Level Agreement
WMA	Work Management Area
HVLAB	High Voltage Laboratory

T&Q	Technology & Quality
W	Watt
VA	Volt Ampere
DTA	Doble Test Assistant®

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CHAPTER 1: INTRODUCTION

1.1 Introduction

Current Transformers (CTs) are used to transform high currents into safer and low secondary currents used for the protection of the power systems and for energy metering (Wright, 1968; Cardenhas et al. (2008a)). CTs are also used to insulate the protection relays and energy meters, by galvanic isolation, from the high voltage on the primary system. The use of CTs enables the standardisation of secondary currents for protective relaying and energy metering to 1 Ampere (A) or 5A. The magnetic core encompassing the secondary windings fulfils the task of measuring, whereas the insulation on the internal and external of the unit provides an isolation task. For all new installations, Eskom Distribution (ED) has maintained a standard of utilising 1A. The effectiveness of CTs in a power system determines the accuracy of the energy metering and the reliability of the protection schemes.

CTs are considered simple pieces of equipment, however when they do fail catastrophically, their increased population throughout the power network is considered with the utmost of attention (Cigré c (1990b)). They are designed to be connected in series with the power system thereby enabling it to operate with the continuous load variations and short circuit transient currents of the power system. In comparison to other high voltage equipment in the substation HV yard, the cost of CTs is seen to be low. However, should a catastrophic CT failure occur, the cost of the consequential damage caused by the CT can far outweigh the initial cost of the CT itself.

CTs are designed and manufactured according to IEC 60044-1 standards and NRS 029 specifications and specific information obtained from their customers. ED then specifies their CT requirements in terms of the type of construction being, a post hair-pin type; the insulation level for the particular voltage application and the number of secondary cores according to secondary plant system requirements.

As a result of the CTs having the potential to fail catastrophically, the main concern is the safety of the operating personnel within the confines of the substation environment. The technical impact of the CTs failing affects the power system stability as the faulted network must be isolated from the healthy portion of the network. The destructive impact of a CTs failure can damage other adjacent high voltage equipment and disrupt system operation due to the fireball that could evolve as a result of the burning oil. The mal-operation of the secondary plant protection schemes receiving the low voltage signals during a fault can cause unnecessary tripping on the healthy portion of the network. The integrity of the secondary plant protection and metering schemes could be disrupted and hence damaged due to the consequences of a CT failure. This may result in power interruptions, longer outage durations and increased revenue losses.

There have been reports of CTs within the ED network that were failing to meet the minimum requirements for insulation power factor according to the NRS 029 specification. In determining the cause and effects of a CT with high insulation power factor values, a literature review encompassing the methodology behind the evaluation of such CTs will be uncovered. Mechanisms of failure related to high values of insulation power factor will be reviewed and explained so as to assist utilities with the possible forthcoming effect of such CTs. The local and international trends of monitoring and mitigating against such occurrences will be used to substantiate the claim of refurbishment of the suspect CTs. In the design of the CT to the phase of construction and manufacturing, all aspects that could have potential implications to increasing the insulation power factor shall be visited.

Testing of CTs, and the results thereof, to prove compliance to international standards and specifications during the design and manufacturing stages are seen as essential for data trending and effective record keeping. Economic impacts as a result of non compliance with the above can be quite substantial to the manufacturer concerned as well as loss of revenue for the utility concerned. In light of the above, ED’s concern pertaining to the suspect CTs will undergo analysis. Suspect CTs that are earmarked for installation on site will be tested for insulation power factor to find a comparison between those that are within specification. Condition monitoring techniques used locally and internationally to assist in the prevention of premature failure in hair-pin type CTs shall be proposed as a medium to circumvent a possible crisis in the event of a CT failure.

1.2 Background to the Research Problem

Current transformers (CTs) are used to transform high currents into safer and low currents, thereby enabling the CT secondary output to be utilised for the protection and control of the power systems and for revenue metering. There have been reports of widespread failures of in-service CTs from a specific manufacturer and a specific type of CT within the Eskom Distribution network. A primary cause of failure is suspected to be a high insulation power factor value of the capacitively graded primary insulation.

Insulation, from the HV of the power system to earth potential, is provided by means of capacitively graded (paper-foil) layers immersed in oil within station post CTs utilised by Eskom Distribution. Figure 1-1 below depicts the capacitive grading shields of a typical hairpin-type constructed CT with the outermost layer terminated to earth potential.

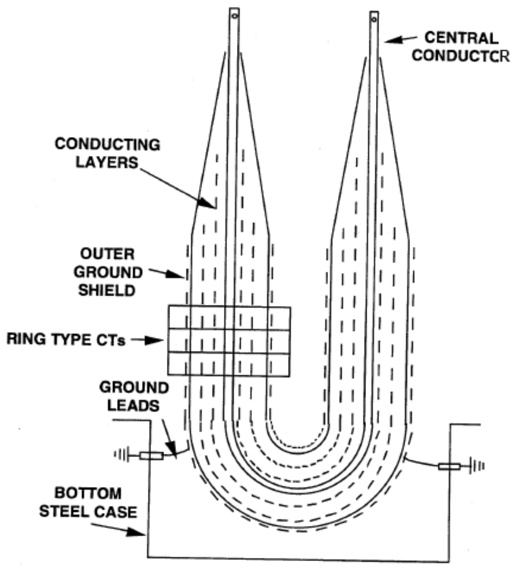

Figure 1-1: Hairpin-type constructed CT
Source: (Ayers et al. (1999b))

Power factor of the capacitively graded CT insulation is the ratio of the capacitive (charging) current to the resistive (leakage) current and therefore gives a direct indication of the watts loss within the primary insulation of that CT. This indicates the degree of moisture content within the CT paper insulation which inadvertently leads to the indication of the insulation degradation within that CT (Bleyer & Prout, 2005a). The measurement of the dielectric dissipation factor as well as capacitance provides a means of detecting the condition of the paper-oil primary insulation within a CT.

Kulkarni *et al* (2002c) considers CTs to be in the category of being one of the important pieces of equipment in an electrical power system that should be maintenance and trouble free for the many years of service that it is designed to provide. The impact of the CTs failing affects the power system stability as the faulted network must be isolated from the healthy portion of the network. The destructive impact of a CTs failure can damage adjacent healthy equipment and disrupt their operation due the fireball that could evolve as a result of the oil being under a high pressure within the CT. This may result in further power interruptions, longer outage durations and increased revenue loss.

1.3 The research problem

In accordance with the Eskom Distribution specification for CTs up to 132kV – DSP0013 Rev 5, reference is made to the Rationalised User Specification NRS 029:2002 which specifies the acceptable values for dielectric dissipation factor for CTs rated at nominal system voltages of 66kV and 132kV. Four years ago (2006), High Voltage Test teams within Eskom Distribution compiled reports of manufacturer A on 66kV and 132kV CTs indicating specifically the substantially high, non-conforming values of dielectric dissipation factor during test. This posed an undesirable situation and a Non-Conformance Report (NCR) was issued to manufacturer A. The outcome of the NCR was the compliance of the manufacturer to the NRS 029:2002 specification and the adherence of stricter quality assurance procedures at the manufacturer's works. The research problem, leading to the hypothesis, identified a gap as to whether Eskom Distribution would still receive the same life expectancy of a CT with such high values, as compared to manufacturer B with a lower than specified dielectric dissipation factor value.

1.4 Research questions

- Do high levels of insulation power factor in current transformers lead to premature failure?
- What mitigating techniques can be employed to reduce the impact of current transformer failures on the power system?

1.5 The Hypothesis

Current Transformers acquired with a high insulation power factor value will fail prematurely.

The methodology into proving the above statement lies with the investigation into current transformer failures in Eskom Distribution and the analysis thereof. As the primary cause of failure is suspected to be a high insulation power factor value of the primary insulation; determination of CT life expectancy, with such high values, needs to be uncovered such that corrective action can be emphasised and implemented to circumvent the recurrence of such failures.

1.6 The Importance of This Study

The importance of this study is based on the fact that the impact of a CT failing affects the power system stability, as the faulted portion of the network must be isolated from the healthy portion of the network. To date, no formal documentation within Eskom Distribution exists that predetermines the outcome of a CT in service with a high insulation power factor value. In this regard, the aim of this research is therefore to investigate the impact of power factor related to the failure of a CT. This research will also attempt to identify whether premature failure is a possibility when a CT is acquired with a high insulation power factor value. This can therefore be seen as offering "decision making assistance" to utilities faced with this situation, as well as manufacturers during their quality control processes.

1.7 Outline of Dissertation

Chapter 1 provides an introduction and background to the research problem.
Chapter 2 indicates a review of the literature.
Chapter 3 details the design and construction of CTs as well as the standards that need to be adhered to.
Chapter 4 provides details of the various tests that a CT must undergo prior to and whilst in-commission.

Chapter 5 describes the effect of partial discharges as a cause of failure in CTs and its relation to insulation power factor as well as accelerated ageing.

Chapter 6 examines the impacts of CT failures from a technical, economic and environmental point of view as well as the taking safety of people as a major concern.

Chapter 7 details the CTs that were found to be suspect within Eskom Distribution and reviews the probable causes for high insulation power factor values with action taken to remedy the situation.

Chapter 8 delves into the insulation power factor testing of CTs as conveyed by the author with a review and analysis of the test results.

Chapter 9 opens up to a discussion of the theory as presented with conclusions and recommendations provided.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

For the accuracy of protection, measurement and indication; the equipment used, such as relays and meters, should ideally be connected directly to that circuit. With the inability and hence costly nature in manufacturing these types of equipment, due to the substantial insulation requirements, CTs were introduced to provide electrical isolation from the high power system voltages and currents (Wright, (1968)). They provide the secondary current in proportion to the primary current and that proportion is known as the ratio of the CT.

The role of the CT is threefold as they provide primary high voltage isolation, safety in terms of the secondary circuits being earthed and provision for the safe measurement of the primary high voltage power system current. CTs are considered as passive elements (Cigré c, 1990b)) in power networks, where the design and construction are taken as simple in nature relating to its relatively low cost as compared to the other equipment on the power network.

This chapter will commence with some of the basic background information on the hair-pin CTs that are currently being used in ED. Further to this, the objectives of reviewing the mechanisms of failure related to the hypothesis of the author are identified in the literature. In relation to the above, selected studies on the experiences of such failures from various utilities worldwide with the associated cause and effect are consulted. The chapter concludes with studies based on the proposed mitigation of such CT failures.

2.2 Background on Current Transformers

1890 was the year that three-phase transmission of electrical energy was introduced and it therefore became evident that the possibility of measurement of current on the primary system, with instruments connected directly to the power network, proved to be no longer an option (Mariani, (2007b)). It was with this foreseen challenge that in 1882, engineers SZ De Ferranti and A Thompson patented the first CT for the indirect measurement of current flowing on the primary HV network (Mariani, (2007b)). In 1900, the use of CTs became inevitable and special attention was devoted to its accuracy of measurement. Following on of approximately nine years later, interventions produced the basic skeletal principles inclusive of the theory of operation behind CTs (Mariani, (2007b)).

In accordance with IEC 60044-1:2003, a current transformer is defined as: "an instrument transformer in which the secondary current, in normal conditions of use, is substantially proportional to the primary current and differs in phase from it by an angle which is approximately zero for an appropriate direction of the connections". The objective associated with a CT is that an accurate transformed replication of the primary current and its associated angle is to be provided to enable the correct operation of the secondary plant protection relays, during system abnormality, and energy metering system during normal operating conditions (Cigré c, (1990b)). The main purpose of designing, manufacturing and utilising CTs is hence seen to provide an accurate resemblance of the primary system current, both in angle and magnitude, to the secondary during normal and abnormal power system conditions.

CTs perform the tasks of measurement and isolation, whereby the measurement is achieved by means of magnetic cores with secondary windings that enable the transformation of the primary high power system current into a value that is easily handled by the secondary plant protection and metering equipment. The task of isolation is provided internally by means of paper-in-oil around the primary hair-pin conductor and enables galvanic isolation whereby the primary high power system voltage is not manifested across the secondary plant equipment.

CTs offer the advantage of standardisation in that the secondary plant equipment that it is connected to has a set input rating thereby eliminating variations in design and hence providing a reduction in cost of both the CT and the secondary plant equipment. The ratio of the CT is then given by the following formula:

$$Ratio\ (k) = \frac{I_P}{I_S} \tag{1}$$

Where: I_P = the primary rated input current.

I_S = the secondary rated output current.

This would then mean that the power rating of the secondary plant equipment need not be substantially high, which inadvertently provides the safe control and operation of the substation assets within the control room (Cigré b, (2009a)).

CTs are seen to be one of the important pieces of equipment in a substation providing many years of maintenance free service into the power system. Figure 2-1 depicts the insulating function that the instrument transformer (CT) provides between the HV portions of the network versus the secondary plant equipment in the control room. The ability of a CT to be able to perform this function is through its internal and external insulation, where the internal insulation consists of either paper-in-oil, sulphur hexafluoride (SF_6) gas or cast resin (Cigré b, (2009a)). It can also be seen that the CT secondary must be earthed at one point only to provide a means of reference during measurement as well as to prevent any stray leakage current affecting its measurement capabilities. In CTs, the main insulation forms a capacitive voltage grading between the primary HV conductor and the secondary windings, as well as the base tank which is terminated to earth potential.

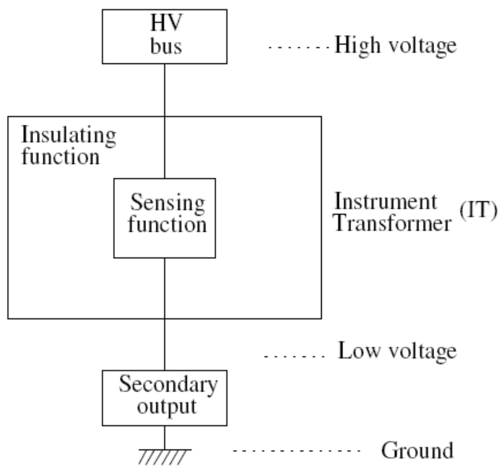

Figure 2-1: CT Functional Diagram
Source: (Cigré b, (2009a))

CTs are considered to be a very simple piece of equipment and although often neglected, they do add to the problems that exist during a power transmission incident (Cigré c, (1990b)). The catastrophic failure of such CTs leads to the damage of adjacent plant which inadvertently leads to unnecessary power outages and additional costs related to the replacement of the damaged adjacent plant (Kulkarni *et al* (2002c)). The deterioration of any piece of electrical equipment starts the moment the equipment is placed in-commission and if not managed properly, in terms of monitoring its deterioration, severe losses can be incurred (Allan & Nichols, (2000a)).

The impact of a catastrophic CT failure, whereby pieces of porcelain are strewn around an approximate radius of 80m to 100m of the failed piece of equipment, poses not only additional and unwarranted costs to the utility, but also an increased risk to operating personnel and members of the public within or near the confines of the substation HV yard (Belinska *et al* (1999c)). The financial implications associated with a CT failing can far outweigh the cost of the CT itself and as a result, additional penalties can be imposed due to the lack of energy supply to consumers. The CT should then not be left open-circuited whilst in-commission, as the impact caused by the generation of a considerably high voltage at the CT secondary will lead to the effects of arcing and damage to the insulation of the secondary windings.

2.3 Mechanism of Failure Mode related to Insulation Power Factor

CTs on the power network are considered to be of a non-problematic type of equipment, however, the population of CTs in the power network are only considered essential after a catastrophic failure. This is even more so, as explained in (Cigré c, (1990b)), if the failure is related to a design defect or a defect during the manufacture stage. Increasing pressure on the utility would surface, as the entire CT population would then require review.

CTs are taken for granted as being non-active pieces of equipment; whereby there are no moving parts within the CT itself as well as being simple in terms of design, however their sudden violent failure necessitates the need to review their design, construction, installation and monitoring (Cigré c, (1990b)). CTs are installed one per phase, on either side of the piece of equipment to be protected. This would then substantiate the figures of the actual installed base of that CT in the utility. The logistical nightmare involved in the replacement of such a large number of CTs can prove to be quite a feat, if a failure mode is considered to be a continuous error with the design and manufacturing process (Cigré b, (2009a); Moore *et al* (1992)).

Faults on the electrical power system do occur and as a result of major faults, significant financial losses can be incurred on both Eskom and the customer as a result of equipment repairs or replacement. This inadvertently leads to insurance claims being lodged with NERSA imposing additional burden on the utility in terms of supply loss penalties. The security and reliability of supply is compromised until the secondary plant protection system operates to isolate the faulted portion from the healthy portion of the power network. With the failure of either primary or secondary plant equipment to operate when required, substantial damages can be incurred.

One of the mechanisms that seem to have a direct correlation with insulation power factor is the inception of partial discharges. This occurs under a high voltage stress, where the distance between the two points are only partially bridged thereby limiting the continuous flow of current (*wikipedia*). These partial discharges, in the paper insulation, evolve as a result of minute holes which eventually strengthen to develop into larger holes leading to chemical imbalances in the paper and insulating oil. Formation of electrical treeing in the paper, due to the production of carbon in the oil, leads to tracking being developed and in the process produces heat thereby damaging the paper insulation to a complete premature failure (*wikipedia*). This in essence indicates a failure mode process whereby an arc is developed within the CT and between the layers of paper insulation which in turn leads to gasses being developed in the oil. The ionisation of the oil, due to the development of the gasses, leads to pressure being built up within the confines of the CT tank thereby leading to its catastrophic explosion of the porcelain insulation and ending up with a fireball.

Effective quality control during construction and manufacture has been seen to limit the effect of cost saving due to the use of inferior material and the use of off-cut material for the primary paper-foil insulation. The increase of capacitance, during insulation power factor testing, can indicate the loss of a screen (Cigré c, (199b)) or the use of pieces of foil to make up a screen thereby providing a break in the capacitive voltage grading. Cowan & Grobler, (1998c) states that CTs rated at 66kV and above that have oil-impregnated paper insulation will have a capacitance value that is dependant on factors such as the paper type, thickness and the number of grading layers. Any increases in the insulation power factor of the internal insulation will be supported by internal insulation degradation of either the paper or oil.

The inception of moisture and other impurities have been identified by Heathcote, (1998e) as serious limiting factors for the dielectric capabilities of the insulating oil and more so for the paper insulation. In an explanation provided by Babos *et al* (1998a), paper degradation is exhibited by the content of moisture, effects of temperature and the type of pulp used in the attainment of the cellulosic paper, which inadvertently leads to the premature life of the CT. For moisture contamination in the oil, dielectric testing to indicate voltage is seen to give clear indication of the point at which the oil breaks down.

A survey performed by Cigré b, (2009a) describes a failure mode of CTs as a result of oil leakage, as with the progression of oil leak starts the ingress of moisture due to the non existence of the hermetic sealing of the CT. The survey also indicated that some of the causes of failure were related to the actual design of the CT inclusive of the quality of materials used and the absence of effective quality control during manufacture. Inadequate maintenance and the non-adherence to procedures for site installation were seen to provoke some of the major causes of early failure as indicated in table 2-1 below.

Table 2-1: Mechanism of Failure Mode in CTs

Primary Cause of Failure	Major Failure (Total 460)	Minor Failure (Total 415)	Defects (Total 2129)	All Defects and Failures (Total 3004)
Design Fault:				
- Electrical	40.0%	15.9%	12.2%	17.0%
- Mechanical	2.0%	10.5%	11.1%	9.6%
- Material	0.2%	2.5%	7.0%	5.3%
- Oil Leaks	0.0%	15.0%	35.2%	27.0%
Total	42.2%	43.9%	65.5%	58.9%
Inadequate Quality at Manufacture:				
- General Quality	4.3%	1.4%	1.3%	1.8%
-Moisture Ingress	3.3%	0.5%	1.8%	1.9%
-Oil Leaks	5.7%	8.9%	6.3%	6.5%
-Gas Leaks	0.0%	0.0%	0.8%	0.6%
-Corrosion	0.0%	0.3%	3.6%	2.5%
Total	13.3%	11.1%	13.8%	13.3%
Ageing	9.6%	12.3%	2.8%	5.1%
Lightning	12.0%	2.4%	0.3%	2.4%
Operation outside Specification	5.7%	14.7%	4.0%	5.7%
Inadequate Maintenance	0.4%	0.7%	1.0%	0.9%
Unknown	17.0%	14.7%	12.6%	13.6%

Source: (Cigré b, (2009a))

From table 2-1, some of the major failures resulted from electrical design faults due to ineffective sealing allowing moisture ingress and oil leakages. Quality control is once again seen as an important factor during the manufacture stage as this also leads to premature oil leakage once the CT is in-commission.

Some of the studies done by Pagan, (1998f) explain the violent failures of in-service CTs experienced at the Red Electrica de Espana (REE). From the tear down approach adopted to find the root cause of failure, some of the findings were related to the actual construction of the CT. The paper-foil combination, used for capacitive voltage grading, differed amongst units even from the same manufacturer. This inadvertently led to the rapid deterioration and hence premature ageing of the CT causing it to fail catastrophically. REE had also found, by means of dissolved gas analysis (DGA), the presence of partial discharges that had led to the formation of gas in the oil and hence caused premature ageing of the paper insulation. During dismantling, some of the findings concluded to the presence of partial discharges related to burnt insulation paper. Insulation power factor testing of the oil at 90°C proved to be higher than the acceptable limits.

Some of the work performed by Chornogotsky *et al* (2002a) explains that some of the failure modes in power transformers are mainly caused by the inception of partial discharges in the oil due to the presence of moisture that is an effective result from bad sealing. With reference to table 2-1, this type of failure mode can also be adapted to CTs, whereby moisture ingress leads to contamination and then dielectric deterioration. The study also shows that the failure modes in CTs are considered as ionisation and ageing mode. In ionisation mode, "cold failures" could result in the colder part of the year from rapid cooling causing the production of air bubbles. In ageing mode, the failures that occurred were for CTs that were in-commission for a period of approximately two decades and were known as "hot failures" due to their failure nature during the warmer months. The results were increased dielectric losses flowing on to thermal increases causing ionisation in the CT Chornogotsky *et al* (2002a). In the experiment performed by Vandemaar & Wang, (1999g), and as indicated by Wilson, (2008e), the mechanisms that were found to be related to increased insulation power factor were related to the increases in the CT operating temperature, moisture ingress causing tracking due to the inception of partial discharges and high hydrogen content in the insulating oil indicative of partial discharge activity.

A mechanism of failure of the internal insulation in a CT, as described by Ali *et al* (1999a), is stated as a thermal form, whereby the insulation resistance decreases to a point where the power flow within the insulation increases with an increasing flow of resistive current. With this increase in power flow poses an increase in the temperature within that insulation and this increase in temperature in turn reduces the insulation even further causing increased insulation deterioration to a point where the insulation breaks down completely. Another mechanism of failure, as described by Ali *et al* (1999a), is the inception of partial discharges within the internal insulation of the CT. Given that partial discharge inception may be minute, if left to continue, it will cause failure of the internal insulation. These partial discharges result in the production of gasses and by-products of carbon in the paper which is then only detectable by DGA.

In some of the network studies performed by Klusman, (1992), the mechanisms of manufacturing defects were found to relate to the failure of CTs. The type of sealing used between the head and base tanks to the porcelain structure caused the porcelain and the clamps to break with the development of oil leaks. The gaskets used during the manufacture stage allowed moisture ingress to values greater than that specified. In another CT failure, Shkolnik, (2008d) stated that the internal insulation failed due to the inception of partial discharges caused by the high levels of moisture in oil.

Studies by Griffin *et al* (1992) show that the quality and properties of the insulating oil in CTs, which is mostly used for electrical insulation, has a great influence over the insulation power factor and is a mechanism leading to increased thermal runaway causing failure. The extrinsic property of the insulating oil take into consideration the insulation power factor, which can change whilst in-commission, and also takes into consideration the moisture content in the oil and paper insulation. A high power factor in new insulating oil presumes the contamination due to moisture, where the high power factor in used oil indicates the presence of moisture, carbon and other deteriorating products that should be further analysed for deterioration identification. Under extreme stresses caused by voltage fluctuations, the oil was also seen to exhibit gasses and the formation of X-wax that could either be dissolved or cause breakdown in larger quantities.

Experiences in CT failures by Kakkar *et al* (2002b) have prompted the need to discover new methods of condition monitoring to curb such failures. In discovering the failures of the paper impregnated CTs, some mechanisms that relate to the failure were due to ageing of the insulation and as a result the dielectric losses were said to increase causing an increase in the insulation power factor. In other CTs, high moisture content and the inception of partial discharges due to the presence of voids in the insulation caused excessive amounts of carbon to be present in the oil and thereby leading to a premature CT failure.

2.4 Failure Experiences Related to High Insulation Power Factor of the Hairpin Type Current Transformer

CTs indicate a rate of failure over time that is similar in nature to the shape of a bath-tub curve as shown in figure 2-2 below. For the first phase, in the first two to three years, defects causing failure arise from the quality of workmanship during manufacture or the quality of materials used for the manufacture of CTs. During the second phase, failures arise due to the possible stresses imposed during system operation or the possibility of moisture ingress during operation thereby leading to the inception of partial discharges. In the third stage of failure, the ageing of the paper insulation results in the paper becoming thinner, thereby relating to a loss in dielectric strength and making it more prone to failure.

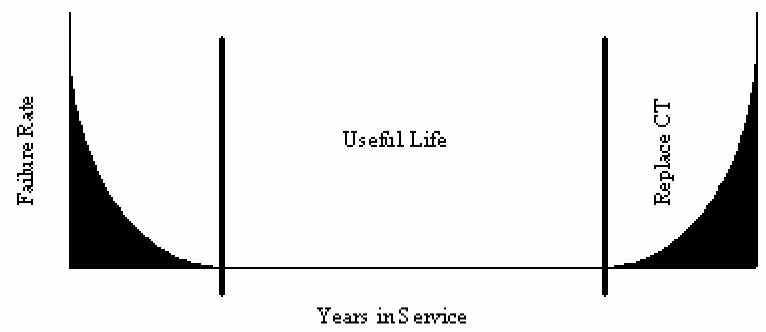

Figure 2-2: Bath tub curve indicating failure with time
Source: (Cowan & Neale, (2000b)

As stated by Heathcote, (1998e), failures resulting from the internal insulation are considered most severe that impose major financial difficulty. In some of the work performed by Chornogotsky *et al* (2002a), some of the failures related to the hair-pin type CT could not be correlated by the inception of partial discharges, yet were found to result from increased insulation power factor and dielectric losses. This then resulted in massive thermal increases in the dielectric due to the presence of high moisture content. The CTs were left in-commission even though the CTs were suspect with high values of insulation power factor. The consequence was an increase in dielectric losses which negatively affected the life of the CT leading to a violent failure during the hotter period of the year.

Experimental accelerated ageing tests on eight CTs were carried out by Vandermaar & Wang, (1999g) in order to establish effective condition monitoring techniques that could assist utilities in the reduction of the high number of in-service failure rates of CTs. During the test phase, certain parameters of continuous measurement on the CT were the measurement of partial discharges, insulation leakage current, insulation power factor and DGA. Moisture, temperature and acoustic sensors were fitted at strategic points on and around the CT to assist with more informed test results. During the accelerated ageing test phase, four out of the eight CTs failed. One CT that had failed was of a hair-pin design in nature. From figure 2-3 below, it was identified in the report by Vandermaar & Wang, (1999g) that the trend in the insulation power factor of the failed CT was ascending towards failure that saw a dramatic step change at the occurrence of failure. The step change in insulation power factor indicated the inception of partial discharge activity thereby providing a direct correlation between the two deteriorating factors.

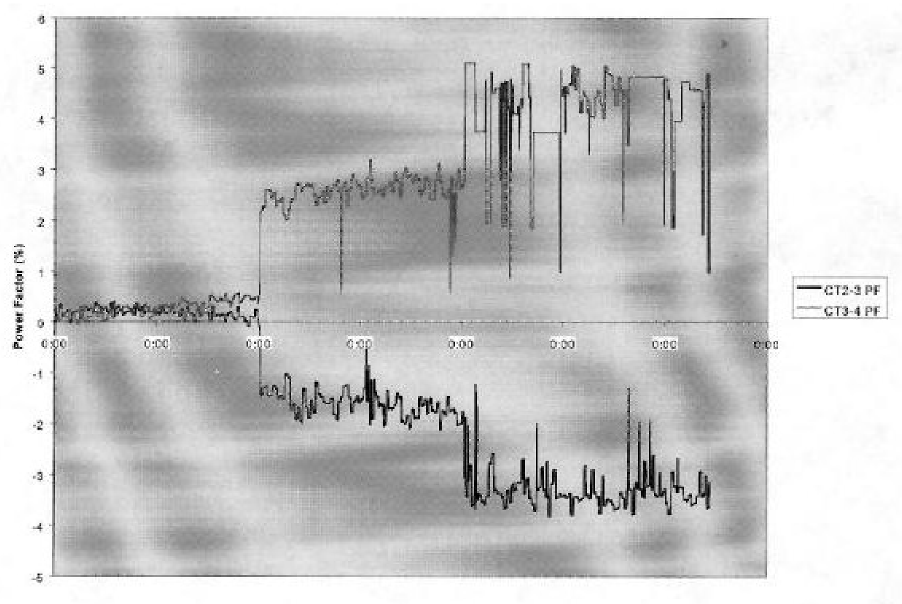

Figure 2-3: Insulation Power Factor change in Failed CT
Source: (Vandermaar & Wang, (1999g))

Upon dissection of the failed hair-pin type CT, the acoustic methods of partial discharge activity matched the evidence of tracking on the paper insulation layers, caused by the inception of partial discharges and were noted as in figure 2-4 below. This is indicative of permanent internal insulation damage, whereby the economic consideration for refurbishment would far exceed the cost of a new CT.

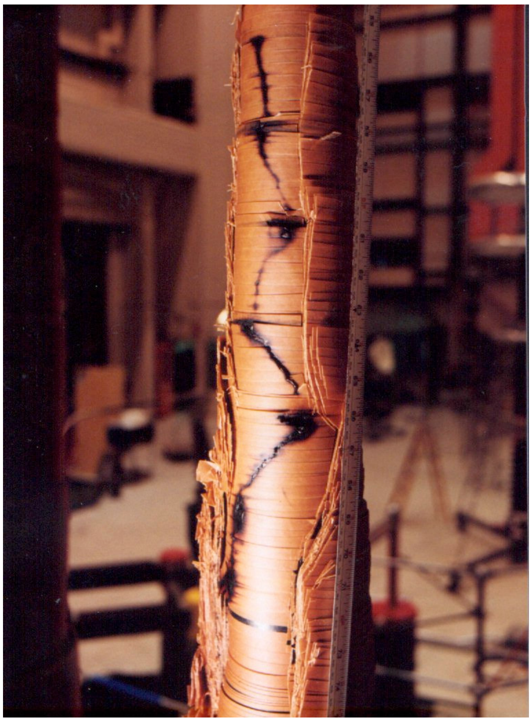

Figure 2-4: Tracking caused by the inception of Partial Discharges
Source: (Vandermaar & Wang (1999g))

In light of the above, Vandermaar & Wang (1999g) concluded that the monitoring of insulation power factor was the best method of warning against a potential CT failure.

To assist with enabling new methods of condition monitoring in CTs, experimental tests were carried out by Ayers *et al* (1999b) on three hair-pin type CTs rated at 345kV that were previously in-commission. The CTs were aged in a laboratory set-up with conditions monitored such as: insulation power factor, insulation leakage current, DGA and acoustic partial discharge measurements. Some of the findings post CT failure was an excessive increase in hydrogen content that reached above 45000ppm at the moment of failure. The results that conclude from the findings were the presence of X-wax formation on the paper insulation and between the turns of the paper insulation. This had developed due to minute partial discharge activity and the oil being electrically overstressed and as a result the oil could not effectively penetrate the paper as indicated in figure 2-5 below.

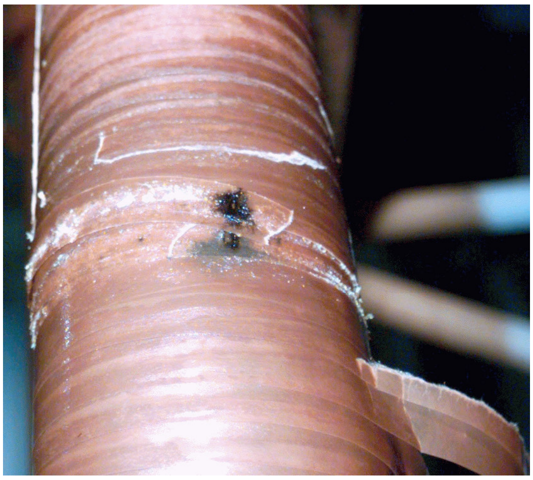

Figure 2-5: X-wax formation in the paper insulation

Source: (Ayers et al (1999b))

From figure 2-5, the formation of X-wax thereby halted all progression of the oil to impregnate the paper leading to a decrease in its dielectric strength capabilities and causing it to dry out and puncture.

Condition monitoring techniques, used by Cormack *et al* (1999e) went under scrutiny due to the large number of in-commission CTs that were failing. The CTs that were installed into the Eskom network were hermetically sealed thereby offering no opportunity of inspecting the condition and quality of the internal insulation. In the study done by Cormack *et al* (1999e), deterioration of the hermetic seal was found to be evident after thirty years of service leading to moisture ingress, deterioration and imminent CT failure. In the experience with the failure of CTs, the one CT that had failed provided signs of high levels of partial discharge activity.

Failures of the hair-pin type CTs, as experienced by Laasko, (1992) on the 500kV CT that had faulted whilst in-commission, showed signs of increased hydrogen content that was in excess of 36000ppm. In this type of oil impregnated paper CT, the inception of partial discharges became evident with the high gas content. The tear down analysis of this CT revealed the burning of the paper insulation and the formation of X-wax between the layers. As indicated in the study by Ayers *et al* (1999b), the formation of X-wax proved that the oil was electrically overstressed leading to the inception of partial discharges. Some of the other suspect CTs was found to have high levels of partial discharge activity that had an inception level of 350pC.

In the number of failures experienced by Moore, (1992), literature searches and tear down analysis indicated that further analysis was required. Some of the findings on the failure of the hair-pin type CTs were related to manufacturing defects causing stresses between the paper insulation layers. The presence of X-wax formation evidenced the presence of severe electrical stresses in the insulation. The insulation power factor of the naphthenic based insulating oil was substantially high relating to temperature variations within the CT. During oil testing, the insulation power factor of the oil increased from 1.06% to 15.07% between the temperatures of 25°C and 100°C respectively. This was alarming as the operating temperature of the CT resided at 75°C where the power factor of the oil was 7.46%. Poor quality of the insulating oil caused a decrease in the dielectric strength of the oil thereby relating to the number of CT failures experienced. Moore, (1992) hypothesizes that the mechanism of failure on CTs are as a result dielectric heating due to the high values of insulation power factor in the oil causing increased dielectric losses. A statement also made is for the insulating oil to be reviewed and replaced in all suspect CTs given the vacuum and temperature considerations.

2.5 Monitoring and Mitigation

From the different phases of proposed failure, phase one failures seem to be the most cost effective phase in which repairs can be performed, as compared to phase two and three. Failures in phase two and three would dampen economic consideration and hence prove to be technically unjustifiable.

Monitoring of the CT by performing visual checks for oil leaks, porcelain insulator damage, effective earthing and oil levels are described by Cigré b. (2009a) as minimal routine checks. From the failure survey performed by Cigré b. (2009a), oil analysis by DGA is considered as a monitoring tool, however the removal and replenishment of the insulating oil is a specialised field and if not performed correctly, will lead to premature failure of the CT.

The degradation of the capacitive paper and oil insulation in a CT is indicative during the tangent delta testing phase. The changing capacitance and an increase in the loss angle (externally influenced) provide evidence of this degradation as stated by Cowan & Grobler, (1998c). In the study performed by Chornogotsky *et al* (2002a), they indicate that the use of off-line diagnostic testing of CTs prove to be less efficient and less effective than that as compared to on-line testing. Belinska *et al* (1999c) suggests that early warning systems, such as the High Voltage Insulation Early Warning System (HVIEWS), used to monitor the insulation status in a CT by monitoring its tangent delta, could provide for that item of plant being removed from service prior to its destructive failure. This then reduces outage times, adjacent equipment damage and harm to personnel. The aim of using online monitoring system is for failure prediction and failure reduction on CTs and power transformers (Cowan & Grobler, (1998c); Chornogotsky *et al* (1998b)).

Ways to mitigate against a premature catastrophic CT failure are described by Pagan, (1998f) as the use of thermographic equipment, on site insulation power factor measurement and the use of DGA. The method employed by Pagan, (1998f) for monitoring the insulation power factor of the CTs was the use of the INSITE diagnostic system from Doble. This assists with the monitoring of the ambient temperature and relative humidity to determine insulation power factor fluctuations that can give forewarning of an impending CT failure.

Monitoring and assessment of partial discharge activity is seen as an essential tool in culminating the effects of a premature CT failure (*wikipedia*). In some of the work performed by Freisleben *et al* (2003c), the measurement of partial discharges is seen as essential in determining the expected life and quality of the internal insulation. They extend to say that the monitoring of such discharges has positive economic influences as the respective action can be harnessed in advance due to the effective trending offered by on-line condition monitoring equipment. The approach taken by Freisleben *et al* (2003c) is the use of phase resolved partial discharge recognition, whereby a partial discharge reference is set and a comparison is then made between the reference value and that obtained from strategic points on the CT itself. This then has a two fold effect in that it provides an indication of insulation condition and is used for data trending.

The use and stringent implementation of effective quality control procedures during the manufacture and construction phase of the CT should be emphasized as the starting point in achieving an increased lifespan of the CT. This would circumvent inferiority and assist with maintaining a reliable piece of power system equipment with no premature ageing. Certain items that are available for monitoring the CT are described by Cigré b. (2009a) as oil level indicators and threshold alarms. In higher voltage rated CTs, the indication and movement of the bellows in the head of the CT could depict low oil volume or the creation of gasses within the unit. Provision is also made by oil sampling valves to allow for dissolved gas analysis (DGA) for moisture and gas content (Ali *et al* (1999a)).

In the experimental tests performed by Vandermaar & Wang, (1999g), monitoring of the insulation power factor in CTs should be prioritised as the first line of defence in premature failure warning. A close follow up to insulation power factor measurement is that of partial discharge detection. The method of monitoring by DGA for the presence of excessive amounts of hydrogen in the oil, relates to partial discharges and with effective monitoring techniques, the CT could be removed from service prior to failure (Ayers *et al* (1999b)).

On-line monitoring techniques for CTs used by Ali *et al* (1999a) are the measure of capacitance and insulation power factor. The measurement of a CTs capacitance utilises the capacitance tapping point available in the secondary terminal box of the CT. The capacitance values are monitored by the measurement of current and the system voltage at the system frequency. Any changes in the typical values obtained are indicative of an abnormality within the CT insulation.

Power factor and capacitance monitoring were studied by Cherukpalli *et al* (1999d) on oil filled insulation equipment such as CTs. The use of the Carmanah Engineering Ltd. Substation Insulation Monitoring System (CEL SIMS) assists by measuring the leakage current from the capacitive tap point of the CT. The ability of the system to generate alarms when certain conditions are met is achieved by the measurement of the capacitance of the CT. The values obtained from this form of monitoring assisted with trending the insulation within the CT. From this, the measurement and monitoring of insulation capacitance and leakage currents could avert a catastrophic CT failure.

Studies performed by Ford *et al* (1999f) have shown that certain parameters such as stresses causing voltage variations, temperature variations and switching transients on the power network relate to accelerated degradation. This is seen to evolve into internal stresses within the turns of the paper insulation that allow a CT to fail prematurely. In relation to the studies that were performed, Ford *et al* (1999f) have decided, after laboratory experiments, to delve deeper into the mechanisms that relate to a failure and have resorted to look into DGA, the occurrence of partial discharges, leakage current and insulation power factor in CTs. An on-line non intrusive monitoring system was then decided upon to monitor the parameters as per the studies. The measurement of electrical and acoustical partial discharges on CTs in-commission has assisted the utility in removing a CT prior to failure.

In the experiences of Klusman, (1992), whereby the failures of CTs have relayed problems into the network, some of the major findings related to the cause of the failure have been noted as either manufacturing defects or the inception of partial discharges on the internal insulation of the CT. As a result of the CT failures, Klusman, (1992) has started certain mitigating techniques that will be seen to assist with partial discharge identification and the revision of certain manufacturing requirements. In doing so, test sets used for insulation power factor testing and partial discharge identification were developed.

Catastrophic CT failures have motivated the studies of Gillies, (1992) to review and enable the use of on-line monitoring techniques that can predict and circumvent an impending CT failure. In the tear down analysis of some of the CTs, evidence of partial discharge activity and the presence of X-wax formation prevailed due to slow degradation of the internal insulation. In mitigating such evidence of degradation, the technique of monitoring the pressure and temperature within the CTs was chosen to be best suited. The thermal increases within the CT provided an increase in volume of the oil which resorted to an increase in pressure within the CT. The pressure monitors verified the presence of a slowly developing fault which provided ample time for the failure to be averted.

In the studies on condition monitoring and diagnostics of high voltage equipment performed by Allan *et al* (1990a), three different types of diagnostic methods have been evaluated. It was postulated that the three methods are electrical, chemical and physical monitoring techniques. In the electrical method, the dielectric dissipation factor (DDF) for the measurement of insulation deterioration was highlighted. Allan *et al* (1990a) claims that this determines the level of moisture within the insulation and the insulating oil. Another method of monitoring was the use of partial discharge testing that can be detected (Wilson, (2008e)) through light, sound and heat. The technology behind this prevented the CT from being removed from service, yet could be inspected whilst in-commission irrespective of substation interference through increased noise levels.

In the chemical method of monitoring used by Allan *et al* (1990a), the checking of moisture content within the insulation was aided by the Karl-Fischer titration method. Further enhancement was when the experiences of Allan *et al* (1990a), on CTs that were marked as not economically suitable for refurbishment, used the CTs internal insulation for moisture content evaluation. DGA was also seen to be in effective use by Allan *et al* (1990a), which proved to provide information of high hydrogen content internal to the CT enabling its removal well in advance of failure. On the physical method of monitoring, the use of acoustic evaluation for partial discharge measurement was used.

In some of the experimental tests performed by Gubanski *et al* (1998d) on CT insulation diagnostics, the use of insulation power factor testing at 50Hz and at 80Hz proved as an alternate means of insulation condition verification. In their experiments, a total of nine CTs were subjected to various tests including insulation power factor testing. The results of the test are as indicated in figure 2-6 below.

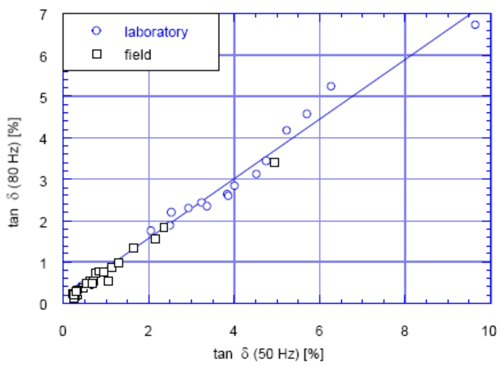

Figure 2-6: A Correlation of the Insulation Power Factor Values between 50Hz and 80Hz with a Voltage of 0.6kV and a Temperature Range of 18-22°C
Source: (Gubanski et al (1998d))

From figure 2-6 above, the tests were carried out in the laboratory as well as out on site and as can be seen, a linear relationship exists between the values obtained at 50Hz and at 80Hz. Gubanski *et al* (1998d) describes a mathematical relationship between the values obtained at 50Hz and that at 80Hz as:

$$\tan\delta_{80Hz} \approx 0.7 \times \tan\delta_{50Hz} \qquad (1)$$

From the above experimental test performed, Gubanski *et al* (1998d) postulated that performing insulation power factor tests at 80Hz is seen as another successful technique in determining the quality of the internal insulation of a CT.

As stated in Arp *et al* (1988), that the insulation power factor of the CT will increase due to deterioration within the insulation, the measurement of such will provide clarity on the quality and reliability of the internal insulation. In some of the monitoring techniques used by Arp *et al* (1988), the power factor monitor has been identified. This measures the voltage on the same bus, through the use of a potential transformer, and uses this as a reference point to the leakage current that is measured on the CT. The point of leakage current measurement on the CT is through the capacitance tapping.

These signals are then fed into a microprocessor for integrated sampling to determine the angle between the respective voltage and current. For good power factor readings, the value should be near 0%, however the above method provides indication of 100%. For compensation, Arp *et al* (1988) decided to delay the voltage by 90° digitally, as current leads the voltage by an angle of 90° for a capacitive circuit. The effect of temperature on the power factor readings indicated to Arp *et al* (1988) that when the insulation power factor has been corrected for the respective temperature, long-term changes in the insulation could be identified; however, if the power factor was not corrected for temperature, an incipient CT failure was then prevalent. In concluding the experiments, Arp *et al* (1988) postulated that the measurement of insulation power factor using the power factor monitor gave the best warning against a premature CT failure.

2.6 Conclusion

The review shows that the use of CTs in the power network is essential to the operation and control of the power system, as it provides the “eyes and ears” to the central control station during normal and abnormal system operation. The catastrophic failure of such equipment is identified to have detrimental effects on the power system, possible injury to personnel as well as a threat to the environment.

The literature review also highlighted that the deterioration of the insulation of CTs begins at the moment of installation, the rate of which is dependant on system conditions and maintenance schedules. From the improper checking and monitoring of this insulation deterioration, come economic impacts, technical losses and premature failures. With catastrophic failures of any piece of equipment installed in a substation, maintenance or the lack thereof is highlighted as a grey area in terms of not being able to identify potential deterioration of that piece of equipment. Most utilities generally carry out site inspections of their substations, but these site inspections do not necessarily provide evidence of a potential danger that might evolve, post inspection.

The review also highlighted various mechanisms relating to a CT failure, such as moisture ingress, leads to the paper insulation within the CT losing its dielectric capabilities thereby causing increased dielectric losses in the form of heat. The heat is then seen to reflect as additional power losses which further degrade the paper insulation. A trend towards the premature failure of the CT is then identified. Another failure mechanism that is directly correlated with the moisture has been identified as bad quality insulating oil. Oil with high levels of moisture was highlighted as a contributing factor to the paper degradation and the inception of partial discharges within the paper. The presence of voids in the paper insulation, due to improper impregnation processes, related to the creation of gasses within the oil that was greater than the solubility level of the oil. This progressed to tracking in the paper insulation adding to a CT failure. The maintenance of instrument transformers; in order to keep them dry, cool and moisture free; prevents the ageing acceleration of the paper and oil insulation (Fabre & Pichon, (1960)).

The literature review further highlighted the defects associated with the manufacturing of the CT, where oil leaks were identified in certain types of designs. Internal insulation differences came into the spotlight during the CT tear down analysis. Investigations indicate that the capacitive voltage grading in the paper insulation among certain units of the same manufacturer differed substantially. This related to the substantially high values of insulation power factor. A combination of high moisture content, bad quality insulating oil and the inception of partial discharges were identified as the main mechanisms related to high insulation power factor of the internal insulation of the CT.

The review shows that from the various experiences of hair-pin type CT failures, the mechanisms related to the failure have three distinct regions. The first region could result from defects during the manufacture stage thereby relating to early failure. The second stage relates to power system condition influence such as switching and lightning surges thereby reducing the lifespan of the CT. The third stage of failure is due to age of the CT after the experience of a number of year’s in-commission and enduring the power system transients. It has been hypothesised by the author that high levels of insulation power factor leads to premature CT failure and in the experiences of the various CT failures, a direct correlation is evidenced with the ingress of moisture causing increased levels of insulation power factor and hence the inception of partial discharges within the internal insulation. The combined effect is then exhibited as a catastrophic CT failure.

The literature identified possible methods that could be utilised for monitoring and mitigation of potential hair-pin type CT failures. Methods of evaluating the CT on-line through thermal and acoustic methods of partial discharge measurement have found to assist utilities worldwide in circumventing certain CT failures. The insulation power factor measurements on-line using the Doble INSITE method is seen to give adequate time, by means of data trending, to take the necessary precautions of an incipient CT failure.

With proper and regular maintenance on CTs, their premature failure can be averted and their operational safety and quality can be maintained. The importance of safety of operating personnel is of utmost importance within the confines of the high voltage yard. It is for this reason that failure modes of CTs and other equipment go under scrutiny. In paper-oil CTs, degradation can start off as a time consuming process that suddenly increases to failure (Cigré b. (2009a)).

CHAPTER 3: THE DESIGN AND CONSTRUCTION OF A HAIR-PIN TYPE CURRENT TRANSFORMER

3.1 Introduction

This chapter aims to review the hair-pin type CT from its principles of operation indicating the various areas of induced errors through to the construction and manufacturing of the CT. Various components that make up the hair-pin type CT are reviewed and that if not designed correctly, could aid to the mechanisms related to the high values of insulation power factor in the CT thereby contributing to its premature life and hence destruction.

3.2 Principles of Operation

The measurement of current is based on the principle of having a ferro-magnetic core with a set or sets of windings to produce the magnetic coupling (Cigré b. (2009a)). A CT therefore constitutes a set of windings wound around this iron core. With the primary conductor through the middle of the iron core, the voltage drop across the CT is negligible in comparison to the power system voltage. CTs operate on the principle of variable flux whereby the alternating voltage and current on the primary winding produces an alternating flux in the core of the CT. This alternating flux then produces a secondary voltage. With an electrical load, being a relay or meter, connected to the secondary of the CT; the flow of the current on the secondary will induce an equal flux in the core that will oppose the flux induced by the primary as depicted in figure 3-1 below.

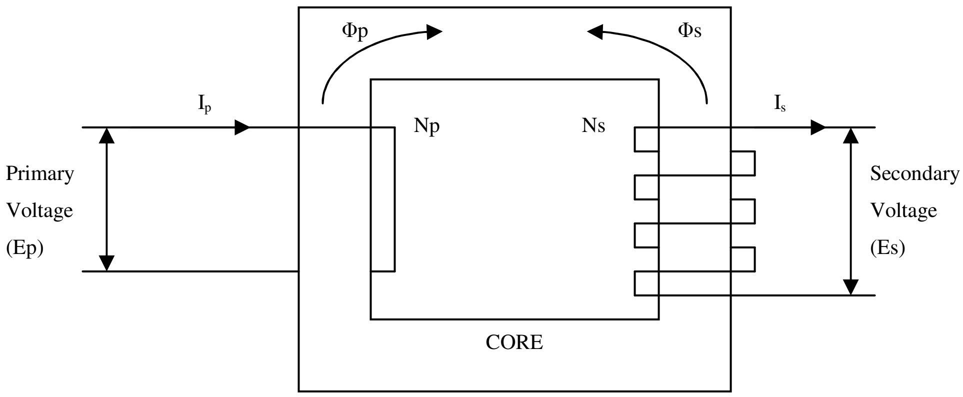

Figure 3-1: Basic CT Equivalent Circuit
Source: (Van Zyl, (1998g))

In the case where the secondary flux resembles the flux created by the primary, the following equations become true:

$$Ep = Np\frac{d\Phi}{dt} \tag{1}$$

$$Es = Ns\frac{d\Phi}{dt} \tag{2}$$

Where,

E_p = Primary Voltage

E_s = Secondary Voltage

N_p = Number of turns in the primary

N_s = Number of turns on the secondary

Φ = Magnetic Flux in Webers

t = Time in seconds

From equations (1) and (2), the voltage across a coil is then equal to the number of turns of wire in that coil around the core multiplied by the instantaneous rate of change of flux linked to that coil.

As the flux is equal in the core, equations (1) and (2) can then be equated to conclude:

$$\frac{Ep}{Es} = \frac{Np}{Ns} \tag{3}$$

A CT can essentially be stated as a short-circuited transformer in which the voltage at the secondary is zero and the current used for magnetization is so minimal that it can be considered negligible (Cigré b. (2009a)). From this, and using the basic transformer principle, the currents produced are seen to be inversely proportional to the voltages on the primary and secondary. The design of a CT goes in to produce a secondary current I_s which is in proportion to the primary load current I_p. This proportionality of the primary to the secondary provides the ratio (K) of the CT. The proportionality can also be extended to the primary and secondary turns and is expressed in equation (4) as ampere-turns balance.

$$K = \frac{I_p}{I_s} = \frac{N_s}{N_p} \tag{4}$$

The primary winding of the CT is connected in series with the power network and this ensures that the secondary output current is completely dependant on the primary current. This also ensures that the secondary current is completely independent of the load terminated on the CT secondary.

Reviewing figure 3-2 below, the following advantages are accounted for through the introduction and use of CTs (Cigré b. (2009a)):

- It allows for the standardisation in ratings of secondary plant equipment thereby assisting with cost reduction and design variations,
- CTs enable the secondary plant equipment to be adequately insulated from the HV thereby enabling its safe operation,
- Versatility is offered in terms of being able to connect more than a single secondary plant device to the CT secondary,
- It permits the use of safe substation operation.

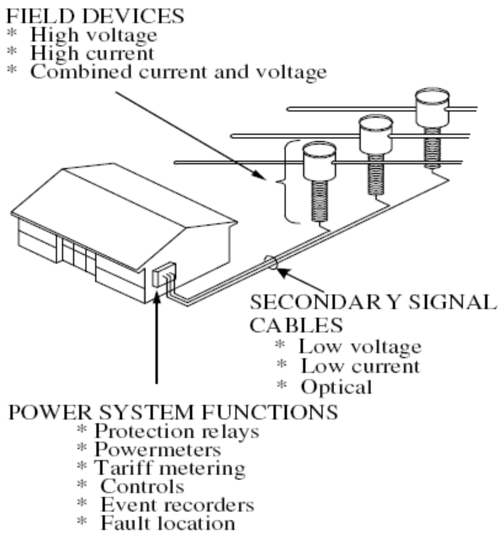

Figure 3-2: CT operational diagram

Source: (Cigré b. (2009a))

3.2.1 Current and Phase Errors

In an ideal CT, the secondary current should be exactly equal (when multiplied by the turns ratio) and opposite to the primary current and equation (4) would stand true. In practical CTs however, some of the primary current is used to excite the CT by magnetizing the core as depicted in figure 3-3, thereby leaving less than the actual primary current to be transformed into the secondary current. A current error (ε) is then introduced in this transformation as the actual transformation ratio is not as rated.

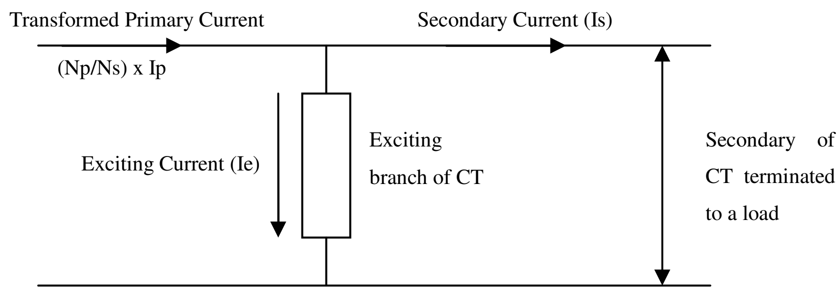

Figure 3-3: Simplified Equivalent CT diagram

Source: (Sjövall, (2005c))

From equation (4), and using figure 3-3, the secondary current can then be depicted as:

$$I_s = \frac{N_p}{N_s} \times I_p - I_e \tag{5}$$

The current error (ε) is expressed in percentage as:

$$\varepsilon = \frac{(K \cdot I_s - I_p)}{I_p} \times 100 \tag{6}$$

The error (Ie) has a magnitude and phase angle, where the magnitude represents the ratio error, and the angle (δ) represents the phase error. This is then depicted vectorially in figure 3-4.

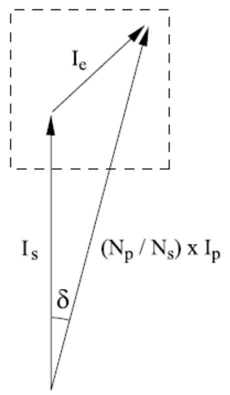

Figure 3-4: Vector Representation of Equivalent Diagram
Source: (Sjövall, (2005c))

From figure 3-4, the lower the value of (δ), the less the exciting current in the branch of the CT. High values of secondary current will produce a positive current error. A positive phase error will indicate the secondary current leading the primary current. CTs therefore need to be manufactured with minimal leakage resistance and reactance and an even lower winding resistance to minimise CT errors during calculations. This then reduces the flux and hence the heating in the core.

3.2.2 Error Variations with changing Current

CTs with a core consisting of grain-orientated steel do not have a linear excitation curve as depicted in figure 3-5 below and as a result; current errors found at two different points such as 2 and 4, with the CT maintaining the same burden, would be different.

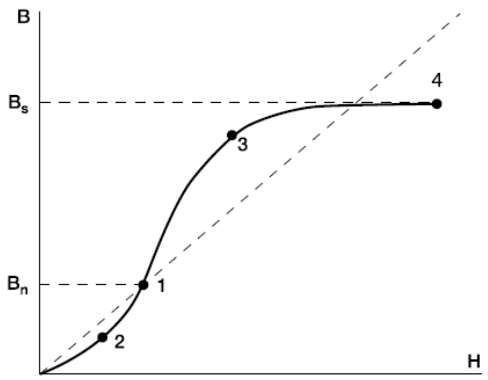

Figure 3-5: Typical CT Magnetisation Curve
Source: (Sjövall, (2005c))

Where: B = Magnetic Flux Density
H = Magnetizing Force

From figure 3-6 below, the error is seen to decrease with an increasing current. This is true until point 3 is reached, where any increase in current accelerates the increase in error. This then signifies the saturation in the core. For a metering CT, I_{ps} indicates the instrument security current and denotes the accuracy limit current for a protection CT. I_{pn} indicates the rated primary current and the ratio of I_{ps} to I_{pn} provides the accuracy limit factor (ALF) of the CT. The ALF of the CT is seen to be burden dependant and is generally indicated by the manufacturer in question.

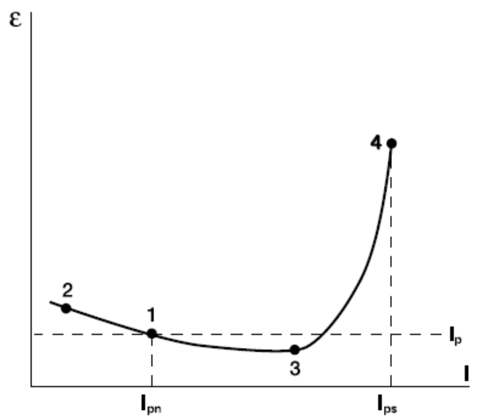

Figure 3-6: CT Error Diagram

Source: (Sjövall, (2005c))

3.3 Components of the Current Transformer

CTs used for HV applications are generally of the post type design. The entire arrangement is enclosed in an earthed base tank, which serves as oil containment as well as a support structure. The external insulator material is either porcelain or polymeric. The porcelain is generally thin and tall to provide the required isolation from earth. Within the arrangement, a hair-pin primary winding generally a conductor bent to the shape of a U, is inserted. At the head of the arrangement is a metal tank and just below this are two terminals marked P1 (primary) and P2, which provide the interface between the hair-pin primary conductor and the line of the HV network. This head tank is generally filled with nitrogen that serves to assist with the expansion and contraction of the oil.

In order to provide the measurement output of the CT, secondary windings made of copper are then mounted around the lower end of the primary conductor. In order to provide the secondary windings at a much lower voltage than the primary conductor, substantial insulation in the form of crêpe paper is provided between the primary conductor and the secondary windings. This solid insulation assists with the dielectric and mechanical isolation between the primary conductor and the secondary windings. With the primary conductor entering the tank, which is at earth potential, substantial insulation between the primary conductor and the tank are provided. In order to control the electric stress between the primary conductor and the secondary windings, metallic foil is inserted with the paper insulation at various levels to assist with the voltage grading.

To improve the insulation qualities of the paper, the entire arrangement is then immersed in naphthenic based virgin transformer oil. This not only serves as a dielectric medium, but also offers cooling by the dissipation of heat in the primary and secondary windings. Heat is generated by the power losses in the conducting materials used. This heat being generated utilises the entire arrangement as a transfer medium between the oil and the ambient air to inadvertently cool the CT.

The porcelain insulator is fixed to the earthed tank in one of two ways; either by clamping with the use of seals between the porcelain and the head and base tanks or by using a metal flange that embeds the porcelain to the two tanks (Cigré b. (2009a)). The two methods are depicted in figure 3-7 and figure 3-8 below. In Eskom Distribution, CTs are purchased with the porcelain insulator clamped to the head and base tanks.

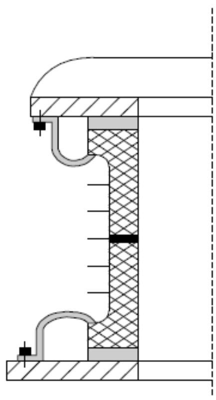

Figure 3-7: Porcelain Insulator fixed by clamping
Source: (Cigré b. (2009a))

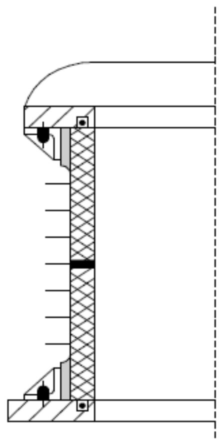

Figure 3-8: Porcelain Insulator embedded by the use of flanges
Source: (Cigré b. (2009a))

The earthed tank of the CT also encompasses the secondary terminal box. The secondary terminal box houses the conductor bushing for the secondary terminals that are insulated from the tank and are also oil tight. The terminal box also houses the terminal for the measurement of tan-delta of the capacitive insulation as well as an earth terminal as depicted in figure 6-1. The components within a hair-pin type CT are summarised using figure 3-9 below.

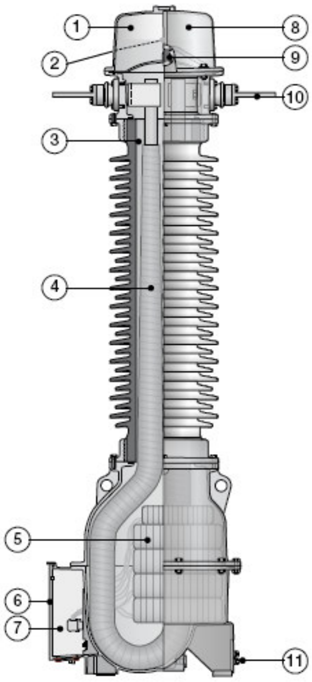

Figure 3-9: Hair-pin type CT
Source: (Sjövall, (2005c))

Where:

1. Nitrogen cushion for expansion and contraction.
2. Oil filling point.
3. Quartz sand filling for stability of secondary cores.
4. Paper-foil insulation.
5. Secondary windings.
6. Secondary terminal box.
7. Tan-delta test point.
8. Head tank.
9. Oil level inspection glass
10. Primary terminals.
11. Base tank earth terminal.

3.4 Design of the Current Transformer

The basic design of every CT is essentially a primary winding with a set of secondary windings uniformly distributed around a gapless toroidal ferro-magnetic iron core (Mariani, (2007b)) as depicted in figure 3-10 below. In a CT design, the efficient coupling (*wikipedia*) between the primary and secondary must be met in order for the accuracy in transformation to be met.

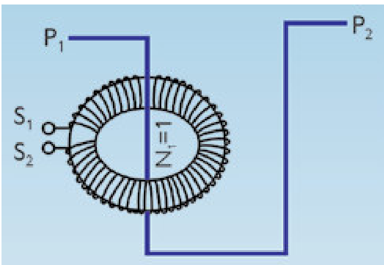

Figure 3-10: Bar primary with secondary winding
Source: (Mariani, (2007b))

Where: P_1 = Input Primary Current
P_2 = Output Primary Current
S_1 = Output Secondary Current
S_2 = Input Secondary Current
N_1 = Number of Turns of Copper Wire on the Primary

Utilising the list of components of the CT as discussed in section 3.3, forms the basis of the design of the CT in its entirety. In terms of the secondary cores containing the secondary windings being stacked on top of one another and hence installed around the primary conductor in the earthed base tank, the hair-pin type CT is then designated to be described as a dead tank design as indicated in figure 3-9. CTs in use for Eskom Distribution are designed to meet the IEC 60044-1 standard and NRS 029:2002 specification with the inclusion of ED's specific requirements. With the CT conforming to these design requirements, their approximate life of 25 years must still be maintained (Cigré b. (2009a)).

The secondary cores of the hair-pin type CT are of a ring core construction and are designed such that the changes in the flux in the core are proportional to the secondary winding due to the ampere-turns balance condition (Wright, (1968)). For the reduction in exciting currents in the CT, cores with a minimal diameter and greater cross-section should be designed. This diameter is dependant on the size of the primary conductor after the incorporation of the paper insulation. The cross-section is dependant on the amount of space available in the base tank. For good accuracy, as in metering, the current in the magnetising branch must remain low. This can be achieved by avoiding air gaps in the core and by using special materials such as grain orientated steel with high permeability. The thickness of the wire used for the secondary windings are dependant on the requirement, be it main or back-up protection, bus-zone protection or for energy metering. These wires are designed using high grade material that is insulated by means of enamel or varnish with uniform distribution around the cores. With the design of these multi-cores, functions can be duplicated leading to increased reliability (Cigré b. (2009a)). In the design, for reducing errors, the high permeability of the core material is seen to be most important (Wright, (1968)).

The design of a hair-pin type CT utilises a primary hair-pin shaped conductor that must be able to continuously transfer its rated current as well as withstand various transient and through-fault currents. The dimensions for the primary terminals are therefore designed to adhere to the NRS 029:2002 specification in terms of its maximum allowed current carrying capability. The outer diameter of the primary conductor is designed for the ease of voltage stress handling between the primary and the last earthed foil screen. To aid oil circulation that assists with cooling and the reduction of I^2R dielectric losses, certain hair-pin designs of the primary conductor of lower voltages encompass laminated sheets of copper that are bound together at the primary terminals (Cigré b. (2009a); Cigré c. (1990b)). As given for power transformer core designs, the laminations prove to be successful in the reduction of eddy currents (Heathcote, (1998e)). At higher voltages of 132kV, solid copper bars in the shape of a “U” are used as the hair-pin primary.

The internal paper insulation is inserted between the primary conductor and the secondary cores and its sole purpose is to supply the primary signal to a much lower voltage secondary signal (Cigré b. (2009a)). The quality of the paper and metallic foil sheets around the primary conductor as well as the oil are essential to the proper, maintenance free operation of the CT. The paper used must have excellent dielectric strength capabilities with low dielectric losses and should have a high mechanical strength (Wright, (1968); Mariani, (2007b)). For internal insulation condition verification, a capacitance tap from the last metallic foil sheet must be provided for insulation power factor measurement purposes as specified by ED. The crepe paper is produced by utilising the fibres obtained from pure

wood pulp thereby ensuring the compliance to standards internationally. The crepe paper used has a wide enough surface area to help with the cooling by oil retention.
The number of effective layers of alternating paper and foil is dependant on the specified voltage rating of the CT. For a 132kV rated CT the number of effective foil screens used for the capacitive voltage grading is six to achieve the 60pF capacitance as per the manufacturer in question. This essentially gives a capacitive voltage grading of 22kV per layer of foil from 132kV to 0V. The last capacitive grading screen is terminated to the base tank in the secondary terminal box which is at earth potential as per figure 1-1. With this tapping in place, the ease of internal primary insulation power factor measurements to determine the quality and reliability of the insulation can be performed. The paper insulation must take into consideration the internal dielectric losses I^2R as this leads to internal heating and accelerated ageing causing paper deterioration.

During the internal insulation design phase, the properties of the insulating paper and oil; with respect to its reaction in the event of partial discharges; must be reviewed in its entirety, after considering its mechanical and thermal characteristics. This paper insulation must be designed to be wound with sufficient overlap (Cigré b. (2009a)) as any large spaces between the layers will allow the inception of partial discharges due to the presence of numerous oil channels. The insulation power factor must be limited to ensure thermal stability, as the factors that could influence the power factor are seen as moisture in oil or contaminants in the insulating oil (Cigré b. (2009a)). For a CTs continuous current rating, the design parameters should prevent the inception of partial discharges (König & Rao, (1993)).
The external insulation of the CT is generally made of the porcelain structure that has a two-fold purpose in that it houses the primary conductor inclusive of the insulating oil and is used for the support of the base and head tanks. The mechanical forces that act on the porcelain as a result of the support, determines the thickness of the porcelain to be used. The porcelain is also designed in a manner that is able to limit the pressure wave caused during faults on the power network. This is achieved by the installation of a fibreglass tube containing epoxy for reinforcement (Cigré c. (1990b)). The outer creepage distance, on the porcelain to increase the tracking distance, must be specified during manufacture and ED specifies a creepage length of the porcelain insulator of 31mm/kV with a shed shape indicative of the prevention of moisture in the event of the rain being at an angle of 90°.

The materials used in the base and head tanks are designed to protect or minimise against the effects of corrosion, as it is the corrosion on the inside of the base tank that leads to premature ageing of the CT (Cigré b. (2009a)). The head tank must be designed to incorporate an oil filling plug as well as a sight glass to indicate the respective oil level with the CT. Different head designs incorporate the use of fins used for heat-sinking, as it is in the head that most of the heat is dissipated due to natural convection of the oil within the CT. The metallic head tank is bonded to the P2 side of the CT and is insulated from the P1 side of the CT such that during a flashover from the head tank to earth, selective clearing of the fault can be achieved. With this bond, the stresses applied between the head and the P1 terminal of the CT must be sustainable to prevent the breakdown of the CT internal insulation or the insulation in existence between the head tank and that of the primary P1 terminal (Cigré c. (1990b)). The base tank is generally designed to accommodate the secondary cores situated around the primary conductor. For the prevention of corrosion, the tank should be hot-dipped galvanised or painted with specific heat and oil resistant paint. The base tank contains four holes that enable the CT to be mounted onto the lattice structure. Both the tanks are joined to the porcelain insulator by using oil resistant "O" ring type seals.

The entire arrangement is immersed under pressure in naphthenic based mineral oil which has specific dielectric as well as cooling properties. The electrical and chemical properties of the insulating oil could affect the quality of the oil and the CT in its entirety and hence must be reviewed prior to the addition of the paper insulation. Gas absorbing properties of the oil should be as high as possible to withstand the high operating voltages and electrical stresses during system abnormality. One of the important criterions for the insulating oil is its ability to act as a heat transferring medium between the secondary windings and the base tank. The aim in adding pressure during design phase is to raise the partial discharge inception voltage (Cigré b. (2009a)). The insulation power factor of the oil must also be measured in accordance with IEC 60296 and a value at 90°C should be 0.3% and a value at 20°C should be 0.05%. Some CT designs incorporate the addition of quartz sand filling in the base tank to assist with the mechanical stability of the primary conductor. Insulating oils are said to exhibit intrinsic and extrinsic (Griffin *et al* (1992)) properties, where the intrinsic properties are crude oil dependant and are generally stable. Extrinsic properties are those properties, as discussed in (Griffin *et al* (1992)), as those that are affected by insulation power factor, moisture content and dielectric voltage.

Sealing together the porcelain with the head and base tanks are essential parameters in the design. The form of sealing adopted and mechanical stability offered by these gaskets is directly proportional to the performance of the paper and oil dielectric. The design based on figure 3-7 is the preferred ED option; however this could be seen as an infringement due to the grinding and clamping (Cigré b. (2009a)) thereby causing undue stress on the porcelain insulator. This type of sealing must also be designed to withstand the various temperature fluctuations of the CT during operation.

The secondary terminal box design incorporates the terminations for the secondary of the CT. These terminations are designed to be insulated from the base tank of the CT, where the quality of material used for the insulation depends on the oil-tightness and the possibility of moisture ingress (Cigré b. (2009a)). It is in this box that must incorporate an earth stud, a gland plate for the secondary cabling as well as a breather to allow the prevention of moisture build-up. A waterproof cover plate is designed in accordance with IEC 60044-1.

In designing CTs, the rated voltage must be withstood for the life duration of the CT. During system short circuits and transients caused by lightning, the capability of the insulation in the CT is designed to withstand the mechanical and electrical stresses and should be determined by the short circuit test phase after manufacture. The ability of the internal insulation to withstand electrical stresses, caused by switching surges leading to high frequency current fluctuations (Cigré b. (2009a)), is essential in the prevention of partial discharge inception that could evolve in the paper insulation and lead to failure of certain designs of hair-pin type CTs.

The design of the CT can then be seen as a steel laminated core of a ring formation containing many turns of copper wire to form a secondary output. The primary is then a single copper bar over which the secondary steel core is situated. In the overall design process, the compatibility of the various materials used in the production of the CT; the internal shielding against faults on the secondary circuit; the internal insulation withstand capabilities against transients; the ability of the CT to handle temperature and stress variations and the ability of the internal and external of the CT to remain stable during transportation is of prime importance to ensure the safe operation of the CT (Cigré b. (2009a)).

3.5 Construction and Manufacturing of the Current Transformer

CTs are manufactured in accordance with the specifications and requirements that are laid down by ED. The secondary cores are carefully placed around the base of the hair-pin primary conductor, as depicted in figure 3-9, and the number of cores as specified by ED for a 132kV CT is six with their respective classification as indicated in appendix 2.

The primary hair-pin conductor, together with the secondary cores, is placed into the base tank. This base tank is welded together for oil tightness and corrosion prevention during manufacture. In the base tank is where the secondary cores are insulated and terminated to the secondary terminal box together with the last capacitive grading screen on the insulation of the primary conductor. This termination of the grading screen is a removable connection to the tank which is at earth potential to allow for insulation power factor testing of the primary insulation.

During construction, the connection to the capacitive tapping should be a strong connection that can be achieved by soldering to the last screen. This prevents unnecessary arcing leading to the deterioration of the CT (Cigré b. (2009a)). It is seen and discussed by Heathcote, (1998e) that the condition of the internal insulation dictates the life of the CT. The porcelain insulator is then placed over the primary conductor allowing the primary conductor to be terminated to flexible terminations at the head of the CT.

To complete the construction of the CT, the head tank is then fitted and fastened to the porcelain insulator. This head tank of the CT has an oil filling plug where the de-gassed naphthenic based oil is then filled through under vacuum to prevent moisture ingress Heathcote, (1998e). It is important to note that as the temperature of the oil increases, so to does the content of moisture within the oil. This can have negative effects of the dielectric quality of the oil whilst in the operating temperature ranges. The top of the head tank is topped with nitrogen gas to allow for fluctuations in oil temperature variations caused by varying weather and power system operating conditions. The CT is then pressure tested for the presence of oil leaks. Of the tests that are performed after construction and manufacture, the measurement of insulation power factor and the presence of partial discharges are considered more important to the operating life of the CT.

For the construction and manufacture of the hair-pin type CT, the internal primary insulation is thoroughly dried in an oven to rid moisture. This paper is effectively degassed and impregnated with the insulating oil under vacuum. Prior to drying, 7% to 10% moisture content is justified; however a 0.2% limit must be reached post drying (Cigré b. (2009a)). If the drying process is too quick, the moisture will not be eradicated effectively and on the contrary; if the process involves an excessively high temperature, vacuum at pressure must be maintained to prevent the deterioration of the paper insulation as seen in figure 3-11 below.

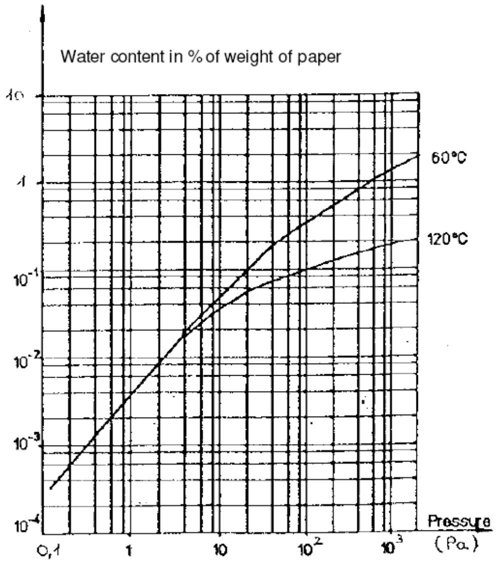

Figure 3-11: Applied pressure and temperature for paper insulation drying
Source: (Cigré b. (2009a))

The composition of the internal primary insulation is alternate layers of paper with foil to assist with the linear voltage grading, as depicted in figure 3-12 below.

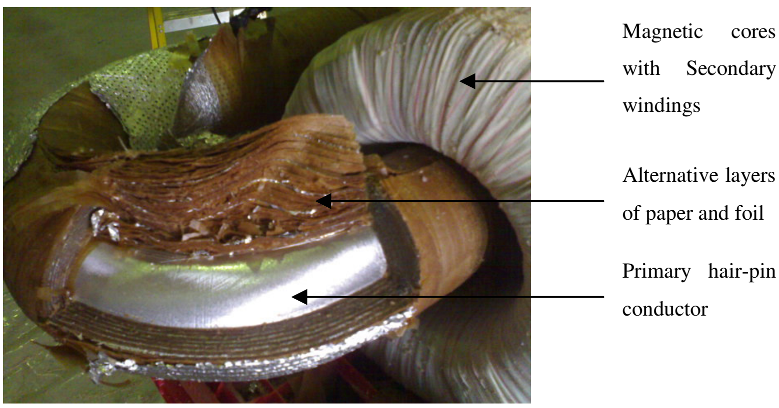

Figure 3-12: Cut-away of internal primary insulation in a hair-pin type CT

From figure 3-12 above, it is evident that the primary hair-pin conductor must be void or burr free to assist with the intimate wrapping of the paper and foil alternate layers. Effective quality control during manufacture is essential to prevent the use of multiple pieces of foil per capacitive layer as the effective capacitive voltage grading would not be maintained. With the presence of impurities, such as moisture, on the primary conductor or in the paper insulation, the inception of partial discharges could then develop leading to insulation deterioration prematurely.

During the design phase of the CT, cost implications and the amount and quality of material used for the construction and manufacture phase of the CT becomes a trade-off factor, as the CT has to function at greater levels of electrical stress. This evidently enhances the possibility of a defect in the internal insulation during the manufacturing phase which could lead to a possibility of partial discharge inception (Bleyer & Prout, (2005a); wikipedia). This partial discharge will continue to exhibit deterioration until failure envelopes the CT (Mariani, (2007b)).

Hermetic sealing of the CT, to prevent moisture ingress and the accumulation of dust and air into the CT, requires careful attention to detail during design and manufacturing. This has a direct effect on the dielectric performance (Cigré b. (2009a); Shkolnik, (2008d)). The use of sealing the porcelain to the head and base tanks of the CT by means of clamping, as described in figure 3-7, is a method employed by the manufacturer in question as specified by ED. This form of sealing, whereby the seals are below the internal oil level, prevents the CT from breathing-in the moisture from the ambient air. The more prevalent oil leak would provide visual indication in the event of a compromise in the hermetic seal through a defective sealing gasket.

3.6 Conclusion

CTs are seen to provide a simplistic and cost reduced method of measuring current flow in the primary HV power system, whilst still maintaining the intended accuracy. The main problem associated with this type of CT is the need to connect the HV of the power system to a very low potential being earth. This then magnifies the issue of the insulation between the primary conductor and the secondary windings in a confined space. Analysing the various technologies involved with the design of CTs, the betterment of one type of design does not necessitate the irrelevance of another (Cigré c. (1990b)), however, a bad design (Cigré b. (2009a)) is singled out to be one of the causes of failure.

From the principles of operation, separate CTs are used to supply the input to the metering and protection schemes. These are of a post type nature where the primary bar is in the form of a hair-pin tube. The insulating oil with the oil-impregnated paper by Wright, (1968) is considered to have high dielectric capabilities. Alternate layers of paper and foil are arranged to reduce the voltage stress between the primary conductor and the earthed base tank. The ingress of moisture into the insulating oil or the paper insulation relates to the serious deterioration of the insulating medium. The requirement from ED is then for all post-type CTs to be hermetically sealed that prevents the internals of the CT coming into contact with the ambient air.

The CTs used by ED are designed to perform under extreme conditions of power system transients and high energy faults. This design must also be extended to extremities in the ambient environment related to temperature fluctuations, rain, storms and increased pollution (Cigré b. (2009a)). During the operation of the CT under such conditions, the limits of accuracy and adherence to specifications must be maintained even with minimal maintenance (Cigré b. (2009a)).

The CT, during transportation to site, can undergo various mechanical vibrations. These are seen as a contributing factor to a CT failure, as leaks could develop by the loosening of the nuts and bolts as well as the disturbance of the stability of the internal oil and paper dielectric (Cigré b. (2009a)). It is evidenced that the quality of the materials during the construction and manufacture stage is of prime importance to ensure reliable and service driven operation of the CT. The equipment used for testing the CT after construction and manufacture on the workshop floor, must be regularly calibrated with a reference standard for the assurance of test results to be within specification and to serve as a point of reference.

CHAPTER 4: TESTING OF A CURRENT TRANSFORMER

4.1 Introduction

The testing of CTs from manufacturing to commissioning is essential for the verification of design parameters and manufacturing quality of workmanship. Every CT that is designed and manufactured must undergo some form of testing to prove compliance and to assure the customer that the specific requirements are met. CT reliability related to its continuous years of being in-commission is seen to be of utmost importance and it is in the testing of such instruments that proves its quality of design and estimated lifespan.

The purpose of this chapter is to distinguish the various tests, related to or has an effect on power factor measurement that the CT must undergo in order to prove its quality and acceptability for use on the Eskom power network. For the purposes of this study, and utilising the IEC60044-1:2003 in conjunction with NRS 029:2002 specifications, the following tests with respect to the hairpin type CTs will be discussed.

4.2 Design Tests

Design tests are intended to prove the integrity of a particular design. Design tests provide assurance as to the ability of the CT to withstand potential system stresses imposed on it for its estimated life expectancy. With concentrated internal insulation, the thickness of the paper insulation is directly proportional to the voltage rating of the CT (Cigré b. (2009a)). For a 132kV (rms) CT, the rated primary conductor insulation level must therefore meet the Basic Insulation Level (BIL) of 550kV as per IEC 60044-1 specification, table 3. Given the maximum current rating of 2500A for a 50Hz, 132kV CT, the design test must also indicate the CTs thermal stability under normal and abnormal operating conditions. In accordance with IEC 60044-1, design testing of CTs should include a power-frequency withstand voltage test that is in compliance with table 5 in that specification, as well as partial discharge measurement testing.

High quality insulation paper combined with metallic foil sheets provides the voltage gradient between the primary conductor and earth. This paper-foil combination is dried thoroughly and is then placed under a high vacuum and impregnated with the insulating oil. This is done to provide the moisture content to be below 0.5% within the paper-oil combination. During the design of the insulation, the number of foil sheets inserted in the insulation must prove to withstand the number of surges induced by the primary system. The last foil sheet layer is soldered to the wire and is then connected to the tap point. This soldered connection must be able to withstand the mechanical vibration influences during transportation as the loosening of this can be detrimental to the life of the CT (Cigré b. (2009a)). It is this tap point where internal insulation power factor measurements are taken to ensure compliance during design phase.

Design testing therefore verifies the quantity and quality of these metallic foil sheets installed and gives an indication to the manufacturer as to the quality of the materials used in that CT design. Experience has proven that one of the main causes of CT failures is as a result of bad design (Cigré b. (2009a)). Appropriate and effective testing to any design change is performed at the manufacturer's works to ensure the verification and suitability of such change. The reliability of the internal insulation and the lifespan of the CT in its entirety can be affected with the variation in designs of the expansion devices, due to the contamination of moisture from the ambient air (Cigré c. (1990b)).

In the design control process, insulation material compatibility and its stress handling capabilities must be taken into consideration and tested. With an exceptionally high electric field stress, rapid deterioration of the internal insulation will occur thereby limiting its expected life of approximately 30 years (Cigré c. (1990b)). The dielectric testing enables the verification of the type of workmanship used and also proves that the design of the CT is suitable for such tests. The oil used for insulation purposes must be tested for any trace of partial discharge as a result of the paper insulation experiencing a few steep front surges. In the IEC 60044-1 specification, the form of stress handling testing used is the multiple chopped impulses test.

After performing the design test, the oil medium is then tested by determining its dissolved gasses. The quantity of the dissolved gasses determines the quality of the oil which inadvertently predetermines the life of the CT. The properties of the oil must therefore be maintained, as poor quality can drastically limit the serviceable life of a CT (Cigré b. (2009a)). Internal insulation deterioration measurement is essential to the determination of the quality of the design of the CT and as a result, the power factor of the internal insulation is scrutinised during the design test phase.

Upon completion of the design testing, an acceptance of design must be provided. The procedure then takes on the next step of performing the type, routine and hence special tests on a single unit of the selected design of CT for design, construction and production verification.

4.3 Type Tests

Each type of CT that is developed with the same specification is subjected to a mandatory type test, as routine tests do not provide an indication that it complies with the requirements as stipulated in the IEC 60044-1 specification. This is then known as a Design Acceptance Test (DAT) that is performed on a prototype CT in the factory, prior to the CT being mass produced, for design approval. As the power network experiences stress variations, so to do the HV equipment installed and type testing of the CT provides assurance to ED that it can withstand those stress variations and various environmental conditions (Cigré b. (2009a)). The validation of type testing depends on the consistency of the materials used during the construction and manufacturing of the CT.

4.3.1 Short-Time Current Test

In the short-time current test, the manufacturer combines the dynamic test with the thermal short-time current test. This test is done with all the secondary cores short-circuited to prevent the substantially high secondary voltage at the secondary from developing, thereby leading to damage of the secondary insulation and hence CT destruction. For the period of this test, an assumption is made whereby the winding is seen to retain the heat as a result of all the energy being produced (IEEE, (1994)). The initial temperature, between 10°C and 40°C, and final temperature of the CT is taken into consideration thereby assisting with the evidence that the CT has passed this type test with no indication of internal insulation damage in accordance with IEC 60044-1 specification.

4.3.2 Temperature-Rise Test

Temperature-rise testing of the CT is essential to life of the internal paper insulation, as with excessive heat can degrade the paper to become brittle. Reduction in insulation can set in leading to voids being produced. These voids engage in partial discharges in the insulation causing rapid degradation of the internal insulation. The measurement of partial discharges provides evidence of design flaws.

4.3.3 Impulse Testing

Impulse testing identifies whether the CT can handle the number of lightning and switching surges on the power system. With the CT tank and secondary cores shorted and earthed, the CT is then subjected to fifteen pulses of both polarities of a value of 0.75 of its BIL. In all circumstances, the internal insulation of the CT should not depict any discharges or provide evidence of degradation or failure.

CTs that undergo type testing and pass prove their stringency in terms of appropriate design parameters, quality of materials used and the ability to meet international standards and specifications. The internal insulation of which, is the most important factor in proving a successful design.

4.4 Routine/Commissioning Tests

Upon completion of the type test on the prototype CT, every CT that is designed, developed and completed undergoes a routine test in the factory that is generally known as a Factory Acceptance Test (FAT) to indicate its compliance to the relevant specifications and hence for the approval of mass production of CTs. Routine tests are effective in the quality verification of the materials used during the manufacture and construction phase and provide an indication that the CT has not been damaged during the type testing phase.

4.4.1 Partial Discharge Test

Partial discharge testing is a non-destructive test and is a factory requirement for every CT manufactured. Partial discharges are described as an electrical discharge mechanism that causes the metallic foil layers in the insulation to be partially bridged thereby weakening the insulation properties of the paper-foil layers. These partial discharges can be existent for many years within the CT that will lead to the eventual breakdown of the CT, as the voltage stress grading around the primary conductor will be compromised (Heathcote, (1998e)). Testing for partial discharges in a newly manufactured CT is therefore of paramount importance and the level of acceptance, in accordance with IEC 60044-1, should be a zero tolerance with a level of charge of not greater than 10 picocoulombs (pC) (Cigré c. (1990b)).

4.4.2 Power Factor Testing

Power factor testing of the oil insulating medium as well as that of the paper-foil combination is performed as a routine test in the factory. This form of test is indicative of the moisture content within the insulation and depicts the conditions during processing of the CT. The moisture content within the oil is most important, as any value greater than 30 parts per million (ppm) measured at its ambient temperature, will contaminate the paper insulation thereby decreasing its lifespan (Cigré c. (1990b)).

Power factor testing is a direct implication of the losses within the CT and hence provides the means of indicating the resistance of the insulation, which should ideally be capacitive with minimal resistance. The value of the power factor must remain constant with increasing voltage; however, any reduction in the power factor value thereby indicates the presence of humidity within the paper-foil insulation. In accordance with the NRS 029:2002 specification, the power factor value of the CT must not be greater than 0.5% and with increasing voltage during the test, the difference in values must not be greater than 0.1%. During the time the voltage is being increased and decreased, the value must be recorded at 10kV on the test certificate for comparison purposes during commissioning.

4.4.3 Site Acceptance Testing (SAT)

Once the CT has been delivered to site, a Site Acceptance Test (SAT) must be performed by ED to ensure that the CT is still within specification and to initiate a log book pertaining to the maintenance of the CT prior to commissioning. The aim here is to determine if the requirements of the CT have differed to that from production and to identify whether the CT had been damaged in any way during transportation from the factory to site. The tests include visual inspection on the oil levels, whereby any substantial decrease in oil level could mean a break in the hermetic sealing thereby leading to an oil leak and the ingress of moisture. On the other hand, a substantial increase in the oil level is indicative of a faulty insulation (Cigré c. (1990b)).

4.4.4 Insulation Resistance Test

The verification of the integrity of the insulation between the primary, the secondary and earth is performed during commissioning to ensure that the CT that is placed in service has its insulation suited for the application. In accordance with Eskom b, (2009b), this test is done using a voltage of 5kV that checks the primary to secondary and primary to earth insulation with the secondary and tank earthed. Values of resistance of not less that 2MΩ/kV must be registered, enabling a value of 132MΩ for a 66kV CT and 264MΩ for a 132kV CT. Values less than that specified render the unit to be removed and inspected due to the possibility of internal insulation damage.

4.5 Special Tests

A special test is an agreement between the manufacturer in question and ED and differs from the type and routine tests performed as stipulated in the IEC 60044-1 specification. As indicated in the NRS 029:2002 specification, these tests are seen to be a direct relation to a Type test on a new make and type of CT and should be performed after the power frequency testing, the switching impulse tests and the impulse test.

Special tests incorporate the concern of measuring Tangent Delta (Tan δ) of the CT to provide an indication on the condition of the internal oil and paper insulation in terms of the power factor of the CT. The measurement of Tan δ on many CTs of the same type substantiates the quality assurance of the CT during its manufacturing process. This is a dielectric form of test that can cause harm to the internal insulation of the CT if tested frequently and with an increased test voltage, the effects can be quite severe (IEEE, (1994)).

CTs that have been in service for a few years do experience degradation of the paper insulation which leads to the development of moisture in the paper and hence oil. This moisture decreases the life of the insulation and causes the power factor value of the CT to increase substantially from the initial manufacture tested value, the limit of which in accordance with NRS 029:2002 is 0.5%.

Tan δ tests utilises a high voltage of 10kV in magnitude between the primary conductor and the last graded screen of the paper foil insulation around the primary conductor. The test measure the capacitive leakage current I_C from the primary conductor through the screen. The determining factor of the resistive current I_R is moisture in the oil, where a high value I_R indicates abnormalities in the insulation. Reviewing figure 4.1 below, the results of the test provide the ratio of the capacitive and resistive currents.

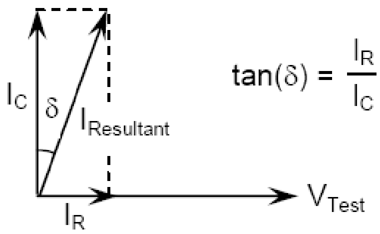

Figure 4-1: Tan Delta measurement indication
Source: (Eskom b, (2009b))

The ratio that tan δ provides must be at a value of 0.5% or lower to be in accordance with the NRS 029:2002 specification. An increased value of tan δ, indicates a decreased value in the resistance within the insulation. This adds to the power loss within the CT, thereby contributing to the reduction of its lifespan.

This test is performed at ambient temperature; with the voltage increased from 5% to 120% of its rated maximum voltage, and at 90°C; where the voltage is increased from 60% to 120% of its rated maximum voltage. The increasing effect of temperature has an increasing effect on the value of tan δ. The CT can be seen to have passed this test only if the difference in absolute value between the 5% and 120% of its rated maximum voltage does not exceed 0.1%.

4.6 Conclusion

Reliability is seen to be one of the key factors that are produced during the testing phase. The quality of the end product is seen to depend mostly on the quality of the components chosen for the specific design and the quality during manufacturing. To enable efficient and non-problematic manufacturing of CTs, the accuracy of testing at every point during construction is deemed essential. With the above in place for the manufacturer in question, the quality assurance can then be seen as a certification that the end product has achieved a high quality status. This can then be congruent with the reliability and stated service life of the CT.

The high quality of the internal insulation of the CT is considered to be especially important in the prevention of a CT failure and premature ageing (Cigré c. (1990b)). To ensure compliance with the high quality; partial discharges, thermal instability, proper and even voltage grading, and the prevention of moisture ingress are highlighted as being important deciding factors. From the tests described above, the test most frequently done is the measurement of power factor of the internal insulation medium. This goes forth to heighten and sensitise that a good quality design adds to the safety factor of the CT from manufacture stage to being in-commission.

During the routine test phase, it is clearly evident that every CT that is produced must pass prior to being sent out to the end user. Test certificates are the only way to identify and compare the test results with conformance to the relevant standards and specifications. Testing of the magnetization curve, polarity and ratio testing give evidence of the CTs performance and deliverables, but is not influenced by the deteriorating paper-foil insulation around the primary of the CT. Dissolved gas analysis (DGA), although very efficient in determining the degradation of the oil caused by the development of gasses by partial discharges, is not adopted by ED as the hermetic sealing can be compromised.

In testing CTs, proof is provided to indicate the quality of the components used that not only describes a good quality design, but that the design of that CT adheres and complies with international standards.

CHAPTER 5: PARTIAL DISCHARGES AS A CAUSE OF FAILURE

5.1 Introduction

Power system equipment insulation and its quality thereof is of utmost importance, as this ensures proper and stable operation of the associated equipment. This insulation can be compromised with the inception of internal partial discharges, whose magnitude of which can result in premature ageing, thereby leading to equipment failure and hence optimal power flow interruption. Sources of partial discharge emanate from the presence of moisture within the primary insulation, the production of tracking on the paper insulation, voids present in the insulation and the formation of gas bubbles in the oil (Wilson, (2008e)).

During the occurrence of a partial discharge, the transfer of energy takes place. A partial discharge is of such a short duration, that it does it does not draw energy from the source voltage during occurrence but rather introduces very short pulsed currents (Fruth & Fuhr, (1990c)). The measurement of partial discharge is based on the quantity of apparent charge (q) with its term of measure in pico coulombs (pC) (Cigré d. (2008b)).

The occurrence of partial discharges is entertained by local electric field ionisation caused when the dielectric strength, being the paper in oil, is less than the strength of the local electric field stress thereby leading to a breakdown in insulation (Cigré b. (2009a)). These partial discharges then emit thermal, acoustical and chemical phenomena in the dielectric that assists in the insulation deterioration (Fruth & Fuhr, (1990c)). Partial discharges are then described as a phenomenon that occurs as a result of the local electric field stress that is either in the insulation or is evident on the surface of the insulation (Kuffel *et al* (2000d)). This chapter aims to investigate and find correlation between high insulation power factor values and the inception of internal partial discharges related to a hair-pin type CT failing prematurely. The physics of the discharges begins the chapter and extends to the international standard and specification limits of partial discharges with premature ageing of the CT insulation as a conclusion to the chapter.

5.2 The Physics of Partial Discharges

PD's internal to the CT do occur in the solid insulating dielectric, that being the crepe paper; and in the liquid insulating dielectric, that being the naphthenic based oil. They are considered as localised gaseous breakdowns (Haddad & Warne, (2004)), whereby a follow up flow of current is not evident and is hence termed as a partial breakdown. The above is known as an incomplete breakdown (König & Rao, (1993)) as the remaining portion of the dielectric may still be healthy enough to resist partial discharge inception and hence breakdown. For discharges to occur, electrons on the side of the cathode need to be present. From (König & Rao, (1993)), and utilising figure 5-1A below, let U be the potential difference between the cathode and anode, d as the distance between the cathode and anode, then the electric field (E_0) in the healthy portion of the dielectric insulation as measured in Volts/cm is determined by equation 1.

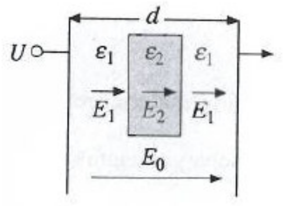

Figure 5-1A: Description of partial discharge evolvement in a dielectric – stage 1
Source: (König & Rao, (1993))

$$E_0 = \frac{U}{d} \tag{1}$$

From figure 5-1A above, E_1 is given as the field strength around the void, E_2 as the field strength in the void; and ε_1 and ε_2 as the constants of the dielectric. E_2 is then described as:

$$E_2 = \frac{\varepsilon_1}{\varepsilon_2} E_1 \tag{2}$$

When ionisation in the critical field of the gas is reached, the cause is then for the positive and negative charges to move in the void as shown in figure 5-1B.

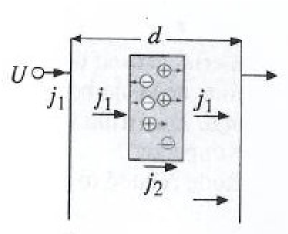

Figure 5-1B: Description of partial discharge evolvement in a dielectric – stage 2
Source: (König & Rao, (1993))

From figure 5-1B, the charge movement is the same as that in normal resistive circuits, as depicted by j_1 and j_2. With this movement of charge, being the electrons and atoms, the electric field E_1 increases with a constant voltage thereby causing the field strength E_2 in the void to decrease. This reduces until there is no current flow thereby leading to a partial discharge and losses in the dielectric hence resulting in insulation degradation. Internal partial discharges in the dielectric introduce voltage fluctuations that in turn introduce current pulses. These current pulses are seen to be the only accessible means whereby measurement of partial discharges is possible (König & Rao, (1993)).

As partial discharges emit heat during their occurrence, the thermal effect is heat being transferred to the insulating oil and causes it to burn thereby resulting in carbon sediments (Adejumobi & Oyagbinrin, (2007a)) deposited within the insulating oil. In a research performed by (Adejumobi & Oyagbinrin, (2007a)), the chemical equation that becomes apparent during this burn stage is depicted as:

$$2CH + O_2 \rightarrow CO + H_2O + C \qquad (2)$$

From equation (1) above and on the left side of the arrow, CH represents the hydrocarbon of the insulating oil and its combination of oxygen during the burn stage. The result is the production of carbon monoxide gas in combination with water and carbon. It is this carbon that is found to be a thermal deteriorating factor in the oil dielectric due to its ability to provide semi conductance (Adejumobi & Oyagbinrin, (2007a)). The production of carbon monoxide stems from the thermal ageing of the paper (Cigré b. (2009a)) partly due to the appearance of moisture in the paper.

In terms of chemical phenomena of partial discharges and its impact on the dielectric insulation, (Adejumobi & Oyagbinrin, (2007a)) explains that the presence of moisture in the insulating oil leads to the production of chemical substances. This moisture reacts with the dibutyl sebacate (being an additive to the insulating oil during manufacture) to form sebacic acid and butanol as depicted in equation (2): (Adejumobi & Oyagbinrin, (2007a)).

$$C_4H_9OOC(CH_2)_nCOOC_4H_9 \text{ (with the addition of } H_2O) \rightarrow$$
$$HOOC(CH_2)_nCOOH + 2C_4H_7OH + 2H_2 \qquad (3)$$

From equation (2) above, a clear description is that if sebacic acid is allowed to develop and strengthen, the dielectric strength capabilities of the insulating oil will be diminished (Adejumobi & Oyagbinrin, (2007a)). The type of gasses that are produced during partial discharges in oil are summarised in table 5-1 below (Haddad & Warne, (2004); Cigré b. (2009a)). From this table, the gasses evolve in the oil as a result of bond scission (Haddad & Warne, (2004)), whereby the quantity of the gasses is related to temperature and the intensity of the partial discharge. Evidence of partial discharge activity internal to the CT is also evident in the production of paper by-products in the insulating oil resulting from the paper deterioration (Haddad & Warne, (2004)).

Table 5-1: Gasses produced in the insulating oil during partial discharges
Source: (Haddad & Warne, (2004))

Gasses Produced in the Insulating Oil During Partial Discharge Activity	
Gas	Chemical Description
Hydrogen	H_2
Methane	CH_4
Ethane	C_2H_6
Ethylene	C_2H_4
Acetylene	C_2H_2

During gas analysis, high levels of ethylene and acetylene provide indication of places within the CT that are exposed to high temperatures leading to the evidence of partial discharges and hence cause sparking (Cigré b. (2009a)). The high concentrations of hydrogen give clear indication that partial discharge activity is present.

5.3 Partial Discharges and Insulation Power Factor

The crepe paper together with the foil sheets used to provide the voltage grading is considered to be a solid form of insulating material. This assists with the mechanical support of the primary hair-pin conductor as well as to keep the hair-pin apart and away from the tank which is at earth potential. König & Rao, (1993) explains that even though the strictest of control may be emphasised during the construction and manufacturing phase of the CT, the possibility of a manufacturing defect is a possibility. The evolution of partial discharges can therefore become a reality and could therefore surface during testing or worse, whilst the CT is in-commission.

One of the main causes relating to the inception of partial discharges in a CT is related to the improper process of the paper impregnation with the insulating oil. Insufficient time allocated for impregnation, results in the paper having dry spots (König & Rao, (1993)) that allows for minimal amount of inception voltage for partial discharges to be present. Another cause related to internal partial discharges of a CT is the formation of bubbles containing air during oil filling under vacuum.

In conjunction with figures 1-1 and 4-1, the paper-foil insulation within the CT is designed to perform as an ideal capacitor (C) that has a considerably high resistance (R), thereby allowing only the flow of capacitive current (I_C) in the insulation as illustrated in figure 5-2A below. With the degradation of the internal insulation, the resistance of the insulation also decreases causing increased heating within the paper insulation. With respect to figure 5-2B below, the flow of resistive current (I_R) introduces greater dielectric losses (I^2R) within the insulation and hence indicates the presence of partial discharges, which inadvertently results in the insulation power factor (δ) of that CT to increase substantially. The measuring of a CTs insulation power factor is therefore seen as essential with the diagnosis of partial discharges (König & Rao, (1993)). As partial discharges are present in the insulation, they contribute to the increase in major dielectric losses (Haddad & Warne, (2004)).

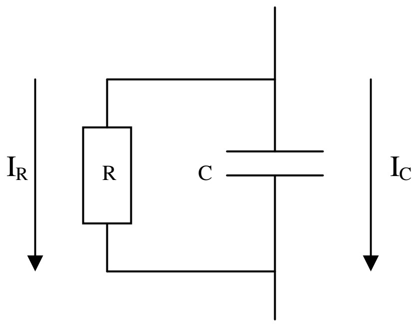

Figure 5-2A: Paper-foil Insulation Equivalent Circuit for a CT

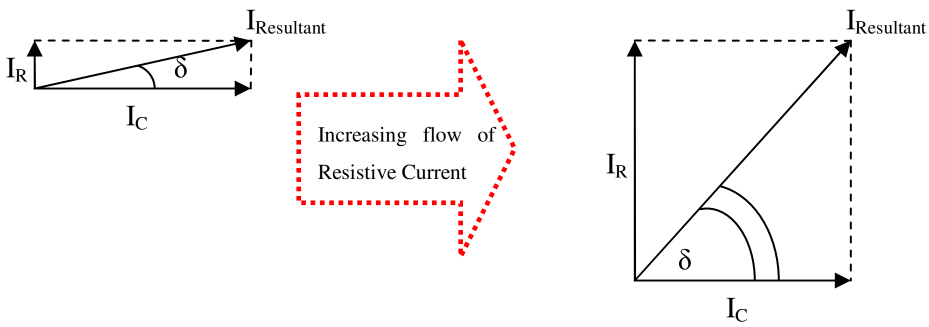

Figure 5-2B: Increasing Resistive Current causing Increasing Insulation Power Factor

Figure 5-2B indicates that with an increasing resistive current through the insulation, dielectric power losses become apparent. This power, in combination with time, relates to the energy transferred through the paper insulation. If this power consumption far exceeds the power dissipation capabilities of the paper insulation, erosion of the paper sets in and the formation of gas bubbles in the insulating oil develop resulting in a thermal increase within the CT (Cigré b. (2009a)). This empowers the introduction and enlargement of partial discharges in the insulation and leads to a possible CT failure. In the report of [47], some of the samples of oil that were aged were found to result in increased insulation power factor, electrical conductivity and moisture content with a short duration of partial discharge activity prior to insulation breakdown.

Work performed by Mariani, (2007b) explains the correlation between insulation power factor and partial discharge in a CT in conjunction with figure 5-3 below.

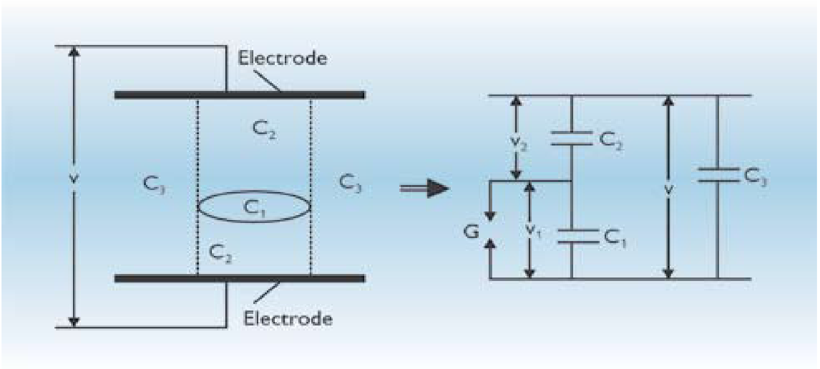

Figure 5-3: Solid Dielectric Simulation and a Partial Discharge Equivalent Circuit
Source: (Mariani, (2007b))

C_1 is representative of the capacitance within the void of the solid insulation. C_2 is indicative of the capacitance of the remaining healthy insulation and C_3 is the capacitance of the entire insulation that does not contain any partial discharges. G gives indication of a spark gap that is bridged during the inception of partial discharges. The charge q that is present in the void is the product of the capacitance in the void as well as the applied voltage across that capacitance. Mariani, (2007b) provides the relationship between insulation power factor and partial discharge as:

$$\tan \delta_D = \omega R_D \left(C_{EQ} + \frac{\Delta q}{V} \right)$$

Where: $\tan \delta_D$ = Insulation Power Factor of the CT during discharge
$\omega = 2\pi f$
R_D = Resistance of the insulation during the discharge process
C_{EQ} = Equivalent capacitance of C_1, C_2 and C_3.
Δq = Change in charge indicative of partial discharges
V = Stressing voltage applied across the electrodes.

For stressing voltages greater than the partial discharge inception voltage, partial discharges will develop and the value of insulation power factor will increase as depicted in figure 5-4 below.

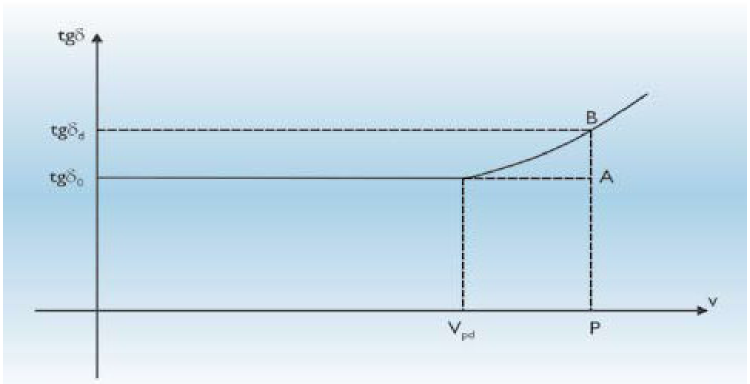

Figure 5-4: Tan delta tip up

Source: (Mariani, (2007b))

Figure 5-4 depicts that for an increasing applied voltage, the value of insulation power factor remains constant at $tg\delta_0$, however with the presence of partial discharges (Wilson, (2008e)), and as soon as the partial discharge inception voltage is achieved at V_{pd}, any further increase above inception voltage results in an increasing insulation power factor value to $tg\delta_d$ (Mariani, (2007b). Point AB is then indicative of the partial discharge in the insulation and the curve from V_{pd} to point B is referenced as a tan δ tip up in the literature (Kuffel *et al* (2000d)).

5.4 Limits of Partial Discharges

Partial discharges are defined in accordance with IEC 60270:2000 as: "localized electrical discharge that only partially bridges the insulation between conductors and which can or can not 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 a duration of much less than 1μs."

In accordance with the NRS 029:2002 specification, for all oil insulated CTs, the moisture content within the insulating oil should not exceed 10mg/kg upon initial filling. The NRS 029:2002 specification and the IEC 60044-1:2003 international standard states that upon completion of the dielectric tests on the CTs, all CTs rated at a maximum voltage level greater of than 7.2kV will undergo a partial discharge test. Partial discharges must be measured as a charge q in picocoulombs (pC), where the maximum measured limit for oil insulated CTs is a value of 10pC when the measuring voltage is 1.3 times the maximum voltage rating at the power frequency of 50Hz for a minimum duration of 60s. The test set used must meet the minimum requirement of sensitivity of being able to detect a discharge value of at least 1pC.

5.5 Partial Discharges Leading to Premature Ageing

High temperature that exceeds the operating capabilities of the CT and the presence of moisture in the paper-oil insulation of a CT are the main contributing factors that cause deterioration of the internal insulation (Pagan, (1998f)). This leads to a knock-on effect whereby the heat generated induces additional dielectric losses and hence causes further increases in temperature (Bertula *et al* (1982)). The insulating oil then carbonises and produces acids that lead to premature ageing and higher insulation power factor (König & Rao, (1993)). Thermal runaway (Pagan, (1998f)) becomes apparent leading to catastrophic CT failure.

Electrical ageing, as described by (Pagan, (1998f); Bertula *et al* (1982)), is related to the presence of partial discharges that leads to insulation deterioration and gas production that will eventually lead to insulating oil saturation. Partial discharges, which are induced in the paper insulation, are led to exist by the presence of this moisture which is identified as a contributing factor in the premature ageing of electrical insulation (Cigré b. (2009a); Cigré d. (2008b); Blackburn *et al* (2003a); Cigré a. (2003b)). This moisture, if not removed effectively, will leave gas-filled bubbles in the form of a void in the insulation, increase the losses within the dielectric thereby causing an increased insulation power factor (Morshuis, (2005b)). In a void, the possibility of a higher local electric stress is possible due to the difference in properties of the solid and void dielectrics (Fruth & Fuhr, (1990c)). Breakdown of the void is them imminent resulting in minute current impulses. The capacitive layers within the paper insulation of the CT will deteriorate leading to the production of tracking in the insulation thereby causing partial discharge activity and hence leading to its premature failure.

In a study performed by (Blackburn *et al* (2003a)), the influence of an increased operating temperature to 145°C on the primary conductor had led to the inception of partial discharges that were although few, but had a consistent magnitude of approximately 110pC. The paper insulation emanated the production of gas bubbles that had no major influence of the production of partial discharges. With the reduction in temperature, partial discharges reduced to an extinction temperature of 100°C. The process was maintained for two weeks, whereby the heating produced water droplets on the bushings. With the contact of the water droplets into the oil, the inception of partial discharges changed substantially. During the test phase, the thermal increases allowed the oil to rid some of the moisture. Partial discharges were then seen to have been non-existent. From this, it can be seen that the effect of moisture has a direct impact on the accelerate ageing of the insulation due to the production of gas bubbles.

The presence of partial discharges is symptomatic of insulation deterioration and is noted to be the leading cause of exceeding the electric stress handling capabilities of the CT. With the inception of partial discharges, due to the substantially high electric stress, the life expectancy of the insulation of the CT is then compromised (König & Rao, (1993)). The inception of partial discharges is caused by defective manufacturing or the process of construction and therefore relates to insulation ageing (Cigré a. (2003b)). It is for this reason that partial discharge detection be reflected as an important criterion for CT optimal life. For the hair-pin type CT that contains paper-oil insulation, leading up to failure, the magnitude of partial discharges is quite substantial (Mariani, (2007b)).

Figure 5-5A and figure 5-5B below, indicate a photographic image of the inception of internal partial discharges be it in the liquid or solid dielectric.

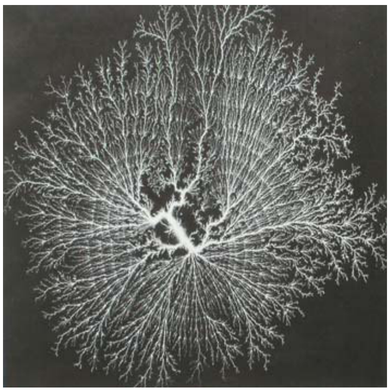

Figure 5-5A: Partial Discharge in Oil
Source: (Cigré d. (2008b))

Figure 5-5B: Partial Discharge in a Solid Dielectric
Source: (Cigré d. (2008b))

Cigré d. (2008b) explains that from figure 5-5A, the discharges become pronounced due to thermal effects leading to the formation of gas bubbles and hence moisture. From figure 5-5B, the inception of partial discharges develop as a result of the voids being present within the insulation during the manufacture and construction phase of the CT (König & Rao, (1993)). These discharges create an effect of irreversibility due to their nature in causing accelerated premature ageing within the insulation, primarily due to the change in properties of the dielectric (Cigré d. (2008b)).

5.6 Conclusion

PDs are seen to be a deteriorating factor in electrical insulation and introduce limitations with regard to the life expectancy properties of the internal paper-oil insulation. They exhibit the breakdown of the internal insulation of a CT by means of optical, acoustical and chemical effects with thermal erosion producing by-products in the dielectric (König & Rao, (1993)). Partial discharges have the ability to envelope a complete insulation breakdown and the on-line monitoring of such is to be taken into consideration. Mitigation of partial discharges is evident only through stringent quality control processes such as temperatures for curing and vacuum pressure used during oil filling.

The evolution of gas discharges and hence gas bubbles in the insulating oil of the CT thereby leading to its breakdown, are clearly evident with the presence of partial discharges. This presence of partial discharges is seen to be a great influence in the premature ageing of the healthy portion of the insulation, thereby resulting in the premature failure of the CT (Cigré b. (2009a)). The method of eradicating such gas bubbles are seen to be provided by either extending the paper-oil impregnation process or by means of heating under vacuum.

Sharp edges or burrs resulting from the primary hair-pin conductor not being effectively smoothened during manufacture are considered a contributing factor to partial discharges. These become more evident after the crepe paper has been wrapped around the primary conductor, as the paper is then punctured. Corona then sets-in during operation of the CT and the eventual result is the catastrophic failure of the CT.

The measurement of a high or increasing value of insulation power factor with applied voltage clearly indicates the presence of partial discharges that has the ability of dominating the dielectric losses (Haddad & Warne, (2004)) within that insulation. The exponential change in increasing insulation power factor value with increasing applied voltage provides a marked indication of partial discharge severity. The measurement of partial discharge (PD) is hence seen as a non-destructive form of test that assists in determining the condition of the internal insulation within the CT.

CHAPTER 6: THE IMPACT OF CURRENT TRANSFORMER FAILURES

6.1 Introduction

Conventional CTs are essential equipment in the chain of protection of the electrical power system. Their specification, usage and placement must be optimised to eliminate failures during operation. Electrical networks involve complex designs that must incorporate safety of people, security and availability of power supply.

The purpose of this chapter will hence investigate the various impacts that a CT has during and post failure. It will also indicate the dire need to curb such impacts as the collateral damage that it exhibits is considerably significant.

6.2 Technical Impact

The potentially violent failure of CTs induces three distinct impacts of a technical nature. The first and foremost is the bay in which the CT is connected must be tripped to isolate the faulty section from the healthy remaining section of the power network. Disruption caused, by the failed CT damaging plant in the adjacent healthy bays, leads to the second form of technical impact. The fireball that evolves, as a result of the oil within the CT being under high pressure, causes the porcelain insulator to explode. The effects of this leads to the damaging of the adjacent healthy equipment aiding to the disruption of the stabilised operation of the power system and causing a potential hazard to personnel within the danger zone of between 80m to 100m (Laasko, (1992)). The devastating fireball breaks down the critical electrical field causing ionisation of the air. The insulation of the air is then compromised thereby allowing potential short circuits to occur within the substation yard.

The substantially high risk factor of the third distinct technical impact is due to the mal-operation and possible damage to the secondary plant equipment. This arises when the earth connection from the capacitively graded screen to the earth point, between the housing for the secondary wiring and earth, on the CT burns off. This is depicted in figure 6-1 below.

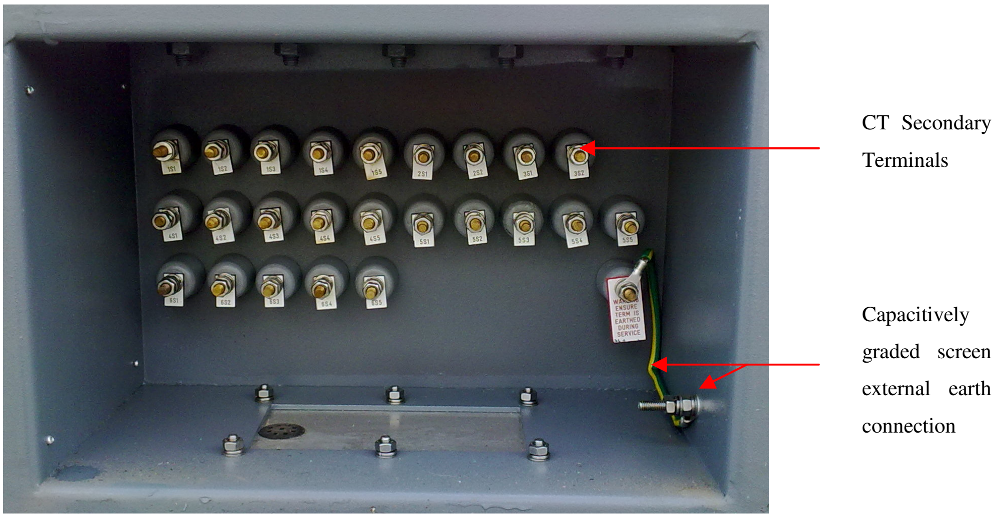

Figure 6-1: CT Secondary Terminal Housing

The HV fault current now finds a path to earth in the protection and metering panels through the secondary wiring. The possibility of damage to relays and meters is imminent, as this high fault current on the secondary of the CT can flow directly into the protection relays and energy meters. With the loss of this earth connection on the CT, the potential difference between the earthed screen in the CT and earth creates an arc leading to pressure build-up. With the pressure build-up exceeding the withstand capabilities of the post insulator, a violent explosion then erupts enabling shrapnel and debris to be strewn across the substation yard.

In consideration for Eskom as a whole and the need for Eskom Distribution to assist with the in-line saving for future projects, additional, unnecessary plant failures are therefore seen as a process hindering the progress of cost saving. For the protection of a power system, security and dependability are essential for the reliability in operation of a protection scheme. Data pertaining to the reliability and performance of equipment is essential during the assessment of the reliability of the power system and security of supply. Failure of CTs causes loss of security, through mal-operations of the relays, and loss of dependability, due to failure or delays in operation. Relating to figure 6-2 below, indicating a healthy substation operation, no abnormalities in terms of technical impacts can be conceived. Reviewing figure 6-3 however, the technical impact can be quite severe as the failure of a CT or its secondary leads to the appearance of an unwarranted false fault. In this case, the differential circuit leads to incorrect tripping of the respective protection schemes.

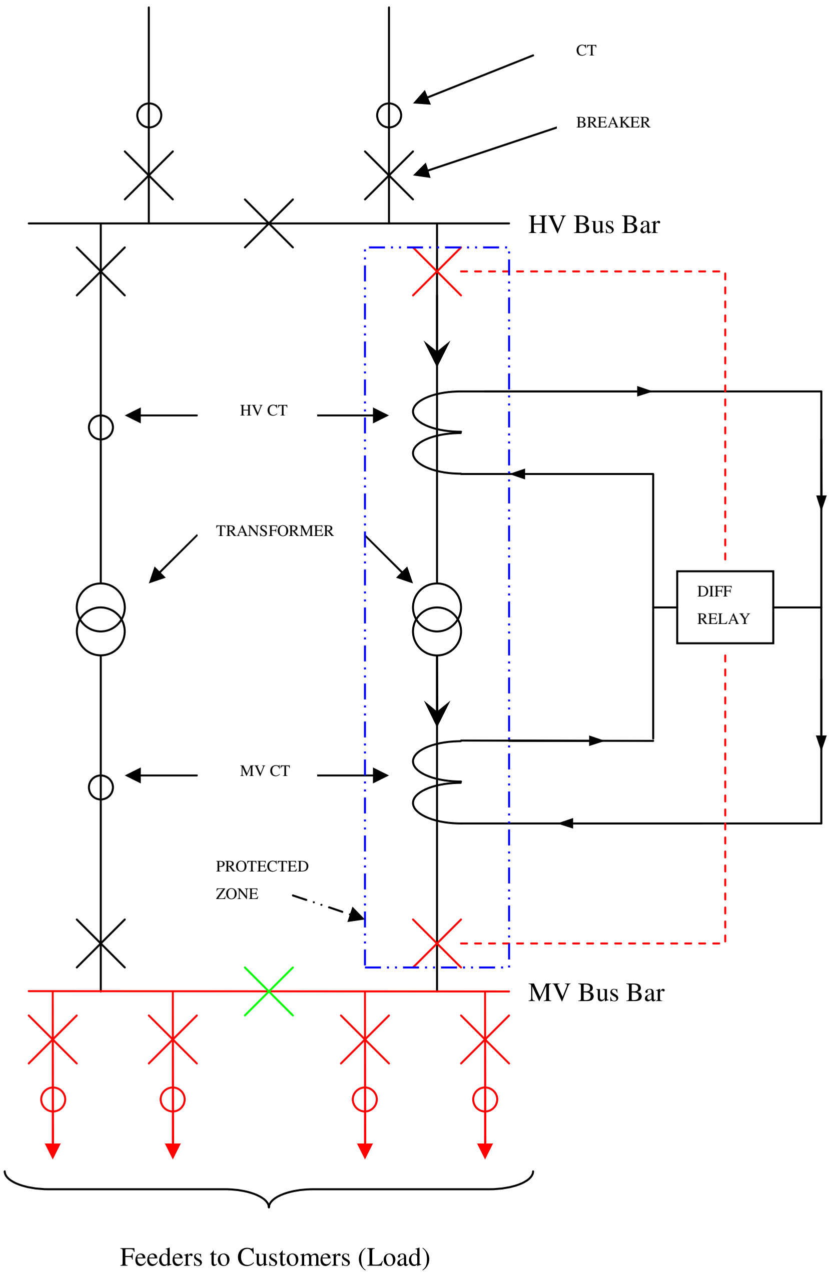

Figure 6-2: Healthy substation operation

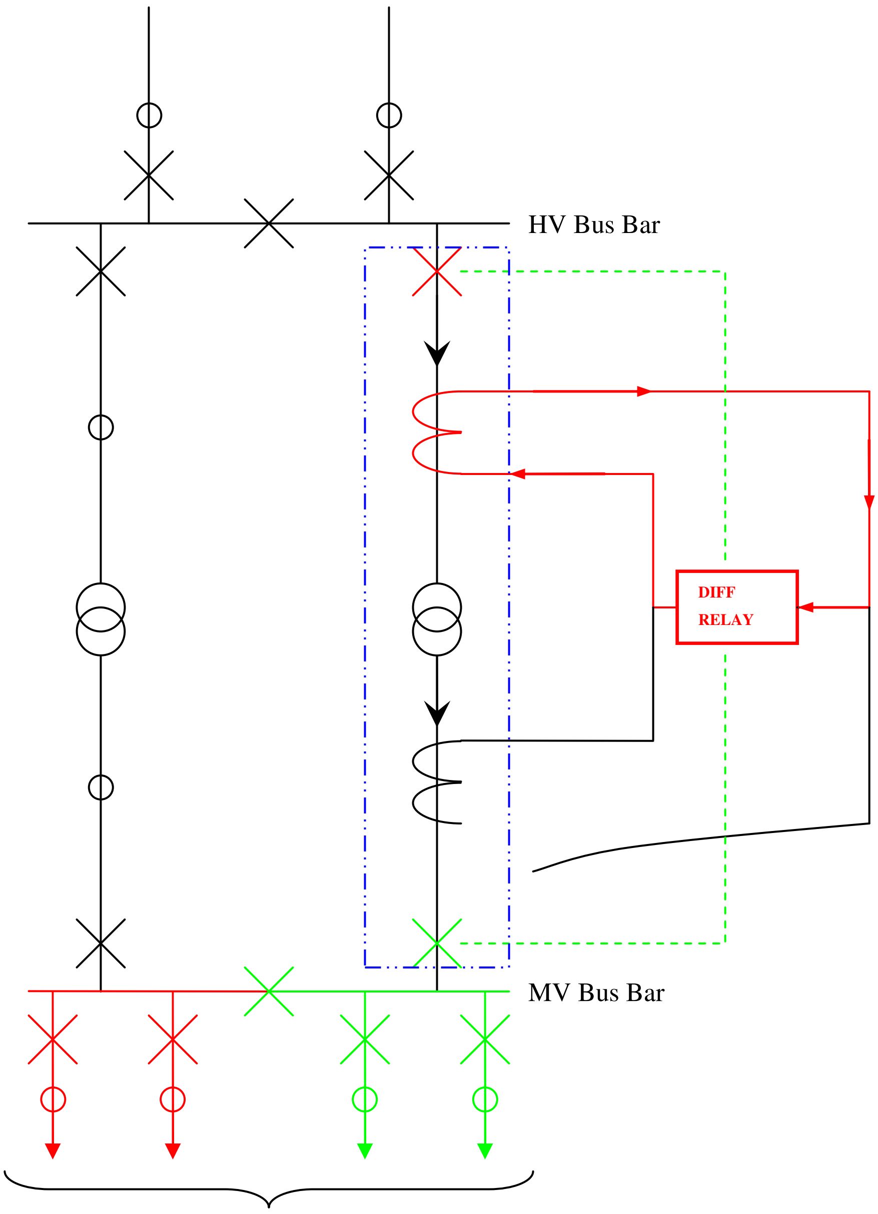

Figure 6-3: Unhealthy substation operation

From figure 6-3 above, it is evident that for a loss of any of the secondary wires, the circuit becomes unbalanced and causes the current to flow through the relay thereby causing it to operate. This then gives a false indication of a fault within the protected zone. The transformer is then tripped out of service causing its associated feeders on that portion of the MV bus bar to lose supply when the MV bus-section breaker is in a normally open state. This can lead to unwanted big area outages causing instability to the remainder of the network. A more sever case is considered when the HV CT fails. This then leads to an unbalance in the HV bus-zone protection scheme causing operation. The entire station is then tripped out due to the failure of a CT or its secondary wiring.

Taking figure 6-3 into consideration and reviewing it in terms of a worst case scenario, where one transformer is taken out of service for maintenance. This then leaves the second transformer to manage the variations in load for the duration of the other transformer being switched out. The in-commission equipment could be pushed to its limit causing undue strain. Equipment failure can then set in as the design characteristics are then exceeded. With the feeders supplying major customers such as smelters or paper mills, who depend on the continual supply of electricity, the impact of a CT failure in the substation environment will have drastic consequences in terms of their productivity.

6.2.1 Regional Performance

The performance of an Eskom Distribution division is dependant on the network reliability technical Key Performance Index (KPI). These KPI's are a measure of the performance (reliability and availability) of supply of the network and of the interruptions experienced Eskom customers (Eskom a. (2004)). The KPI's are obtained from the Network and Equipment Performance Management System (NEPS) and this enables the plant department to ascertain the effects of the various incidences on the network. The use of the KPI definitions standard in accordance with NRS 048-6:2006, provides the requirements for Eskom Distribution in determining its network performance with those of other utilities around the world.

With a fault on the primary system, an event is created. As the protection relays operate the circuit breaker to clear the fault, a state change to the event is developed. These state changes also contribute to the KPI's of the regions and with duration of greater than 2 minutes; the benchmarking of Eskom Distribution in terms of network reliability, poses a negative impact to the regions performance index. In view of this statement, a CT failure in any of the regions and the duration thereof will certainly prove a negative performance.

The National Energy Regulator of South Africa (NERSA) utilises the NRS 048-6:2006 document as a yardstick to ensure that the reliability and availability of electricity supply to customers is maintained. Eskom Corporate uses the following key sustained interruption indices to measure network performance target setting and performance compacting per Distribution region (Eskom a. (2004)).

- System Average Interruption Frequency Index (SAIFI) provides the average number of interruptions per connected customer and is mathematically represented as:

$$SAIFI = \frac{Total\ number\ of\ customer\ interruptions\ per\ annum}{Total\ number\ of\ customers\ served}$$

- System Average Interruption Duration Index (SAIDI) provides the average interruption duration per connected customer and is expressed as:

$$SAIDI = \frac{\Sigma\, Customer\ interruption\ durations\ per\ annum}{Total\ number\ of\ customers\ served}$$

- Customer Average Interruption Duration Index (CAIDI) indicates the average duration of a customer interruption and is depicted by:

$$CAIDI = \frac{\Sigma\, Customer\ interruption\ durations\ per\ annum}{Total\ number\ of\ customer\ interruptions}$$

  Hence CAIDI is a ratio of SAIDI to SAIFI:

$$CAIDI = \frac{SAIDI}{SAIFI}$$

The SAIDI, SAIFI and CAIDI are a measure of the customers experience in terms of the interruption performance. They also provide further information into issues with the design of the network as well as the performance of the network once the supply has been restored. In accordance with NRS 047-1:1999, to ensure consistency in monthly reporting from the different Distribution regions, the following table with respect to customer restoration times must be adhered to.

Table 6-1: Customer Restoration Times

Source: (Eskom a. (2004))

Customer Restoration Time (hours)	Cumulative Percentage Customers Restored
1.5	30
3.5	60
7.5	90
9	97
24	99

A graphical representation of the table 6-1 above is depicted in figure 6-4 below. This gives a clear indication of the regions performance. The greater the number of customers restored in a shorter space of time, the greater the performance of that region. Greater performance heightens customers perceptions and integrity in the utility and therefore decreases the overall capital expenditure from a utility perspective.

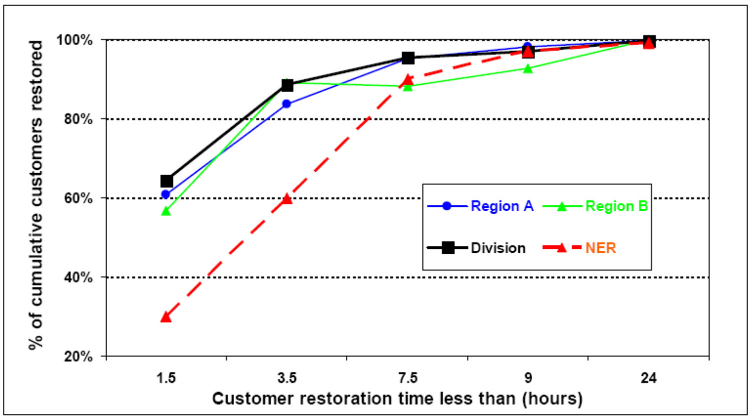

Figure 6-4: Example of customer restoration times curves reported monthly

Source: (Eskom a. (2004))

6.3 Economic Impact

Power and its level of quality thereof are of great economic value to industrial customers. This level of quality must be maintained at a substantially high level to prevent a negative economic impact. Any unexplained incident that affects the network stability must be quantified in terms of the customers affected and the Mega Volt Amperes (MVA) lost to achieve an intrinsic value of its impact. Quantifying the costs associated with a violent CT failure; in a typical distribution station as depicted in figure 6-3 above with the side view depicted in figure 6-5 below, implies drastic financial circumstances to Eskom. For the purposes of this study, the cost quantification is based on the following assumptions made.

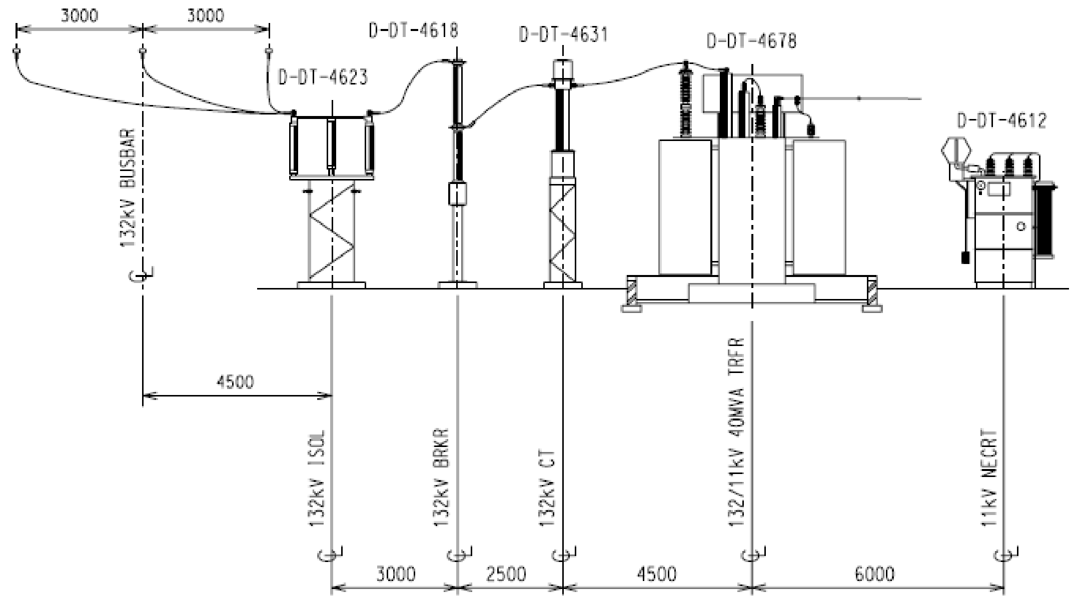

Figure 6-5: Substation Layout (Side View)
Source: Eskom

Assumptions made:

- The centre phase CT of a three-phase system on an HV transformer bay fails violently causing oil spillage and damage to all adjacent equipment.
- The adjacent transformer bay has been taken out of service, prior to and post failure, for maintenance.
- The substation is a direct feed to a smelting industrial customer.
- 24 Hour unplanned outage duration for repairs.

6.3.1 Cost Quantification

The current replacement cost of a single 132kV Post-type CT is R55, 000.00. With the failed CT being positioned in the centre phase, the adjacent CTs on either side will also require replacement due to the collateral destructive nature of the failed CT. Total cost calculated for three 132kV Post-type CTs are R165, 000.00. Damage to 132kV manually operated isolators requiring replacement equates to R55, 000.00. Breakers rated at 132kV, installed between the isolators and CTs and hence being damaged by the CT, has an average cost of R245, 000.00. If the shrapnel from the violent explosion causes damage to the power transformer by chipping of the porcelain bushings or the severity increased by puncturing the tank, that transformer will then require replacement. The replacement cost for a 40MVA 132/11kV power transformer is R8, 650, 000.00.

These equipment, once purchased, needs to be transported to site for replacement of the damaged equipment. Transportation costs are calculated only for the CTs, isolators and breakers and give a figure of R13, 900.00. The replacement cost of the transformer includes transportation to site, rigging of the new transformer into its respective bay and removal of the existing transformer.

On site, the existing damaged equipment has to be removed and replaced with the newly purchased equipment. The removal and replacement cost associated with this scope of work is calculated to be R31, 000.00. This includes the use of a crane truck to perform the task. Items such as clamps, nuts and bolts for the fastening of the equipment to the structure and setting of the isolators to ensure proper operation equate to a value of R17, 000.00.

From the assumption of the oil spillage of the CT, clean up operations need to be implemented to prevent any further environmental impact. Cost implications can be quite substantial depending on the extent of the damage and can easily be in the region of R20, 000.00.

The above costs purely reflect the primary plant involvement. The extent of the damage can also be extended to the secondary plant equipment such as protective relays and energy meters. Costing a transformer protection scheme and its associated energy metering extends to a value of R252, 000.00. These panels then need to be transported to site and commissioned with the associated primary plant to enable normal system operations. Existing damaged panels need to be removed from site and recovered. Costs associated with this activity inclusive of the installation of all the required secondary cabling, can be in the region of ± R182, 000.00. The total costs reflected above results in a total of:

$$R165{,}000 + R55{,}000 + R245{,}000 + R8{,}650{,}000 + R13{,}900 +$$
$$R31{,}000 + R17{,}000 + R20{,}000 + R252{,}000 + R182{,}000 \approx R9{,}63mil$$

These costs are not withstanding the fact that Eskom has incurred revenue loss between the time of equipment failure, to re-instatement. Energy loss can then be calculated as:

$$80MW \times 24h = 1920MWh$$

Utilising the Active Energy Charge from (Eskom c. (2009)), the cost of unserved energy incurred by Eskom for the 24 hour period:

$$1920MWh \times 122.27c / kWh = R2{,}35mil$$

A further extension to this case is reflected in the statistics of CT failures, whereby an average of five failures per year can be considered. Annual loss of revenue pertaining to a violent CT failure can equate to:

$$R2{,}35mil / failure \times 5\ failures / year = R11{,}75mil / year$$

Clauses within the Service Level Agreement (SLA) between the customer and Eskom also play a role, as the customer has experienced a loss of production during the time of failure. These are costs incurred by the customer as a result of the loss of production. This then makes Eskom duty bound for these costs to the customer, for the equivalent downtime or agreed upon signature of the SLA upfront.

6.4 Safety of People

6.4.1 Safety of Personnel

Despite the fact that there have been a number of violent CT failures over the years, no injury or loss of life of personnel resulting from the failure has occurred. The reason behind this fortunate result is due to the comparison between the amounts of time spent allowing exposure of personnel to the HV equipment and the possibility of a violent CT failure being moderate. With this moderate probability, it is still essential to reduce the potential danger of personnel being exposed to a violent failure. This can be achieved by limiting durations within the confines of the substation environment and unnecessary site investigations.

Safety of personnel is of paramount importance in Eskom. A disabling injury to a member of staff relates unnecessary pressure and stress on the associated family and poses a de-motivating factor to the morale of fellow employees. A loss of life of a breadwinner is devastating to the family of the deceased. A loss of personnel is detrimental to the business as it indicates a loss of skills. The business then needs to undergo a transition phase to train new staff to the level of expertise as that of the lost member of staff. This then means additional costs that the company must incur. With respect to the NOSA star grading, the utility undergoes demerits as the disabling injury rate and the loss time injury rate has increased.

6.4.2 Safety of Public

The criteria for the graphical location of substations must include the probability of members of the public being inadvertently exposed to the potential dangers of a violent CT failure. Distribution substations offer the effect of over-exposing members of the public to the danger zone with the aid of constructing low cost housing, bus stops and even business office parks near to the HV yards. Considering this statement, the regional town planning department and Eskom should work together in eradicating this dangerous situation from occurring.

6.5 Environmental Impact

The environment consists of the surroundings around human beings being the land, water and the atmosphere of the earth, as well as micro-organisms, plant and animal life. Oil is considered to be a valuable resource that originates from fossil fuels (crude oil). CTs contain napthenic based (mineral) oil as a dielectric insulating medium as well as for cooling purposes. The release of such insulating oil and other related hydrocarbon compounds into the environment can deliver a serious issue in terms of pollution. This oil also poses a fire hazard, thereby adding to the existing air pollution. A single litre of oil has the ability of contaminating more than a million litres of water, thereby leading to water pollution.

Water pollution can also be extended to the fact that oil can rapidly penetrate certain soil types thereby impacting the environment negatively through contact with groundwater resources. Experience has shown that operational or human error and equipment failures are the main causes of oil spills. A CT failing violently will spew the high pressure oil onto the local surface thereby enabling the possibility of the oil coming into contact with the subterranean groundwater resources. As this oil has been used, its slow degradation and insoluble properties renders a substantial health threat to humans, flora and fauna and most importantly the environment. With respect to the National Water Act (Act No 36 of 1998, Section 19), Eskom has to ensure that the water resources are protected against the effects of pollution in the event of an oil spillage.

Incidents involved with oil spillage are seen as high risk and causes ecological harm that can lead to legal issues, financial and publicity risks. Appendix 1 provides images of an oil spillage at a substation and it is clearly evident that the oil spillage from the CT does pose an environmental risk. The oil can also be seen to 'stain' the structure and stones in the substation HV yard. This oil can then seep through and into the ground thereby causing contamination.

In terms of the National Environmental Management Act (Act No 107 of 1998, Section 28), it is clearly stated that reasonable measures must be undertaken to prevent the occurrence or continuation of pollution or degradation of the environment and in the event of this not being an option, the minimisation and hence rectification of such pollution or degradation must be achieved. Eskom therefore is obligated to adhere to such Act.

6.6 Conclusion

The failure of CTs can be seen to have drastic negative impacts for both the utility and the end consumer. The analysis of the technical impact of a CT failure indicates that with the major undue network disruptions induced, system constraints could compound the problem. With substations continuously being maintained and distribution network configurations being operated on a daily basis to assist with the varying load conditions, network optimisation would then need to be catapulted to a higher level to counter the effects of CTs failing.

Given the present South African economic conditions, the economic implications concerned can be seen to hamper utility growth, both in terms of technical infrastructure and the available manpower required. Given the four distinct impacts, the significance of life is seen to be the main priority driver to reduce the substantial number of CT failures. With the preaching of safety practices and policies, the strict adherence to such is seen to assist in the mitigation of loss of life related to catastrophic CT failures.

Water, as a natural resource, is essential for the sustainability of life. Contamination thereof can see a deterioration in natural processes which ultimately has an adverse effect on daily life. It is therefore imperative that oil spillage prevention be seen as the first line of defence to minimise risk to protected life, property and the environment as a whole.

CHAPTER 7: SUSPECT CURRENT TRANSFORMERS

7.1 Introduction

Testing of CTs in ED is of extreme importance in order to verify the manufacturer's ratings and to ensure the CTs compliance to standards and specifications. Over the past four years, ED has experienced numerous CTs, of voltages specifically rated at 66kV and 132kV, which have been tested for insulation power factor and as a result were found to exceed the acceptable value as stipulated in NRS 029:2002 specification for insulation power factor. Test results obtained for insulation power factor give a good indication of the classification of the internal insulation of the CT and allow the prevention of that CT from being installed on site or the more costly disassembling of the CT for refurbishment (Shkolnik, (2008d)).

For the purposes of this study, only CTs that were found to be non-compliant in the Central Work Management Area (WMA) will be considered. This chapter highlights the extent to which ED has experienced the non compliance of CTs, in terms of high insulation power factor values, and explores the possible causes leading to such high values with steps assisting in corrective action.

7.2 Suspect Current Transformers with High Insulation Power Factor

Majority of the CTs tested by the High Voltage Laboratory Department (HVLAB) in the Central Work Management Area (WMA) as per figure 7-1 below, were found to be suspect. These CTs, as identified in Appendix 4, were designed to meet the NRS 029:2002 specification regarding insulation power factor values, yet were found to exceed the acceptable limit as stipulated in the specification for insulation power factor and were hence marked as suspect units.

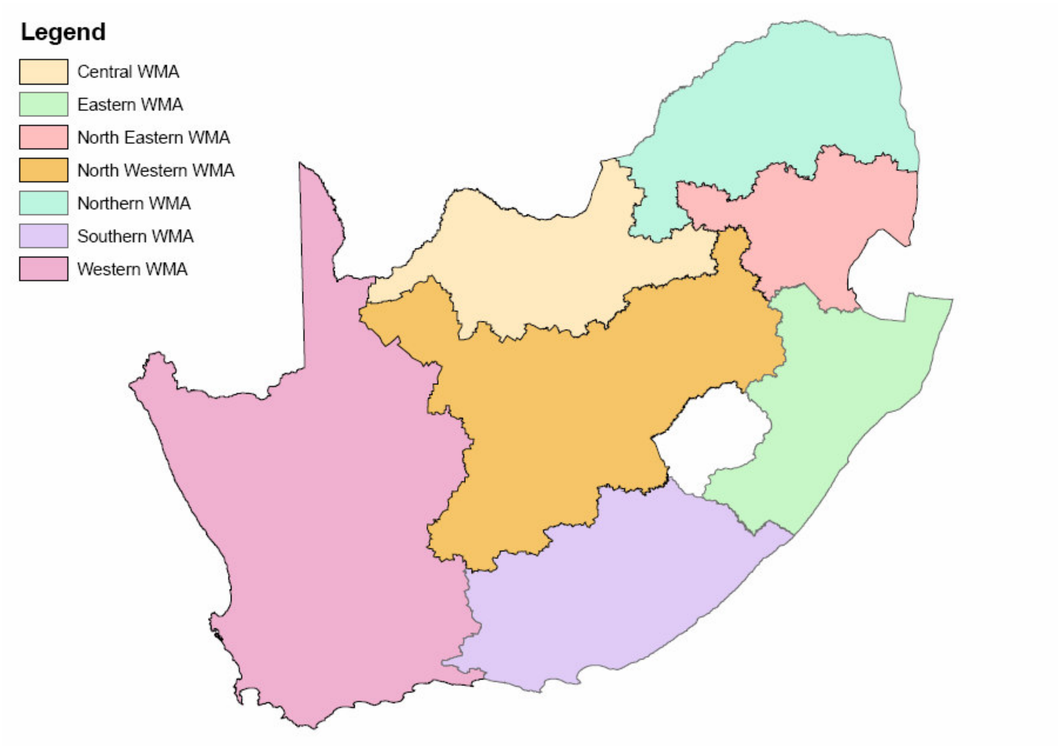

Figure 7-1: Map of South Africa indicating the Regional Eskom Distribution Boundaries Source: Eskom

The results of the insulation power factor test performed on the suspect CTs versus their vintage are represented in figure 7-2 below.

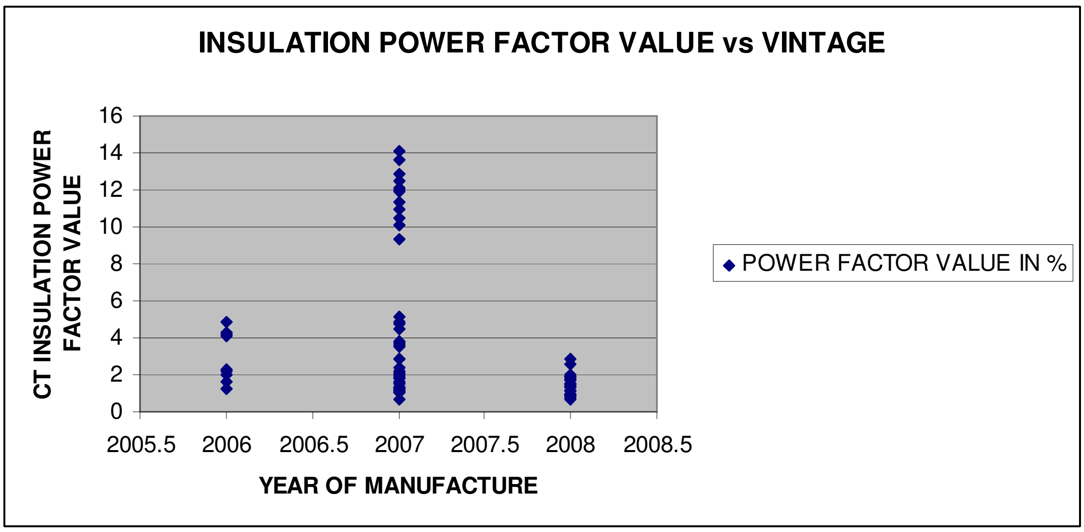

Figure 7-2: CT Insulation Power Factor Value vs Vintage

From figure 7-2 above and in relation to Appendix 4, CTs manufactured by the specific manufacturer and more specific in the year 2007 are seen to be most prone to high values of insulation power factor. The possible causes leading to such high values during that year had to be investigated with sufficient reasoning provided from the manufacturer in question.

Appendix 4 gives clear indication that a substantial number of CTs were found to be non-conforming to ED's requirements and the NRS 029:2002 specification. The economic impact to Eskom in respect of this vast number heightened the need for an investigation by the T&Q department.

7.3 Probable Causes

The overall test results from ED indicated that the CTs from the specific manufacturer could not meet the required specification due to abnormalities in the quality of the internal paper-oil insulation. Some of the causes leading to the CTs obtaining a high insulation power factor were due to a manufacturing defect assisting in the high moisture content within the crepe paper insulation prior to the addition of the insulating oil. Poor processing during manufacture leading to inadequate drying of the insulating paper was a contributing factor. Insulating paper containing a considerable amount of moisture had been identified to assist with premature ageing leading to its thermal degradation (Vandermaar & Wang, (1999g)).

Another possible cause relating to excessive insulation power factor values was the bad quality of insulating oil added to the CT for the paper impregnation process. Bad quality oil with a high moisture content of greater than 5 parts per million (ppm), as specified by the manufacturer in question, is considered as contaminated oil and is seen to add to the excessive degradation of the internal paper insulation. This causes high values of insulation power factor that inadvertently leads to the inception of partial discharges and hence an ultimate CT failure whilst in-commission (Laasko, (1992); Vandermaar & Wang, (1999g)).

This contaminated oil with an excessive moisture content added to the excess moisture content in the paper and the result that followed was an indication of high insulation power factor. Comparison of ED’s test results versus the values obtained during manufacture could not materialise due to lack of quality control at the manufacturer’s works. Actual testing during manufacture was not performed.

Good quality impregnating oil allows for a good quality insulation that has low dielectric losses and offers high dielectric strength. For values of moisture in oil greater than 25ppm, the level of moisture can be substantial enough to decrease the internal dielectric capabilities thereby adding to its reduction in estimated life (Cigré b. (2009a)).

In a study performed by Laasko, (1992), the summary concludes to state that a possible cause of the CT failure is due to partial discharges eroding the internal primary insulation and hence leading to high values of insulation power factor. Any increase in the insulation power factor of the CT, as compared to the value obtained from the manufacturer, gives clear indication of a defective or changing internal insulation that could be as a result of humidity, or pollution (Shkolnik, (2008d)).

Probable causes were then seen to be inferior insulating paper and contaminated oil with excessive moisture content. Inadequate quality control and the haphazard process during manufacture strengthened the cause.

7.4 Action Taken on Suspect CTs

The CTs that were found to be suspect, in terms of the related high insulation power factor values, were listed and documented in a Non-Conformance Report (NCR) against the manufacturer responsible. The manufacturer, together with the help of ED, had then to put forth a system in place to assist with corrective and preventive action. Requests were made from ED that the suspect CTs needed to be within the NRS 029:2002 specification regarding the insulation power factor values to enable the CTs to be installed and placed in-commission. With the substantial number of CTs failing to meet the specification requirement and the urgent need for Eskom's project management department to implement approved projects, a stance had to be taken to assist in resolving the situation.

With the problem being considered as major, the CTs could not be placed in-commission. All CTs related to the specific manufacturer were quarantined either at the substations it had been delivered to or at the central storage facility. ED's Technology and Quality (T&Q) department had then arranged for insulation power factor verification testing on the entire list of suspect CTs. For the batch of CTs that were found to be compliant, the T&Q department issued a subsequent approval for release.

Refurbishment of the internal paper-oil insulation on site proved inappropriate as the requirement for special process and test facilities for quality approval and acceptance proved to be an impractical task. Although the problem was considered to be major, the economic impact to ED in terms of scrapping the suspect CTs proved to be an unviable option. The option chosen was to refer the suspect CTs that were non-compliant back to the manufacturer in question in order for the suspect CTs to be refurbished and then re-issued to ED in a satisfactory condition.

Considering the large number of CTs that were found to be suspect, a practical decision was then forecast by ED to inspect the entire quantity of CTs purchased at the voltage levels of 66kV and 132kV that were supplied by that specific manufacturer. At the manufacturer's works, the cause and effect were diagnosed and the team responsible for insulation power factor testing and verification had then to instil corrective action on the list of suspect CTs. The manufacturer in question had then extended further corrective action to its supplier, related to the quality of the components that they had supplied.

The CTs found to be suspect were repaired by means of disassembling. They were then cleaned, drained off the insulating oil and then had the napthenic based insulating oil replaced. The entire primary insulation had to be vacuum dried once again for the removal of excess moisture. Certain suspect CTs with exceptionally high insulation power factor values ranging above the 10% value could not be effectively vacuum dried, as damage to the crepe paper insulation was imminent. These CTs were then earmarked and scrapped at the manufacturer's works and expense.

In order to prove compliance, the manufacturer in question, in conjunction with ED, had agreed to refurbish the suspect CT's. Reviewing figure 7-3 below and in conjunction with appendix 4, prior to and post refurbishment insulation power factor values are presented for a selection of suspect CTs rated at 132kV.

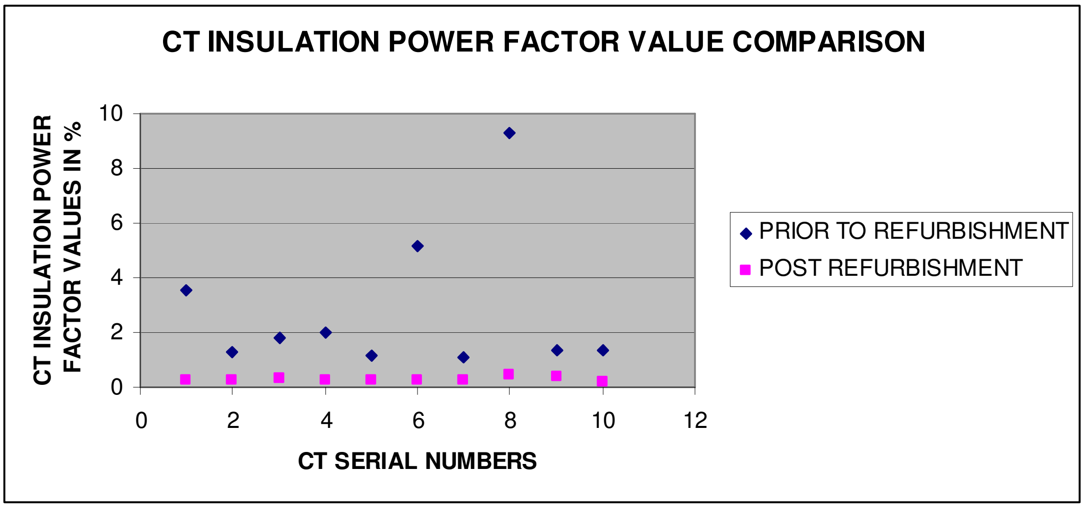

Figure 7-3: Original vs Refurbished CT Insulation Power Factor Values

Figure 7-3 above gives clear indication that the selection of suspect CTs with high insulation power factor values was refurbished to be able to meet the NRS 029:2002 specification that it was originally designed for. The manufacturer had retained the suspect CTs at the works and assisted by vacuum drying the CTs paper insulation to rid moisture to be below the 5ppm level. With the finding of the insulating oil in the CTs being contaminated with high moisture content, the insulating oil was then replaced under vacuum.

The figure 7-3 above goes on to indicate that although the CTs had obtained insulation power factor values of greater than one percent prior to refurbishment, sufficient and careful drying under vacuum conditions proved economically and environmentally efficient in reducing the values to within specification. Acceptance testing for conformance to the IEC 60044-1 specification had then to be performed on the batch of CTs that were refurbished.

7.5 Conclusion

Reviewing the number of CTs being defective and the need for Eskom Distribution to test all the CTs purchased, it is seen that comparison of the test results between that of Eskom's versus the manufacturer are essential in proving that the CT is designed and manufactured as per specification. Non conforming CTs provided clear indication that poor workmanship together with the absence of quality control at the manufacturers works, meant that the specifications and requirements as laid down by ED were not met in succession. Insufficient quality control leading to contaminated internal insulation on CTs issued to ED can therefore be seen as a primary cause of failure.

Ayers *et al* (1999b) describes the process of failure as a thermal mechanism, whereby the power dissipation is effectively increased with an increasing resistive current leading to decreasing insulation resistance. The deteriorating loop is enclosed by increased thermal feedback adding to greater power dissipation with decreasing insulation resistance and increasing resistive current. This power dissipation increases to a level that is greater than the power dissipation withstand capabilities of the internal insulation and insulation breakdown becomes evident.

The value of insulation power factor testing proved the degree of moisture in the paper-oil insulation and from the values obtained prior to refurbishment, the moisture content was considerably high that exceeded ED's specification. In light of the information obtained from the previous chapter, should these CTs have been installed into the power system, the consequences of the CTs failing could have been catastrophic.

CHAPTER 8: INSULATION POWER FACTOR TESTING OF CURRENT TRANSFORMERS

8.1 Introduction

CTs provide the input signal to control circuits in a power system and require insulation between the primary high voltage terminals and that of the secondary low voltage terminals. With the materials used for insulation not being perfect, the influence of environmental conditions, electrical and mechanical stresses and designs not flawless, insulation degradation will develop with time aiding a gradual process to failure, however premature failure is seen to occur suddenly with consequences reaching far beyond that of the CT. Off-line insulation Power factor or Tan δ is the standard test used and provides a safe means in determining the level of insulation deterioration within the CT. The insulation power factor is defined as the ratio of the resistive component of current, calculated from the active power (W) to the capacitive component of current, calculated from the apparent power (VA). This dictates that the smaller the value of insulation power factor, the more credible is the insulation within the CT.

Testing of the internal insulation of a CT, which comprises of oil impregnated paper and metallic foil sheets, is considered essential and is effective in the determination of the defectiveness of the insulation. High moisture content in the oil is one of the largest causes of oil quality deterioration as its proportionality is a direct contribution to accelerated ageing and should therefore be substantially minimised to prevent flammable gas build-up leading to the high volatility of the insulating oil (Kakkar *et al* (2002b)). Any changes in the insulation power factor are indicative of the losses in the dielectric (Kakkar *et al* (2002b)).

The purpose of this chapter is to collate the insulation power factor tests, known as the Doble Test, on a sample of three CTs manufactured between the years 2007 to 2009, with the test results obtained from the specific manufacturer. It will aim to identify the differences associated those CTs that are within the specified limits to those that exceed the limits. The methodology, test results and the analysis thereof will be reviewed in conjunction with the results from the previous chapter in order to ascertain whether the specified manufacturer was able to resolve the issues of high insulation power factor and spearhead the factors contributing to such high values.

8.2 Methodology

With any form of testing performed in Eskom, safety of the test personnel, the test equipment; and safety of the public is considered to be of paramount importance. The Doble insulation power factor test, although being an off-line non-destructive form of test, can prove to be fatal to the test personnel due to the 10kV being generated from the test system.

The CTs selected for this test were based on the manufacturer in question (manufacturer A), whereby a sample of three CTs manufactured between the years 2007 to 2009 and rated at a nominal voltage (U_n) of 132kV was chosen. The 132kV CTs are rated to enable a higher power transfer as compared to the 66kV CTs and were hence selected, and as depicted in chapter 6, the impact of their insulation failing leading to a destructive CT failure can be quite substantial. The nameplate of a standard 132kV CT that ED uses is depicted in Appendix 2. It can be noticed that this CT contains 6 cores, whereby cores one and four are representative of the main and back-up protection systems; cores two and three are used for bus zone main and check; and cores five and six are used for energy metering. From this, the deterioration of the internal insulation of a CT leading to its ultimate violent explosion will affect the operability of the secondary plant system connected to it.

The methodology used for testing the CTs was based on the Doble Test Procedure (Doble c. (2000c)) and adapted for use in Eskom. All CTs that are purchased and used in ED must be tested to prove compliance with IEC 60044-1 and NRS029:2002 specifications as well as Eskom's specific requirements as specified in the technical schedules A and B within the document DSP0013 Rev 5. CTs that were currently in storage and earmarked for projects within ED were thus chosen for testing the insulation power factor.

8.2.1 Test Instrument

The instrument used to perform the non-destructive insulation integrity test on the three CTs was the Doble M4100 diagnostic test system. The capability of this test instrument to measure the insulation power factor and the capacitance of the insulation has proven to be an acceptable test instrument by Eskom Distribution to assess the internal insulation characteristic of paper-oil insulated CTs. Electrostatic interference caused by neighbouring electrical equipment, is non-existent in the M4100 test system due to the Line Frequency

Modulation™ (LFM) technology that it uses. This allows the test system to use frequencies that are independent of the system frequency thereby producing accurate test results. The M4100 test system assists with acceptance on-site and at the manufacturers works and is an essential tool for predictive maintenance scheduling and during emergency testing (Doble c. (2000c)). The M4100 test system has the capability to do the following tests:

- Insulation Power Factor testing to determine the quality of the internal insulation.
- Capacitance testing to determine if the test object had undergone any physical changes.

The technical specifications of the M4100 test system are tabulated in table 8-1 (Doble b. (2010))

Table 8-1: M4100 Technical Specifications

Power Specifications	
Input Supply Range	95 – 264V AC and 47 – 63Hz, 10A maximum at 220V
Voltage at Output	0 – 12kV AC
Current Range at Output*[1]	100mA continuous at 10kV 200mA > 30 minutes at 10kV 300mA > 4 minutes at 10kV
Sinusoidal Power at Output	3kVA
Test Frequency	
Range of Test	45 to 70Hz
Resolution Stages	0.1Hz
Accuracy of Test	± 1% of Reading
Test Voltage	
Range of Test	25V to 12kV
Resolution Stages	1V
Accuracy of Test	± 1% of Reading, ± 1V
Test Current	
Range of Test	0 to 5A
Resolution Stages	0.1µA
Accuracy of Test	± 1% of Reading, ± 1µA
Capacitance	

Range of Test		0 to 100μF
Resolution Stages		0.01ρF
Accuracy of Test		± 0.5% of Reading, ± 1ρF
Inductance		
Range of Test		6H to 10MH
Resolution Stages		0.01H
Accuracy of Test		± 0.5% of Reading
Power in Watts		
Range of Test		0 to 2kW
Resolution Stages		0.5mW
Accuracy of Test		± 2% of Reading at 10kV ± 0.03% of VA, ± 0.5mW
Dissipation Factor		
Range of Test	%PF	0 to ± 100%
	PF	0 to ± 1
	%Tan δ	0 to ± 999.99%
	Tan δ	0 to ± 9.9999
	mW/Var	0 to ± 9999.9
Resolution of Test		0.01%
Accuracy of Test		± 0.5% of Reading ± 0.04% PF/Tan δ ± 0.0004 PF/Tan δ
Measurement of Temperature *[2]		
Range of Test		-20°C to +50°C
Resolution Stages		0.1°C
Accuracy of Test		± 4°C
Environmental Concerns		
Temperature	Operating	-20°C to +50°C
	Storage	-40°C to +70°C
	Humidity	90% that is non-condensing
Dimensions of the M4100 Test System		
Test System		Height: 26cm; Width: 50.8cm; Depth: 64.1cm

High Voltage Cable		18 m
Weight of the M4100		45.5kg
Conditions leading to Interference		
Frequency	Electrostatic	15mA rms of the interference current into any cable and provides a ratio of 20:1 between the interference current and the test object current.
	Electromagnetic	500µT at a frequency of 50Hz

*[1] *An operating temperature of 50°C is used to determine the operating time.*

*[2] *A separate temperature probe is required for temperature measurement.*

For the control and operation of the M4100 test system, the Doble Test Assistant® (DTA) windows based software must be installed and run through a personal computer. This software allows easy compilation and storage of data from the tests performed on all electrical equipment. Trending analysis and data comparison of the equipment under test is easily accessible thereby enabling test efficiency and accurate record keeping of test results.

The M4100 test system used to perform the tests was within its calibration certification requirements and ISO 9001:2000 certified, thereby ensuring that the test results obtained are referenced as true and correct. The test instrument used is depicted in figure 8-1 below.

Figure 8-1: Doble M4100 Test System used in Eskom Distribution

From figure 8-1, the field calibration reference module that comes standard with the M4100 test system, has been removed as part of Eskom's requirement is to have all test equipment tested externally with a traceable certification.

The M4100 test system comprises of the following components used for testing:

- An AC 220V supply to power the test system.
- The high voltage transformer capable of producing the 10kV as required by NRS 029:2002.
- Two 'push-to-make' safety switches in the event that the test system is a distance away from the CT thereby ensuring safety during testing, as one switch would be used at the test system and the other at the CT.
- An amber strobe light that provides visual indication of a test in progress.
- The high voltage test hook that is used on the primary of the CT as depicted in figure 8-2.
- The LV (Blue) return lead that is terminated onto the un-earthed capacitive tap point in the CT secondary terminal box.
- A temperature humidity sensor that determines the temperature of the ambient air during testing.
- A ground lead that sets the test system to be the same potential as that of the CT under test.
- Doble Test Assistant® software that is used to operate the test system and compile the test results.

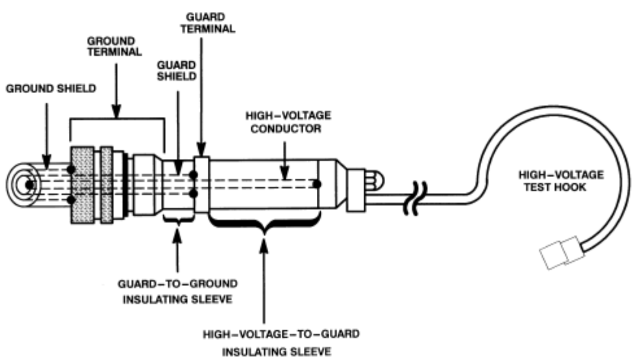

Figure 8-2: Doble High Voltage Test Hook

Source: (Doble c. (2000c))

It is essential that the high voltage test hook must not be wrapped or draped on the CT porcelain sheds or the CT tank as this will cause the tank to be energised at 10kV during the test phase.

Some of the advantages of using the M4100 test system are (Doble a. (2010)):

- Any external interference is eliminated during testing, to provide an accurate representation of the quality of the internal insulation.
- The test system has a self check system that eliminates errors during setup.
- The software that accompanies the system is extremely user friendly to enable efficient testing.
- Test results are printable in a format that makes for easy and understandable reading.

In a study performed by Ayers *et al* (1999b), the Doble test system and method of testing for insulation power factor, has performed for many years and has proved its ability in detecting CTs that are not suitable for being in-commission. A further statement indicates that the test system has been used for all insulation power factor tests performed on the HV equipment with a drastic reduction in violent CT failures due to early detection, since routine Doble insulation power factor testing has been introduced. This factor influences safety and offers a reduction in the risks associated with a violent explosion of a CT failure, as that piece of equipment can be identified for insulation deterioration.

The Doble test system offers three different test modes for CT insulation testing: Grounded Specimen Test (GST); Grounded Specimen Test – Guard Test (GST-G); and Ungrounded Specimen Test (UST), the latter of which is discussed and used during this test due to the availability of the capacitive test point in the CT secondary terminal box.

8.2.2 Test Set-up

As the CT under test has an available capacitive test point in the secondary terminal box, the test was then conducted between one of the CT primary terminals and the capacitive test point. This method of connection is known as the UST method and measures the capacitance between the primary hair-pin conductor and that of the second last capacitive screen of the primary insulation within the CT and is noted as C_{12}.

The following steps were followed during the test set-up on the CT for the UST mode:

- Ensure that all the surfaces are clean, neat and clearly visible for termination and testing.
- In the CT secondary terminal box, short-circuit all the secondary cores and terminate to ground on the CT tank as depicted in figure 8-3.
- Disconnect the earth connection between the second last capacitive grading screen (CAPTAP) of the primary insulation and the CT tank.

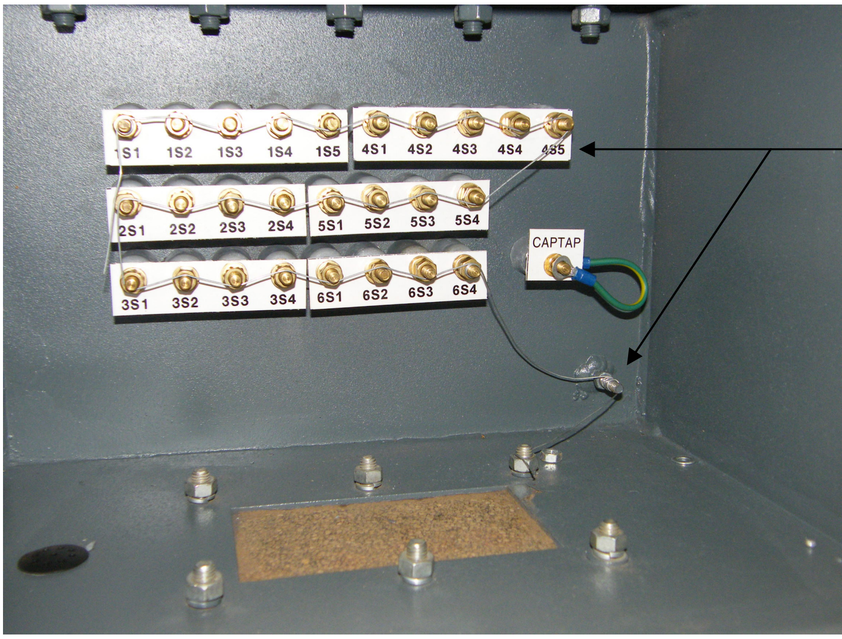

Figure 8-3: Doble test connection in the CT secondary terminal box

The surfaces required for testing had to be cleaned to prevent any leakage current to earth by means of tracking caused by dust. The earth connection was removed and this therefore made available the last grading screen for testing to the primary. All secondary cores were short-circuited and earthed to prevent unnecessary high voltages being present at the secondary terminals during testing.

The following steps were followed during the test set-up on the Doble M4100 Test System:

- Plug in the safety strobe light cable and position the strobe light near to the CT under test.
- Twist and lock in the earth cable, on the M4100 test system, that is bonded to the tank of the CT.

- Plug in the temperature/humidity sensor cable and position the sensor near the CT under test.
- Plug in safety switch 1 and 2 and run safety switch 2 to the CT under test.
- Plug in the Blue low voltage test lead and terminate the other end to the un-earthed CAPTAP stud in the CT secondary terminal box.
- Clip in the high voltage test hook and hang the hook over the primary (P1) terminal of the CT under test.
- Install the serial connecting cable between the M4100 test system and the laptop use for the testing.
- Plug in the 220V AC supply cable and leave the supply switch at the test system and at the plug socket turned off.

The connection of the earth cable ensured that the M4100 test system as well as the CT under test was at the same potential. The flash of the strobe light is indicative of a test in progress as well as the presence of high voltage near to the test equipment. The temperature sensor is independent of the test CT and indicates the temperature of the ambient air, as this influences the value obtained for the power factor of the CT. The temperature at the time of test must be noted and referenced back to the reference temperature of 20°C as specified in NRS 029:2002.

The safety switches are a 'push-to-make' type whereby both have to be depressed for the test to run and for the duration of the test. These switches were made available at the test system and at the CT under test. The high voltage hook formed the supply of the high voltage across the CT whilst the blue low voltage test lead formed the return path of the test set-up.

The following steps were followed during the test set-up on the Doble Test Assistant® software:

- Open the Doble M4000 software and in the DTA, choose the test to be performed on CTs.
- Populate the general information such as the company name, CT location, CT serial number, date and time of the test.
- Under the Nameplate tab, information specific to the test was populated from the nameplate of the CT under test such as: the name of the manufacturer, year of manufacture, CT type, the rms voltage rating, the maximum permissible current that

the CT can safely transfer under normal operating conditions as well as the internal insulation type as depicted in figure 8-4.

- Under the Overall tab, select the Ungrounded Specimen Test (UST) mode as a single test with a test voltage of 10kV as stipulated by NRS 029:2002 specification.
- The testing conditions were set as indoors, as the CT under test was currently on the floor in the Eskom store.
- The circuit description was then set to be UST-B.

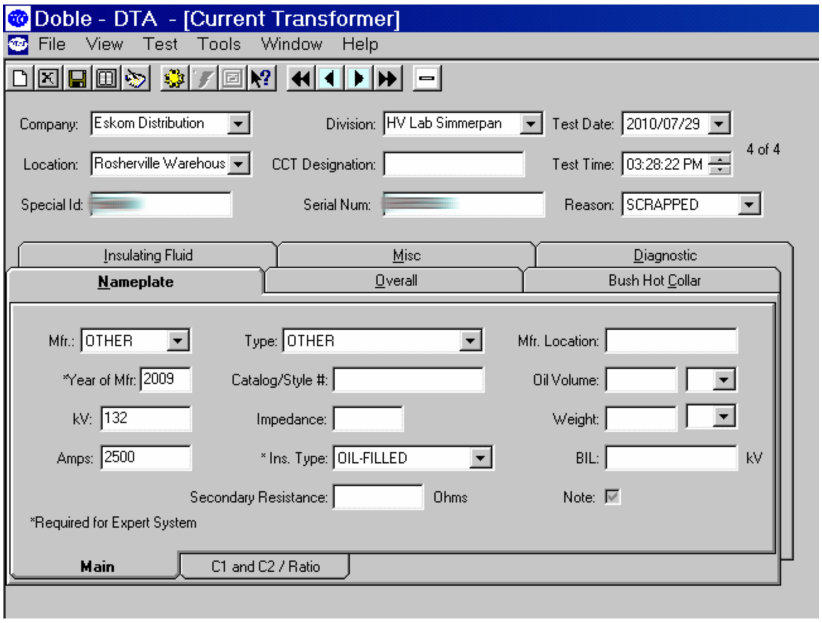

Figure 8-4: Doble Test Assistant® Set-up Snapshot

The DTA allows the results of the test to be traceable and also ensures that a library of information can be stored regarding the CT under test. As the CT under test had been in storage, it was not installed onto any structure; however it was raised off the ground by means of a pallet. In the UST mode of testing, the red LV return lead, that was not used, had been automatically grounded internally to the M4100 test system. In this test configuration, a direct replication of the condition of the internal insulation of the CT is provided, as the ‘guard’ connection on the test system forms part of the ‘ground’ connection as well, thereby making the guard a ‘cold’ connection.

8.2.3 Test Procedure

Upon completion of the test set-up and ensuring that the parameters were correct, the actual test had then to be performed on the selected CTs. The MCB's supplying power to the M4100 test system was then switched to the 'ON' position and visual indication of the input power and processor was provided by the lighting up of the yellow LED's alongside the MCB's. Prior to the performing of the actual test, the DTA software opens a separate window to allow the operator of the test to acknowledge the correct parameters of the test set-up as indicated in figure 8-5.

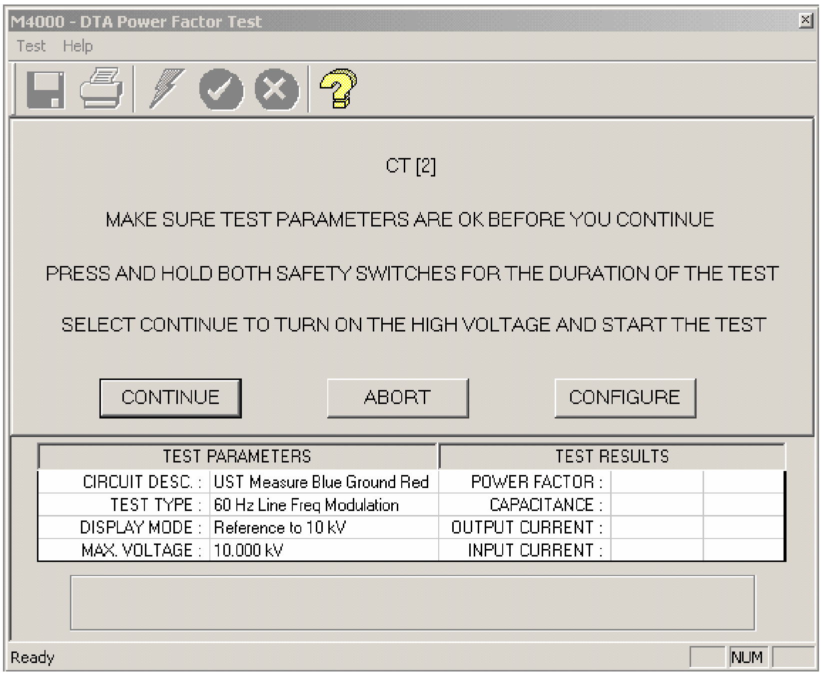

Figure 8-5: Doble Test Assistant® Test Start Snapshot

From the above snapshot, the DTA has a built in safety feature that prompts the user to accept the input data as true and correct prior to performing the test. Both the safety switches; one at the CT under test and the other at the M4100 test system; had to be held depressed whilst the 'Continue' button was depressed to start the test as depicted in figure 8-5. Safety of the assisting personnel had to be ensured and was highlighted with the use of the strobe light during the test in progress.

Whilst the test was in progress, a snapshot of the 'ramp test' in progress was highlighted and represented in figure 8-6 below. The voltage across the CT was ramped up from 0kV to

10kV and ramped back down to 0kV. Whilst the voltage was being ramped up and down, the current flow from the primary of the CT through to CAPTAP of the CT was also ramped up from 0μA to 300μA and ramped back down to 0μA. With the M4100 test system designed and built in America, the system frequency used in America is 60Hz, thereby enabling this test to be performed at the standard frequency of 60Hz. During the ramp up and ramp down of the test voltage and current, the M4100 test system automatically calculated the power loss in mW of the CT internal insulation. After completion of the test, a 'Test Done' indication appeared in the test window and the results were then saved. The safety switches were then released thereby preventing the high test voltage from being present across the CT.

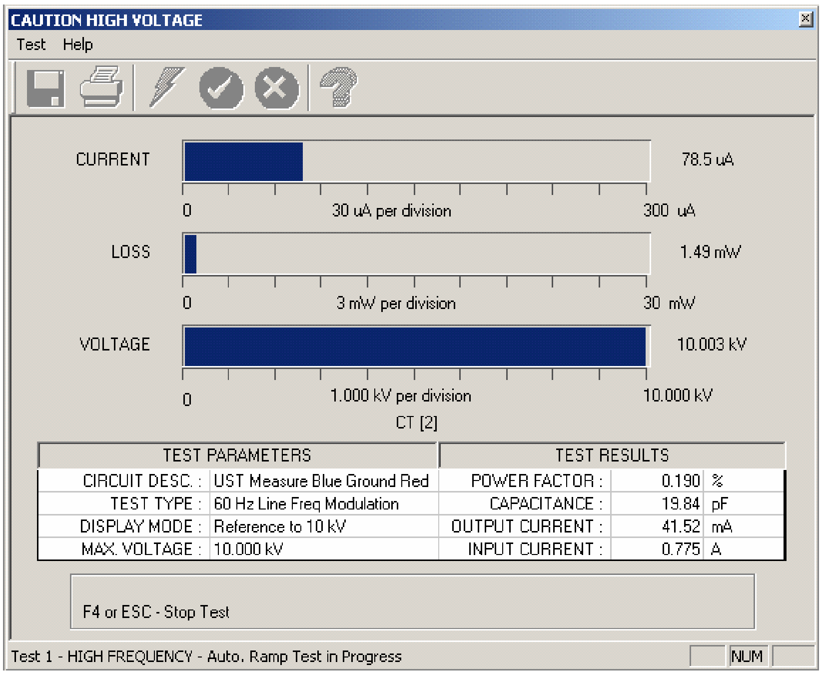

Figure 8-6: Doble Test Assistant® Test in Progress Snapshot

8.3 Test Results and Analysis

The expected test results from the test performed above were scheduled to be below the values as stipulated in NRS 029:2002 in that the value of insulation power factor should not exceed 0.5% where the test has been performed at a temperature of 25°C. For tests performed at a temperature other than 25°C, a compensation amount of 15% per 10°C must be used to allow for linear temperature compensation. The test results obtained for the three

CTs tested are indicated in Appendix 3. Only the UST method of testing was performed, as the CTs were currently placed in storage for use in future projects. With the CTs having a rating of U_M > 24kV, the recommended test voltage to be applied to assist with standardisation is a rating of 10kV.

The information populated on the DTA software, with respect to the year of manufacture, voltage level of the CT as well as the internal insulation type, formed the information processed onto the test results as per Appendix 3. Other information, such as the test date and time, the ambient temperature during test as well as the percentage humidity, had been generated from the personal computer used as well as the temperature/humidity sensor linked to the M4100 test system respectively.

Capacitance and power factor testing provides a convenient means of condition monitoring of the CT internal insulation. A purely capacitive insulation is indicative of a dielectric loss free insulation as compared to a more resistive insulation, where the resistive current through the insulation gives a direct impact of the dielectric power loss within that insulation. This suffices to say that an increase or a high value of insulation power factor after testing the CT gives evidence of deterioration in quality of the internal insulation (Kakkar *et al* (2002b); Shkolnik, (2008d)).

The capacitance and insulation power factor must remain essentially constant with increasing voltage, as insulation systems are linear systems and any increase of the insulation power factor with voltage is an indication of partial discharges in the primary insulation which can lead to a failure of the insulation system (Mariani, (2007b)). With the results of the power factor obtained from the CT whilst still new, a benchmark figure is used to compare the periodic readings and any deviation in the values indicates the deteriorating health of the paper insulation within the CT. The results were then analysed in conjunction with the standard NRS 029:2002 specification.

The actual value of insulation power factor as tested by the specific manufacturer was unavailable thereby preventing a direct comparison between the tests results obtained in this test versus that obtained from the manufacturer. In analysing the results of the test performed, Mariani, (2007) explains the analysis in terms of dielectric losses within a real capacitor and uses this as a basis for the losses within a CT. In this capacitor, the losses can be lumped as a single resistance that is connected on parallel with the ideal capacitor as indicated in figure 8-7 with its associated vector diagram in figure 8-8.

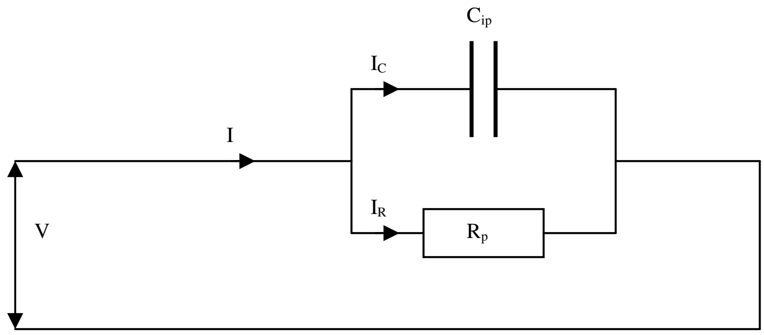

Figure 8-7: Real Capacitance with Losses

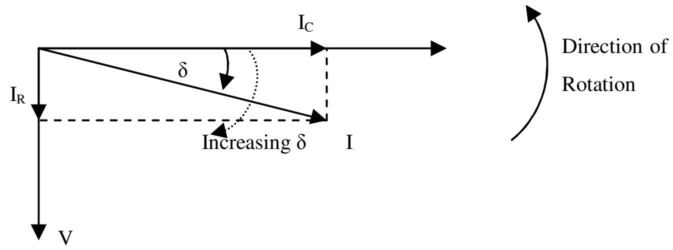

Figure 8-8: Vector Diagram

From the above figures 8-7 and 8-8, the active power is indicated as:

$$P = VI_R = \omega C_{ip} V^2 \tan\delta \qquad (1)$$

Where: $\omega = 2\pi f$

The value of current I_C through the ideal capacitance is calculated as:

$$I_C = 2\pi f CV \qquad (2)$$

Where: f = System Frequency of 50Hz

The value of current I_R through the resistive branch is calculated as:

$$I_R = I_C \tan\delta \qquad (3)$$

Using equation 1 above, the results of the active power dielectric watts loss within the CTs tested, as per Appendix 3, are tabulated in table 8-2 below.

Table 8-2: Analysis of Test Results

	Current Transformers Tested		
	AA/XX1	AA/XX2	AA/XX3
I_C (mA)	1.436	1.436	1.436
I_R (μA)	368.62	5.744	1.866
P (W)	28.09	0.437	0.142

From table 8-2, a value of 60pF was used as the design base from the specific manufacturer for a capacitance value, the value of tan δ was calculated from the Doble test and the voltage was selected as the phase-to-ground voltage as per the CT rating of 132kV. In review of table 8-2, evidence is provided that the higher the value of insulation power factor, the greater is the value of the resistive current thereby leading to excessive dielectric power losses (I^2R) in the form of heat within the insulation as depicted by CT serial number: AA/XX1. This heating of the internal insulation leads to the heating of the primary hair-pin conductor causing undue mechanical stresses within the CT.

CT AA/XX2 and CT AA/XX3 have been tested to be within the NRS 029:2002 specification for insulation power factor and in comparison with the power loss value as obtained with CT AA/XX1, an increase in the insulation power factor value gives a substantial increase in the flow of resistive current leading to excessive heat being generated and energy being transferred as depicted in figure 8-8. With an increasing value of insulation power factor, the heat being generated within the CT insulation will exceed the maximum value of heat dissipation that the CT can handle during normal operation thereby leading to thermal instability and hence a destructive failure (Cigré b. (2009a)). Another method of analysing the results is viewed from the standpoint whereby the internal insulation power losses is summated for the numerous CTs installed on site thereby leading to an even larger value of power drain on the power network.

The excessively high value of insulation power factor is indicative of impurities such as moisture within the primary insulation caused either by the addition of impure insulating oil or the improper drying of the primary paper insulation prior to the addition of the insulating oil (Cigré b. (2009a)). Another conclusion that can be drawn is based on the CT being damaged internally prior to delivery to ED or the use of impure materials during design and construction phase of the CT. Referring to figure 1-1, the decrease in the value of capacitance gives indication of the loss of a capacitive screen thereby causing a larger voltage stress value to exist between the remaining screens. This then leads to the screens being degraded exponentially due to the presence of partial discharges between the paper-foil layers.

8.4 Conclusion

Insulation Power factor and capacitance testing is described as a method aiding in economic considerations and offers the advantage of early warning of an impending CT insulation failure. This assists in the CT being re-conditioned instead of the more costly replacement. Predictive and pre-emptive measures can be sought resulting in a planned maintenance outage being scheduled to remove the CT prior to extensive insulation failure. Power factor testing therefore provides a convenient means of monitoring the condition of the CT primary insulation. Periodic power factor testing enables trending of the CT insulation that can be used for the life of the CT and provides clear indication of possible insulation deterioration, thereby preventing an unexpected failure.

Risks associated with the failure of the CT and accelerated ageing is clearly evident in the type of quality of the internal insulation (Cigré c. (1990b)). The Doble insulation test system M4100 has been proven to be successful in effectively determining the deteriorating internal insulation of a CT (Ayers *et al* (1999b); (Doble a. (2010)). With its internal shielding of using LFM, the M4100 provided an accurate representation of the internal insulation. Safety of personnel and equipment was highlighted as the main priority during the testing phase of the CT, due to the presence of the high voltage from the M4100 test system.

From the results obtained above, a high value of insulation power factor was obtained and possible causes leading to such high values are moisture ingress through defective sealing, accelerated ageing of the internal insulation due to thermal depolarisation which leads to the formation of water or impure oil that has been added to the paper insulation during impregnation.

The Doble insulation test offers the ability to check on the dryness of the insulation that is directly related to the quality of manufacture. Checking the same type of CT from the same manufacturer also provides information on the consistency of the manufactured CT as well as the state of its condition for site installation. A term of reference is enabled that can be accessed during diagnosis of in-service abnormalities (Heywood *et al* (2008c)). With reference to the analysis of the test results, the dielectric loss in the form of heat is a deteriorating factor in the estimated lifespan of the CT. The quality of the insulating oil is a contributing element to the increased levels of insulation power factor. Impure materials and inadequate design lead to high values of insulation power factor and without proper testing; these defective CTs can be installed into the power network and with normal operating conditions the serviceable life of the CT is then shortened.

CHAPTER 9: DISCUSSION OF FAILURES IN LIGHT OF THE THEORY

9.1 Introduction

The research objective of this study was to investigate the CT failures within ED by means of hypothesizing that CTs acquired with high insulation power factor values will fail prematurely. By doing this, information related to the above could be shared world wide to assist with curbing such catastrophic failures in CTs. The literature review highlighted the various aspects that assisted in identifying a methodological approach to the related causes, effects and experiences of CT failures related to high insulation power factor values in hair-pin type CTs.

The various designs of hair-pin type CTs, their associated construction and manufacturing phase's concern the quality of materials used and is identified as a factor that requires most attention to detail. The overall quality of the CT can then be negatively influenced relating to drastic consequences. In the testing of suspect CTs, the results provided evidence of CTs that were within specification against that which was not. Had the suspect CTs been installed, the possibility of their premature failure would be imminent. The hypothesis as stated by the author can then be seen as effective and the study as giving a foreground for further research.

9.2 Recommendations

One of the main objectives during an investigation is to obtain results. From these results two options exist. Option one is a simply "do nothing" approach whereby option two is to review the results to find a solution that can minimise, monitor or eradicate the main cause of CT failures. The economic considerations of option one can severely impact ED due to the consequential damage of a possible CT failure exhibiting catastrophic destruction. This can far outweigh the costs associated with option two. In light of option two, condition monitoring of CTs is the first line of defence in that the detection of an incipient fault arising and the condition of the internal insulation of the CT and even trend analysis can be performed for the life of the HV equipment. This will assist in capital expenditure and increase reliability and quality of supply to the end user.

As the premature failure of CTs is relatively quick in nature, the time to failure cannot be predicted by normal off-line methods. This is a motivating factor for ED to review various monitoring techniques to forewarn of a possible premature failure. The aim of condition monitoring of CTs is therefore to monitor any changes that might be prevalent in the structure of the internal insulation.

As part of a project done by Allan and Nichols, (2000a), condition monitoring by Dissolved Gas Analysis (DGA) is seen to be an approach to assist with the level of deterioration within a CT. This method however, needs to be carefully considered prior to implementation, as the high probability of moisture ingress is imminent during sample taking. High hydrogen content, during DGA, is indicative of partial discharge activity thereby promoting the need for the CT to be removed from service. Allan & Nichols, (2000a) Goes on also to explain that insulation power factor and partial discharge measurement of CTs has economic benefits of being able to maintain the CT for its rated age duration and that utilities consideration in the implementation and use of such is a viable option.

The ability to provide information irrespective of weather or load variations is a possibility with on-line measurements that gives a more dynamic approach on the capability of the CT whilst in operation at its rated voltage. Pagan, (1998f) explains that even though the CT may have been tested off-line, certain criteria might not have been met related to the CTs deterioration. It is for this purpose that on-line condition monitoring be considered as essential. This prevents economic pressure on ED as early detection of the failure mode is possible thereby allowing timely replacement or maintenance techniques, only where required, to materialise.

One of the main concerns was the absence of accurate record keeping and post mortems in ED on suspect or failed CTs to determine the root cause of failure. This should be emphasised and practiced within all regions of ED as a standard form of reporting that can be seen to assist with the improving of CT designs, requirements and the overall quality of the CT. A system of “fingerprinting”, where all test data is obtained from the date of inception to the date of possible failure, of all CTs within all regions of ED should be strived for, that will enable data trending that can assist in finding the root cause of the CT insulation deterioration.

As described in the literature, the method of testing and verification of insulation power factor at 50Hz and at 80Hz, as described by Gubanski, (1998d), is a method that should be reviewed by ED for all CTs currently installed and those that are currently being manufactured. Utilising this technique, a correlation can be drawn and verification can be achieved using the formula as described by Gubanski, (1998d).

9.3 Conclusion

This research has not directly proven that high values of insulation power factor cause premature failures of CTs. However the research has shown that suspect CTs that were tested had high levels of insulation power factor which exceed the acceptable specified limits. Two CTs that were tested as part of this research were found to have insulation power factor levels that were higher than the specified limit of 0.5%. All suspect CTs that were tested by Eskom before being commissioned were found to also have insulation power factor levels that were higher than the specified limit of 0.5%.

Literature review has shown that there is a link between higher levels of insulation power factor and premature failure of CTs (Cowan & Grobler, (1998c); Pagan, (1998f)). Insulation power factor increases with time under normal system operating stresses and would be accelerated under abnormal loading conditions (Vandemaar & Wang, (1999g); Cowan & Neale, (2000b)). It is therefore safe to assume that, if the CTs with insulation power factor levels exceeding the specified limits were to be commissioned and be in service, the insulation power factor would rise to levels where the likelihood of premature failure would be high. Such CTs may fail prematurely and catastrophically.

In order to conclusively relate high levels of insulation power factor in CTs to premature failure, it is proposed that long term on-line monitoring of CTs suspected to have high levels of insulation power factor be undertaken on a larger scale. This will enable the trending of partial discharge levels up to the point of failure in CTs.

Knowledge and understanding of insulation power factor of CTs is critical for the health and successful operation of a power network. Early detection of CTs with high levels of insulation power factor enables power utilities to take corrective action well in advance to prevent premature failures and their associated negative consequences. Failure of CTs would severely affect power availability, endanger the safety of personnel and put associated nearby plant at risk of being damaged.

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APPENDIX 1

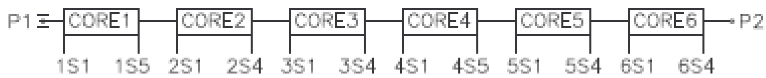
Figure A1-1: Installed 132kV CT showing oil spillage on trench covers

Figure A1-2: Installed 132kV CT with oil leaks on base tank

APPENDIX 2

Table A2-1: Nameplate of a Typical 132kV CT

CURRENT TRANSFORMER		SPEC: IEC 60044−1	
TYPE:	SERIAL No.:		YEAR:
IL: 145/230/550 kV	CREEPAGE: 31 mm/kV		RATED FREQUENCY: 50Hz
Ith 25 kA 3 sec	Idyn 64 kA	R.P.C. 2500 A	MASS: 810 kg



CORE'S	TERMINALS	RATIO	VA	CLASS	Ual	Ial	Rct@75°C
1&4	S2−S3	1/ 200T		TPS			0,8Ω
	S1−S2	1/ 400T		TPS			1,6Ω
	S1−S3	1/ 600T		TPS			2,4Ω
	S4−S5	1/ 800T		TPS			3,2Ω
	S3−S4	1/1000T		TPS			4,0Ω
	S2−S4	1/1200T		TPS			4,8Ω
	S1−S4	1/1600T		TPS			6,4Ω
	S3−S5	1/1800T		TPS			7,2Ω
	S2−S5	1/2000T		TPS			8,0Ω
	S1−S5	1/2400T		TPS	2400V	42mA	9,6Ω
2&3*	S1−S2	1/1000T		TPS*	550V	50mA	2.0Ω
	S1−S3	1/1200T		TPS*	660V	42mA	2,4Ω
	S1−S4	1/1600T		TPS*	880V	31mA	3,2Ω
5&6	S1−S2	400 /1	5	0,2			
	S3−S4	800 /1	10	0,2			
	S2−S3	1200/1		0,2			
	S1−S3	1600/1		0,2			
	S2−S4	2000/1		0,2			
	S1−S4	2400/1		0,2			

* U_{al} +10% → $I_{al} \leqslant$ 50%

APPENDIX 3

Table A3-1: Test Results of CT No: 1

Nameplate - Current Transformer

Company	Eskom Distribution	**Serial Number**	AA/XX1
Location	Rosherville Warehouse	**Special ID**	
Division	HV Lab Simmerpan	**Circuit Designation**	132kV
Manufacturer	A	**Class**	
Yr. Manufactured	2007	**Type**	HAIR-PIN
Mfr. Location		**Insul. Type**	OIL-FILLED
Catalog/Style		**Weight**	
Impedance	%	**Secondary Ohms**	
Oil Volume		**BIL**	kV
kV	132	**Amps**	2500
C1 %Power Factor		**C2 %Power Factor**	
C1 Capacitance		**C2 Capacitance**	
Note	Indoors testing		

Test Date	2010/07/29	**Test Time**	3:51:33 PM	**Weather**	
Air Temperature	22 °C	**Tank Temp.**	°C	**RH.**	17 %
Tested by		**Work Order #**		**Last Test Date**	
Checked by		**Test Set Type**		**Retest Date**	
Checked Date		**Set Top S/N**		**Reason**	FAILED
Last Sheet #		**Set Bottom S/N**			

Overall Tests

Test Mode	**ENG**	**GAR**	**UST**	**Test Mode**	**Test kV**	**mA**	**Watts**	**%PF corr**	**Corr Fctr**	**Cap (pF)**	**IR_{auto}**	**IR_{man}**
UST	H1,H2		TAP	UST	10.004	0.0300	0.0770	25.67	1.00	7.609	I	
GND	H1,H2	@2kV		GND	2.0							

Table A3-2: Test Results of CT No: 2

Nameplate - Current Transformer

Company	Eskom Distribution	**Serial Number**	AA/XX2
Location	Rosherville Warehouse	**Special ID**	
Division	HV Lab Simmerpan	**Circuit Designation**	132kV
Manufacturer	A	**Class**	
Yr. Manufactured	2008	**Type**	HAIR-PIN
Mfr. Location		**Insul. Type**	OIL-FILLED
Catalog/Style		**Weight**	
Impedance	%	**Secondary Ohms**	
Oil Volume		**BIL**	kV
kV	132	**Amps**	2500
C1 %Power Factor		**C2 %Power Factor**	
C1 Capacitance		**C2 Capacitance**	
Note	Indoors Testing		

Test Date	2010/07/29	**Test Time**	3:18:10 PM	**Weather**	INDRS
Air Temperature	21 °C	**Tank Temp.**	°C	**RH.**	87 %
Tested by		**Work Order #**		**Last Test Date**	
Checked by		**Test Set Type**		**Retest Date**	
Checked Date		**Set Top S/N**		**Reason**	PASSED
Last Sheet #		**Set Bottom S/N**			

Overall Tests

Test Mode	**ENG**	**GAR**	**UST**	**Test Mode**	**Test kV**	**mA**	**Watts**	**%PF corr**	**Corr Fctr**	**Cap (pF)**	**IR_{auto}**	**IR_{man}**
UST	H1,H2		TAP	UST	10.006	0.1010	0.0040	0.40	1.00	26.893	I	
GND	H1,H2	@2kV		GND	2.0							

Table A3-3: Test Results of CT No: 3

Nameplate - Current Transformer

Company	Eskom Distribution	**Serial Number**	AA/XX3
Location	Rosherville Warehouse	**Special ID**	
Division	HV Lab Simmerpan	**Circuit Designation**	132kV
Manufacturer	A	**Class**	
Yr. Manufactured	2009	**Type**	HAIR-PIN
Mfr. Location		**Insul. Type**	OIL-FILLED
Catalog/Style		**Weight**	
Impedance	%	**Secondary Ohms**	
Oil Volume		**BIL**	kV
kV	132	**Amps**	2500
C1 %Power Factor		**C2 %Power Factor**	
C1 Capacitance		**C2 Capacitance**	
Note	Indoors Testing		

Test Date	2010/07/14	**Test Time**	1:14:07 PM	**Weather**	INDRS
Air Temperature	17 °C	**Tank Temp.**	°C	**RH.**	100 %
Tested by		**Work Order #**		**Last Test Date**	
Checked by		**Test Set Type**		**Retest Date**	
Checked Date		**Set Top S/N**		**Reason**	PASSED
Last Sheet #		**Set Bottom S/N**			

Overall Tests

Test Mode	ENG	GAR	UST	Test Mode	Test kV	mA	Watts	%PF corr	Corr Fctr	Cap (pF)	IR_{auto}	IR_{man}
UST	H1,H2		TAP	UST	10.004	0.0750	0.0010	0.13	1.00	19.835	I	
GND	H1,H2	@2kV		GND	2.0							

APPENDIX 4

Table A4-1: List of Suspect Current Transformers Tested during Commissioning…/cont

MANUFACTURER	SERIAL NUMBER	VOLTAGE LEVEL IN kV	VINTAGE	TEST DATE	AMBIENT TEMPERATURE IN °C	POWER FACTOR VALUE IN %	STATUS OF TEST
A	XX/1	132	2007	12/06/2008	20	3.58	FAILED
A	XX/2	132	2007	12/06/2008	21	1.27	FAILED
A	XX/3	132	2007	12/06/2008	24	1.78	FAILED
A	XX/4	132	2007	12/06/2008	25	2.00	FAILED
A	XX/5	132	2007	12/06/2008	24	1.15	FAILED
A	XX/6	132	2007	12/06/2008	24	5.13	FAILED
A	XX/7	132	2007	04/11/2008	28	2.83	FAILED
A	XX/8	132	2007	04/11/2009	28	3.57	FAILED
A	XX/9	132	2007	04/11/2009	29	1.09	FAILED
A	XX/10	132	2006	31/03/2009	27	2.02	FAILED
A	XX/11	132	2007	31/03/2009	26	1.57	FAILED
A	XX/12	132	2007	31/03/2009	26	1.21	FAILED
A	XX/13	132	2007	31/03/2009	25	1.89	FAILED
A	XX/14	132	2006	31/03/2009	25	1.66	FAILED
A	XX/15	132	2007	31/03/2009	27	4.48	FAILED
A	XX/16	132	2007	18/11/2007	29	1.10	FAILED
A	XX/17	132	2007	18/11/2007	27	12.89	FAILED
A	XX/18	132	2007	18/11/2007	27	9.31	FAILED
A	XX/19	132	2007	11/11/2007	29	1.33	FAILED
A	XX/20	132	2007	11/11/2007	29	1.38	FAILED
A	XX/21	132	2007	02/02/2010	38	2.19	FAILED
A	XX/22	132	2007	18/11/2007	29	1.14	FAILED
A	XX/23	132	2007	18/11/2007	29	1.03	FAILED
A	XX/24	132	2007	18/11/2007	29	1.27	FAILED
A	XX/25	132	2007	18/11/2007	29	1.08	FAILED

…/cont

MANUFACTURER	SERIAL NUMBER	VOLTAGE LEVEL IN kV	VINTAGE	TEST DATE	AMBIENT TEMPERATURE IN °C	POWER FACTOR VALUE IN %	STATUS OF TEST
A	XX/26	132	2007	18/11/2007	29	3.75	FAILED
A	XX/27	132	2007	18/11/2007	29	3.80	FAILED
A	XX/28	132	2007	18/11/2007	29	1.06	FAILED
A	XX/29	132	2007	18/11/2007	27	1.05	FAILED
A	XX/30	132	2007	18/11/2007	27	10.06	FAILED
A	XX/31	132	2007	18/11/2007	27	1.58	FAILED
A	XX/32	132	2007	18/11/2007	27	14.09	FAILED
A	XX/33	132	2007	18/11/2007	27	12.50	FAILED
A	XX/34	132	2007	18/11/2007	27	13.66	FAILED
A	XX/35	132	2007	18/11/2007	27	1.53	FAILED
A	XX/36	132	2008	11/11/2007	29	0.95	FAILED
A	XX/37	132	2008	11/11/2007	29	1.13	FAILED
A	XX/38	132	2008	11/11/2007	29	0.81	FAILED
A	XX/39	132	2008	11/11/2007	29	0.98	FAILED
A	XX/40	132	2008	11/11/2007	29	1.29	FAILED
A	XX/41	132	2008	11/11/2007	29	0.69	FAILED
A	XX/42	132	2008	11/11/2007	29	1.86	FAILED
A	XX/43	132	2008	11/11/2007	29	0.77	FAILED
A	XX/44	132	2008	11/11/2007	29	0.87	FAILED
A	XX/45	132	2008	11/11/2007	29	1.44	FAILED
A	XX/46	132	2006	11/11/2007	29	2.25	FAILED
A	XX/47	132	2006	11/11/2007	29	1.22	FAILED
A	XX/48	132	2006	11/11/2007	29	2.19	FAILED
A	XX/49	132	2006	18/11/2007	30	4.12	FAILED
A	XX/50	132	2006	18/11/2007	30	4.17	FAILED

…/cont

MANUFACTURER	SERIAL NUMBER	VOLTAGE LEVEL IN kV	VINTAGE	TEST DATE	AMBIENT TEMPERATURE IN °C	POWER FACTOR VALUE IN %	STATUS OF TEST
A	XX/51	132	2007	14/12/2007	28	2.38	FAILED
A	XX/52	132	2007	14/12/2007	28	1.09	FAILED
A	XX/53	132	2007	14/12/2007	28	0.71	FAILED
A	XX/54	132	2007	14/12/2007	28	10.45	FAILED
A	XX/55	132	2007	14/12/2007	28	2.09	FAILED
A	XX/56	132	2007	14/12/2007	28	1.21	FAILED
A	XX/57	132	2007	14/12/2007	28	11.31	FAILED
A	XX/58	132	2007	14/12/2007	28	1.31	FAILED
A	XX/59	132	2007	14/12/2007	28	11.97	FAILED
A	XX/60	132	2007	12/06/2008	26	4.83	FAILED
A	XX/61	132	2007	12/06/2008	26	4.79	FAILED
A	XX/62	132	2007	12/12/2008	28	1.82	FAILED
A	XX/63	132	2007	12/12/2008	28	1.79	FAILED
A	XX/64	132	2007	12/12/2008	28	1.84	FAILED
A	XX/65	132	2007	12/12/2008	28	2.01	FAILED
A	XX/66	132	2007	12/12/2008	28	2.86	FAILED
A	XX/67	132	2007	12/12/2008	28	1.01	FAILED
A	XX/68	132	2006	10/11/2007	26	4.87	FAILED
A	XX/69	132	2006	10/11/2007	26	4.29	FAILED
A	XX/70	132	2007	10/11/2007	26	12.13	FAILED
A	XX/71	132	2007	10/11/2007	26	11.87	FAILED
A	XX/72	132	2007	10/11/2007	26	10.98	FAILED
A	XX/73	132	2008	14/06/2009	21	1.56	FAILED
A	XX/74	132	2008	14/06/2009	21	0.87	FAILED
A	XX/75	132	2008	14/06/2009	21	0.98	FAILED
A	XX/76	132	2008	14/06/2009	21	1.14	FAILED

…/cont

MANUFACTURER	SERIAL NUMBER	VOLTAGE LEVEL IN kV	VINTAGE	TEST DATE	AMBIENT TEMPERATURE IN °C	POWER FACTOR VALUE IN %	STATUS OF TEST
A	XX/77	132	2008	14/06/2009	21	1.78	FAILED
A	XX/78	132	2008	14/06/2009	21	2.01	FAILED
A	XX/79	132	2008	14/06/2009	21	1.35	FAILED
A	XX/80	132	2008	14/06/2009	21	1.57	FAILED
A	XX/81	132	2008	14/06/2009	21	1.86	FAILED
A	XX/82	132	2008	15/06/2009	21	1.73	FAILED
A	XX/83	132	2008	15/06/2009	21	1.11	FAILED
A	XX/84	132	2008	15/06/2009	21	1.15	FAILED
A	XX/85	132	2008	15/06/2009	21	1.89	FAILED
A	XX/86	132	2008	15/06/2009	21	1.76	FAILED
A	XX/87	132	2008	15/06/2009	21	2.89	FAILED
A	XX/88	132	2008	15/06/2009	21	2.56	FAILED
A	XX/89	132	2008	15/06/2009	21	1.17	FAILED
A	XX/90	132	2008	15/06/2009	21	1.38	FAILED
A	XX/91	132	2008	15/06/2009	21	1.47	FAILED
A	XX/92	132	2008	15/06/2009	21	1.56	FAILED