CONTINUOUS ON LINE RELATIVE TAN DELTA MONITORING OF HIGH VOLTAGE INSULATION

In fulfillment of the requirement for a research Masters of Science in Engineering degree for candidate Roger Cormack, University of Kwazulu-Natal Student Number 991263768

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Declaration

I declare that this thesis is my own, unaided work. It is being submitted for the degree of Master of Science at the University of Kwazulu-Natal, Durban. It has not been submitted before for any degree or examination in any other university.

Signed : ______________________.
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Place : **Durban**

Date : **15/09/04**

Abstract

The thesis discusses the findings of an investigation into the use of novel condition monitoring techniques for oil-paper insulated high voltage equipment as used on the Eskom Main Transmission System. This research into the monitoring of the condition of high voltage (HV) insulation was undertaken because of the high failure rate of high voltage current transformers (CT's) and transformer bushings on the Eskom Transmission National Grid. These failures reached unacceptably high levels in the 1990's. The extent of failures has been quantified and was the driving motivation behind this research.

Techniques for the condition assessment and condition monitoring of oil-paper filled high voltage equipment have traditionally focused on off-line techniques, in particular off-line tan delta measurements. This requires that the equipment be removed from service temporarily, but at widely spaced intervals before a measurement may be taken (typically every 3 to 6 years). Such techniques will not be able to detect faulty equipment where the insulation integrity deteriorates rapidly, resulting in catastrophic failure with risk to both adjoining equipment and personnel. The need for an on-line technique for detecting deteriorating insulation prior to failure was identified in the early 1990's and various systems were developed.

This research investigation has focussed on assessing the use of on-line relative tan delta monitoring of HV insulation and compares this to off-line monitoring. In particular, the ability of such a relative tan delta measurement system to detect deteriorating oil-paper insulation has been assessed. The investigation has included the design, construction and commissioning of a dedicated test facility located at Eskom's Tugela substation. This test facility is unique in the world. This test facility has resulted in a number of experiments that have provided invaluable insight into possible failure modes of oil-filled high voltage equipment and the ability of on-line techniques to detect rapid failure modes has been carefully assessed.

Further assessment of the on-line monitoring systems was also undertaken at various Eskom operational installations. The results of these tests and operational monitoring are addressed in this research. The research work and its findings are assessed against published literature and global activity in this important area.

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 Overview of the installed base of current transformers and bushings within Eskom

Table 1.1 below indicates that Eskom Transmission has the following hermetically sealed high voltage current transformers and transformer bushings installed in the 135 transmission substations, which comprise the National grid. These 135 substations comprise equipment operating at voltage levels from 66kV up to 400kV. The value of this plant is in excess of R700 million.

Voltage Rating	**Number of Current transformers**	**Number of transformer Bushings**
220,275, 400kV	5007	1350
66,88,132kV	3879	1350
Total	8886	2700
Average per Substation	66	20

Table 1.1: The installed base of current transformers and transformer bushings on the Eskom, Transmission Network [1].

The current transformers (CT's) listed above have been manufactured by over 10 manufacturers, one or two of these being local South African designs, but the bulk of them have been manufactured in Europe.

The transformer bushings listed above were mostly supplied by the original transformer manufacturers. The earlier model transformers (manufactured from the 1940's to late 1970's) were mostly manufactured in Europe, but the later models were made in South Africa and all the transformer bushings were imported.

In the 1980's to mid 1990's, there was little access to the latest technology as most manufacturers refused to supply the SA market, as international sanctions were imposed on South Africa. Most equipment purchased during this period was the only equipment that could be sourced at the time.

All the CT's and bushings mentioned in Table 1.1 for the 132kV – 400kV range were manufactured having HV insulation consisting of a composition of vacuum dried paper and mineral oil rather than resin impregnated paper. The sheets of paper are wrapped around the conductor, in layers, then vacuum dried and oil impregnated, the insulation is protected inside a porcelain shell, which is filled with mineral insulating oil and hermetically sealed to prevent moisture and oxygen ingress.

Due to the hermetic seal, the quality of the high voltage paper and oil insulation cannot be easily evaluated, without breaking the seal and introducing moisture. The quality of the hermetic seal deteriorates over the 30 years of service life in the harsh South African conditions, where summer temperatures of 40 degrees Celsius are common and moisture ingress and oxidation may deteriorate the insulation quality in time. The result may be the unexpected failure of the paper and oil insulation and the violent destruction of the current transformer or transformer bushing. Associated with this failure is the potential damage to adjacent plant. This would include the adjacent CT on the nearest phase to the failed CT. There are also outages caused to busbars and other circuits when the protection clears the fault, as well as outages and voltage depressions caused to customer supplies.

Table 1.2 below lists the recorded fault failures of CT's in the period 1983 – 1999. Included are the estimated costs of these failures to Eskom Transmission. It is noted that accurate records have not always been kept.

Year (19--)		83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	Total	**Values**
Line voltage	400kV	2	1	2	2	1	7	2	1	7	1	1	0	2	2	0	1	0	32	**R 3,2M**
	275kV	1	0	1	5	8	11	1	2	4	0	2	0	0	3	1	1	1	41	**R 4,1M**
	Other	0	0	3	1	1	5	2	0	13	6	6	7	0	6	2	3	1	56	**R 0,8M**
Total failures		3	1	6	8	10	23	5	3	24	7	9	7	2	11	3	5	2	129	**R 8,1M**

Table 1.2: Recorded current transformer failures on the Eskom transmission network Other, denotes 132kV, 88kV and 66kV [1].

Table 1.2 indicates that there have been a total number of 129 recorded CT's that failed, which cost the utility R8.1 million in 1999 in SA rands. Of particular concern were the high failure rates observed in 1988 and 1991. The tabulated data is shown graphically in Figure 1.1 below.

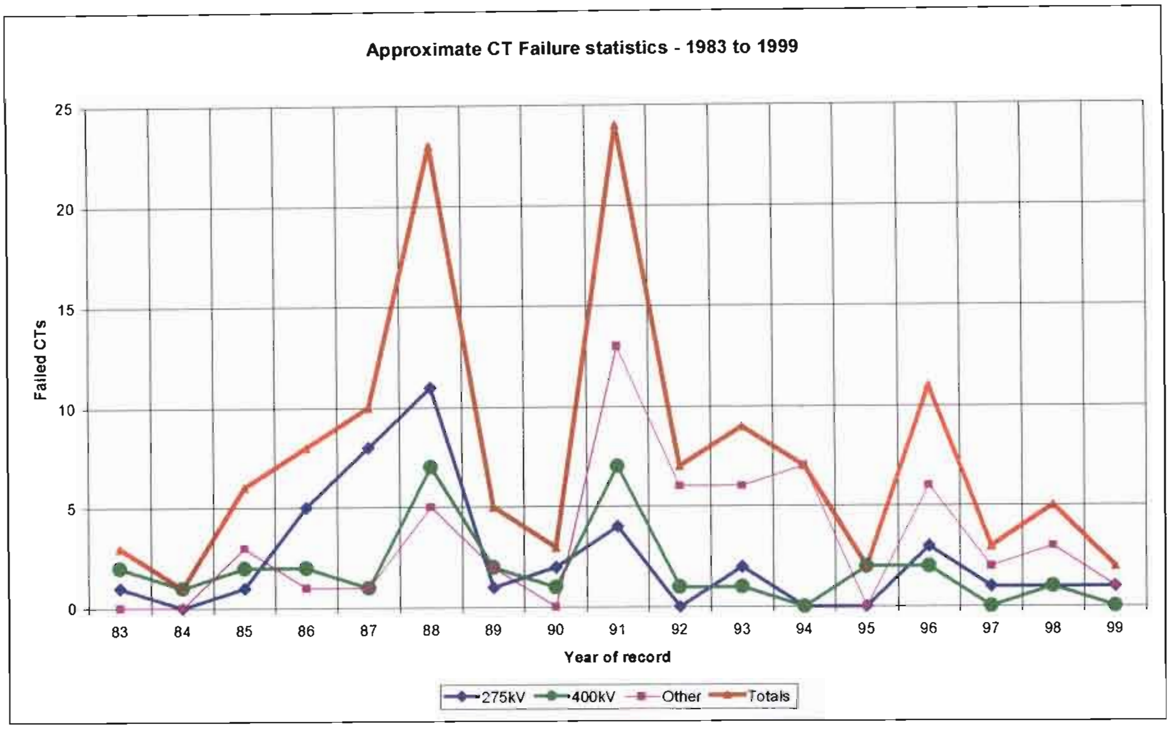

Figure 1.1: Graph of CT failures on the Transmission network, 1983 – 1999 [2].

1.2 The cost of HV plant failures

The failure of a CT if positioned on a bus coupler bay in the HV yard of a substation results in the fault causing the shut down of all the equipment at that voltage level. Thus, if a 275kV CT fails, then the entire 275kV supply will be switched off in that area. This results in the total loss of supply to customers in the particular area. One example would be the failure of a bus coupler 275kV CT at Illovo substation in 1996 shutting down the station. In the case of Illovo substation, where the shut down of the station affects the supplies to the National petrol refineries and other major industries, with the consequential risk of fire, damage, customer plant outages and damage to the product. Damage to customer plant and equipment can result in a drop in petrol production and this reduction in supply may affect the country and the economy.

Similarly a CT failure at Impala substation in Richards Bay may result in the loss of electrical supply to the major smelters, long-term damage to customer's plant and damage to and a loss of product.

From recorded failures and the cost to re-establish the circuit, the adjacent circuit and the loss of sales, Eskom estimates a cost of R250 000 per 275kV or 400kV CT failure incident, whereas the cost of one new unit is R100000. This cost of a replacement CT increases the total value of incidents on 275kV and above, from R7,3 million to R18,25 million (a factor of 2,5 X the cost of the failed plant), resulting in a loss to Eskom of over R1million per year. Obviously some individual incidents have resulted in more serious damage. An example would include failures at a power station where the failure of a current transformer caused the shutdown of several generators at a cost of R3 million. This value excluded the cost to customers due to loss of supply and production losses caused by outages and voltage dips.

The number of bushing failures for the period of 1996 – 1999 is shown in Table 1.3 below.

Year	**1996**	**1997**	**1998**	**1999**	**Total**
Number of Faulted Bushings	2	2	-	-	4
Number of transformers totally destroyed	2	1	-	-	3
Cost	R13M	R12,5M	-	-	R25,5M

Table 1.3: Recorded transformer bushing failures on the Eskom transmission network

Note: Transformers were totally destroyed, because of fire originating from the bushing failure and the power arc that followed, setting the oil alight, burning the whole unit [1].

The average cost of destroyed transformers over the previous 3 years was R8.5 million per year.

The possibility also exists that during the failure of a current transformer or a transformer bushing, operating personnel could be present and could have their lives at risk or face possible injury.

1.3 Current transformers investigated

The particular CT utilized in this research is the Balteau SAX 245 CT. The failure rates of these CT's are included to indicate the reason for the choice of this CT as the device under investigation.

There are 493 Balteau SAX 245 CT's installed on the Transmission Grid [3]. A number of these have failed (records show 7 in the last 9 years). These failures have caused an increase in the risk level to the reliability and security of the system, especially in the KwaZulu-Natal Grid area, during specific incidents at Illovo substation and three incidents at Impala substation where the CT's failed. The life expectancy of the CT is 25 to 30 years and in most cases the CT's which failed in operation had achieved this expected age since they were installed between 1971 and 1974 in the high humidity, high temperature areas along the East coast of South Africa. The area is well known for high rainfall, high summer temperatures reaching as high as 40°C, and high relative humidity (in the 90% range). As the area is along the coastline, the porcelain sheds are regularly polluted with a coating of marine pollution and have to be cleaned about twice per annum (normally done using hand washing with suitable solvents). A diagram and explanation of the Balteau SAX 245 CT is included in Appendix 1.

1.4 The failure mechanism

The mechanism of the degradation of the HV insulation and electrical failure of a CT or bushing [3] results in a power arc being formed inside the porcelain shell under the oil. The arc generates large quantities of gas, namely acetylene, methane, ethane and ethylene. The generation of these gases in turn builds up the pressure in the porcelain shell. Under high fault level conditions the pressure may exceed the strength of the shell and the CT may explode. When this occurs the porcelain is shot in all directions (up to 70 metres away from the failed CT). The flying porcelain pieces may damage adjacent plant and if personnel are in the area, the shrapnel may pose a risk to life. Damage to adjacent plant may be in the form of porcelain damage to breakers, CT's, isolator's etc., which may require replacement. The exploding porcelain may puncture adjacent transformers resulting in a loss of oil. The exploding CT may catch fire which may spread as the oil burns. Eskom Transmission has considered the probability of the damage to adjacent plant and the repair thereof and has adopted a figure of 2.5 times the cost of a CT to reinstate the circuit. The cost of such an incident to the economy of South Africa can far exceed the cost to get the plant operational. Consideration must also be made for the voltage depression experienced at neighboring Transmission stations where these depressions will affect customer's supplies and cause plant outages and product damage [3].

Due to the high cost of the failure of a CT, and the influence of the Transmission Charter listed below, a number of the high risk Balteau SAX 245 CT's were removed from critical service areas and replaced with modern "fail safe" CT's at Illovo and Impala substations. These removed Balteau CT's then became available for testing and research purposes. The Transmission Charter called for the following conditions:

- 100% Availability and sustainability of plant and operating capabilities
- Zero faults on the electrical system
- Zero accidents on the electrical system or in the operation thereof
- Service excellence from satisfied and safe employees
- The lowest cost (Rand per MWH) of electricity in the world [4].

During 1996 there were 11 CT failures and these had impacted seriously on the performance of customer supplies. These 11 CT failures were the highest number recorded per annum for the last 5 years and had caused multiple generator unit failures at power stations and resulted in cities being left without power. The Transmission Group had identified the failure of CT's as one of the greatest threats to the sustainability and availability of South Africa's power supply and to the

Transmission business. During 1996 two power transformers had also failed and burnt to the ground due to the failure of HV insulation on bushings.

1.5 Cause of failure of Balteau SAX 245 CT

Failure investigations indicated that the rubber thermal expansion membrane on the top of the unit (bellows), which seals off the oil from the air (the hermetic seal), perishes in the harsh African conditions over a number of years and moisture enters the unit. An internal Eskom report [3] concluded that the moisture degrades the HV insulation, reducing the dielectric strength, resulting in electrical failure and flash over of the HV voltage to the earthed secondary core shield.

1.6 Problem statement and procedures

1.6.1 The problem statement

An on-line condition monitoring system, High Voltage Insulation Early Warning System (HVIEWS), has been installed on the Transmission network to try and eliminate the failures discussed above. The system is intended to trend the insulation integrity and to suggest maintenance or removal and replacement before the danger stage.

The problem statement:

In relation to the hermetically sealed insulation in HV plant and the known symptoms that indicate degradation, the specific parameters generated by the installed on-line condition monitoring system (HVIEWS) points towards the present condition of the plant.

1) Does the HVIEWS system track the insulation condition?
2).Does the HVIEWS system alarm the operator to an unhealthy condition of HV insulation, in time for the operator to take the necessary action to secure the plant before failure?

1.6.2 The procedures to be followed

The following procedures are to be followed in order to answers the questions above:

- Trend the failure of hermetically sealed insulation under accelerated degradation conditions
- Monitor the associated effect on the dissipation factor (tan delta) measurement and quantify the accuracy of the data in relation to the degraded insulation condition. This will define the extent to which HVIEWS tracks the failure;
- Determine the amount of warning time given by the HVIEWS monitoring system to enable safe removal of the faulty unit from service prior to failure.

1.7 Thesis Layout

The thesis initiates with a review of HV oil/paper insulation and the characteristics of the oil and paper which affect the capacitive and the resistive leakage current flow in the insulation. This highlights the sensitivity of tan delta of oil-paper insulation to the applied voltage and temperature of the insulation. Chapter 3 then expands the literature review to summarise what experience utilities have had with on-line condition monitoring, with particular emphasis on current transformers. It is noted that there have been relatively few reports on installed systems and this may be due to the relatively limited experience of such systems world-wide. Chapter 4 provides an overview of the techniques used for both the off-line and the on-line, relative tan delta monitoring that were implemented at the Tugela Test Bay. Chapter 5 then describes the design and layout of the test station which was constructed as part of this research and highlights the safety and environmental aspects of the design. Chapter 6 then proceeds to discuss the experimental work carried out at the Tugela Test Bay and the results achieved. Chapter 7 presents the results of a laboratory based experimental program that investigated some of the effects observed at the Tugela Test Bay, in more detail. Chapter 7 also discusses the results obtained from the on-line monitoring system at sites installed in sub-stations. Chapter 8 presents an assessment of the findings of all the work (both field and laboratory based) and recommendations for further research work in this field. Chapter 9 presents the conclusions of the thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Review of insulation used in high voltage current transformers

High Voltage (HV) equipment is the backbone of the Eskom Transmission National Grid in South Africa. This grid is made up of 135 substations, rated at 400,275,132 and 88kV and interconnected by 26,510kms of overhead lines, rated at 400, 275 and 132kV [5]. The substation equipment comprises circuit breakers, isolators, busbars, current transformers (CT's), voltage transformers (VT's) and power transformers. A typical substation layout can be seen in Figure 1.

TUGELA SUBSTATION

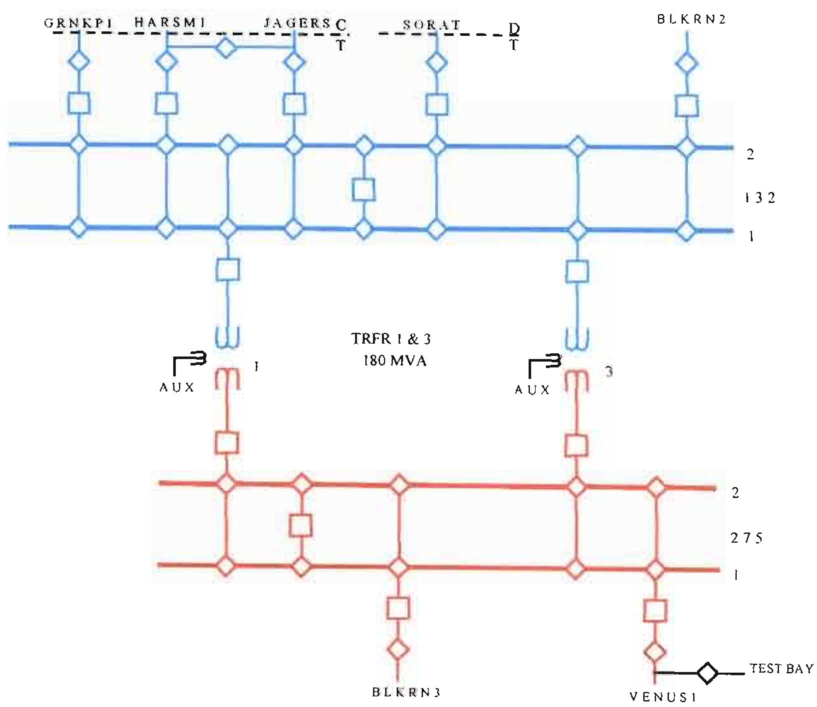

Figure 2.1: Tugela substation layout indicating the 275kV infeeds in red and the 132kV supplies in green [5].

The most important component of the HV equipment is the HV insulation, which enables the equipment to be operated safely, for the total lifetime, in the confined space available in the substations. CT's, VT's and transformer bushings are mostly insulated with oil impregnated paper. There are other types of HV insulation, which may be used for CT's, VT's and transformer bushings. These include gas (SF6, sulfur hexafluoride) or resins (considered more seriously by Eskom since 2000). The predominant HV insulation chosen for this equipment, for voltage levels from 11kV through to 400kV, from the earliest installations (early 1900's), until today, is the oil impregnated paper combination.

The selection of this oil impregnated paper insulation is the result of years of experience and research by the HV insulation community world wide, and then finally the design engineer, responsible for the specific substation must select the most suitable material for the specific application. The selection must consider the lifelong electrical, mechanical, chemical, environmental, physical, operational and economic requirements of the material to meet the primary function of the insulation, namely "to insulate, i.e. to prevent the flow of electric current between oppositely charged conductors for the satisfactory operation of the equipment" [6].

This thesis is focussed on the use of an on line relative tan delta measurement system for the detection of deteriorating oil-paper insulation as used in bushings and CT's. Tan delta is related to the losses in the insulation and hence issues related to these losses (particularly what effect moisture content and temperature have on these losses) as applicable to oil-paper insulation are briefly reviewed. A very thorough review of the factors affecting the loss tangent of oil-paper composite dielectrics is provided in Clark [6]. A brief summary of the findings reported in Clark [6] and as applicable to this thesis are given below.

2.2 The voltage stress distribution

Most commercial dielectrics are normally made up of composite materials such as oil impregnated paper, which has one dielectric of oil, and in series, the other of paper, or similarly for paper and air. If in the oil impregnated paper combination, the paper has not been thoroughly impregnated then even a third dielectric exists, namely air, which may exist as a void. Under alternating current (AC) voltage, the electric stress is permanently distributed across the composite insulation material in a ratio inversely proportional to the dielectric constants of the materials. Thus when equal thickness of mineral oil (dielectric constant of 3), and cellulose paper (dielectric constant of 5), are in series, approximately 72% of the voltage is absorbed by the oil and 28% by the paper. If an air void (dielectric constant of 1) is present, it absorbs an even greater voltage stress, and a void or gas pocket has the weakest dielectric strength, of ~$3*10^6$V/m as compared to oil which has a dielectric strength of about $12*10^6$V/m [6]. The normal expansion and contraction of the insulating material under operating conditions, coupled with the slow absorption of the gas by the oil, tend to reduce the pressure in the gas and further lower the already poor dielectric strength. Only sufficient drying and vacuuming of the paper prior to impregnation can reduce the possibility of voids, and so reduce failures.

2.3 Insulation life

Insulation life is accepted as that period of time during which voltage can be applied to the insulation under exaggerated service conditions without dielectric breakdown. Normally this also incorporates exaggerated temperature conditions. Where mechanical criteria are critical, attention must be placed on tensile strength, creep, impact strength, elasticity, brittleness etc. Where liquids are used, the problem of chemical stability becomes most important. Chemical instability results in the formation of sludge, gases, highly corrosive or highly conductive degradation products [6]. In the past the most active agents promoting insulation degradation have been oxygen and temperature and these should be excluded at all costs, these are normally excluded by hermetically sealing off the insulation.

2.4 Dielectric loss

A perfect insulation, if subjected to voltage, would consume no power. The charging current under AC voltage, would lead the voltage by 90 degrees. But all solids show some degree of conductivity. Only purified gases approach the condition of a perfect dielectric. The value of dielectric loss varies as a function of the applied voltage and temperature and frequency. Generally, as the molecular constitution of the dielectric material departs further and further from that of electrical symmetry, the effects of temperature, frequency and moisture on the dielectric loss become more pronounced. The tested value of the dielectric loss of the insulation during the factory manufacture and the use of the equipment, offers a non-destructive tool for the maintenance of the insulation. A change in dielectric loss may be due to contamination such as the absorption of moisture from the air, or degradation of the insulation, which is frequently the frontrunner of overheating, ionization and insulation failure [6].

2.5 Dielectric Absorption

Composite dielectrics, when subjected to AC voltages, show a loss which is greater than may be accounted for by their conductivities. One of the reasons for this is dielectric absorption. When submitted to a continuous voltage, the charge continues to flow into the dielectric over a period of time. The dielectric does not give up its charge instantaneously when shorted out. This charge dissipation requires time. The dielectric may even accumulate a charge after having been shorted out. This is most evident in cables, as a period of time is taken to reach a steady value of continuous current after a DC voltage is applied.

2.6 Dielectric constant

The electrical stress distribution across composite dielectrics is inversely related to the capacitance of the insulation when subjected to AC voltages. Since the capacitance of each insulating layer is directly related to the dielectric constant of the material, the stress distribution for an equal thickness of insulation layers in series is inversely related to the dielectric constant of the material. Changes in the dielectric constant require further engineering assessment.

2.7 Thermal evaluation

It is important to consider the thermal limitations of dielectrics as increases in temperature may have an impact on the life and serviceability of dielectric material. Oxidation may occur if the insulation is in contact with air. For temperature increases of between 8–10°C, it is reported that the rate of oxidation will increase twofold [6]. Also gaseous products are produced which lower voltage ionization and breakdown, acids are produced, as well as higher loss products and mechanical changes, including brittleness, loss of tensile strength and shrinkage, leading to voids. The effects of moisture may also cause chemical reactions resulting in both mechanical and electrical degradation.

2.8 Drying and impregnation of insulation

All insulating materials absorb moisture. However, to operate at their greatest dielectric efficiency, this moisture must be removed. All insulation is normally "air saturated", this needs to be removed and replaced with a liquid of a higher dielectric strength, for this reason the insulation needs to be thoroughly dried, vacuumed and impregnated, to enable it to operate effectively. Most high voltage insulation is vacuum dried at reduced pressures, care must be taken not to damage the insulation by overheating the organic material, at temperatures above 120°C. Air pockets must be vacuumed out of the insulation before impregnation as residual air pockets will form voids. The impregnant must have a low viscosity to enable it to penetrate the insulation, this low viscosity can only be obtained under high temperature conditions and the level of the impregnant must be increased slowly into the body of the insulation, so that the liquefied impregnating material is preceded by an area of insulation which is saturated by capillary action. A reliable manufacturing process incorporates (a) the use of the highest practically obtainable vacuum, (b) processes which eliminate wide temperature variations, (c) the use of temperatures substantially below the limits imposed by the time/temperature degradation characteristics of the most sensitive insulation, (d) a drying process which quickly removes the moisture liberated during the drying cycle,.(e) a process to remove air and moisture from the impregnant prior to impregnation, (f) a process to slowly introduce the impregnant to ensure effective impregnation [6].

2.9 Cellulose and mineral oil used as insulation in HV CT's

Most HV insulation consists of a combination of cellulose and mineral oil and it has been used successfully up to the higher voltages of 400kV. Commercial cellulose insulation is manufactured from coniferous woods. The removal of the organic contaminants such as the pentosans and the lignan is accomplished by boiling the wood with an alkaline solution of sodium sulfide and sodium hydroxide. The most common application of cellulose insulation is as paper sheets, pressboards and tapes. Cellulose is known to be hydrophilic, and has the following defects: (a) high dielectric constant; (b) reacts with oxygen; and (c) thermally unstable. These defects impose limitations to the life of the insulation and the equipment. The oil referred to is a light napthenic hydrocarbon [6].

2.10 Mineral oil impregnated cellulose

HV electrical equipment depends for its usability on the integrity of oil impregnated cellulose insulation. Wherever high voltage gradients are encountered, engineering dictates the use of oil-impregnated cellulose. It is best categorized by a usable value of dielectric loss, electrical and chemical stability and good mechanical properties. But the progress of this insulation is not free from industrial problems. The inspection of failures of this insulation has shown misapplication, manufacturing defects, and operating misuse, resulting in electrical breakdown. Oil impregnated cellulose is subject to serious and frequently rapid degradation if its limitations are not clearly recognized and controlled. The most serious limitation is its sensitivity to chemical and dielectric degradation. Experience has shown that the dielectric requires two types of strength, namely short-term voltage surge application and long-term application of rated voltage. The short-term strength requires a highly effective manufacturing process including proper drying and impregnating. The long term withstand ability depends on : (a) the chemical stability and the products produced by chemical, mechanical and dielectric degradation; (b) the dielectric loss increase due to chemical change and contaminants; and (c) the heat dissipation characteristic [6].

The objective of the drying process is to remove the moisture and thereby decrease the dielectric loss, but the cellulose is very sensitive to the degrading effects of temperature. The impregnation process eliminates the presence of air, which effects the dielectric strength and the dielectric constant. The mechanical aging of cellulose insulation continues throughout the life of the insulation and normally firstly manifests itself in chemical changes. In accordance with findings the rate of mechanical degradation for cellulose insulation, doubles with each increase of 8°C in operating temperature. The environment also effects the degradation of the insulation particularly where high humidity and high ambient temperatures are experienced [6]. The exposure to air and moisture is now mostly eliminated by using hermetically sealed equipment.

The degradation effects of moisture on oil-impregnated cellulose are far more pronounced than the effects of air. The effect of moisture on oil-impregnated paper is shown to accelerate the degradation. The removal of moisture by vacuum drying significantly increases the ability of cellulose to resist degradation. Once initiated, the chemical changes, which occur in cellulose under conditions conducive to thermal degradation may result in the formation of water, which then further affects the stability of cellulose insulation.

2.11 The change in dielectric constant, dielectric loss and insulation resistance of cellulose when impregnated with oil

When cellulose paper is impregnated with an insulating liquid, the dielectric constant is changed to an extent dependent on the dielectric constant of the impregnating liquid [6]. The presence of air in the dried paper gives an effective dielectric constant ranging from 1.0 (the dielectric constant for air) to as high as 6.35, which is the dielectric constant of dry paper. The oil impregnation of the paper results in a dielectric constant ranging from 2.25 (dielectric constant of mineral oil) to as high as 6.35 When the liquid impregnant has a lower dielectric constant, the dielectric constant of the impregnated paper is lower than that of the cellulose, when the impregnant has a dielectric constant higher than the cellulose, the dielectric constant of the impregnated paper is higher than that of the cellulose.

The dissipation factor of oil-impregnated paper is increased by an increase in the density of the paper. This increased power factor may become a problem when drying the paper as it becomes more difficult to dry as the insulating structure is increased. With increased density, the dielectric strength increases. This may be used to advantage in the grading of insulating paper, as the maximum voltage gradient is found in the insulation adjacent to the copper conductor. Dense insulating paper, with a high dielectric strength, may be used near the conductor.

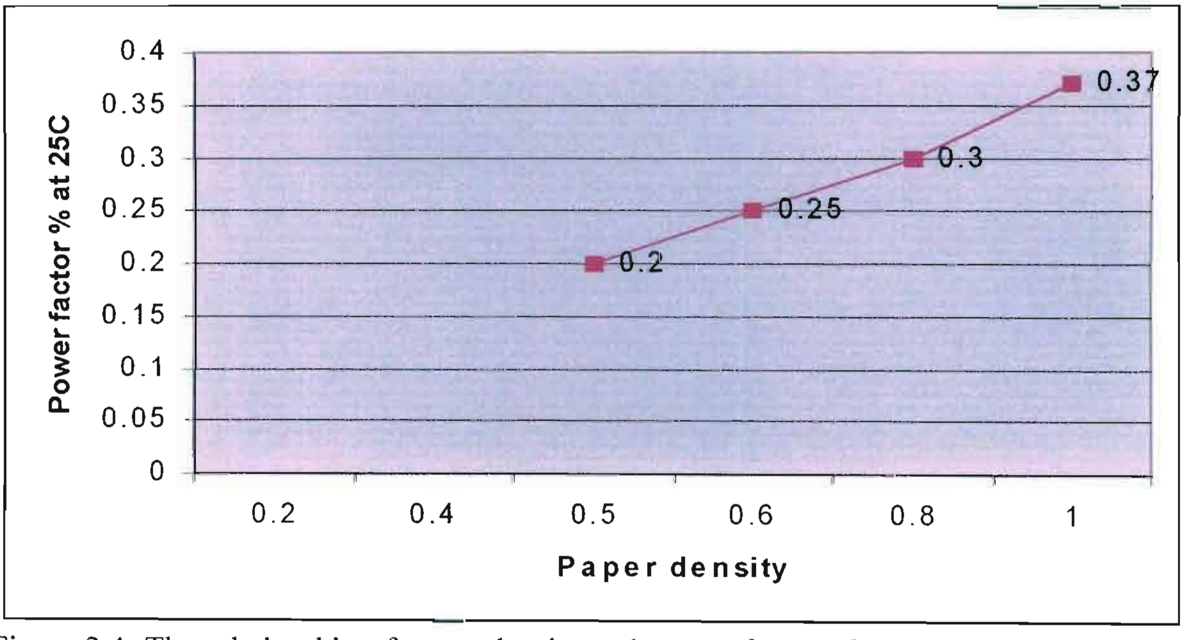

Figure 2.4: The relationship of paper density and power factor of vacuum dried and impregnated paper [6].

The insulation resistance of oil-impregnated paper is influenced by many factors including the effectiveness of the drying. This is essential in obtaining the highest insulation resistance values. Highly viscous impregnating oils result in an increase of the insulation resistance. The resistance of oil impregnated paper decreases with an increase in temperature. This is shown in Figure 2.5 below.

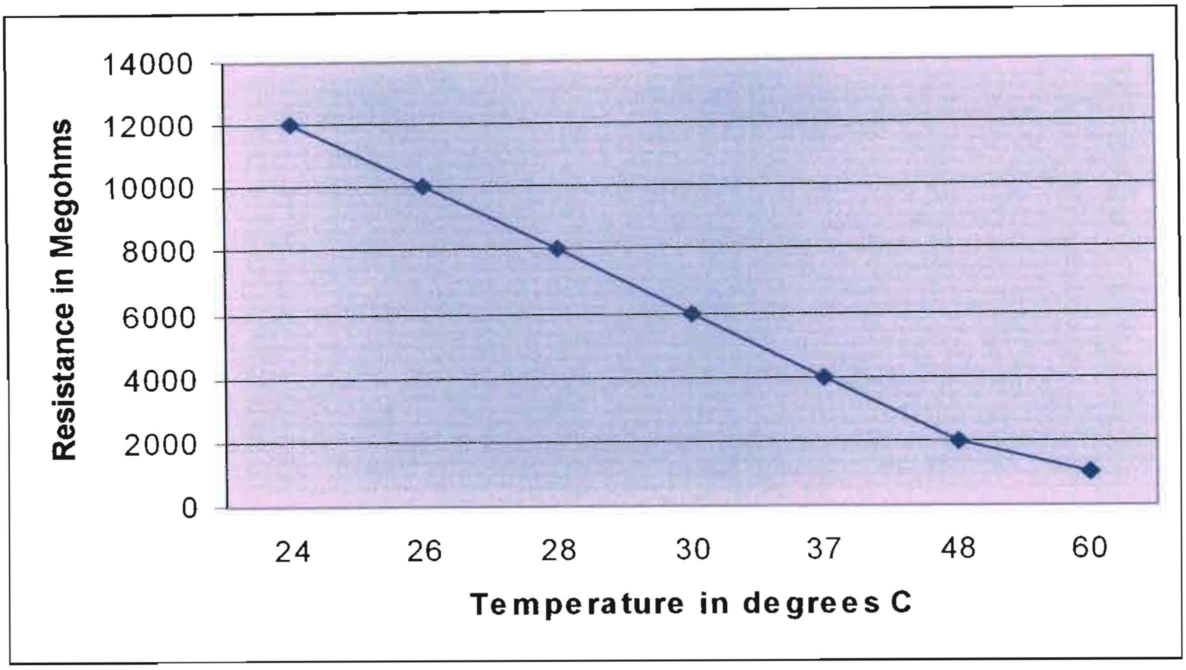

Figure 2.5: The effect of temperature on the dc resistance of vacuum dried and oil impregnated paper [6].

The problem of ionization and corona formation, leading to dielectric breakdown, is most generally manifested by a carbonized area, with undeniable evidence of localized overheating. From this standpoint, dielectric failures may be ascribed to thermal causes. This is later manifested as an electrical discharge designated as corona, formed at rated voltage, when left to run unchecked, leads to localized heating and failure. The term ionization refers to the combined effects of a phenomenon which leads to an initial increase in the dielectric loss. As the voltage is slowly increased from zero there is initially no form of electrical discharge. As the voltage is increased, the ionization phenomenon merges into a type of glow discharge that is designated as corona.

2.12 Dielectric changes in oil impregnated cellulose insulation caused by aging

The dielectric strength of paper-oil combination remains practically unchanged up to temperatures of 100°C, but at higher temperatures the decrease in dielectric strength becomes pronounced.

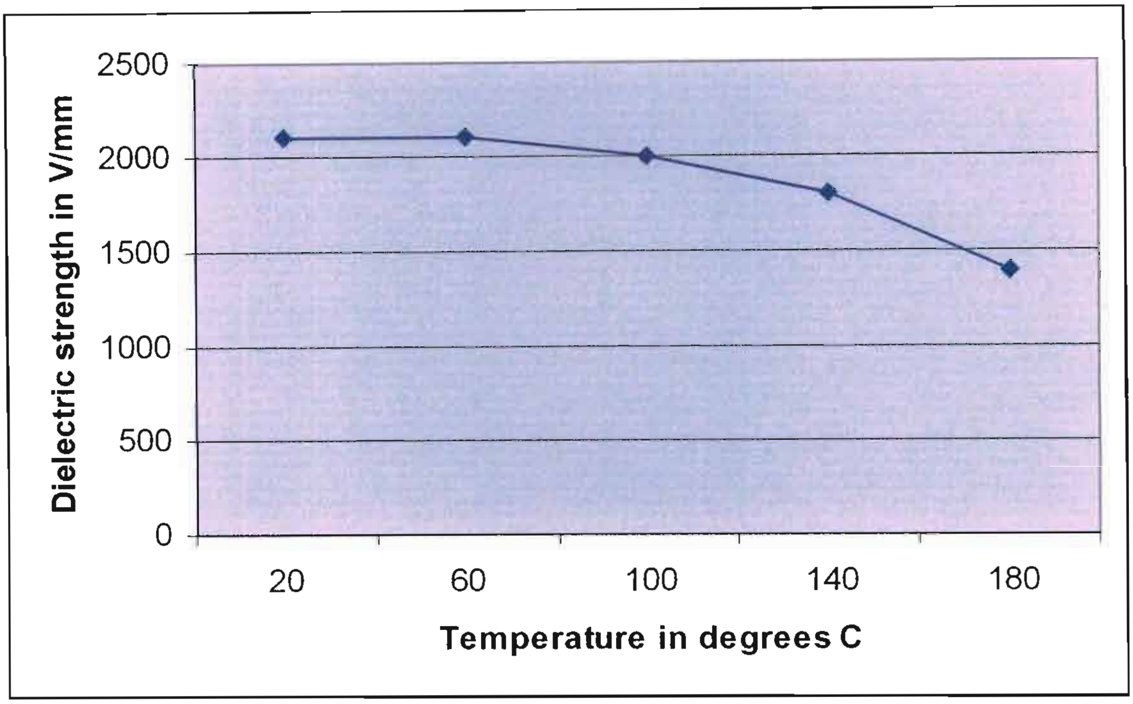

Figure 2.6: The effect of temperature on vacuum dried oil impregnated paper insulation [6].

The power factor characteristic of oil impregnated cellulose remains constant at rated voltage, but if the applied voltage is increased by 66% above the rated voltage and the temperature is increased, then the power factor also increases [6].

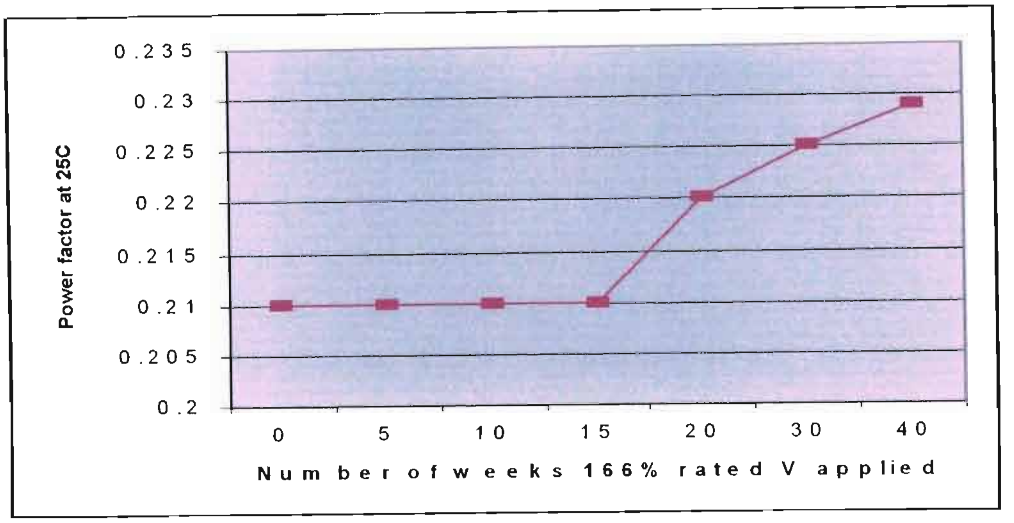

Figure 2.7: The increase in power factor at 25°C as a function of time at 166% rated voltage [6].

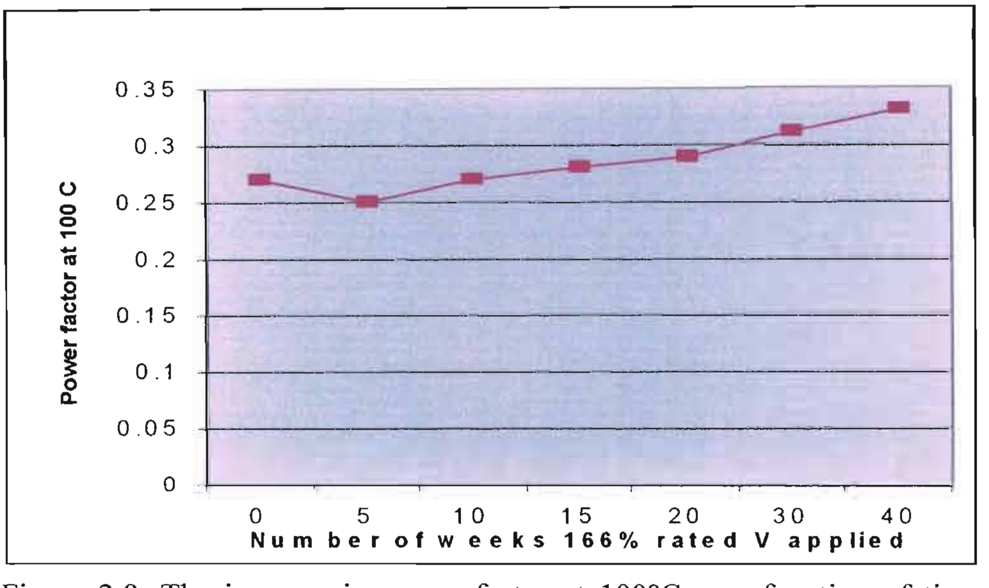

Figure 2.8: The increase in power factor at 100°C as a function of time at 166% rated voltage [6].

Figures 2.7 and 2.8 clearly show the increase in the dielectric loss of oil impregnated cellulose as gauged by the power factor value when subjected to 166% of rated voltage at 25°C and 100°C. At 25° C, there is a rapid increase after 15 weeks. At 100°c, the increase is somewhat slower but the power factor magnitude starts at a higher level [6].

2.13 Power Factor of oil-paper insulation.

The power factor (cos ϕ) or the dissipation factor (tan δ) is a measure of the power loss in the insulating material and therefore a general indication of the quality of the dielectric. A simple model of a stressed dielectric is shown in Figure 2.9 below. The power factor of mineral oil is a good tool for evaluating the efficiency of the dielectric and a sensitive test for evaluating the dielectric degradation. It responds quickly to the presence of contaminating materials, picked up by the oil during improper manufacture or use. The power factor test will indicate the presence of soluble varnishes, resins, moisture and will also indicate degradation due to oxidization in the oil. The direct effect of an increase in power factor is increased heating. The indirect effects of an increase in power factor are: (a) increased metallic corrosion; (b) increased mechanical and electrical insulation degradation; (c) increased water solubility; and (d) increased oxidation. In sealed units, the hazards experienced from an increase in power factor, do not arise.

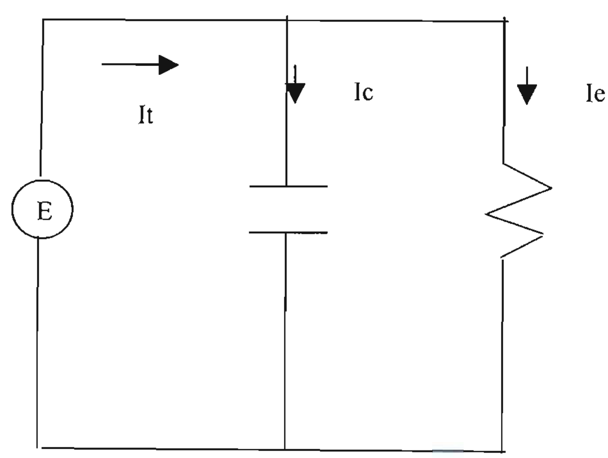

Figure 2.9: Circuit diagram showing current flow in a typical dielectric insulation

The power factor of an insulation is the ratio = Loss in dielectric (Watts)/apparent power (volt-amperes).

$$PF. = W/VA$$

The power factor of new refined insulating oil is extremely low, less than 0.001 when tested at 50Hz and at 100 °C. When power is applied across a perfect dielectric, there is no loss. The power factor is therefore zero when there is an induced capacitance current (Ic) which is 90 °C ahead of the voltage (E). But a perfect dielectric does not exist, every dielectric posses a degree of conductivity when subjected to AC or DC voltage, this current (Ie) is very small and in phase with the applied voltage (E). The vector sum of the two currents (It) leads the voltage by less than 90 degree as shown in figure 1.4.3 below. The cosine of the angle ϕ by which the current (It) leads the voltage (E) is the power factor of the dielectric. The angle δ (90-ϕ) is designated as the dielectric loss angle, if the angle δ is small, than Cos ϕ is equal to tan δ.

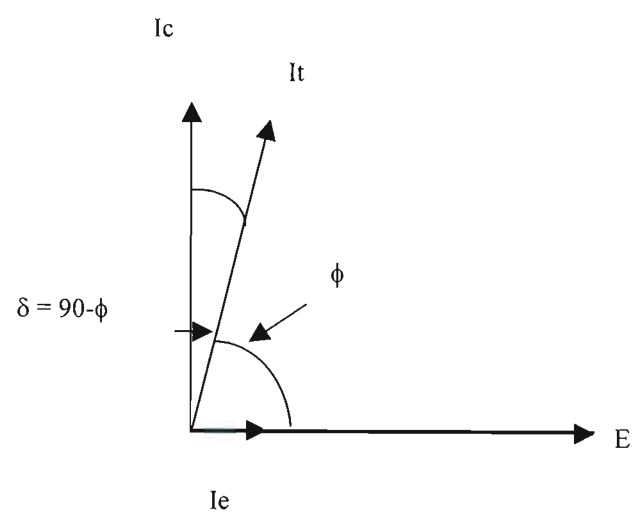

Figure 2.10: The vector relationship of voltage and current in a dielectric system.

The measurement of the power factor of a dielectric is made at low voltage and low frequency by means of an AC bridge. At voltages up to 10kV and frequencies up to 10 kilocycles per second, a Schering bridge is used.

2.14 Summary

Oil impregnated paper composite insulation has proved over 100 years to be very successful as an insulation medium for HV apparatus. A thorough understanding of the characteristics and the influence the operating, the environment, and the aging regimes is necessary prior to application. There are always losses through the insulation when subjected to an AC voltage, it is important to ensure these losses are maintained at the lowest possible values, by precise manufacturing (drying and impregnating), and during operation (reducing exposure to high temperatures, oxygen and moisture). The effect of any of these extreme conditions will result in the increase of the losses and increase the internal heating until destruction takes place. Tan δ testing is a relatively easy way of ensuring the satisfactory condition of operational insulation. However an on-line tan delta condition monitoring system would need to ensure that detected changes in tan delta on a specific unit are not due to normal external variations caused by ambient and/or load correlated temperature variations.

CHAPTER 3
REVIEW OF RESEARCH INTO ON-LINE DIAGNOSTIC AND MONITORING TECHNIQUES FOR IN SERVICE HIGH VOLTAGE INSULATION.

Off-line techniques have been implemented by utilities for the monitoring of high voltage equipment over many decades [27]. Overall experience with these off-line systems is not reviewed but the more recent developments of using on-line techniques is reviewed below. Included is a review of the work performed by the Electric Power Research Institute (EPRI) on evaluating the practical use of such on-line systems to detect developing faults in CT's and bushings.

3.1 Review of worldwide techniques

New diagnostic and monitoring techniques were developed within the Queensland Electricity Commission of Australia for use on HV in service plant [8]. The drivers for the implementation of this on-line system was a high failure rate of instrument transformers and transformer bushings, causing serious explosions, damage to nearby equipment, oil fires, safety of staff, and high costs. Conventional off-line tests are costly, labour intensive, require plant isolations. A dielectric dissipation factor (DDF) device was developed for use in an existing instrument transformer test device (ITTD).

The device is portable and uses hydraulics to raise a high voltage capacitive probe to make contact with the busbar feeding power to the bushing under test. This allows the leakage current flowing through the probe to be compared to the leakage current from the bushing. The system incorporates matched transducers ("Caplinks") for signal conditioning, phase encoders to convert the signal to a digital output, and the DDF resolver, which compares zero crossings between the incoming signals and displays the results.

The system has been used in laboratory and field applications. Some faulty field units have been detected and when removed from service off-line testing reportedly confirmed the results. Laboratory comparative testing against a conventional bridge indicated a high rate of accuracy [8].

A permanent system was installed on a 275kV set of CT's and bushings [9]. The system is reportedly performing well, but atmospheric influences are being considered. This system also makes use of the leakage current flowing through the insulation and compares this to a reference voltage. Any variation is further investigated by using off-line techniques to confirm the findings. The basic principle of operation of this system is similar to the monitoring system used as the basis of this thesis (High Voltage Insulation Early Warning System –HVIEWS), but using different software and logic to determine the condition of the insulation relative to the known healthy condition of a similar device. Of importance to this thesis are the problems being experienced with the HVIEWS system are manifesting themselves with this system as well, as the future direction includes, "the development of software for the continuous DDF system to recognise and ignore changes due to influences such as heavy rain and system glitches, as well as the inclusion of temperature compensation into DDF measurements" [9].

Vujovic and Fricker [10] report on the development of a continuous on-line tan δ monitoring system was developed in South Africa. This is the HVIEWS system which was used as the basis for the research presented in this dissertation. The system is based on the comparison of tan δ values and trends of units being monitored at a particular time and the comparison of these measured values against historical data. Diagnosis is based on identifying HV insulation with abnormal changes and comparing these with similar units being measured. Relative measurements reduce the influence of ambient temperatures, operating voltages, loading, ageing, different designs and operating conditions.

A high voltage CT was initially compared to a gas capacitor and the relative results indicated the absolute tan δ increase of the CT over the period 8h00 at 16C until 12h00 when the temperature had increased to 24°C. As the ambient temperature increased, so did the tan δ of the CT from 0.55% to 0.62%. When two CT's were compared against each other, the relative tan δ result was lower at 0.16% without any increase when the ambient temperature increased.

The system was installed on 95 x 275kV and 88kV bushings and CT's, in the Fordsburg substation in Johannesburg. Trends and patterns indicate variables to be considered such as loading differences, low loads on weekends, as well as reduced fluctuations in the relative tan δ when loadings and load patterns are similar. Absolute tan δ may also be measured if a reference gas capacitor is installed on the substation busbar. This particular system was the origin of both the SOS system [14] and the HVIEWS system [10].

At the end of 1998 the Beijing Power Supply Bureau had installed 9 on-line systems in one 500kV and eight 220kV substations monitoring 890 capacitive types of insulation on HV equipment [11]. The system makes use of absolute values of tan δ by comparing the phase angles of (a) the leakage current through the insulation, processed through a current transducer, filtering and converted to digital signals and (b) the running voltage at the busbar.

Analysis of the data indicated that as the temperature in the substation increased, so the tan δ values of the plant became unreliable (increased beyond the permitted limits), although the voltage, frequency, leakage current, and capacitance remained stable. In depth investigation revealed that the current transducers became inaccurate as the ambient temperature changed. Historical data taken over the previous 2 years was used to compare data from the exact dates from the previous 2 years to the present day's data to see if the same trends were present. This filtering of the data reportedly brought credibility back to the data, showing that the previous data was similar to the present data. Through the use of this filtering of the historic data, 8 units were identified over a two year period, as having faulty insulation and were removed from the system, preventing serious system faults. Off line testing confirmed that the insulation was faulty.

This absolute tan δ on-line monitoring system proved to be successful since the temperature fluctuation problem on the transducers has been eliminated by the filtering of the trended data [11].

The short comings of other on-line monitoring systems which make use of system voltage and leakage current (PT method) to determine the absolute tan δ value of the insulation include phase angle shift on the secondary of the PT, temperature, rainfall and humidity. There is a tendency to ignore (filter) the data when these conditions manifest themselves, which can result in a failure going undetected. The alternative is the Synthetic Relative Measuring Method (SRM method) [12]. This method uses a relative comparison system which compares the leakage current of the insulation of one device to at least two but possibly even more other devices. This method allows for the easy detection of a faulty unit, as when discrepancies arise between item 1 and 3 and between 1 and 2, but not between item 2 and 3 then the fault exists in unit 1. Using this method it eliminates the interference from weather, rain, temperature, humidity, voltage as all units are subject to the same external influences. The system has been installed on plant in Yinchuan Power Bureau, China, and many years of experience have been successful. Comparisons between on line and off line methods show a very good correlation [12].

Research was conducted on a 230kV CT at Manitoba Hydro's Dorsey substation in Canada [13]. Wang et al [13] list the reason for the research work as the short comings in: a) the periodic monitoring of insulation condition of HV apparatus, using laboratory established techniques; b) the need to remove equipment from service for these tests; c) possibly interrupting supply or d) missing the dielectric changes due to long periods between consecutive tests. Other problems experienced by Manitoba Hydro include the short comings of the existing on line-systems, namely: (a) the inaccuracies of the absolute monitoring system caused by connecting cables, phase angle error of the potential transformer and capacitive linkage with phases not involved in the measurement; b) the relative tan delta system needing to match Caplink units so the phase shift of the applied voltage can be neglected and c) the inaccuracies introduced in the sum current method by the influence of ambient temperature, humidity and system conditions.

This digital technique discussed by Wang et al [13] is based on the discrete Fourier transform being performed on the analog voltage and current system, these results are passed through a software analysis package to implement digital computation of dissipation factor and capacitance to produce accurate results, verified by off line laboratory tests. The digital computation simulation accounts for errors due to synchronisation of the sampling rate, effects of harmonics and sampling rate fluctuations, by adjusting the trigger point of the measurement. The laboratory tests confirm that the measurement precision of this developed method is 0.05% for dissipation factor [13].

The SOS tan δ on line monitoring system for transformer bushings was installed on 69 bushings at Deserset Power Plant in Utah [14]. Bonanza Unit 1 at the station was cited as the best performing power plant in the USA in 2001, based on a capacity factor of 97.66%. Difficulties were being experienced to get outages to test plant off-line, forced outages were costly to customers and bottom line. A risk management plan identified minimizing unscheduled down time on HV plant as key to improving service to customers. The HV bushings had a record of failures, they were aging and the resulting failures would lead to long down times. On-line testing was identified as the only viable option. This would have the added benefit of reducing the time taken by staff to do off-line testing. Discussion with manufacturers resulted in identification of the SOS tan δ system for bushings.

The system makes use of on line equipment and the principle of the measurement of the magnitude and phase of the leakage current flowing to earth through one unit compared to the leakage current flowing through similar units in the same substation. This measurement results in a relative tan δ, which is achieved by trending the leakage current flowing through the insulation of the bushings (caused by the losses in the insulation). The signal is compared to a reference voltage from another adjacent unit. Differential results are quantified into an insulation condition, namely good, alarm condition or bad. The signals are also processed to calculate capacitance and dissipation factors.

The system is cost justified on the basis of reduced maintenance and the reduction of maintenance down time, the safety aspect has been cited as justification alone. After four months of operation, the system is gaining confidence amongst the operators who monitored it daily are now monitoring it weekly as the alarming function is gaining trust. No mention is made of the environmental impact on the system. This system operates on a similar principle to the HVIEWS system [14].

3.2 A review of research into the prediction and prevention of the failure of HV CT's and bushings

During the late 1990's the Electric Power Research Institute, EPRI, in the USA, undertook research to identify key parameters indicative of condition and impeding failure of oil filled high voltage CT's and bushings [34]. The focus of this effort was to develop mitigation techniques to reduce the catastrophic transformer failures. The background to this research was the numerous explosions of CT's and bushings that were experienced by many utilities. The failures of oil filled bushings internal to large transformers have caused many catastrophic transformer failures and financial consequences in the order of several million dollars. HV CT's and bushings are similar in their insulation structures and therefore experience similar failure modes. EPRI initiated a project to age HV CT's and bushings to failure in the laboratory while monitoring various parameters. The tests were designed to age the insulation at an accelerated rate. This was done by energising the equipment at higher than rated voltage, thermally cycling the insulation, in some cases applying high voltage impulses and/or introducing moisture to the insulation structure. After failure of the test unit, a forensic analysis of the insulation was undertaken to determine the failure mode.

3.2.1 Powertech Labs Inc. tested 8 CT's and 4 of these failed. The CT's were subjected to voltages of up to 2.1 p.u. or 650kV, and subjected to rated primary current [15].

CT Number	Hours Under test	Indications	CT Dissection
1	10500	No indication of failure	
2	10500	No indication of failure	
3	5400	No indication of failure	
4	5400	No indication of failure	
5	3400 (Failed)	Power factor increased days prior to failure from 0.5 to 2, increases in Hydrogen (967 – 8556), Methane increase (126-969), Ethane increase (21 – 83)	PD started at edges of graded layer paper, causing tracking from layer to layer.
6	72 (Failed)	Power factor increased 0.3 – 1.5, hydrogen increased	Hole in top centre of insulation caused by overheating.
7	4100 (Failed)	Power Factor increased 0.5 - 4	Not dissected
8	10 (Failed)	PD increased, Power factor increased 4 – 6.	Not dissected

Table 3.1: Results of accelerated aging tests on HV CT's undertaken by Powertech Labs Inc. [15]

Results showed that power factor was a very good indicator of impending failure. Partial discharge (PD) and DGA gave some warning but were found unreliable in this investigation [15].

3.2.2 Bonneville Power tested 7 CT's and 5 of these failed. Tests were conducted by starting the 60Hz voltage at 350kV and increasing by 25kV a week. Current was back-energized via the secondary cores to give rated current flow in the CT primary [16].

Monitor	CT1	CT2	CT3	CT4	CT5
Relative TanD	10 min	7hrs	None	18min	9 hrs
Cap ratio	8min	7hrs	None	45min	32hrs
Acoustic PD	1hr	None	None	none	25hrs
Leakage Current	None	5hrs	None	46min	34hrs
Electrical PD	N/A	N/A	N/A	N/A	52hrs
Gas in oil	None	None	N/A	N/A	N/A
Temp	None	None	None	None	None
Time to failure	40hrs	5days	58days	28days	41days
kV at failure	350	350	575	500	525

Table 3.2: Results of accelerated aging tests of HV CT's undertaken by Bonneville Power, indicating imminent failure warning time. [16]

The dissection of CT 1 and 2 indicated the evidence of partial discharge between the grounded shield that houses the secondary cores and the feed through conductor, with voids in the paper insulation wrapped around the doughnut. Overheating of the secondary cores was also observed. Results indicated that no monitoring technique will catch all types of failures, relative tan delta and capacitance ratio show the most promise for detecting imminent failure [16].

3.2.3 American Electric Power Service Corporation tested 3 CT's and 1 failed, the CT's were supplied with half rated current and test voltage of 200kV for four months, then the voltage was increased to 220kV for four months , then again increased to 250kV after one month, when the unit failed [17]. After dissection, the failure mode was determined to be localized overstressing of the oil between paper insulation layers. This stress breaks down the oil and forms X wax as a byproduct of the small partial discharges. Once the X wax forms in sufficient quantities, it prevents liquid oil from impregnating the area, the insulating paper becomes dry and dielectrically weak and then punctures. The most effective method of predicting failure was found to be a hydrogen-monitoring device [17]

3.2.4 NEETRAC tested 5 HV transformer bushings at EPRI laboratories and failed all 5 bushings over a period of 18 months [18]. The bushings were supplied with rated voltage which was stepped up 25% per week up to 2.3 times rated voltage, the original bushing current transformers were back fed to circulate rated current in the bushings. Four bushings failed in the same mode, which was due to the heat from the current transformers, the dissection indicated a hole burnt through the insulation at the level of the CT's. The early indicator of failure was tan delta, increasing 2 – 3% from 2 weeks before failure, which is an indicator that many layers are degrading. At this point the back feeding of the current transformers was switched off to with twice rated voltage applied. Periodic voltage spikes were applied to the energised bushing. The final failure was caused by insulation breakdown due to voltage stress and was detected by acoustic and electrical PD increasing by 2000pC, 30 days before failure [18]. The summarized findings of the EPRI research project [19] concluded that:

- HV CT's have a low failure rate, but most fail catastrophically. The failure rate for surveyed utilities was 0.2% per annum.
- Most HV CT failures occur in summer peak loading, indicating thermal runaway as the commonly identified failure mode. Other failure causes include moisture ingress, X wax build up, switching transients, poor workmanship, and poor designs.
- Periodic off line gas in oil testing is a useful indication of insulation degradation.
- The most effective parameters to monitor on line are partial discharge and dissipation factor.
- HV CT monitoring systems cost up to 25% of the cost of the CT.

3.3 Summary

There is little experience that has been a obtained and reported on in the interpretation of data gathered from on-line tan delta monitoring systems. There is evidence that the reliability of the system needs to be carefully assessed prior to installation with particular reference to the impact of climatic parameters (rain, high humidity) have on the tan delta measurements reported back to a central monitoring point.

Laboratory investigations undertaken to deliberately fail CT's have indicated that quite significant overstressing is required in order to fail a CT from a healthy condition. Another technique that was initially adopted for this research project was to back energize the CT secondary windings. This technique created failures in every instance in other investigations.

CHAPTER 4

THE TEST METHODS AND TEST EQUIPMENT USED

4.1 The operational experience gained in the monitoring of paper/oil insulation from a population of operational CT's.

There are various methods of testing HV insulation to evaluate the integrity thereof for operational use. These include the following methods:

Test method	**Advantages**	**Disadvantages**
Electrical test of insulation resistance	Easy to perform test	Results are not conclusive, decreasing resistance indicates deterioration but further investigation required
Off line Power factor/ loss tangent	Advanced technology, widely employed.	Plant must be removed from service
Partial discharge	Very sensitive test. Results are conclusive.	Due to interference in HV environment, this test is best suited to a test laboratory
Hi Pot	Easy to perform test	High voltage could induce failure
Dissolved gas analysis	Very sensitive test. Results are conclusive.	Plant must be removed from service to take sample.
On line, continuous tan delta monitoring	Plant does not have to be removed from service to perform test. Monitoring is continuous	Technology still in its infancy

Table 4.1: The suitability of various methods of HV testing in the field.

From the above table, it can be seen that a number of different test methods can be used to establish the integrity of the HV insulation. A brief discussion of some of the available techniques is included in order to highlight some of the practical problems that have been experienced with off-line testing.

4.1.1 The electrical resistance test of insulation is widely used and serves as a basis for more sophisticated tests. This test is used in all field testing of HV insulation. Decreasing resistance values indicates deteriorating insulation. Test results must be adjusted back to standard temperature conditions and insulation age. Results are best evaluated when compared to previous results and trends are established. The test is performed with a portable, battery powered Meggar™ insulation tester, which can supply various voltage magnitudes in the range from 200V to 5kV DC applied between the conductor and the earthed housing, across the insulation. The instrument measures the current and the result is supplied in a range of Ohm values from one Ohm, 1Ω, to a number of Gigohms. A high resistance reading indicates the integrity of healthy insulation.

4.1.2 Off-line tan delta testing is a mature technology, which is regularly applied by utilities worldwide to measure insulation losses. As indicated in Figure 2.8 and 2.9 above, the power factor ($\cos \phi$) or the dissipation factor ($\tan \delta$) is a measure of the power loss in the insulation material, and therefore a general indication of the quality thereof. There are a number of instruments in commercial operation. Most make use of the balanced bridge measuring method. These instruments are reasonably priced and so are readily available for testing. These instruments are generally portable, easy to set up in a high voltage substation, compensate for temperature changes or various levels of humidity. These units operate on different voltages or frequencies, depending on the manufacturer. Different makes require the item under test to be disconnected from any other conductors or devices. This becomes a cumbersome task in the operational arena and for this reason testing is carried out very seldom. The target is to test each item only every 3 to 6 years. A rapidly developing fault will not be captured and prevented, during these large intervals. This off-line tan delta testing is the HV test most frequently used to measure insulation in the field within Eskom.

4.1.3 Partial discharge testing is conducted by applying a high test voltage to the device to be tested and then monitoring any discharges in the body of the insulation by sensing these discharges either acoustically or electrically. Should the discharge magnitude exceed the insulation limit, then the device would not be suitable for operation. This test method, when applied in a HV substation, may measure discharges from other devices. These discharges may interfere with the discharge from the device under test, resulting in inaccurate results. The background noise affects the sensitivity of the test results, so that this test should preferably be performed in a noise free laboratory. Although this test is extremely useful and sensitive it is normally only performed on new devices, prior to installation and on suspect or refurbished devices. The cost of removing a CT or bushing from the field to have it partial discharge tested in a laboratory is extremely high, so this test is seldom performed on in-service equipment.

4.1.4 High potential (Hi Pot) testing

The test equipment used for this testing is normally a high voltage DC source, which is portable and moved around to different sites on a truck. The unit is very costly and so not readily available, and on site testing requires considerable organization. The test method uses high voltages and these are applied to the unit under test. The leakage current to earth is measured. The high test voltage, which is normally above the rated voltage of the unit under test, may damage the test object. This test is seldom applied in the operational arena and only used for special cases where the consequences of poor HV insulation have a high risk attached. This is not generally used for routine testing.

4.1.5 Dissolved Gas Analysis

Dissolved gas analysis (DGA) is performed on mineral insulating oil. A sample of the oil is drawn from the insulation to be tested. The sample volume is normally 100ml. The container holding the sample is taken to a laboratory for analysis. The sample is prepared for testing and the headspace gas just above the liquid is sampled. An analysis is done on the relevant gases found. The presence of certain gases at levels above the accepted normative values (given in Table 4.2 below) indicates different insulation degradation conditions.

Regular samples of the impregnating oil can be taken from the HV equipment and can be sent for dissolved gas analysis. Care must be taken not to reduce critical pressures, nor to introduce contaminants. Increases in the levels of various gases indicate increasing degradation.

Type of gas	**Normal concentration PPM**
Hydrogen	140
Methane	40
Ethylene	30
Ethane	70
Acetylene	2
Carbon Monoxide	1000
Carbon Dioxide	3400

Table 4.2: Table indicating the gas concentrations in insulating oil in transformer bushings considered normal [7].

Abnormal levels of specific gases maybe interpreted to be associated with specific fault mechanisms. These are indicated in Table 4.3 below.

Abnormal level of gas	**Interpretation**
Hydrogen	Arcing, corona or partial discharge
Methane	Sparking
Ethane	Local overheating
Ethylene	Severe overheating
Acetylene	Arcing
Carbon monoxide	Severe overloading

Table 4.3: The type of degradation taking place in the insulation due to excessive amounts of the relevant gas found in the sample. [23].

Sampling of the oil was undertaken on a part the population of Eskom CT's (see Table 1.1) during the late 1980's and early 1990's. This sampling was later thought to have possibly contributed to the high levels of failure seen in the CT's over this period. The failures were later attributed to the opening of the CT's for sampling and the ingress of oxygen and moisture during this sampling, coupled with the fact that seals were not restored to their original integrity. Sampling of oil was stopped in the 1990's and was only began again in 1999, on a certain population of transformer bushings which are indicating high levels of gassing. DGA sampling of the oil is no longer considered a low risk test method of determining the quality of insulation on CT's and transformer bushings and is only applied in special cases by highly skilled staff.

4.1.6 On-line continuous tan delta monitoring

On-line continuous tan delta monitoring is a method of determining the integrity of the HV insulation that had never been undertaken in an outdoor situation in RSA. Research had, however, been undertaken in the USA [15] and at the laboratory of the Council for Scientific and Industrial Research (CSIR) in South Africa [10]. The CSIR research had expanded to an indoor substation, where CT's were monitored [20,21]. This dissertation will expand on research undertaken to establish the accuracy of one such on line tan delta monitoring system, HVIEWS.

4.2 Off-line tan δ techniques utilised

As part of this research required comparisons to be made between the on-line and an off-line system, the off-line system utilized in this research is discussed below.

The major off line tan delta test set used during this research is the Circuit System Design (CSD) unit. The unit used was the CSD Model Type: LAB, Serial Number: 103293-12-01. This is a portable, self contained, instrument, capable of measuring accurately (these limits are discussed in more detail below) the loss tangent and capacitance of items of distribution equipment, particularly condenser bushings, to enable engineers to make rapid tests as part of routine maintenance. This unit belongs to the Transmission Depot at Pinetown and has been used as the only type of test set to test the HV bushings and CT's in Kwa Zulu Natal Transmission Grid. Whilst the CSD system is discussed in some detail, use was also made in this work of the DOBLE M4000 tan delta measurement system [24]. The major difference between the two units (the CSD and the DOBLE M4000 systems) is that the DOBLE M4000 operates with a variable test voltage (0-12kV rms) whereas the CSD operates at a fixed voltage of 600 Vrms.

4.2.1 CSD background information.

Oil impregnated insulation systems as used in bushings and current transformers have typical loss tangents of 0.005, which should be measured to an accuracy of 5% or better if meaningful comparisons are to be made between different CT's. The CSD bridge has a quoted accuracy that exceeds this requirement. The *in-situ* measurement of the bushing or CT is made between a tapping point connected to the grading foil immediately inside the outermost (earthed) foil and the helmet (live end). The capacitance between the tapping point and earth is approximately 50 times that of the bushing itself (about 25000pF and 700pF respectively).

4.2.2 Accuracy of measurement.

The CSD loss tangent bridge can measure loss tangents with a resolution of $5*10^{-5}$ and an accuracy of better than 1% for loss tangents greater than 0.005. Loss tangents of up to 0.1 can be measured. There are three capacitance ranges 0 to 1000pF, 0 to 10000pF, and 0 to 0.1microF with a resolution of 0.05pf on the lowest range. The operating frequency of 79.58Hz is used because it is close to the power frequency but allows for rejection of power frequency interference in the bridge detector circuits. A frequency above 50Hz allows greater sensitivity of the bridge and improvement of the loss tangent discrimination.

The operating principle and circuit diagram of the unit may be found in Appendix 2.

4.2.3 Operational experience of the CSD tan Delta test set.

The Transmission Grid in KwaZulu-Natal has 4 CSD units in operation. These units are used to test all the HV transformer bushings and CT's in the area. These comprise about 300 bushings and about 700 CT's, and the test sets have been in service since 1993, each CT and bushing requiring testing every 3 years.

The Grid uses absolute values as a guideline, to indicate the serviceability of the HV insulation, should the measured value exceed the guideline value the unit is removed from service.

Plant Item	**Maximum Absolute Tan Delta Value**
CT	0.5%
Bushing	1%

Table 4.4: The maximum allowable tan delta value for plant in service [27].

Bushings and CT's tan delta values are also compared amongst the three units on the three phases of the plant on which they are situated. Should the measured tan delta value of any unit vary by more than 30% (i.e. either 30% higher or 30% lower) when compared to the other units, the differing unit is removed and replaced with a new unit [27].

The determined capacitance value is compared to the capacitance value on the name plate of the CT or bushing and any deviation of more than 10% is considered as cause to remove the unit from service for further tests [27].

The CSD test set was used to test 6 CT's and the results of these tests were compared to similar tests performed on the same 6 CT's using a 10kV Doble test set.

CT Serial Number.	Capacitance in pF Doble	Capacitance in pF CSD	% Tan delta Doble	% Tan delta CSD	% Difference
	10kV	650V	10kV	650V	
54678/17	656.38	653.75	0.682	0.425	38
54679/18	684.25	682.5	0.404	0.210	48
54679/13	660.13	658.7	0.352	0.210	40
403	709.67	709.11	0.294	0.183	38
404	754.65	753.07	0.274	0.172	37
414	746.16	745.46	0.322	0.205	37
Average	701.87	708.43	0.388	0.234	39
Standard deviation	42.26	42.699	0.151	0.095	4.227

Table 4.5: The similarities in the capacitance values and the 39% average difference in the % tan delta values of 6 CT's when tested with the CSD 650V tester and the Doble 10kV tester. [25]

4.3 The continuous on-line relative tan δ system

The continuous on-line relative tan δ system utilized in this research is the commercial system marketed under the name HVIEWS. This system and its operating principle is briefly reviewed.

4.3.1 System overview

The HVIEWS system is a continuous, on line insulation monitoring system for CT's and Bushings. The system monitors the insulation integrity of the devices by measuring the internal leakage current and calculates the tan δ of a unit as a relative value compared with a reference voltage from another unit that it is grouped with. Since the system uses relative measurements, there is a minimum of three units to be grouped for each phase of evaluation. Tan δ is a measure of dielectric losses, which are caused by the capacitive leakage current in the dielectric material used to make a bushing core or CT insulation and are generated within the paper insulation of the core. One of the symptoms of insulation deterioration is its increased sensitivity to changes in temperature and voltage, which manifests itself in the form of increased dielectric losses. A relative tan delta value is calculated for each device being monitored.

The relative tan delta values are then trended over 28 days and compared to the values stored from the original 28 days. Any increasing deviation is indicated on a condition report. When the deviation reaches a certain set level then the plant condition is alarmed and a healthy condition (green) changes to an alarm condition (yellow), if the condition continues to deteriorate then a danger condition (red) is reached at which time the plant should be removed from service. Plant cannot be left in service at this stage, as the risk of failure in service and the chance of damage or danger to staff, cannot be tolerated.

Tan δ and capacitance are properties of the bushing/CT design and the dielectric material used in the design. Monitoring and measurement of the tan δ gives an indication of the quality of insulation and its sensitivity to temperature and voltage changes.

The HVIEWS system components are discussed in detail in the operating manual of the system [26]. A brief description of each component is given below.

4.3.2 Outdoor equipment

The function of the outdoor yard equipment is to provide a voltage signal to the indoor cubicle which is representative of the internal leakage current of the device being monitored. It comprises of the tapping units, cabling, signal conditioning and junction boxes.

4.3.3 Indoor equipment

The function of the indoor equipment is to digitize the appropriate internal leakage current signals and to compute the insulation condition of the devices. This data is stored to a database locally and exported to a central database.
Alarms are generated for certain conditions when these conditions are exceeded.

4.3.4 Remote database

The remote database is where all historic information is stored and where daily/monthly reports are generated.

4.3.5 System software

The system is based on the principal of the measurement of the phase angle and magnitude of the leakage current flowing to earth in several units. Software is then used to derive a relative tan δ measurement of the insulation. The system has been optimized using software with minimal hardware. The deterioration of the insulation is gauged by its sensitivity to changes in the on line operating conditions. The versatility of the system installed at substations allows for continuous accumulation of data.

The signals are sampled and the data processed to calculate the capacitance and dissipation factor changes. Since a second unit of equipment is used as a reference instead of a standard capacitor, the values are relative to that unit. The principle is extended to several units within the substation.

With specific configurations, relative measurements eliminate common mode effects, such as ambient temperature, operating voltages and load conditions and accentuate the differences, such as design and sensitivity to changes in insulation. [14].

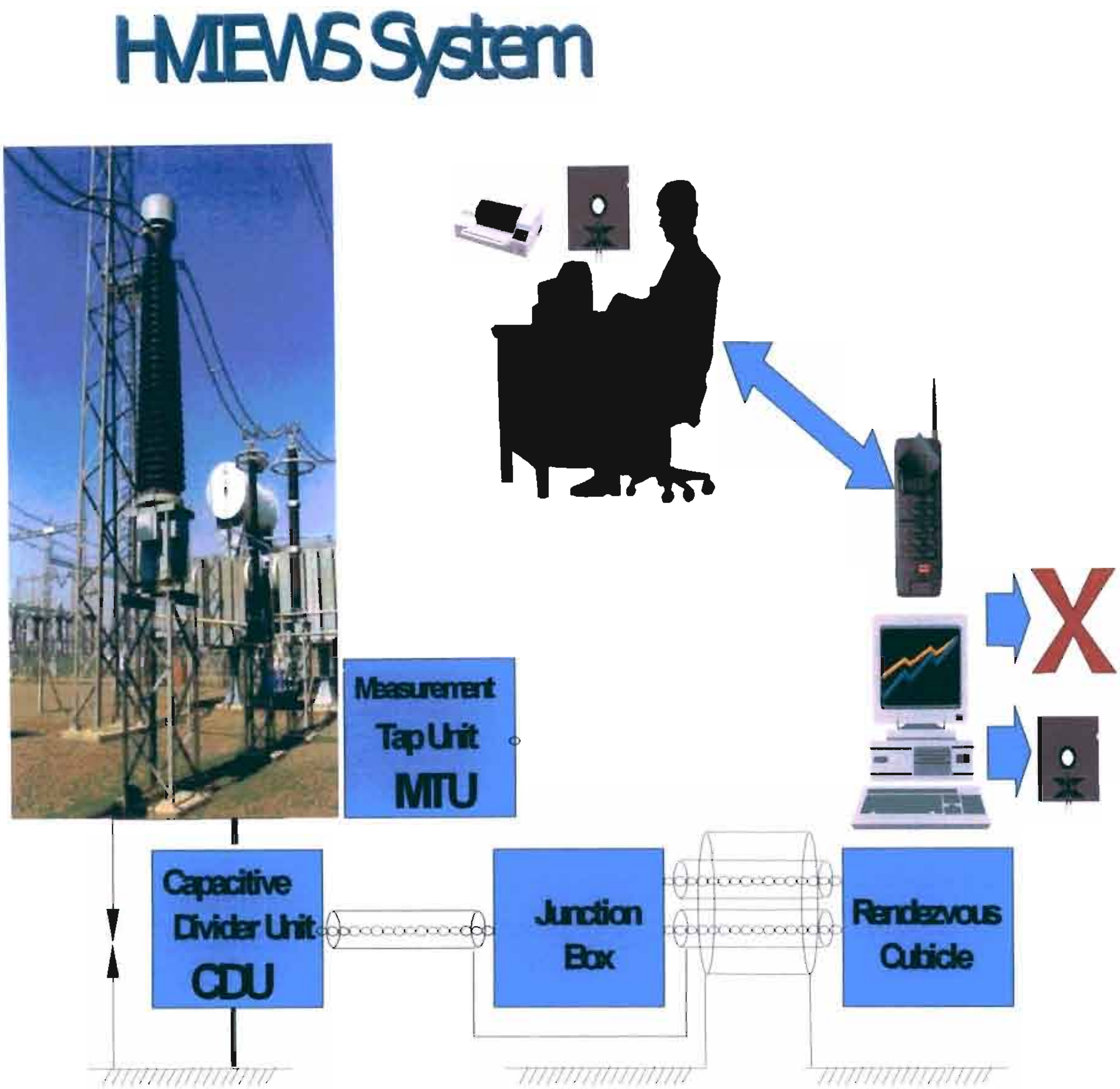

Figure 4.1: Overview of the total HVIEWS System [26].

4.3.6 Comparison of on-line and off-line techniques utilized

Table 4.7 below is a comparison of the on-line and the off-line techniques reviewed. The benefits and disadvantages of each technique are highlighted in this table.

On-line technique (HVIEWS)	Off-line techniques (CSD and Doble M4000)
• On line continuous measurements no outage required except at installation	• Periodic, off line 3 yearly outage required to perform tests, necessary to disconnect droppers
• Tan δ measurement relative to other unit in same set	• Absolute measurement of tan δ
• No compensation needed for ambient temperature, loading and voltage levels on similar units	• Temperature compensation to be applied
• Relative measurement between several units	• Measurement made on Schering bridge principle
• Changing insulation condition takes time to filter through software to results	• Insulation condition measured instantaneously
• Measurements and recording of condition is automated	• Measurement and recording of condition must be undertaken manually
• Measurement influenced negatively by environmental conditions e.g. insulation condition and rain,	• Measurement not influenced negatively by environmental conditions e.g. insulation condition and rain,
• Unit installation is permanent	• Unit is light and portable
• Compares measurements to historic values automatically	• Does not compare measurements to historic values
• Operates at system voltage	• Operates at reduced voltage (eg 650 Vrms or up to 12 kVrms)

Table 4.7: comparing the attributes of the HVIEWS unit, the CSD unit and the Doble unit.

In 1995 and 1996 at Eskom's Mersey substation, two separate incidents occurred where current transformers faulted and plant was damaged, resulting in the loss of supply to large industrial power users. At this time Eskom transmission and the CSIR installed a pilot test site at Mersey substation to evaluate the on line monitoring system in an outdoor substation [23]. The installation of the system in the harsh outdoor environment was very difficult as this had not been done previously and many customized parts, fittings and installation methods had to be produced for the first time. The CT's were insulated by lifting them with a crane and slipping a layer of insulating material between the CT base and the metal equipment support. Many problems were experienced with moisture bridging the insulation during the rain season and possibly periods of very high relative humidity. Approximately 40 units were monitored at Mersey. These included transformer bushings and current transformers.

The system detected a current transformer which appeared to be failing and the conservative approach agreed on was to remove the unit from service and send it for laboratory tests. The off line 10kV tan delta test was not conclusive, but partial discharge tests 300pC showed the unit to be well above the acceptable level of 10pC [23]. The Mersey test site had proved that it was possible to successfully monitor outdoor plant.

4.3.7 Extension of the on-line tan delta system to other Transmission substations.

During 1996 two current transformers failed at Impala substation, resulting in load losses to a large municipality and two major industrial customers and damage inside the substation.

The CSIR's on line tan delta monitoring system was purchased from the CSIR and installed by Eskom personnel at Impala substation. Many of the problems experienced at Mersey substation were improved upon, and in the place of the original insulation, insulators were manufactured out of resin and installed. Cabling was installed in the underground cable trenches and permanent power supplies were arranged for the monitoring system. These were some of the issues, which had caused problems at Mersey. A total of 42 units are being monitored at Impala.

In 1997, a current transformer at Illovo substation failed and caused a power supply outage to industrial customers. Due to the strategic nature of the customers supplied from Illovo, petrol refineries, motor car manufacturers and paper manufacturers, and the impact of a current transformer failing and interrupting the supply, the on line tan delta system was extended to Illovo. The HVIEWS system was installed at Illovo substation in 1998. This new system improved on previous failure areas of the original system. Thirty three units are being monitored at Illovo.

The pilot site at Mersey was upgraded by the vendor to incorporate the latest installation methods and equipment. This was done in 1999 and 105 units are being monitored at Mersey.

4.3.8 Extension of the on-line tan delta system to Generation stations HV plant.

In 1998 failures of current transformers in two high voltage yards of two different power stations caused multiple generator tripping and extensive financial losses to the power stations. These customers were demanding that Eskom Transmission take some action to provide assurance that the HV plant was operationally safe. This pressure resulted in the on line tan delta monitoring system being expanded into the power station's HV equipment.

Site	Voltage Level	Year installed
Impala	275 kV	1998
Illovo	275 kV	1998
Mersey	400/275 kV	1999
Kriel	400 kV	1999
Matla	400 kV	1999
Duvha	400 kV	1999
Hendrina	400 kV	1999
Arnot	400 kV	1999
Tutuka	400 kV	1999
Vulcan	400 kV	2000

Table 4.6: Sites where HVIEWS is installed:

The installations described above provided condition monitoring of about 800 devices at a capital cost of R4M or R5000 per device or 3,3% of capital cost.

4.3.9 Field maintenance of insulation

The objective behind the field maintenance of HV equipment is to ensure the plant is safe for operation and to attempt to determine the useful life still available in the equipment. This evaluation is done by engineers having manufacturing and operational experience and a long term understanding of tests and test results that can be used to assist with this evaluation. The absolute values of test results in most cases cannot be used, but rather reference is made to the results of previous test results found on the same equipment as well as results found on similar equipment in various operating circumstances. If the results show increasing degradation, then other engineering actions need to be undertaken. Regular scheduled tests need to be undertaken and the results need to be properly kept and managed. The intervals between tests on the equipment in service need to be determined by the type of the equipment, the harshness of the environment, the history of the previous test results, the age of the equipment, the ease of testing, the impact of failure and the risk of failure.

4.4 Summary

Commercially available off-line techniques have been reviewed. The advantages and disadvantages of each technique have been highlighted as have the overall advantages and disadvantages of off-line testing. The major disadvantage is the duration of the testing interval which highlights the desirability of an on-line technique. One particular on-line technique commercially available and utilized in this research has also been reviewed and then compared to the off-line technique.

CHAPTER 5
THE 275kV TUGELA TEST STATION

5.1 Background

In 1996 Transmission identified the failure of CT's as a major threat to the business [4, 22]. These issues had driven the business to undertake the following actions:

- To identify and categorize high risk CT's on the network
- To identify and remove high risk CT's from critical circuits
- To reduce the risk to the system by limiting the number of CT's in service
- To develop and implement a maintenance procedure for CT's and bushings
- To identify/develop and implement condition monitoring systems for CT's and bushings
- To reduce the number and consequences of CT and bushing failures on the network [4, 22].

As a result of the action to identify/ develop and implement condition monitoring systems for CT's and bushings, a number of strategies were undertaken, namely

- Off line monitoring – 7 off line Doble M4000 test units purchased and in use
- On line monitoring, the HVIEWS system, 10 systems installed.
- On line monitoring, the Insite system, 1 system installed at a power station.
- Oil sampling and analysis, routine oil sampling undertaken on 350 bushings

Although the HVIEWS system was installed at 10 substations, the ability of the system to track failing insulation in the field situation was not confidently known and the ability of the system to provide an early warning in time for an operator to isolate plant safely before failure was also not known.

In order to determine the capability of the HVIEWS system to meet the above criteria, a project was undertaken to trend the accelerated degradation of the HV insulation on CT's in a controlled environment.

The rationale behind the establishment of a controlled environment for the accelerated degradation of the HV insulation included the following requirements:

- The most credible environment to test the CT's would have been the normal operating environment in a substation near to the researcher, for easy access. This was not possible due to the high fault levels near the Durban area, the effect a failure would have on the voltage supplies to local customers, the effect of the damage to plant and risk to personnel.
- All research work could have taken place in a laboratory, but this would not simulate the exact environmental conditions found in the field. Latest information on the 10 HVIEWS units installed in the substations, indicated that the environmental conditions were effecting the measurements.
- A test facility could be built in a suitable location to facilitate all aspects of in service conditions.

5.2 Tugela Substation

After scanning the Transmission and Distribution Networks, a suitable site was identified at Tugela Substation, to erect a facility suitable for conducting accelerated aging tests on HV insulation, resulting in failure and destruction of the unit under test.

The test station that has been built by Eskom is situated at the Transmission Tugela Substation, 35 km form Bergville in the foothills of the Drakensberg Mountains in KwaZulu Natal. This is the first such test site built by Eskom where primary plant can safely be tested to destruction. The site has been professionally built, to cater for the safety of personal and adjacent equipment. This site was built to original specifications as no other similar test facility could be traced, and is available for the testing of manufacturer's primary plant equipment and problematic Eskom equipment. The name Tugela is synonymous with the Tugela River flowing nearby from its source at Mount Aux Sources in the Drakensberg Mountains (3282 meters above sea level).

5.2.1 Choice of location and design features

The site is situated in a remote farming area where the farming population is very sparse and access is via a dust road, which is used mainly by the local farming community. The road runs about 200 metres from the equipment and the nearest neighbour is about 700 metres from the station. Only Eskom authorised personnel have access to the site. There are no major industrial customers connected to this electrical network, the local customers are mostly farmers and mountain holiday resorts, and the electrical distance from major nodes reduces the effect of an electrical voltage depression to any major customers.

An environmental impact assessment (EIA) was done in the area to assess the suitability of installing the test station at Tugela. Details of this EIA are included in Appendix 3.

5.2.2 Test Station Design Features

The test station was designed bearing in mind that on the failure of any plant under test, pieces of porcelain or shrapnel would be exploded around the immediate area. Neither personnel nor plant should be put at risk, nor should the failure impact on any customers in the area. Further there should also be no adverse impact on the environment. Figure 5.1 is an identical diagram of the substation indicating the incoming feeders.

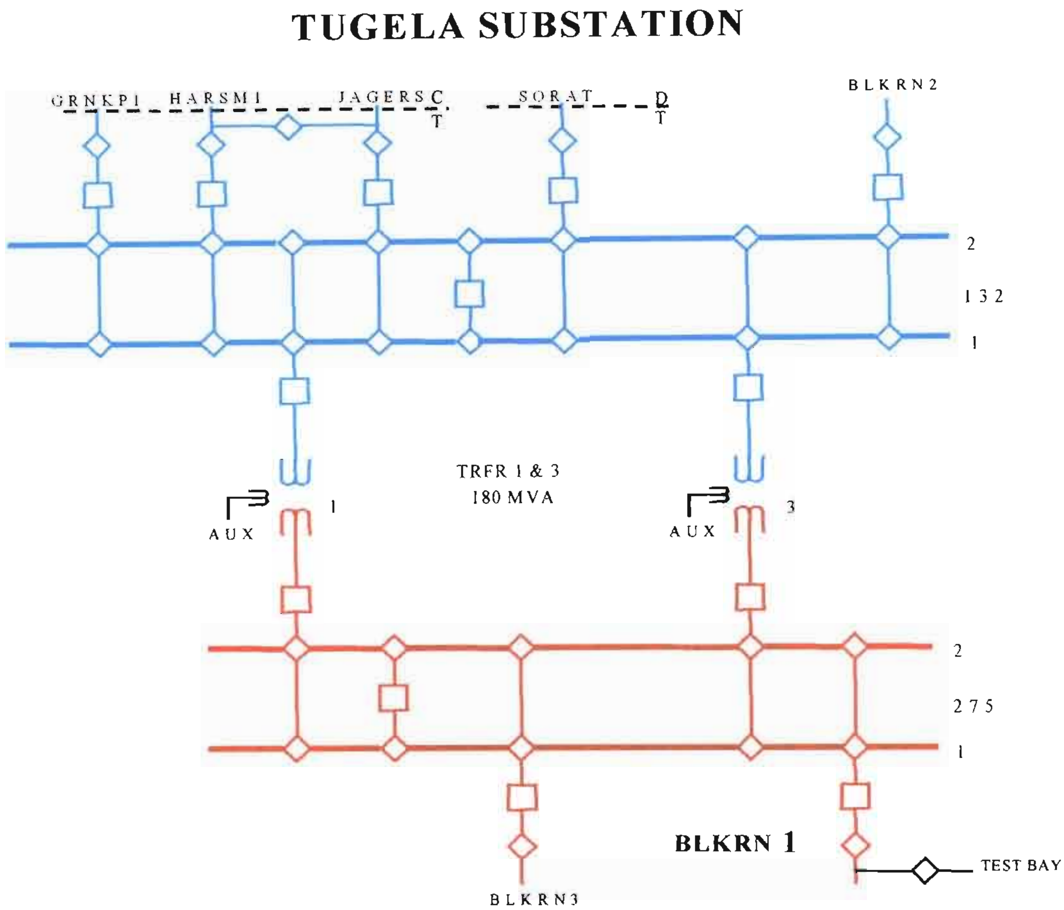

Figure 5.1: Tugela Substation electrical layout, indicating the 275kV infeeds in red and the 132kV feeders in green [5].

The supply into Tugela on the 275kV network is via Bloukrans 1 and 3 feeders, emanating from Bloukrans substation about 62km's away. Also feeding into Tugela via the 132kV network is a third line, the 132kV Bloukrans 2 line. System studies have shown that with either one or two of the 275kV lines feeding into Tugela being out of service, the load full can still be maintained via the 132kV

Scenario 1, 2 X 275kV and 1 X 132kV lines in service				
Line	**kV**	**MW**	**% loading**	**Fault current A**
Blkrn 1	275	48.5	10	3839
Blkrn 3	275	48.3	9.9	3787
Blkrn 2	132	4.2	5.5	364
Scenario 2, 1 X 275kV and 1 X 132kV lines in service				
Blkrn 1	0	0	0	0
Blkrn 3	275	92.8	18.5	5242
Blkrn 2	132	7.6	9.4	618
Scenario 3, 0 X 275kV and 1 X 132kV lines in service				
Blkrn 1	0	0	0	0
Blkrn 3	0	0	0	0
Blkrn 2	132	74.5	90.8	1177

Table 5.1: Fault and load currents for infeeds into Tugela substation [28].

The system studies indicate that when both Bloukrans – Tugela 275kV lines are out of service, and only the 132kV line in service, the 132kV line is loaded up to 93% at the 75°C thermal rating. Hence the load can be maintained. Following the loss of the second 275kV line, a voltage drop from 138kV to 122kV can be expected at the Tugela 132kV busbar. With the appropriate tapping of the transformers at Bloukrans, this voltage can be increased to 126kV, which is 95.5% of the normal voltage.

The fault current on each Bloukrans – Tugela line when there is a fault at Tugela is presently 3.8kA, giving an overall fault current of 7.6kA. For the condition where one line is out, the overall fault level decreases and the fault current on the remaining line increases to 5.2kA [30].

The system studies confirm that the station is secure under normal operating conditions as well as when one 275kV feeder is out for maintenance and the other 275kV line trips due to a fault, under these circumstances the supplies at the station are still secure. Load and fault studies are attached as per Appendix 4.

As indicated on the diagram Figure 5.1, the supply to the test station will be taken from the 275kV Bloukrans 1 feeder. This feeder has a breaker with only one mechanism, resulting in a 3 pole trip for single and 3 phase faults. The breaker on the Bloukrans 3 feeder is capable of single pole tripping for single phase faults and for 3 phase tripping for 3 phase faults, making it more secure for the system when it is the only 275kV feeder in service.

5.3 The test station

5.3.1 Layout

As the CT test facility only requires a single phase supply, the test station design entailed tapping off the red phase of the Bloukrans 1 feeder, as the line entered the HV yard on the station side of the last line tower. At the Tee off at the point the test station was strung with a single Centipede conductor as shown in Figure 7.3 of Appendix 7 and was fed into the test station via a 275kV single phase isolator and two control and protection CT's onto a single busbar which transverses the centre of the test station. The busbar was suspended from one 12-meter wooden pole, with a set of silicon 400kV insulators on each end of the station. The isolator and insulators were recovered from a project at Invubu substation, where they had become redundant. The single pole isolator was motorised and could be remotely controlled from National Control at Simmerpan.

5.3.2 Protection scheme

The key to the successful operation of the test station was to ensure effective protection to minimise the impact of CT faults deliberately caused on the system. The protection scheme for the test bay included instantaneous earth fault protection installed on the first control and protection CT (C1) closest to the single-phase isolator. During normal steady state conditions no current would flow through the CT, but under fault conditions the single red phase current would flow via the CT to the fault and return via the earth. At this point fault current would flow and with the relay set safely to the minimum setting the relay would operate instantaneously, opening the local Tugela Bloukrans breaker in 50 milliseconds and isolating the infeed from the Tugela side. Simultaneously a carrier signal would be sent to the remote Bloukrans end, where the distance (impedance) protection would have detected a fault via the impedance starters in zone 3 and with the receipt of the carrier signal would trip the remote breaker in 70 milliseconds and thereby isolate the fault.

The protection scheme implemented also included the standard line impedance protection still in service on this line via this lines own 3 CT's. For a fault in the test station, this would trip the local end instantaneously in 50 milliseconds and the remote Bloukrans end would trip in Zone 2 time which was reduced to 100milliseconds.

The standard back up overcurrent and earth fault protection is in service in case the main impedance protection should fail. In this case the local and remote end would trip in back up Inverse Definite Minimum Time (IDMT) earth fault protection time of about 200milliseconds.

The control system was programmed to operate as follows, on the receipt of an alarm from the HIEWS system, indicating an imminent CT failure, the alarm would get transmitted to National Control in Simmerpan, and they would manually via remote control, trip the local Tugela Bloukrans 1 feeder. The line would now be off load and they would open the single red phase test station isolator, thereby removing supply from the test station. Control would then reclose the local Tugela Bloukrans feeder and put the feeder back on load.

Should a failure occur in the test station, the local instantaneous earth fault protection would operate and trip the local breaker. At the same time sending an alarm to National control indicating that the line had tripped due to a failure in the test bay, and sending a carrier to the remote end, which would trip. Control would manually via the remote control system, open the red phase isolator feeding the test station and would then reclose the line breaker at Bloukrans and then the line breaker at Tugela and so secure the station supplies.

The auto reclose (ARC) facility was switched off on this line, thereby avoiding any chance of reclosing onto a fault in the test station.

Should the feeder trip for a normal line fault and not a fault in the test station, National Control would not get the alarm from the instantaneous earth fault relay on the test bay, indicating a fault in the test bay. National Control would understand this to signify a standard line fault and would reclose the circuit.

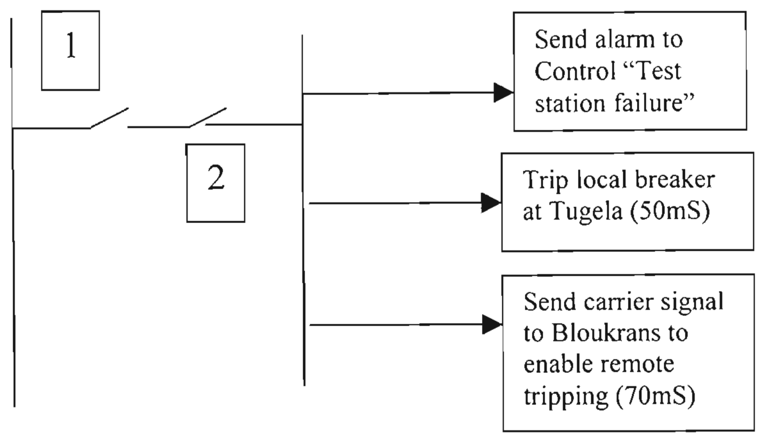

Figure 5.2: Block diagram indicating tripping logic at Tugela Test station.

Note 1 = failure of unit under test in test station

Note 2 = operation of instantaneous earth fault relay at Tugela

From the above information on the security of the supplies into Tugela and the enhanced protection system installed, including the standard Transmission remote control and alarm system via the X25 network and the microwave system to ENCORE at National Control, it can be seen that the supplies at Tugela are secure enough to cope with any N-2 contingency. The low fault levels of 7.6kA and fast fault clearance times of maximum 100 milliseconds ensure that any energy supplied to the fault is minimised. The voltage depressions in the immediate vicinity will not impact on any customers. Local customers have bought into the test station idea and support Eskom in this research in order to improve the electrical performance in the long term.

For the majority of the time the station is unmanned with no one on site. The property is fenced off with a normal 3-meter high perimeter fence. Inside the outer fence is an electrified security fence, which has alarms that are monitored 24 hours a day. Access to the HV yard is then via the prohibited area fence. Access to the test station is via a live chamber fence, the keys to which are locked in a safe and only available if the test station is isolated and earthed. Only authorised staff have access to the station. The design of the protection schemes was a key component of the safe operation of the test station (and the network) during the period of the study. There were, however, a number of other key design issues that had to be addressed due to the explosive nature of the failure mode of oil-paper insulated CT's. These are discussed below.

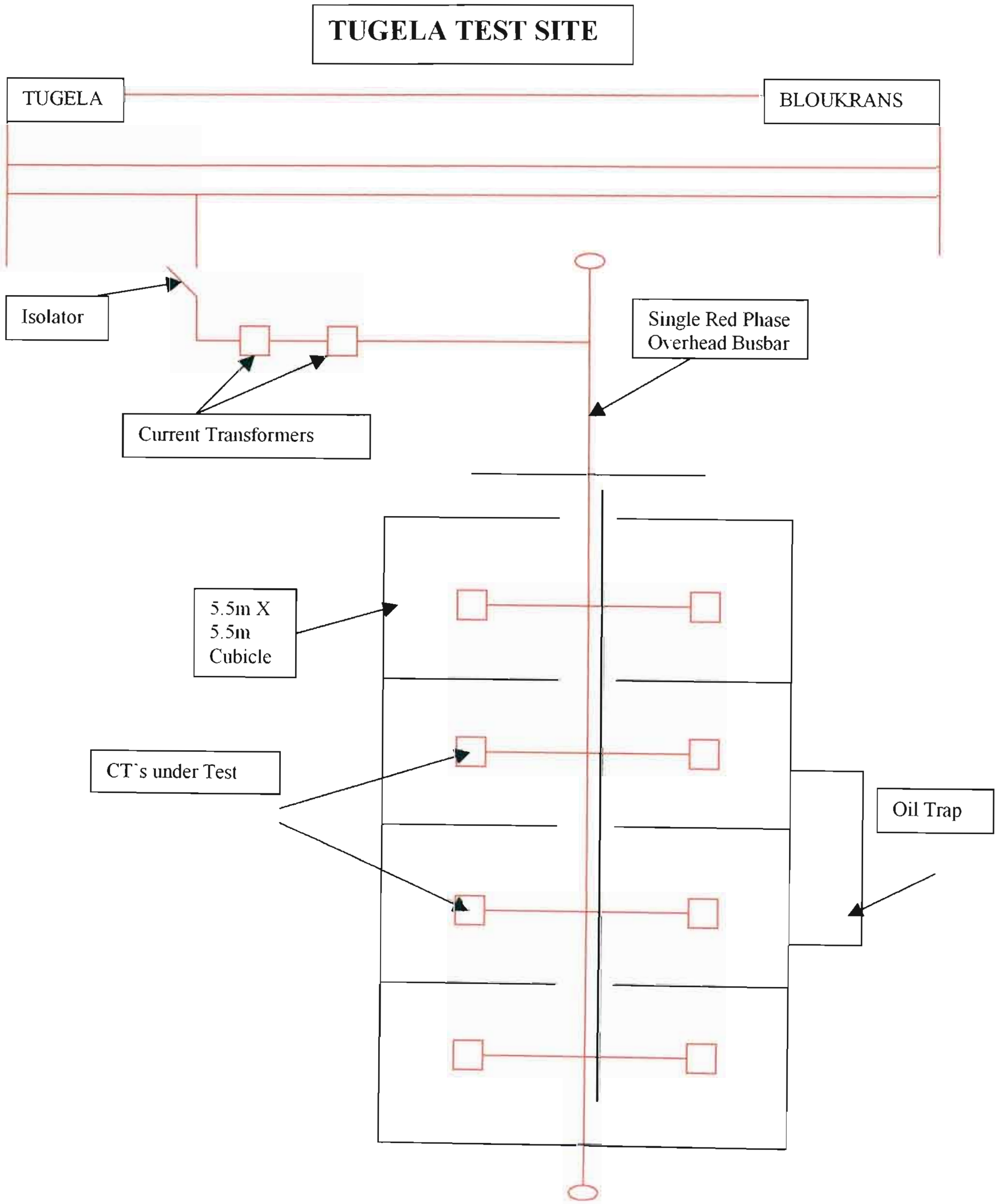

Figure 5.3: Tugela Test Station

5.3.3 The safe civil design of the test station [29].

The test station had to be designed to cater for the case of exploding porcelain, oil spillage, possible fire hazards, and compliance with Eskom Operating Regulations for HV Equipment, and was not permitted to pose a risk to the operational plant nearby nor to the personnel who worked on site. To ensure that none of the abovementioned aspects left out of the design, a design team consisting of the local Inspector of Machinery, a professional civil engineer, electrical engineers, station operators, academics and contractors was put together to attend to the design.

5.3.4 Positioning of the test station at Tugela

The HV yard at Tugela was originally constructed with an additional terrace on the South side of the 132kV yard, to accommodate a future Distribution 33kV yard. This area had already been levelled and was situated between the incoming 275kv Bloukrans 1 and 3 lines. Distribution no longer had any plans to make use of this area. A 33kV feed from Tugela was not required for the next 10 years at least.

The proximity of this terrace to the incoming lines and the fact that it was the only flat terraced area requiring little rework led to the choice of this area as the best area for the test station.

The test station was erected with 8 individual bays, where 8 different pieces of equipment could be tested at once without anyone interfering with any of the others. The overhead busbar was erected in such a manner that the test station could be extended in the future, if this was required without having to move the busbar. So the busbar was extended to its maximum reach over the area. As the operating voltage was 275kV, the Occupation Health and Safety Act concerning electrical clearances had to be adhered to. This meant that all clearances to earth of not less than a minimum of 2.35meter had to be observed.

As can be seen from Figure 5.3 the single red phase dropper tees off the red phase of the Bloukrans 1, 275kV feeder and is conducted via the motorised isolator (IS1) and via CT 1 and CT 2, the protection and control CT's, to the single Centipede conductor busbar. The busbar spans the full length of the present and future test bays. The use of Centipede conductor for the single busbar, was based on the cross sectional area of 415.22 square millimetres, consisting of 37 strands with a 50°C thermal rating of 833A. This size of conductor is regularly used at 275kV and introduces minimal corona effects.

5.3.5 The foundations and walls of the test station [29].

Originally the test station was to be built with a standard 400mm x 400mm concrete foundation below the walls, but after excavation of the foundation channels, the soil was found to be clay. This had never been recorded on the original soil analysis report, taken at the time of building the substation in 1988. The clay would not hold the building but would move under the weight to the point that the building broke up and collapsed. This required a raft foundation to be built out of one solid construction for the total building. This raft was designed to take the full first phase of the test station, namely the first 8 cubicles. It was constructed out of reinforced iron and reinforced concrete. The cost of the raft increased the project cost by R350000.

Each cubicle was to have walls 4,5 meters high above ground to cater for the height of the CT and the equipment frame base it is mounted on (3.75metres) and still give the CT clearance so as not to protrude over the top of the wall. As any failure had to be contained inside the walls and not spray debris over the wall and into the adjacent equipment. Each cubicle was dimensioned 5.5m by 5.5m to allow for the equipment to be mounted in the centre and to have clearances of a minimum of 2.35m from any point of the equipment to any earth point, to satisfy the requirements of the OHS Act.

The clearances for this 275kV test station were designed on the clearance limit for 300kV namely 2.35m to any point. The roof of the test station was designed to be open, to simulate the normal environment which the equipment under test would be subjected to in any HV yard. The open roof also allowed for easy access into the cubicles from the overhead busbar of the 275kV supply. Had the roof been closed, the test item would not have been subjected to the normal outdoor conditions, and the 275kV supply would have to be introduced via roof/wall bushings. This complication and unnecessarily high cost would have resulted in this project being considered as uneconomical. Leaving the roof open had the added value of allowing any shock waves from exploding CT's to dissipate without destroying the test station. The civil diagrams of the test station are in Appendix 7.

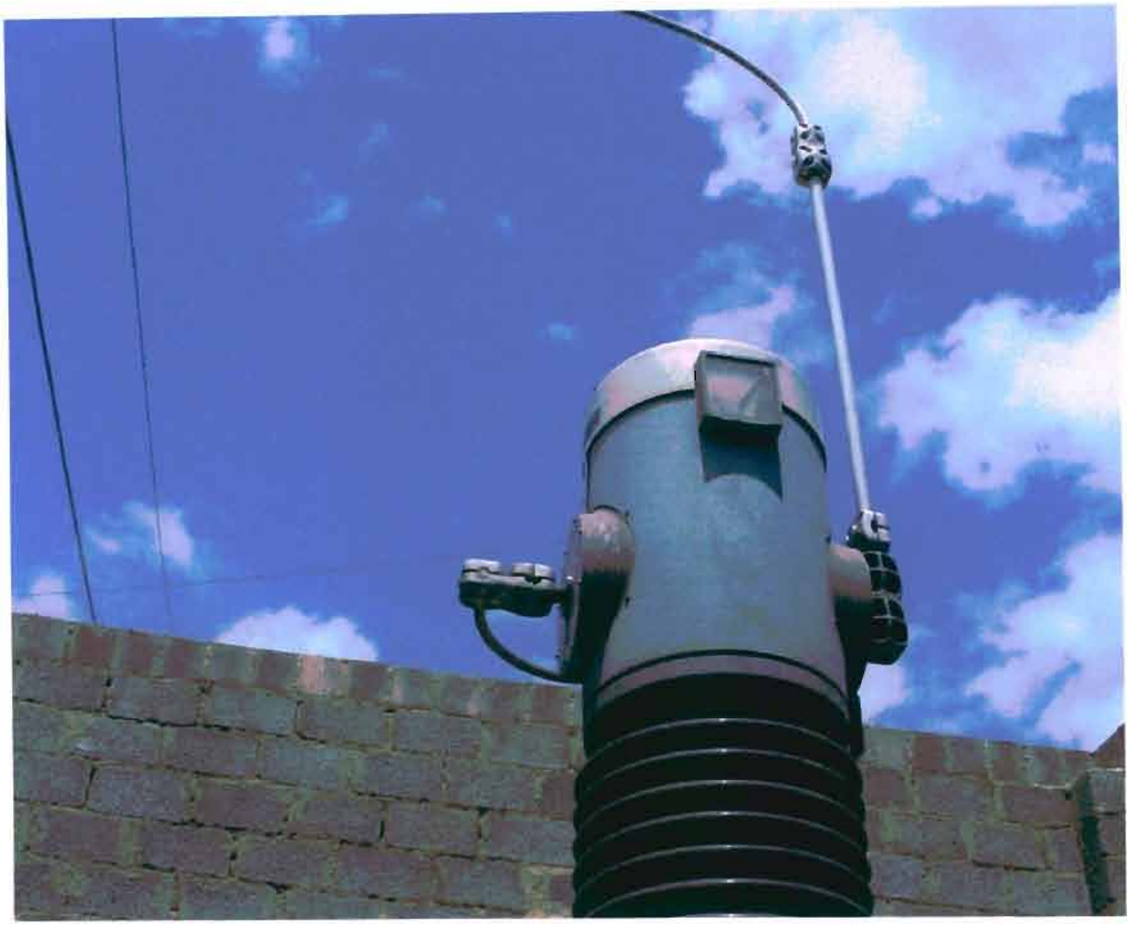

Figure 5.4: Balteau SAX245 CT installed in the test station at Tugela.

The photo in Figure 5.4 clearly shows the connection to the 275kV overhead busbar as well as the shorting conductor across the bar primary, where the rated current induced from the secondary windings, is circulating. The CT's mounted on the equipment frame were fitted with clamps on the top connections as well as the extension stems and the connection to the overhead busbar. The extension stems were required to ensure the minimum safety clearance to the wall was maintained. Access between adjacent cubicles is via a common walkway on each side of the centre wall. The walls of the test station were constructed to British Standard BS5628.1.1992 out of concrete blocks M200 measuring 190mm, by 190mm, by 380mm, with reinforced brick force wire between every row. 3.5 MPa blocks and class 3 mortar was used. The wall's first design calculations required only 1 layer of blocks and the tensile stress was found to be excessive. The second design calculation was tried with a double layer of blocks up to half the height and the design was found to still be unstable as the stresses were still too high. The final design was with piers from the ground to the top of the wall staggered at 5.5m centres. With a wind load, the stresses of this design were within limits. The design of the wall was calculated using Prokon Software. The top of the wall was capped with capping blocks to prevent rainwater from getting into the blocks [29].

Figure 5.5: Construction nearing completion. Visible are the isolator, protection CT and the poles for the overhead busbar on either side of the building.

Figure 5.6: The lifting of a CT over the wall of the test station during the initial installation.

5.4 Safety features of the Tugela test station

5.4.1 Station Access

The access to the test station is via the standard access, namely the station is surrounded by a 3 meter high, outer perimeter fence, inside that fence is two security fences, one is energised with high voltage, and is monitored by alarms 24 hours per day. The entrance is through a 3 metre high gate, control access is only via security permit. Once inside the station, access to the test station, which is inside a 2m high fenced area, is via a locked gate, of which the key is kept in a safe and may only be removed if the station is isolated from the electrical supply and earthed. Under the Eskom Operating Regulations for High Voltage Systems (ORHVS), access is prohibited unless the station is isolated electrically and grounded. This is due to there being the possibility of making inadvertent contact with HV conductors as the CT's are mounted so low to the ground, only 500mm off the ground level, in a conventional situation the CT would be mounted 2m off the ground level. There are three 6m long gates in the test station perimeter fence to allow for vehicle and crane access.

5.4.2 Fire protection and oil spill protection

The fire protection at the station is a major feature of the design, as a CT failure is well known to result in fire and oil spills. The internal cubicle floors are all slanted individually into a channel, where any spilt oil would flow into a specially constructed oil sump tank. The sump is capable of holding 500 litres of oil and is designed to ensure that the burning oil would be extinguished safely. The floors of each cubicle are laid with concrete, so any spilt oil could only flow into the oil sump and no oil could enter the water system, nor sink into the ground. Once in the oil sump the spilt oil has to be manually pumped into drums for disposal. The principal operation of the oil system is to allow the spilt oil to flow into an airtight concrete chamber filled with water and so preventing air from getting in. As the oil flows into the chamber, it displaces some of the water, still maintaining the air block. As the oxygen, which was originally in the chamber, gets burnt up, the fire will extinguish. Any rainwater, which flows via the oil ducts into the sump, will flow out into a subsoil drain. Around the test station at 5 meter spacing, portable fire extinguishers are mounted to put out any fires. A water/foam 200 litre tank is available at the station in case it maybe needed. Inside each test cubicle there is only the test object and no other combustible material. Each cubicle is separated from all the others by 4,5m high walls to ensure that fire cannot spread beyond the effected cubicle. The area around the test station for a distance of 7 meters is covered with stone to prevent growth of vegetation and the build up water. The area set aside for spare equipment and oil drums, is a bunded concrete surface, where any oil spill is kept in the bunded area and so cannot damage the environment. A drawing and explanation of the operation of the oil collection and fire extinguishing system is attached in Appendix 8.

5.4.3 Blast walls

The outer wall of each cubicle has been designed to cope with the percussion blast experienced when a CT fails. As the HV insulation of the CT degrades to the point of failure, the dielectric strength decreases to the point that electrical flash over takes place. The arc under oil rapidly generates large quantities of gas causing a pressure build up inside the porcelain housing, which ruptures and discharges fragmented porcelain around it up to reported distances of 70m. The force to launch this flying porcelain sets up a shock wave that has to exit from the cubicle without knocking over the walls. In order for the test station to accommodate the shock waves, in each compartment a 2 x 2-metre hole in the outside wall covered by a 30mm thick rubber blast mat. Usually this mat is used at blast sites to allow the blast shock wave to escape but to contain any flying debris.

Figure 5.8: The blast mat covering a 2 X 2 metre opening in the wall, designed to allow the shock wave produced by a faulting CT to escape, but to retain any flying debris.

5.5 Operational experience of the Tugela test station

Once the test site had been put into operation and failures of CT's were experienced a number of operational problems were experienced. Some repairs and alterations to the original design were required. However, in general, the test bay performed to specification and in particular the test station withstood the failure of a number of CT's and was available for further testing of plant. Further, the shock wave was safely dissipated through the rubber blast mats and the exploding fragments of porcelain were contained inside the cubicle walls. Some slight damage was caused to some concrete blocks from exploding fragments of porcelain. However, this damage was easily repaired by removing and replacing these with new blocks. Also encouraging was the fact that the failed unit in no way affected any of the other units under test.

Environmentally, whilst the oil spill was correctly channelled into the oil sump, the fire was not correctly extinguished as fire fighters were unable to get near the lid of the sump to extinguish the flames due to the heat of the flames. Further, the voltage depression experienced at the time of the fault, although having no effect on local customers, affected other substations further removed from the generation source. A third problem related to communication with National Control which resulted in the reclosing of the feeder back onto the failed CT. However, the protection system had operated correctly and had isolated the faulted CT and infeed.

The experiences described above led to some modifications to the test station. These are listed below:

- A small number of concrete wall blocks in the cubicle of the failed CT, that experienced some cracks, were removed and replaced with new blocks
- The oil sump was repaired where damage was caused by fire. The operation of the sump centres on the correct level of water in the sump and local staff were trained on the operating method of the sump. The heavy metal cover of the sump was cut into four smaller covers for easy removal.
- A procedure was prepared for National control to ensure that they did not reclose the infeed onto the faulted CT without first opening the test station isolator.
- The voltage depression had effected the electrical Quality of Supply (QOS) at neighbouring substations and a series reactor was fitted to reduce the fault level.

A further major modification undertaken involved the fitting of a fault current limiting reactor at the in-feed to the test station. This is discussed below.

5.5.1 Installation of reactor

The local Transmission Grid had a compact agreement with the local Distribution Region on the standard of power, which Distribution received from Transmission. The criteria in the agreement centred on the quality of the power supply, which was supplied to local customers and the effect this had on the customers' product. One of the QOS parameters concerned the types and levels of faults and the voltage depressions caused by the fault. If the voltage depression was greater than a prescribed level, this voltage depression would be responsible for customer's supplies switching off in order to protect motors restarting, or the depressions destabilising control equipment. These disturbances would shut off supplies and damage product, which was in the process of being manufactured.

During 1999, the first year of the operation of the test station, the limit for X class dips (voltage depression of between 20% to 60% for a duration of between 20 and 120 milliseconds) at Bloukrans substation was 7 and the Grids performance had already reached 5. The first three CT failures at the test station caused the limit at Bloukrans to be exceeded. Throughout the Transmission substations there are QOS instruments recording the various dips at different substations. When the 3rd CT failed on 29/12/1999 while under test, the dips were recorded at various substations and Table 5.2 indicates the various dips recorded. This dip was on the red phase, showing a voltage depression of 39.5% for a duration of 110mS and causing the Transmission Grid to exceed the QOS agreement with Distribution. Voltage dips of the Y class category were recorded at Ingagane, Georgedale Ariadne and Illovo, a Y class dip was insignificant and did not impact on customer supplies. Action needed to be taken to ensure no further failures would create X class dips at Bloukrans.

In order to address the QOS problem, it was necessary to reduce the fault current which was experienced at Tugela test station during the failure of a test CT. This had to be undertaken without effecting the correct operation and performance of the substation and plant and the operation of the protection and isolation of the faulted CT in the test station.

A 275kV reactor was located at the Apollo AC/DC converter station, the reactor had never been used before as it had been dropped off the ship on the wharf in Durban when it was being unloaded. It had minor damage, which could be easily repaired. The reactor was installed in the test station on the incoming red phase supply conductor between CT 2 and the overhead busbar. This positioning would insure that under steady state conditions the reactor was not carrying any current but only came into operation when a CT failed and the fault current passed through the reactor. Civil modifications had to be made to accommodate the reactor on a plinth near the incoming feed and the busbar. The fault studies undertaken with the reactor indicated that the reactor would limit the fault current sufficiently to prevent an X class dip at

Bloukrans. The voltage dip was reduced to a Y class dip, which was not counted, as it had no impact on customer plant.

All Dips between 1999/12/29 and 1999/12/31

SUBSTATION	DIP DATE_TIME	MAXIMUM DEPTH	MAXIMUM DURATION	PHASES	OVERALL CLASS	RESPONSIBLE PARTY
Snowdon 2 - 5th 275/88 kV	29/12/1999 12:15:24 AM	31.6	180	W	S	Unknown
Komatipoort	29/12/1999 12:35:37 AM	12.1	60	B	Y	Unknown
Acornhoek	29/12/1999 12:35:53 AM	12.6	1170	B	Y	Unknown
Neptune	29/12/1999 4:08:37 AM	12.9	80	R	Y	Transmission
Grassridge	29/12/1999 4:08:37 AM	29.7	90	R	X	Transmission
Buffalo	29/12/1999 4:08:47 AM	11.9	70	R	Y	Transmission
Delphi	29/12/1999 4:09:07 AM	17.9	80	B	Y	Transmission
Marathon	29/12/1999 4:48:10 AM	13.1	80	W	Y	Unknown
Komatipoort	29/12/1999 4:48:14 AM	67	90	WB	T	Unknown
Prairie	29/12/1999 5:11:51 AM	14.6	80	RB	Y	Unknown
Marathon	29/12/1999 5:12:58 AM	28.4	90	RWB	X	Unknown
Komatipoort	29/12/1999 5:13:02 AM	28.5	90	RWB	X	Unknown
Foskor	29/12/1999 5:13:18 AM	58.8	110	RWB	X	Unknown
Acornhoek	29/12/1999 5:13:19 AM	49.8	90	RWB	X	Unknown
Tabor	29/12/1999 10:17:49 AM	63.1	90	B	T	Unknown
Ingagane 275/132kV	29/12/1999 3:27:54 PM	14.3	30	R	Y	Unknown
Ilovo SVC 275/275kV	29/12/1999 3:28:05 PM	10.3	30	R	[illegible]	Unknown
Bloukrans 275/132kV	29/12/1999 3:28:08 PM	39.5	110	R	X	Unknown
Georgedale 275/132kV	29/12/1999 3:28:14 PM	11.7	30	R	Y	Unknown
Ariadne 400/132kV	29/12/1999 3:28:22 PM	12.4	30	R	Y	Unknown
Esselen 275/132/88 kV	29/12/1999 3:32:25 PM	16.5	90	RW	Y	Unknown
Esselen 275/132 kV	29/12/1999 5:45:45 PM	11.4	50	WB	Y	Unknown
Warmbad	29/12/1999 5:46:15 PM	38.4	350	WB	S	Unknown
Warmbad	29/12/1999 6:04:14 PM	18.5	120	R	Y	Unknown
Neptune	29/12/1999 10:06:19 PM	11.3	200	RWB	Y	Unknown
Buffalo	29/12/1999 10:06:29 PM	12.9	220	RWB	Y	Unknown
Watershed	29/12/1999 10:07:50 PM	33.3	90	W	X	Unknown
Pluto	29/12/1999 10:08:27 PM	23	70	W	X	Unknown
Trident	29/12/1999 10:08:36 PM	18	70	W	Y	Unknown
Ararat	29/12/1999 10:08:37 PM	17.3	70	W	Y	Unknown
Bighorn	29/12/1999 10:08:39 PM	19.7	70	W	Y	Unknown
Bacchus	29/12/1999 11:06:21 PM	13.6	150	R	Y	Unknown
Witkop	30/12/1999 12:08:36 AM	11.9	80	W	Y	Unknown
Delphi	30/12/1999 12:42:03 AM	16.6	80	W	Y	Unknown
Ingagane 275/132kV	30/12/1999 1:03:42 AM	25.9	90	W	X	Unknown
Ilovo SVC 275/275kV	30/12/1999 1:03:56 AM	11.5	30	W	Y	Unknown
Bloukrans 275/132kV	30/12/1999 1:03:56 AM	35.4	90	W	X	Unknown

Table 5.2: The X class dips, which affected the Transmissions Grid performance for 1999 can be seen on the recording of voltage dips.

The protection continued to operate correctly for all the failures that took place at the test station and a recording of the fault as seen by the Tugela protection at Bloukrans is indicated on Appendix 5, firstly the breaker at the Tugela end opens and the current increases as the full load current is fed from the Bloukrans end of the feeder. At point 2 the Bloukrans end of the feeder opens and isolates the fault. The recording is for the failure of the 2nd CT, on 14/12/99, prior to the installation of the reactor. The recording indicates the fault was on the red phase to neutral, with a peak current of 9kA and a duration of 120mS.

The fault studies show that there is a substantial decrease in the fault currents flowing at Tugela when the 57mH series reactor is installed. Table 5.3. and 5.4 shows the comparative fault currents with and without the reactor.

Feeder	Fault current without the reactor (A)	Fault current with the reactor (A)	Change (%)
Tugela – Bloukrans 1	2900	1589	45.2
Tugela – Bloukrans 2	2861	1568	45.2
275/132kV transformer 1	1148	647	43.6
275/132kV transformer 2	1143	643	43.7
Total fault current (phasor sum)	7970	4311	45.9

Table 5.3: Fault current contributions at Tugela 275kV busbar [30].

Substation	Faulted phase voltage without reactor / % dip	Faulted phase voltage with reactor / % dip	% improvement
Tugela 275kV	0kV 100%	78.2kV 54%	46
Bloukrans 275kV	92.9kV 45%	128.5kV 24%	46
Danskraal 275kV	101.7kV 40%	133.0kV 21%	48
Venus 400kV	186.6kV 24%	214.6kV 13%	46
Chivelston 400kV	209.4kV 14%	225.6kV 7%	50

Table 5.4: Phase voltages during a single-phase fault [30]

Table 5.4 shows that there is a 46% improvement at Bloukrans in the magnitude of the voltage dip on the faulted phase when the reactor is installed. The previous faults without the reactor in service indicated voltage depressions of 39.5%, an improvement of 46% with the reactor in service would see a dip of only 21%. With the dynamic state of the system, where all plant is not in service all the time, this indicates that the faults would fall out of the X class and into the less significant Y class. The 4th and 5th CT failures caused voltage depressions of less than 20% in the Y class [32]. Figure 5.10 shows the completed test station with the current limiting reactor installed in the 275kV circuit between the control CT (also shown) and the overhead busbar.

Figure 5.10: Tugela test station with the 275kV, 57mH reactor installed.

Figure 5.11 below shows an aerial photograph of the test station. The reactor is installed on the left-hand side, with a clear view of the 8 cubicles where the CT's are installed and the blast mats installed in the walls. The single phase 275kV overhead busbar can be seen transversing the top of the cubicles. In the foreground is the 275kV yard of the substation.

Figure 5.11: Completed 275kV-test station with reactor in position.

Figure 5.12 below shows a a single line diagram of the test station, indicating the single red phase 275kV connection between the test station and the overhead Tugela/Bloukrans feeder, the current limiting reactor, the 8 cubicles, the overhead busbar and the oil disposal and safety trap.

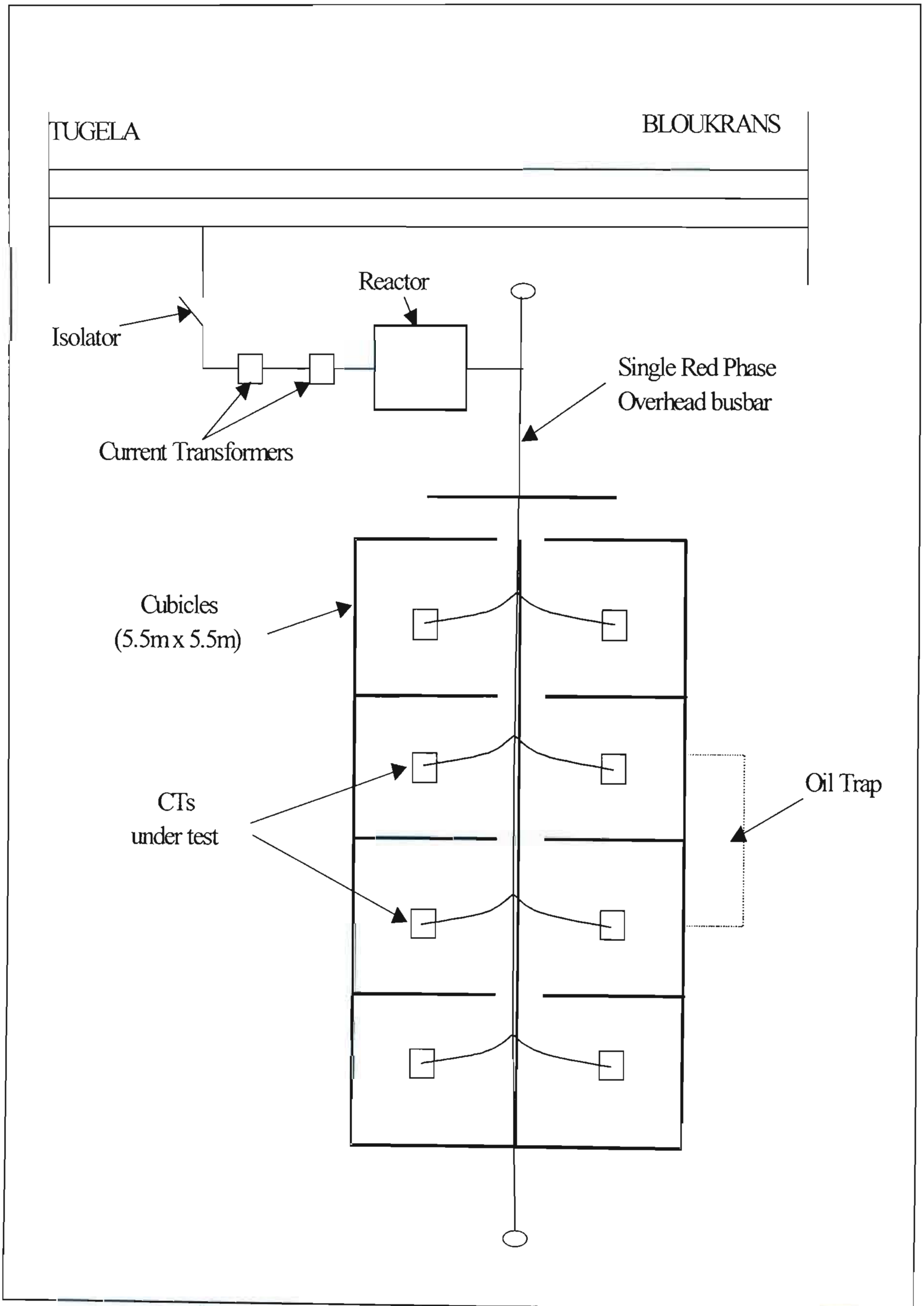

Figure 5.12: Tugela test station with the series reactor positioned between the protection CT's and the overhead busbar.

5.6 Summary

The original planned cost of the Tugela test station was R1.1 million. The final cost of establishing the test station was R380 000. These cost-savings were achieved without compromising the design requirements. The station may accommodate up to 8 test objects. The objects may be energized at a system voltage equivalent of 275 kV and subjected to aging mechanisms without creating problems for the National Grid. The Tugela Test Station is a station built to tight standards to assist the High Voltage industry in solving any HV electrical problems, which may arise.

CHAPTER 6
RESEARCH UNDERTAKEN AT TUGELA TEST STATION.

6.1 Introduction

Investigations and research was carried out in three locations, depending of the suitability of the location for the specific task. The locations were the High Voltage Laboratory at University of Natal, the Tugela test station and in various Transmission substations where the HVIEWS system was installed.

The aim of the research was to determine:

- Whether the HVIEWS system tracks the insulation condition?
- Whether the HVIEWS system alarms the operator to an unhealthy condition of HV insulation, in time for the operator to take the necessary action to secure the plant before failure?

The procedures to be followed were:

- To trend the failure of hermetically sealed insulation under accelerated degradation conditions
- To monitor the associated effect on the dissipation factor (tan delta) measurement and quantify the accuracy of the data in relation to the degraded insulation condition. This will define the extent to which HVIEWS tracks the failure
- To determine the amount of warning time given by the HVIEWS monitoring system to enable safe removal of the faulty unit from service prior to failure.

A number of Balteau SAX 245 CT's were removed from Impala substation. These CT's were chosen for the following reasons:

- These CT's had been in service for longer than 25 years (the economic life span) and the condition of the HV insulation was unknown
- It was suspected that the rubber bellows, at the top of the CT, for oil expansion, was perishing and allowing moisture into the HV insulation.

- A number of similar CT's had failed, 3 at Impala, 1 at Illovo and 1 at Mersey and this had large financial and power outage complications for Eskom and local customers.
- The violent nature of the failures had focused attention on the safety of personnel and plant.

One of these CT's was removed and installed in the laboratory at the University of Natal, and 10 other CT's were removed to Tugela test station. Eight were installed for operation.

6.2 Research carried out at Tugela test station.

The initial aim of the research performed at Tugela test station was firstly to determine the state of the insulation of the CT's as delivered from Impala substation. Secondly to then energize the CT's and monitor them for an initial settling in period and thirdly to then cause degradation of the CT's and monitor them until failure for a number of fault mechanisms.

The following investigations were carried out at Tugela test station

- Measurement of electrical parameters of CT's
- Energisation of 8 CT's at 275kV
- On line tan delta measurements
- Off line tan delta measurements
- Oil sampling and analysis
- Accelerated degradation of HV insulation by back energisation of CT secondary circuits – 3 failure incidents
- Accelerated degradation of HV insulation by reducing HV insulation – 1 failure incident
- Tear down and analysis of a failed CT

6.2.1 Measurement of electrical parameters of CT's at Tugela test station

Eight CT's had been installed at Tugela test station, each one in its own cubicle. Once installed and connected to the HVIEWS system it was necessary to measure all the electrical parameters of the CT's to determine if the CT's could still be operated safely and to be able to trend the results of on going tests with base case conditions. All relevant data was recorded.

6.2.2 Measurement of electrical parameters of CT's at Tugela test station

All CT's installed are Balteau SAX 245, rated at 21kA for 3s, 275kV, 25 years old, each with 5 secondary cores, with ratios of 2400/1, ex Impala substation. All CT's indicate acceptable results.

Tan delta and capacitance tests were done on all remaining CT's after every CT failure and the results were compatible with the results in Table 6.1.

Test bay No	Serial Number	Tan delta Value	Name plate Capacitance (pF)	Measured Capacitance (pF)	Meggar Reading values
1	76/53288/01	0.0043	657.07	589.4	Infinity
2	76/53288/17	0.0056	657.53	584.2	Infinity
3	76/53288/07	0.0055	627.28	588.8	Infinity
4	76/53288/11	0.0051	644.35	589.4	Infinity
5	76/53288/02	0.0044	650.3	585.5	Infinity
6	76/53288/08	0.0056	655.56	587.1	Infinity
7	76/53288/21	0.0052	635.14	588.6	Infinity
8	76/53288/15	0.0051	650.3	586.6	Infinity

Table 6.1: Electrical parameter measurements from CT's installed at the Tugela test station.

6.2.3 Back-Energisation of 8 CT's at 275kV

The CT's were all connected overhead to the 275kV single-phase (red phase) conductor of the Bloukrans/Tugela 1 275kV feeder. The CT's were not exposed to load current but were back energised in an attempt to simulate the heating created by load conditions. The back-energization was achieved by firstly a jumper connecting the primary terminals P1 and P2 together was installed. This allows primary current to circulate in the presence of any secondary current. A separate $220V_{ac}$ supply (single phase from a three-phase supply installed outside the test bays) was connected via programmable contacts to selected secondary windings to force a current through the secondary windings.

The result was a primary current that could be applied and removed as required. As shown in figure 6.1 below, three of the five secondary cores of the CT under test were back energised at 220 volts (single phase from a three-phase 380 volts supply). The two remaining secondary cores were short-circuited. The selected secondary cores have a ratio of 2400/1. With the measured secondary winding load current of 0,5 amps, 1200 amps was induced in the primary bar. A timer that switched the circuit on at 08h00 and off at 16h00 each day as required for each test, controlled the back energising circuit.

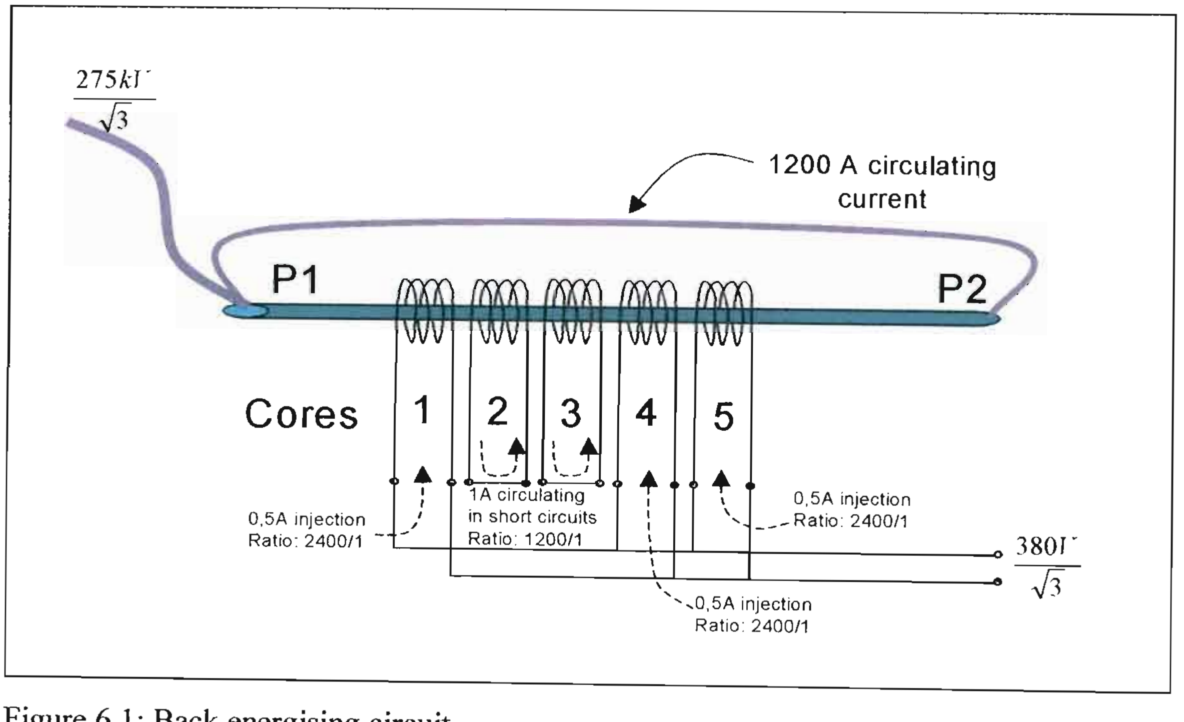

Figure 6.1: Back energising circuit.

6.2.4 Energisation of 8 CT's at 275kV

On 25/11/1999 at 12h00 the Tugela test station was energised at rated voltage (1pu). The back energising was not energised immediately as the HVIEWS system required time to register the initial data on the system. The back energising circuit was set to come into operation at 8H00 on the following day, 26/11/99 and to stay in service until 16h00 when it would be automatically disconnected.

6.2.5 On line tan delta measurements

The CT's were all connected to the HVIEWS system and the following parameters were recorded.

Unit Id	Channel	Phase	Feeder	Relative tan delta	HVIEWS input voltage
1	28	R	Test CT1	1.5	42
2	27	R	Test CT2	2.1	44
3	26	R	Test CT3	1.5	43
4	25	R	Test CT4	1.2	41
5	21	R	Test CT8	-3.6	44
6	22	R	Test CT7	-2.4	43
7	23	R	Test CT6	-1.8	41
8	24	R	Test CT5	-3.6	45
9	20	R	Ref CT1	-2.7	43
10	19	R	Ref CT2	1.64	44
11	16	R	Blouk R	1.9	44
12	17	W	Blouk W	Nil	43
13	18	B	Blouk B	Nil	42

Table 6.2: table indicates relative tan δ values recorded from by HVIEWS at Tugela.

Table 6.2 Indicates that all the relative tan δ values of the CT's in the test were being recorded by HVIEWS, all instantaneous parameters were in specification. The relative tan delta required a number of hours of operation before enough data was accumulated to make a relative tan delta calculation.

6.2.6 Off line tan delta measurements

The off-line tan delta measurements were all taken as part of the electrical parameters required to be used as a base case for trending of any insulation degradation. These measurements taken with the CSD Loss tangent Instrument as shown in Table 6.1 are compared to the on-line measurements shown in Table 6.2. No repeatable comparison could be made between the on-line relative tan delta measurements and the off-line CSD tan delta measurements. As can be seen, no repeatable comparison can be made. CT4 and CT8 both have the same off-line measurement of 0.0051, but the on-line measurements are 1.2 and –3.6 respectively. The reason for this is because the on-line measurement for CT4 is the value of the difference of tan δ measurements of CT4 and CT5 (relative tan δ), whereas the off-line measurement is the absolute tan δ value at the time.

6.2.7 Oil sampling and analysis

Oil samples were taken from CT's in each test bay and sent for Dissolved Gas Analysis (DGA), The samples were taken prior to the energising of the CT's by removing 100ml of oil from the reservoir on the top of the CT. The oil sample is removed with a special device, which opens a ball valve just below the top of the reservoir and then the collection of the oil via a tube into a bottle. The bottles were sent to the Eskom TSI laboratory in Rosherville, where the headspace method of analysis was completed. The headspace method ensures that the gas just above the liquid in the bottle, once stirred up is analysed. This analysis is undertaken to ensure that the CT's HV insulation is not degrading from heat or electrical stress. The results were to be used to trend the condition of the insulation.

6.2.8 Oil sampling and analysis

Oil sampling was undertaken on all CT's remaining in the test station after every failure of a CT and the analysis was compatible with the results below, indicating that CT's which had not failed were still healthy. After the second failure CT 2 indicated elevated Hydrogen levels, a 10kV tan delta test was done and the CT was found to be in specification. This CT never failed.

Bay	1	2	3	4	5	6	7	8	Limit
H2	1	4	1	3	1	1	3	4	**140**
Methane	2	3	3	3	5	3	2	2	**40**
CO	15	7	7	5	12	7	5	8	**1000**
CO2	661	819	619	616	535	584	545	520	**3400**
Ethylene	3	2	2	2	3	3	3	2	**30**
Ethane	3	3	2	2	2	2	2	1	**70**
Acetylene	0	0	0	0	0	0	0	0	**2**

Table 6.3: DGA results for each CT indicating no signs of overheating or electrical stress. All values are well within limits [31].

6.3 Accelerated degradation of HV insulation by back energisation of CT secondary circuits – 3 failure incidents.

The Tugela test station, including the 8 test CT's were energised at 275kV for the first time on 25th November 1999. The whole purpose of this experiment was to rapidly fail CT's and determine if the HVIEWS system tracked the evolution of the failure mechanism. This was necessary to determine if the HVIEWS system could timeously indicate an imminent HV insulation failure (i.e. in time for the unit to be removed from service prior to failure).

Three CT failures are reported on here. Three occurred with the back energisation circuits switched in.

6.3.1 Failure one

On the 26th November 1999 at 08h00 the secondary windings were energised to allow the load current to flow in the bar primary of the CT. Approximately 5h30minutes later (i.e. at 13h35), the CT in bay number 5 failed catastrophically. The epoxy head of the CT shattered, as did the porcelain, sending debris flying into the walls. This caused a fire, which set the oil alight and burnt the CT to the ground.

The protection operated correctly isolating the Tugela Bloukrans 1 feeder. The local control centre operators who were new to the test bay operations assumed that there was a line fault and re-energised the line, once from each end of the line, resulting in an additional two voltage dips. Although alarms had been received at the local control centre the change from the normal operating procedure had caused confusion with the operators.

Figure 6.2: The remains of the failed CT in test bay 5 (26 November 1999 at 13h35).

The burning oil was difficult to extinguish, as was the rubber blast mat, which had caught fire. These items re-ignited every time they were extinguished. The fire burnt in the oil sump until the oil had burned out.

The burning oil damaged the oil sump and set the blast mat alight. The fire fighting capability was not adequate to extinguish the oil fire. The failure of the CT was initially assumed to be due to equipment damage during transport and installation. After inspecting the debris, a number of small arc marks were found all along the bar primary of the CT. Due to the fact that the CT had been exposed to repeated fault currents across the damaged insulation, the mechanical damage had been too extensive to draw conclusions from the debris.

The test station had successfully withstood its first plant failure. There were some minor holes in the walls requiring minor repairs. The station was repaired and a new CT installed in bay 5. New and improved fire fighting equipment was installed. Additional alarms and procedures were sent to the local control staff.

6.3.1.1 HVIEWS results for the first CT failure

The above failure on the 26th of November 1999 had occurred too soon after energising, for the HVIEWS system to produce a fingerprint. In the event that this failure simulated real apparatus insulation failure, the system did not detect the failure. On further analysis of the captured HVIEWS data, the calculated relative dissipation factor reflected a change associated with the failing CT. The HVIEWS recorded a rapid change in relative dissipation factor over a period of only 1 hour and 24 minutes prior to the final catastrophic stage of deterioration. The relative tan delta changed from 0.5 to – 6.85, a change of 7.35 over the last hour and 24 minutes prior to failure.

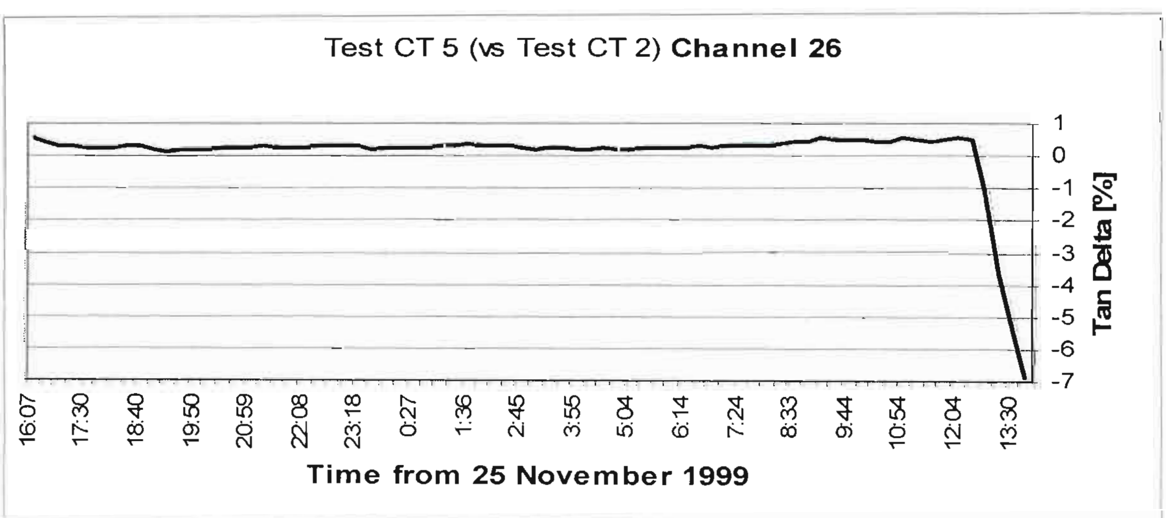

Figure 6.3: HVIEWS relative tan delta of the CT in test bay 5 relative to the CT in test bay 2.

Figure 6.3 above shows the HVIEWS recording of test CT5 (the CT in test bay 5) relative dissipation factor (tan delta) relative to CT2 (the CT in test bay 2). The influence of the circulating primary and secondary currents can be seen from 08h33 where the calculated relative dissipation factor (tan delta) showed a marginal increase due to the back energising circuit.

From 12h04 this same variable shows a rapid change in amplitude in the opposite direction to the back energising fluctuation. The CT failed at 13h35. Typically prior to a failure of the magnitude experienced here, the failing insulation would be accompanied by an increase in the resistive current (leakage current) flowing through that insulation. The increase in the relative tan delta may be ascribed to one or more actual mechanism. The back energisation may cause overheating of the secondary coils and hence a temperature rise of the insulation in the vicinity of these coils. This temperature rise, as discussed in Chapter 2, may then lead to an increase in tan delta. Another mechanism may be related to the production of bubbles by the overheated windings and hence partial discharges (pd) may occur. This bubble related pd may lead to a carbonised path (puncture of the paper) and hence a reduction in the stressed region i.e. an increase in electrical stress across the unbridged portion of the insulation, being reflected as an increase in tan delta. A third possibility is the bubbles are responsible for introducing very large pd in the CT and that such large pd events may be reflected as an increase in tan delta. Such a relationship is discussed by Kuffel [35].

6.3.2 Failure two

Still using the back energising experimental procedure, at 17h40 on 13 December 1999 the test bay was re-energised. At this stage there were 8 Balteau CT's under test, seven of the original ones and a replacement in bay 5. The secondary windings were not energised at this time.

At 08h00 on the 14th December 1999, the back energising circuits were switched on and at 15h21 (i.e. approximately 7h20minutes later) the CT in test bay 5 failed. The local control centre correctly handled this failure and all alarms had functioned correctly. Only one voltage dip was recorded and a minor fire was successfully extinguished. The damage to the CT was minor with only the epoxy head splitting and the porcelain remaining intact. The cause of the failure was initially assessed as moisture collecting in the head of the CT and forming a conductive path between the earth shield around the secondary cores and the line potential conductive tape in the epoxy head. Heating due to the high levels of dissipated power within the secondary cores was not discounted as the primary cause of failure.

Figure 6.4: Second CT failure in test bay 5 (14 December 1999 at 15h21) minor cracks in the epoxy head are visible.

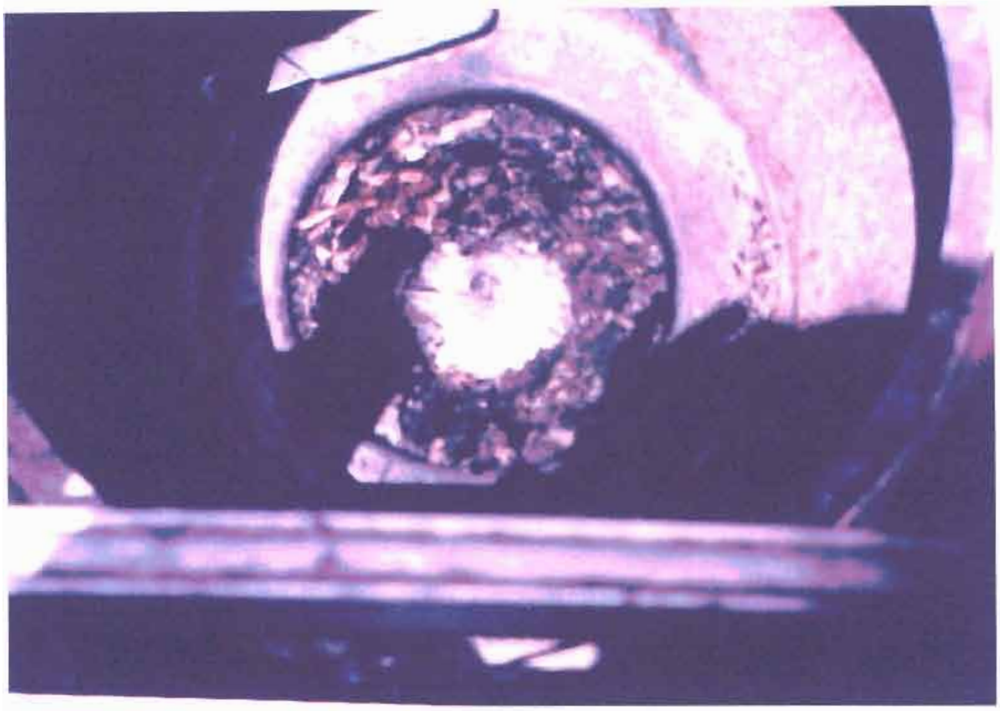

Figure 6.5: Top view - Paper insulation cut back to expose the arc point.

Figure 6.5 indicates the top of the CT with the paper insulation cut back to expose the point where the electric arc from the HV conductive tape flashed to the top of the earth shield of the secondary cores. This supports the hypotheses that maybe the increased voltage stress across the paper insulation, caused by the overheating and the bubbles led to pd and resulted in the flashover.

6.3.2.1 HVIEWS results for the second CT failure

During the second failure on 14 December 1999, the test station had once again been energised for too short a period to develop fingerprints of the relative dissipation factor (tan delta). Therefore the established algorithms do not identify the failures being simulated in this fashion. Further analysis of the recorded data again indicated a rapid change in leakage current prior to the final catastrophic failure.

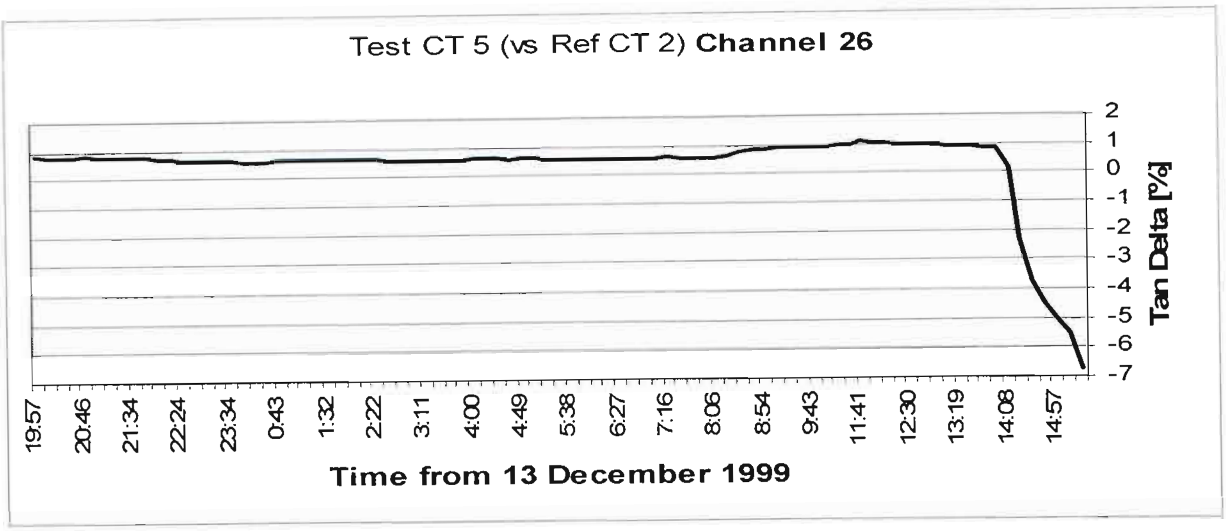

Figure 6.6: HVIEWS relative tan delta of the CT in test bay 5 relative to the CT in test bay 2.

According to the data shown above in Figure 6.6, the relative dissipation factor (tan delta) increased from 08h06 when the back energising circuit switched on. At 14h08 the relative dissipation factor again (as in failure one above) rapidly changed direction (polarity) and increased towards failure at 15h21. The relative tan delta changed from 1 to 6.8 a change of 7.8% in a period of 1 hour and 13 minutes. Due to pressure from the region to limit the number of voltage depressions, the supplier added algorithms to their HVIEWS system to alarm in the event of any leakage current measurement changing by more than 1% from the previous measurement (i.e. over a period of two data samples, or 12 minutes).

6.3.2.2 Tear down and analysis of a failed CT

The CT was stripped of the helmet, the oil drained, the metal base removed, the porcelain shell was removed, leaving the epoxy cast head containing the secondary cores and the paper insulation around the earthed shell and connecting cables. The epoxy head had to be cut off with an angle grinder, taking care not to get injured by exploding epoxy as the cast pressure was released. This was a very difficult process and then fine epoxy dust, from the grinding covered the whole area. Once the epoxy was removed, the paper insulation and secondary cores were removed to allow analysis to determine the cause of failure.

The CT was stripped and the cause of failure was found to be the overheating of the secondary CT cores, caused by the back energisation of these circuits. The resultant power dissipated in the secondary windings as a result of the applied voltage has produced abnormally high temperatures in the windings given the power dissipated as a result of the applied voltage of 219 volts and load current of 0.5 amps. The windings were rated at 10 watts and the actual power injected into these windings was as high as 100 watts. These conditions could not be considered "normal" and the insulation was not designed to dissipate this type of heat. This heat was also proved during the laboratory experiments under back energisation, see Table 7.1.4 which indicates an average temperature increase above ambient by 13°C, and a tan delta increase from 0.0039 to 0.0045 in 4 hours of back energisation.

The dissection of the CT showed that burning had taken place in the insulation around the CT secondary cores. The burning under oil caused gas production, which bubbled up through the metallic shell housing the secondary cores. The bubbles lodged in the paper insulation in the top of the CT, where signs of partial discharge were found in the paper insulation as indicated in Figure 6.8. The insulation and dielectric strength was severely degraded and failed through the top of the CT as show in Figure 6.4 and 6.5.

As the paper insulation was removed some small areas of X wax was found. This insulation degradation was assumed to have come from the 25 years of operational duty and was not near the site where the flash over had occurred.

The tear down confirmed the hypotheses of overheating of the CT secondary windings resulting in large amounts of pd and hence tracking as the primary cause of failure.

Figure 6.7: The damaged CT with epoxy stripped back, exposing damage to HV screen which flashed over to earthed shell around secondary cores.

Figure 6.8: Stripped back insulating paper showing signs of partial discharge and treeing between paper layers.

Figure 6.9: The dissected CT showing the HV stress screen attached to the bar primary conductor and in service at HV potential.

Figure 6.10: The stripped secondary cores of the damaged CT showing the burning marks caused by the overheating from the back energisation.

Figure 6.11: The CT secondary cores inserted inside the metallic, earthed shield.

6.3.3 Failure three

Using the back energising experimental procedure, the station was re-energised at 13h46 on the 23rd of December 1999. Only the original 7 CT's were left in service and the failed CT in bay 5 had been isolated. At this time the back energising circuits were left out of service, as this was considered a possible cause of the sudden failure of the first two CT's. HVIEWS requires a fingerprint of the relative dissipation factor (tan delta). To enable this fingerprint to be generated a minimum period of 5 days of measurements are required with no external ageing influences in service during these first 5 days. At 08h50 on the 29th of December 1999 after a fingerprint had been established, the back energising circuit was put back in service. At 15h28 on the 29th of December 1999 the CT in test bay 8 failed (i.e. approximately 7h30 minutes after back energising).

This third failure was catastrophic, with flying epoxy and porcelain. The consequential fire was difficult to extinguish. The analysis of the failure was once again difficult due to the extensive damage and fire eliminating most of the evidence. The only remaining evidence was an arc mark once again on the earth shield surrounding the secondary cores. In this case a link between the back energising, secondary winding burnout and the failure was more likely.

After this third failure, the Transmission regional management recommended that the test station oil sump and the fault levels inflicted by the test station be attended to before any further tests continue. The test station was shut down until (1) a current limiting reactor could be installed, (2) the oil sump design was improved and (3) the sub soil drains improved. This was duly completed.

6.3.3.1 HVIEWS results for the third CT failure

During the third failure of a test CT at 15h28 on the 29th of December 1999, the CT's had been energised for a period long enough to establish fingerprint references. The failure related HVIEWS data did not reflect a gradual change in relative dissipation factor (tan delta). The system algorithms reflect moving averages over 540 samples. Therefore any rapid changes do not translate to a change in condition until sufficient samples change the overall weighting. Hence the original design parameters of the system did not detect the impending failure. The new algorithms with the rapid change alarm did detect the impending failure and could send an alarm to the National Control Centre. The HVIEWS systems' attempt to transmit the fax was recorded in the HVIEWS log files. Unfortunately the facsimile system set up to send the alarm failed and the alarm never reached the Control Centre. The alarm was initiated in time for the operators to have taken action to timeously switch the plant out.

Figure 6.12 below shows that the rapid alarm is initiated on a minimum 1% step change in relative tan delta that occurred at 15h02, 24 minutes prior to the failure. The tan delta variable started increasing from 14h37 and at 15h28 the unit failed, the rapid changes took 51 minutes and the relative tan delta changed by 4.6%.

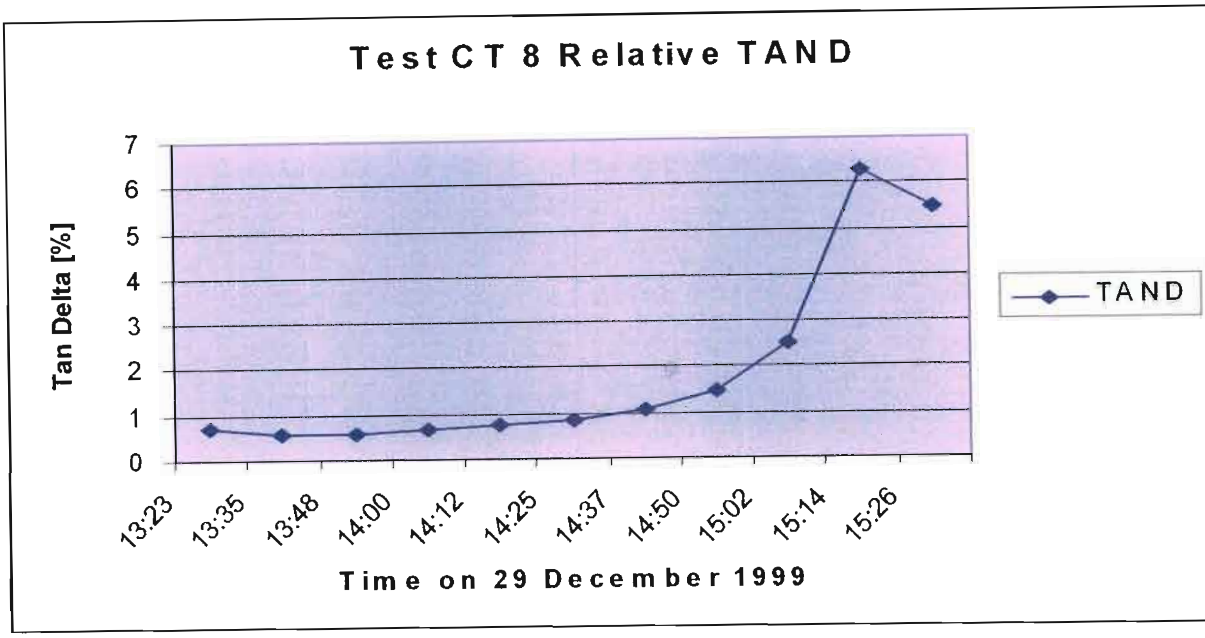

Figure 6.12: HVIEWS "% relative tan delta" of CT in test bay 8.

The 24 minutes between alarm and failure would be sufficient for an operator to respond appropriately to isolate the faulty CT prior to failure.

6.4 Accelerated degradation of HV insulation by reducing HV insulation – 1 failure incident

The back energisation experiment was abandoned due to the very rapid failure modes resulting from this procedure. In an attempt to achieve a slower fault mechanism a second method to degrade the insulation was undertaken, this method is explained below.

6.4.1 Establishing voids in the insulation layers

The insulation within a CT is graded by connecting the outermost layer to the primary voltage and the innermost layer to ground. Therefore all layers in between will carry a portion of the electric field stresses. The design ensures that each layer can accommodate the electrical stresses exerted on that layer. The experiment carried out included using 10 metallic nails to puncture the insulation to a depth of half the overall primary insulation. The nails were then withdrawn. The basic procedure is shown in Figure 6.13 and 6.14.

The result was expected to be a series of voids. Since the paper insulation is oil impregnated, the holes left by the nails will not remain open. Oil would seep into the spaces and the pressure from the existing paper insulation would force the damaged paper edges back into the holes. The extent to which the paper would refill the holes could not be controlled and as such it was expected that a series of non-uniform voids would remain capturing air in some places where the paper and oil closed before the air could escape.

These new voids were expected to change the capacitance of the insulation and consequently the angle between system voltage and insulation leakage current was expected to change. The difference between the previously healthy insulation and the newly damaged insulation should be reflected as a step change in the "insulation condition". Whilst no insulation in a high voltage apparatus will experience a transition from perfectly healthy to this severe condition without some intermediate indication of deterioration, the impact of the experiment will be sufficient to define a controlled change in insulation state.

Figure 6.13: The top reservoir of the CT showing the insulation below the oil. The nail was used to damage the insulation.

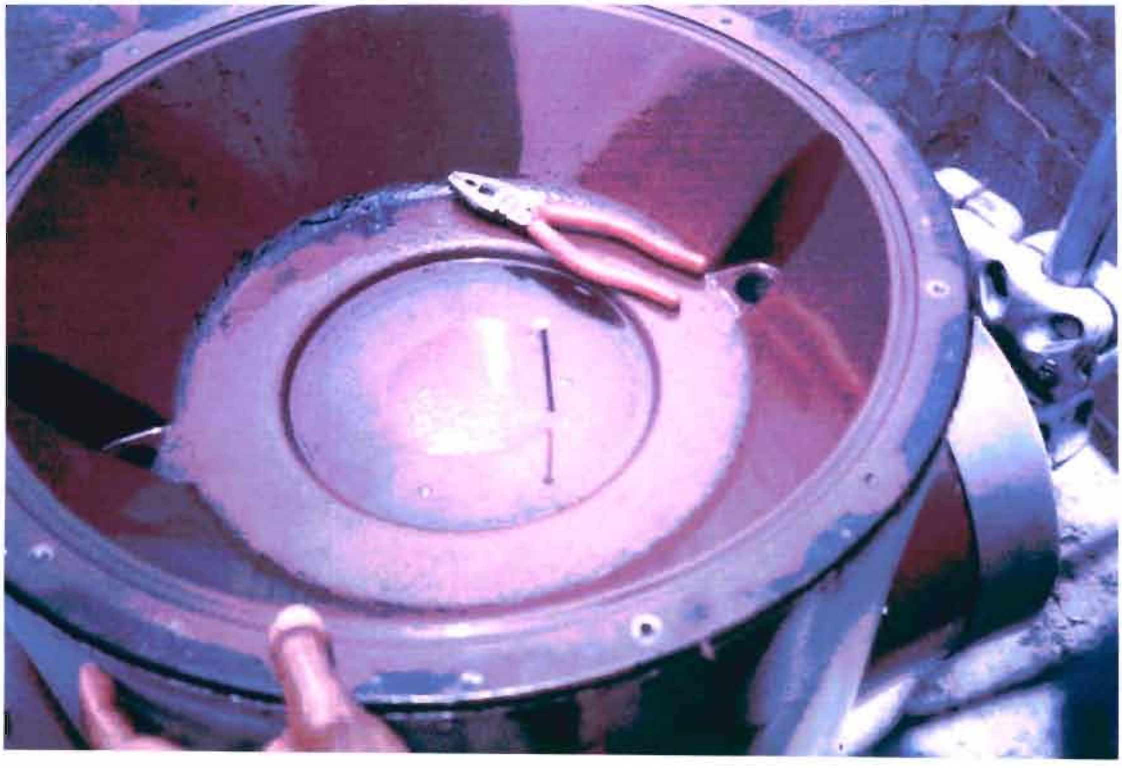

Figure 6.14: The nail was used to make 10 holes in the HV insulation to a depth of half of the paper insulation The holes were made in an evenly spaced circle 80mm from the centre.

Figure 6.15 below illustrates the manner in which the insulation was damaged. Without the presence of pressure from the insulation walls surrounding the cavity and the oil in the paper, the distortion in the paper insulation would be longitudinal holes (figure c).

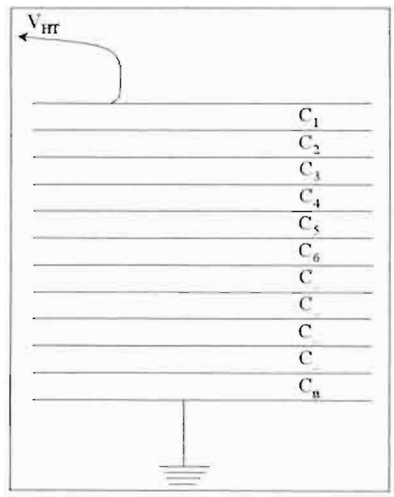

Figure 6.15a : Undamaged layers

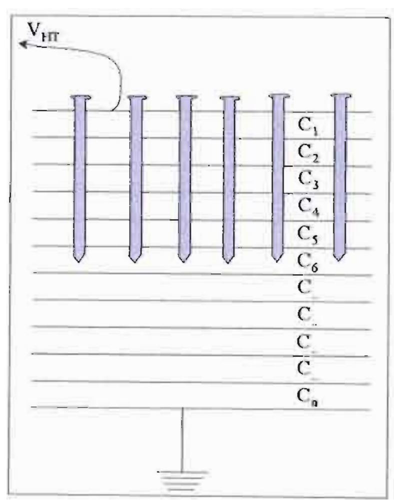

Figure 6.15b: Nails into insulation bridging layers.

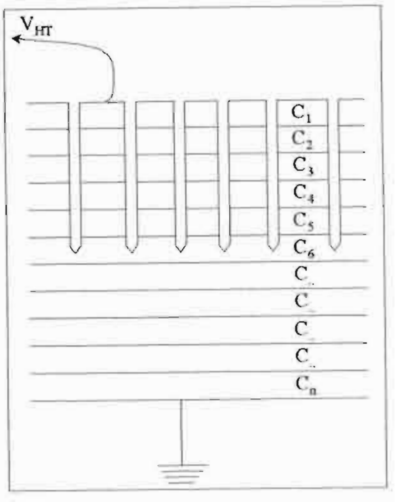

Figure 6.15c: Nails removed

Figure 6.16 below represents an untested hypothesis of how the paper insulation may close around the cavities from layers C_5 and C_6 illustrated in Figure 6.15 above.

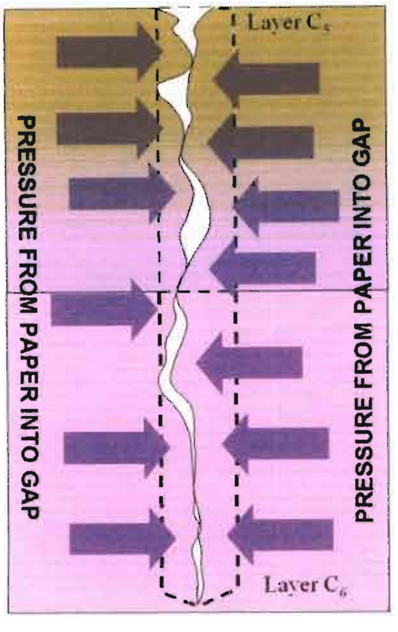

Figure 6.16a: Non-uniform cavity closure creating voids.

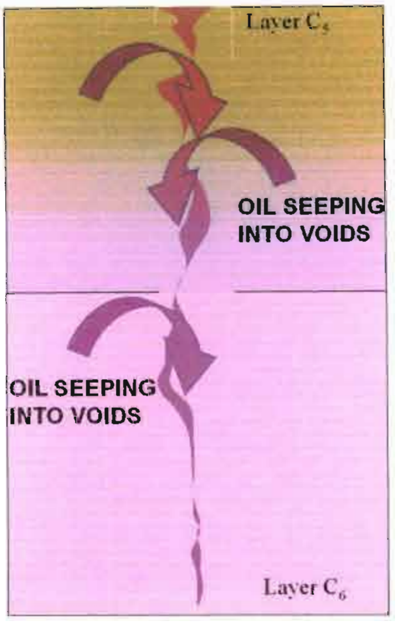

Figure 6.16b: Oil seepage into voids.

The current before the nail damage should primarily be as a result of the capacitive layers. After the damage, the leakage current may increase in relation to the damage done and the partial discharge taking place. This new current may contain a resistive component resulting in the angle between the system voltage and leakage current adjusting in accordance with the ratio between capacitive and resistive currents. The available area exposed for the experiment is relatively small. Given that 10 nails were driven into the insulation to a depth equal to half the total insulation thickness, the presence of voids would be evident across the entire insulation surface to a depth of 50% of the insulation. A significant step change in "insulation condition" should be reported by HVIEWS [32]. Such gross damage to the insulation may also be expected to generate very large pd and hence tracking in the insulation.

6.4.2 Failure four

Using the experimental procedure creating voids in the insulating layers as described above, the CT in test bay 5 was damaged. The station was re-energised at 14h28 on the 20th of December 2000. The CT failed at 03h39 on the 21st of December 2000 (i.e. approximately 13hours after energisation). The protection system at the Tugela substation triggered instantaneously on the test bay protection, and tripped the Tugela breaker. A carrier signal was sent to the remote end to accelerate tripping of the remote end breakers at Bloukrans substation. The carrier signal was not received at Bloukrans substation. The remote end protection did however operate as a result of "zone 3" triggering. The fault was isolated 1.07 seconds after the failure.

The test bay was remotely isolated by Mkondeni control and the Bloukrans Tugela 1 275kV line was re-energised on load within 3 minutes.

6.4.2.1 HVIEWS results for the fourth CT failure

Figure 6.17 below shows the relative dissipation factor (tan delta) reported by HVIEWS following the nail damage to the insulation.

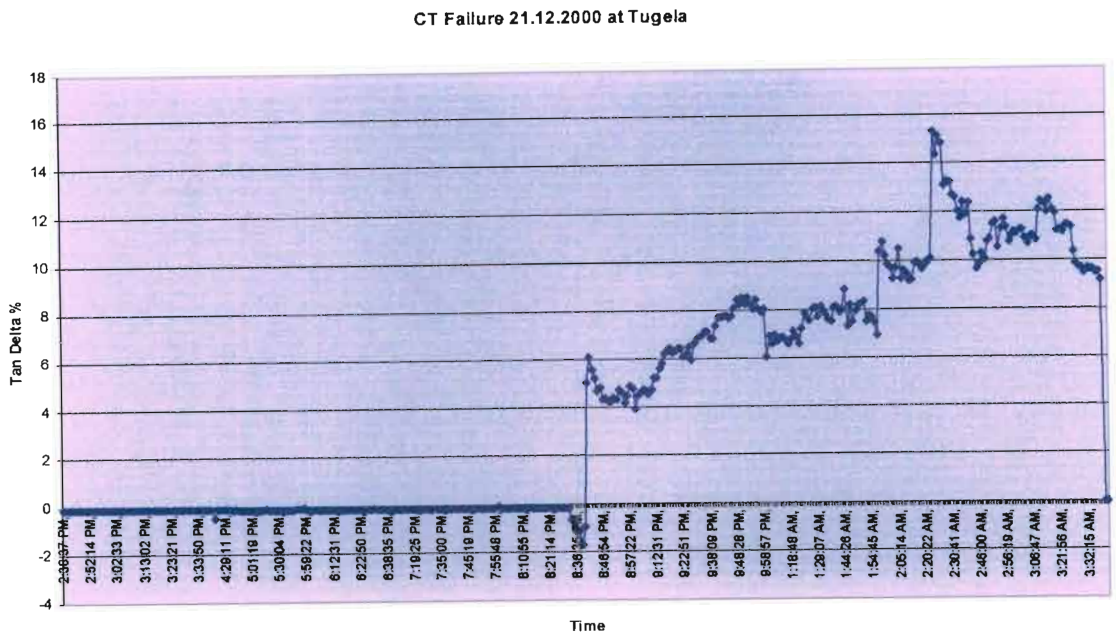

Figure 6.17: CT Failure in the Tugela test station on 21 December 2000.

After energizing the CT, the relative dissipation factor (tan delta) increased rapidly from –2% to +6%. From the time the CT was energised, the HVIEWS reported relative dissipation factor (tan delta) gradually increased to 15% before falling away to 9% at destruction. Several step changes were observed both upwards and downwards.

The increase in relative dissipation factor as seen over the 6 hour period from approximately 8:20pm to 2:30am may be interpreted as a "gradual" increase given the severe damage done to the insulation. The damaged insulation has further deteriorated under the stresses of the operating voltage. The remaining insulation carries more electrical stress than it was designed for and deteriorates at an accelerated rate. It may be possible to extrapolate this severe damage to less severe deterioration.

Under normal conditions, less severe and more typical insulation deterioration will also transfer more stresses to the remaining insulation. The increase in stresses across the remaining insulation may be negligible until a limit is reached. Above this limit, the stresses will breakdown the insulation in a similar fashion as reported by HVIEWS here. The relative dissipation factor figures produced by HVIEWS here have not been translated to actual dissipation factor values as the CT was destroyed during this test.

6.5 Summary

The back energisation of the CT's to rapidly induce failure was found to be reliable and very quick. 3 CT's failed within a few hours of energisation. The HVIEWS system tracked the varying tan delta recordings, which were all similar.

The second failure mode of damaging the HV insulation was also successful as on energisation the CT condition changed immediately as was expected. The HVIEWS system also tracked this failure.

The test station operated as designed and successfully contained the violent and explosive failure of the damaged CT's.

CHAPTER 7
RESEARCH UNDERTAKEN AT THE UNIVERSITY OF NATAL LABORATORY AND AT VARIOUS TRANSMISSION STATIONS WHERE HVIEWS IS INSTALLED.

7.1 Research carried out at the laboratory at University of Natal.

Certain investigations were carried out in the laboratory of the University of Natal. The objective was to analyze in a more controlled environment some of the issues and problems experienced at the Tugela Test Station. In particular, the impact of the back energisation of the CT was investigated, as was the impact of the climatic parameters (moisture ingress onto the standoff insulator) on the accuracy of the recorded tan delta values. The total set of measurements performed in the laboratory thus comprised:

- Measurements of electrical parameters of a CT
- Back energisation of a CT
- Temperature rise tests under back energisation
- Measurement of changing tan delta and capacitance values as quality insulation medium (oil) is changed
- Varying the tan delta values by introducing resistance paths into the measuring circuit (spraying water onto the insulators)

The CT listed below in Table 7.1 was transported from Impala substation and installed in the HV laboratory at University of Natal

7.1.1 Measurement of electrical parameters of CT

The following electrical parameters were recorded and measured on the CT

- All the name plate data was recorded
- Secondary core resistances
- Secondary core ratios
- Meggar test of secondary and primary cores
- Resistance of bar primary

- Resistance of bar primary loop with shorting conductor installed
- Magnetisation curve of all secondary cores
- CT tan delta
- CT capacitance

The purpose of these measurements was to determine the state of the CT prior to testing, to ensure it was in a healthy condition for the experiment. The results obtained are listed in Table 7.1 below.

Balteau SAX 245 Serial Number 54679/18. Ratio 275kV, Amp 1600/1, TanD 0.00391, Capacitance 588.5pF. Temp 19.7°C, oil 318L, weight 1100kg, Fault rating 21kA for 3s. Date 21/1/2000.						
Secondary core	**Resistance Ohm**	**Megger to Earth 500V**	**Megger to Prim 500V**	**Mag Curve Volts**	**Mag Curve mA**	**Ratio.**
1	13,5	Infinity	Infinity	200/400/ 600/800	3.5/4.9/ 6.0/7.2	1600/1
2	13,4	Infinity	Infinity	200/400/ 600/800	2.9/4.7/ 5.8/6.99	1600/1
3	2.9	Infinity	Infinity	200/400/ 600/800	10.6/19.1/ 36.9/96.3	1200/1
4	2.8	Infinity	Infinity	200/400/ 600/800	10.1/17.3/ 35.8/103	1200/1

Table 7.1: Measurement results of CT in the laboratory indicating the CT to be in a healthy state.

Notes:

1.Resistance measured with Fluke 77, No PP10132

2.Insulation measured with Bridge Meggar University 17981 Inst. 290 at 500V.

3. Tan delta and capacitance was measured with Hathaway CSD. PTM 5892 Loss Angle Bridge

Resistance measurements (i.e. resistance measurements determined by using a high current and measuring the volt drop to determine the resistance) were performed on the complete primary loop, consisting of bar primary, 1,64m of Centipede conductor, and 2 clamps. The instrument used was an AB Chance Digital Micro Ohmmeter, AO 00172413 (Pinetown Depot) at a temperature of 19°C.

Resistance measurement	**Resistance in micro ohm.**
1	45.6
2	45.7
3	45.6
Average	45.63

Table 7.2: Resistance test results of primary CT circuit.

The values obtained for the CT in the laboratory were similar to those obtained at Tugela Test Station for similar CT's.

7.1.2 Temperature measurements under back energisation of the CT.

The following method was used to inject current on the secondary cores of the CT. The CT's in the laboratory are not exposed to a load current, as is the case with CT's in full operation. The same procedure as was used at Tugela was used to back energise the CT's in the laboratory.

Figure 6.1 shows that two of the four secondary cores of the CT under test were back energised at 380 volts. The two remaining secondary cores were short-circuited. The selected secondary cores in this case have a ratio of 1600/1. With the measured secondary windings load current of 0,5 amps, 800 amps was induced in the primary bar.

The results of different configurations of injection of 220V AC onto various secondary CT cores with the Primary of the CT short between P1 and P2 are recorded below.

Configuration of secondary cores	Current on secondary Is	Voltage on secondary Vs	Current on primary Ip	Calculated ratio
Core 3 and 4 short circuit, inject on core 1, core 2 open	9.6mA	358	6A	623/1 Note 1
Core 2, 3 and 4 shorted, inject on core 1	250mA	385	395A	1580/1 Note 2
Core 3 and 4 shorted, inject on core 1 and 2	1.02A	385	796A	1592/1 Note 3

Table 7.3: Results of back energising secondary cores in various configurations.

Note 1: Core 2 is open and creating a high impedance path, which reflected to the primary of the CT is still seen as a high impedance and so restricts the primary current.
Note 2: Injection is only on one secondary core and the ratio is 1580/1 which is indicating that the back energisation is operating correctly as the actual ratio is 1600/1 and shows a correlation
Note 3: Injection is on 2 cores in parallel, and the ratio is correct, as each core would take half the injected current of 1Amp. making the ratio 1600/1 as per nameplate.

While the CT was being back energized, the temperature rise was recorded over a number of days, see Table 7.4 below.

The purpose of this was to determine the effect of the heat caused by the back energisation of the secondary cores. It is a well know fact that the tan delta measurement changes with increased temperature, and the degradation of insulation is rapidly increased with the increase in temperatures. Temperatures were measured and recorded on certain critical spots on the CT body, while the heat created by the back energisation was in service. Recordings were taken until the temperature rise reached a stable condition. The purpose of this research was to determine if the back energisation was the cause of the failure or if the failures could be attributed to any other cause, which was experienced in the operational conditions.

The temperature was measured at various places on the CT where heating was indicated. The temperature measurement was made with the CT Thermal Camera, No 47952, supplied by Distribution East Region, Condition Monitoring Section. The ambient temperature was 20°C.

Date and Time	**Hours energised**	**Primary current in Amp**	**Temp. at Bar Primary °C**	**Temp. at body at CT cores °C (Note 1)**	**Temp Shorting conductor °C**	**Tan Delta**	**Capacitance pF**
21/1/2000	0	780	20.4	20.4	20.4		
21/1/2000	35mins	782	32.8		61.5		
21/1/2000	1hr	785	38.1		67		
21/1/2000	2hr	783	40.2		65.5		
21/1/2000	3hr	785	42		67		
23/1/2000	0hr	0	20	20	20	0.0039	587.5
23/1/2000	20 min	780	26.3		46.8		
23/1/2000	40 min	775	28.8	31	58.1	0.00391	587.4
23/1/2000	1 hr	770	29.2	32	62.6	0.00395	587.4
23/1/2000	2hr	770	32	32	65.6	0.00415	587.3
23/1/2000	3hr	770	33.1	33	66.2	0.00423	587.4
23/1/2000	4hr	770	32.6	33	64	0.00425	587.5
23/1/2000	48hr	770	32.6	33	68	0.00425	587.5

Table 7.4: Temperature response of CT to back energisation

Note 1: The temperature of the CT body measured at the point of the secondary cores was measured with an infra red camera on the epoxy body. This is not an accurate measurement of the temperature in the secondary cores, as the temperature dissipated from the secondary cores to the outer epoxy.

Table 7.4 indicates that the back energising causes heating in the bar primary, the CT body near secondary cores and on the shorting conductor. The temperature saturates after 4 hours but remains about 13°C above the ambient temperature at the CT cores and the bar primary. The temperature on the shorting conductor is at an elevated level due to the higher resistance of the conductor when compared to the solid conductor. The capacitance remains constant, but the tan delta increases with the temperature increase. At the end of this temperature rise test the resistance of the secondary cores of the CT were measured to determine if any damage had taken place.

Core	Winding resistance in Ohm at 20 degree C
1	13.89
2	13.51
3	2.87
4	2.83

Table 7.5: Indicating the secondary core winding resistances are still consistent with the original measurements, indicating no damage to windings due to heat run.

7.1.3 Tan delta and capacitance changes induced by changes to the oil

The insulating oil was drained from the CT. At various intervals, off line tan delta and capacitance measurements were taken. The purpose of this was to verify that as the insulation medium changed so to the measurement results changed, to determine if the results could be quantified.

Oil level (l)	Tan delta	Capacitance pF
318(l)/100% full of oil	0.00391	586.7
250(l) oil/68(l) air	0.00391	586.23
200(l) oil/118(l) air	0.00435	584.6
100(l) oil/ 218(l) air	0.00459	581.9
0(l) oil/318(l) air	0.00459	578.55

Table 7.6: Indicating an increasing tan delta and a decreasing capacitance as the insulating oil is removed and air is introduced as the insulating medium together with the oil impregnated paper.

The above results show that as the insulation medium changes from a higher purity (namely oil) to a lower purity (air) with the probable additional influence on the leakage current of resistive leakage across the inner surface of the porcelain where the oil has been removed, the absolute tan delta readings are affected significantly. The capacitance value also reduces.

7.1.4 The impact of contamination of standoff insulators on the measured tan delta values.

Early experience with field installations of HVIEWS indicated that the system was sensitive to environmental factors, especially rain. To investigate this further and recommend mitigative measures that could be applied in the field, the following experimental program was undertaken.

The CT metal base was mounted on disc insulators. These insulators were installed between the CT metal base and the earth plane. These insulators enabled the leakage current for the tan delta measurement of the HV insulation to be collected between the CT metal base and the earth conductor. Various concentration levels of saline solution were sprayed onto the insulators. This introduces a parallel resistance path into the measuring circuit, thereby changing the tan delta reading and falsely indicating degraded insulation. This same situation was occurring with the HVIEWS installations in the field where during rain conditions, the parallel resistive path caused by the rainwater across the insulators was negatively effecting the tan delta measurement results. The purpose of this investigation was to determine the effect of a parallel resistive path caused by rainwater on the tan delta measurement.

Figure 7.1 below indicates how the rain/introduced saline water, bridges across the insulators, a parallel path for the leakage current to flow and so distort the tan delta measurements.

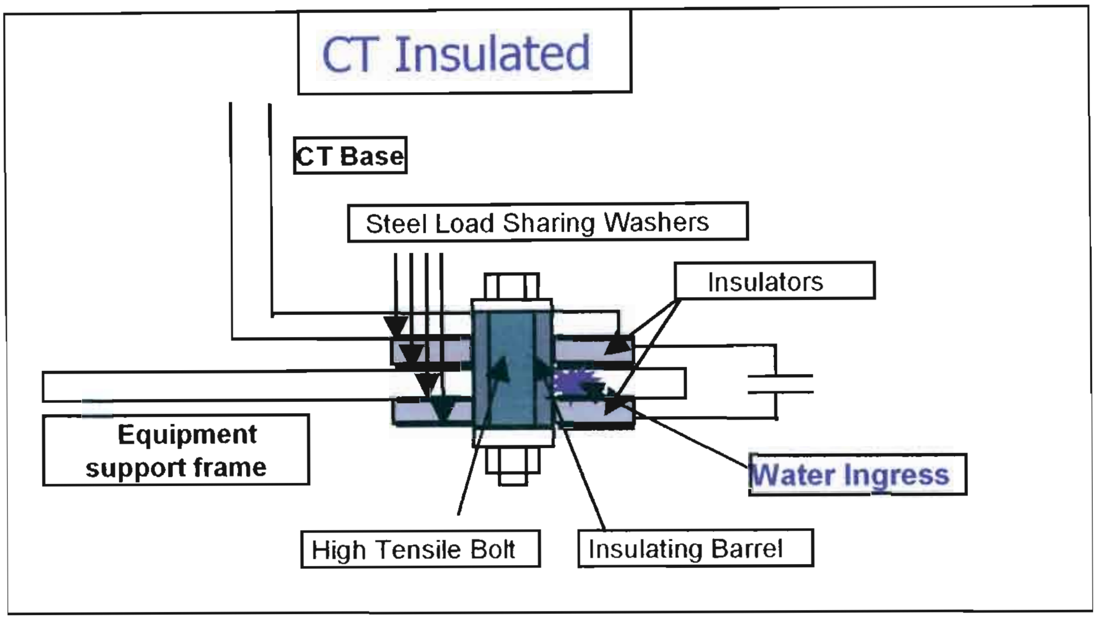

Figure 7.1: The insulator on the base of the CT being bridged out by rainwater ingress effecting the tan delta measurements [33].

The circuit used (Figure 7.2) consisted of the CT having a capacitance of 588.5 pF in series with the capacitor divider unit (CDU) with a capacitance of 2.2micro farads. Water with different saline concentrations was sprayed across the insulators. This effectively introduced a parallel resistive path across the 2.2-microfarad capacitor the voltage source was 265 volts injected across the circuit. The magnitude and phase displacement of the output voltage over the 2.2 micro Farad capacitance was monitored. This voltage is equivalent to the voltage supplied to the HVIEWS system, under rain conditions.

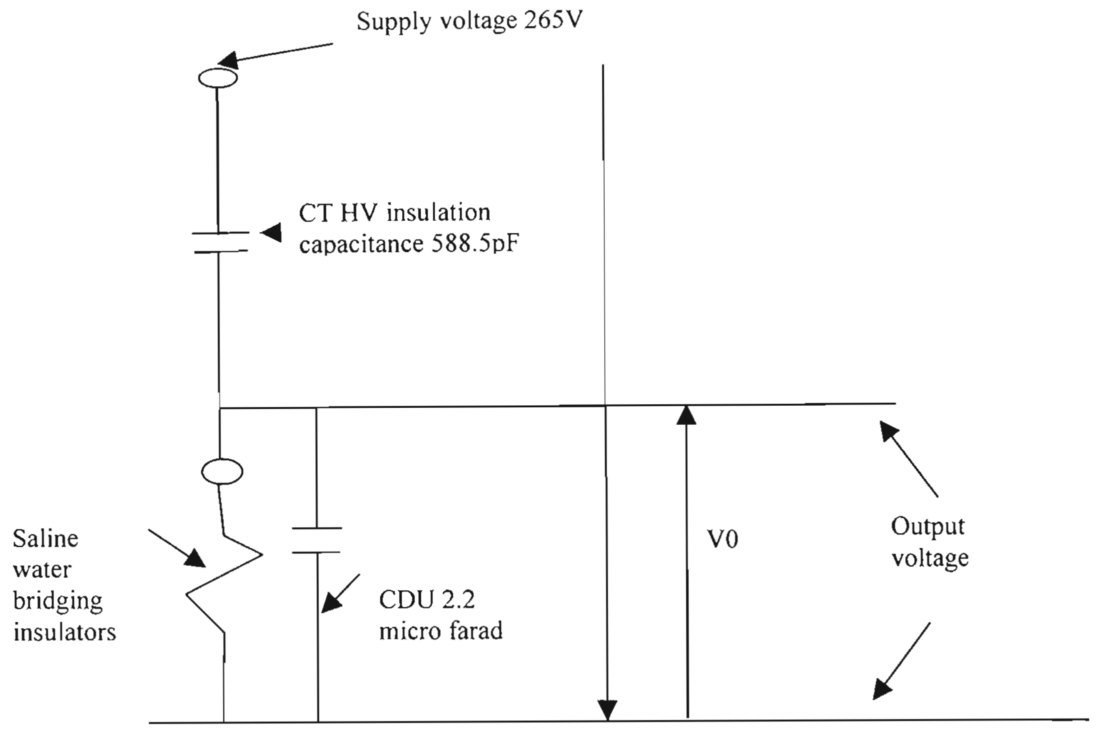

Figure 7.2: The model of the circuit used to test the influence of saline water on the output leakage current to the HVIEWS unit to determine the change in relative tan delta.

This research experiment equates to the similar effect experienced in the field during rain conditions. All tests were conducted with an input voltage of 265Vac across the circuit and measuring the output voltage magnitude with a Fluke 77 and comparing the output sine wave in each case to the original case on an oscilloscope.

Saline water Concentration (microSiemens per cm)	Output Voltage	Changes to the output Sine wave, V0	Relative tan delta on HVIEWS to reference
No water	63.5	Clear	0%
Tap water (250)	45.77	Distorted, shift in phase	-52%
Saline (345)	28.9	Slight phase shift from reference	
Saline (500)	29.22	Further phase shift from reference	
Saline (912)	28.89	Further phase shift from reference	
Saline (2400)	25.9		+33%
Saline(10000)	25.4		-7.2%
Saline (75000)	21.5	Further phase shift from reference	-20.54%

Table 7.7: Indicating that the introduction of a saline solution applied across the test unit insulators, distorts the leakage current input to the HVIEWS system in both magnitude and phase displacement, rendering the results inaccurate.

Silicon grease was smeared onto the insulators, and when saline water was introduced, the tan delta measurement was stable as the water droplets collected on the surface of the silicon grease. Only when the water droplets built up into a pool of water and covered the total surface of the grease and bridged the area across the insulators, did the tan delta readings distort again. The silicon grease was later used in the field application, where tan delta results recorded during rain conditions were influenced to a lesser degree, than was found prior to the use of the grease, and proved to maintain their accuracy.

7.1.5 Summary of laboratory work

The laboratory work indicated the following:

- prior to the electrical testing undertaken, the CT tested was in a good condition

- the back energisation enabled the circulation of the full load primary current in the primary of the CT. This full load current could be used to simulate load heating conditions as would be experienced in the normal operational condition
- the back energisation causes heating in the secondary coils of the CT which could be detected through the body of the epoxy head of the CT
- the tan delta measurement of the CT insulation increases as the temperature increases
- damage caused by overheating the secondary CT coils is not easily detected by electrical resistance testing of the coils
- changes in the composition of the insulating material is detected in the tan delta measurements
- any bridging of the measurement circuit of the HVIEWS system results in the false indication of degrading insulation in the CT being measured.

7.2 Research carried out in various substations where HVIEWS is installed

During the period that this research was being carried out at Tugela and in the laboratory of the University of Natal, on-line relative tan delta monitoring systems were in operation at various transmission substations. A number of incidences occurred at these stations during this period and the transmission operational staff requested assistance in determining the impact of these incidents. The following incidents were investigated:

- Illovo CT incident
- Duvha power station CT incident
- Hendrina transformer bushing incident

7.2.1 Illovo CT incident

At Illovo substation the HVIEWS system had indicated that one of the CT's was trending an increasing relative tan delta condition. The CT was removed from service and sent to the HV test laboratory at ABB in Pretoria for testing and analysis. The incident was investigated to verify the performance of HVIEWS.

Test Results

- Partial discharge test at 450kV to earth - < 20pC.
- Tan delta – 0.0038
- Capacitance - 650pF
- Insulation resistance – infinity

The CT was found to be in good condition. A second CT was put in the place of the removed CT, this CT had been off line tan delta tested prior to installation and was found to be in order. Once energised the HVIEWS continued to display an increasing tan delta trend. The installation was tested and rainwater was found to have penetrated a surge arrestor effectively creating a parallel path for the leakage current and distorting the trending.

7.2.2 Duvha power station CT incident

At Duvha Power station the HVIEWS system indicated a CT on generator number 5 was experiencing an increasing relative tan delta condition. The 600MW generator was switched out of service for off line tests to be done to the CT. The incident was investigated to verify the performance of HVIEWS.

At Duvha power station the 600MW generator was shut down, the off line tan delta test on the CT proved that the CT was in order. The installation was checked and a piece of insulating rubber between the CT metal base and the CT secondary core, cable gland was found to be pinched and creating a resistive parallel path for the leakage current, thereby distorting the tan delta trend. The rubber insertion was found to have been installed with the wrong thickness material and was replaced with thicker rubber. After re-energisation of the generator circuit the relative tan delta reading was found to have returned to the normal reading.

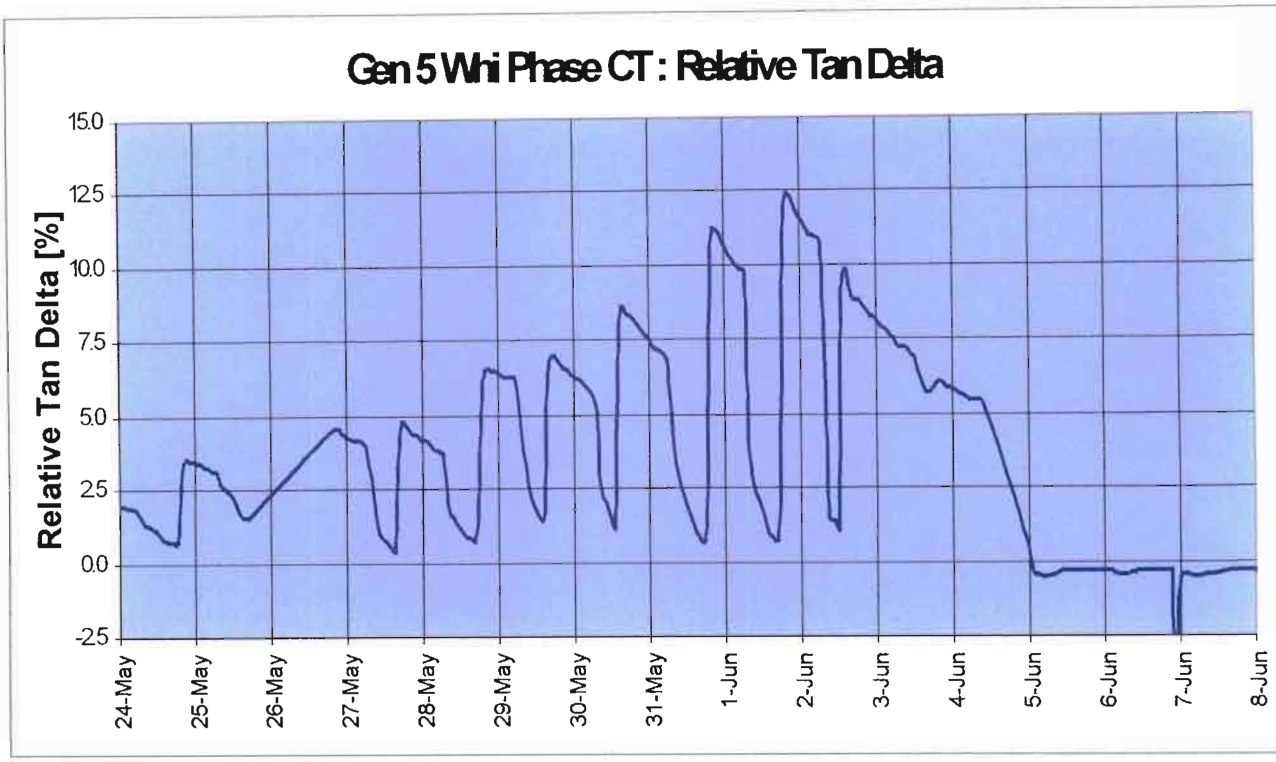

Figure 7.3: HVIEWS relative tan delta trend for Duvha CT, caused by poor insulation quality, negatively effecting trending.

Figure 7.3 above is of great interest as it shows a variation in the relative tan delta measurement due to a fluctuation in the leakage current caused in this case by faulty insulation. As can be seen in the figure, in the early morning when the dew condensed across the pinched rubber insulation, the relative tan delta increased and as the heat of the day dried out the condensation, the relative tan delta measurement returned to normal. After the insulation was repaired, the relative tan delta measurement returned to normal.

7.2.3 Hendrina transformer bushing incident

At Hendrina power station, the HVIEWS system was installed on a coupling transformer. Within days of the installation the transformer failed and the imminent failure was not detected by HVIEWS. The failure was investigated to verify the performance of HVIEWS.

The failure of the transformer bushing had not been captured and alarmed by the HVIEWS system. The investigation into the failure had found that a particular bushing was the cause of the failure. The type of bushing had caused 3 other failures of transformers on the system. These failures were caused by increasing partial discharge in the bushing, degrading the insulation and resulting in a short circuit. When a drill down was done into the HVIEWS data that had been captured it showed that not enough data had been stored to set up a trend as the service period had been too short, but instantaneous data indicated that a failure was imminent.

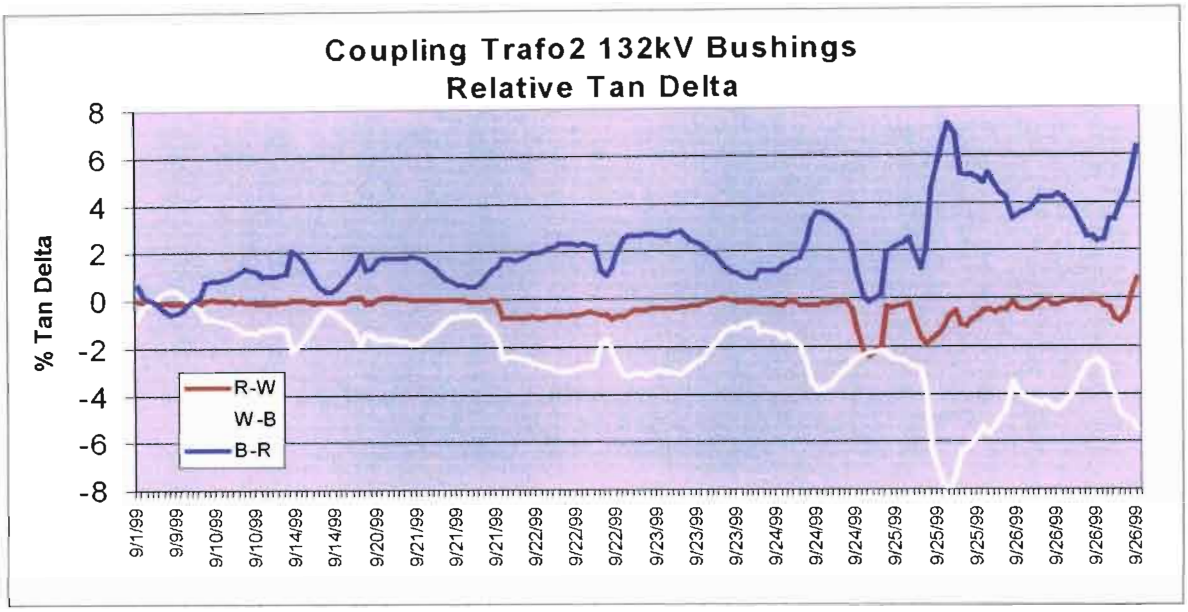

Figure 7.4: Instantaneous data signals from HVIEWS at Hendrina power station.

From Figure 7.4 above it can be seen that the relative tan delta signals from the leakage currents of the 132kV bushings on the B–R and the W-B phases started to increase. The common signal was the B phase, which was distorting the signal, probably due to the increasing partial discharges degrading the insulation. The investigation into the transformer failure proved that the failure of the B phase bushing was root cause of the incident. Figure 7.4 indicates that the increase was gradual from 0 to 2% relative delta over a period of 16 days (9/9/99 to 25/9/99) On 25/9/99 the relative tan delta readings increased from2% to 8% rapidly over a period of about 10 hours.

The curve in this figure above was the first positive feedback from an operational bushing failure, and indicated that HVIEWS could monitor failing HV insulation. This was also the first indication of the rapid nature of the failure.

7.3 Summary

The research undertaken in the laboratory of the University of Natal as well as at various Transmission stations to investigate the climatic influence on the recorded measurements of the on-line monitoring system concluded that these external influences introduced changes to the measurements that closely followed measurements captured during the failure of HV insulation. These influences may impact on the credibility of the system. It is important to understand and isolate these influences when utilizing the HVIEWS system in the current format. The results of this problem may have costly implications if healthy plant is removed from service due only to the external influence of climatic conditions. The laboratory research also indicated hat the secondary windings of the CT's were heating up as a result of the back energisation.

CHAPTER 8

DISCUSSION AND ASSESSMENT OF FINDINGS

The CT's installed at Tugela test station, and in the laboratory, although they were 25 years old, were tested and found to be in operational condition. The assumption that the bellows was perishing and introducing moisture was unfounded.

The research undertaken at EPRI, indicated that accelerating the failure was not as easy as expected. Many previous projects involving the introduction of water or air had not induced failure. The most responsive method to ensure accelerated aging and failure had been the back energisation of the secondary CT circuits.

As this project required the establishment of the capability of the HVIEWS system to track insulation degradation, the success of this project could only be established if accelerated insulation aging took place. For this reason the back energisation of the secondary circuits was introduced.

Laboratory tests indicated that the back energisation induced some heating in the unit. The power output of the secondary cores, which were back energised, exceeded the core rating by a factor of 10 times. Although the back energisation in the laboratory was in service for days on end (48 hours), and the temperature increase measured was 13°C, electrical tests indicated no damage to the cores.

The CT's at Tugela which were subjected to the HV stress (275kV) only (without the back energisation) were found to have experienced no damage, even for periods of up to 5 days as in the case of CT failure 3. Only when the back energisation was introduced together with the high voltage, did failure take place. Failures took place as indicated in Table 8.1 below.

CT Failure	Period back energised	Period of rapid tan delta variations	% Relative tan delta variation
1	5H35	1H24	7.35%
2	7H21	1H13	7.8%
3	6H36	0H51	4.6%
Average	6H31	1H13	6.58%

Table 8.1: Indication of the period of back energisation, period of rapid variations and the tan delta variations on the units that failed under test.

Although the cause of failure was thought to have been caused by the back energisation, this fact could not be confirmed after failure 1 and 3 as these units were burnt out beyond the point where the root cause of failure could be determined.

Failure 2 had not been a catastrophic failure and the subsequent tear down of this CT indicated that the secondary cores had overheated. This heat caused the insulation of the secondary cores to burn, forming bubbles in the insulation gap between the earthed secondary core shield and the HV, on the outer conductive tape on the outer layer of the insulation. This bridging of the insulation probably caused the flash over and failure.

The HVIEWS system had been programmed to trend slow moving variations of relative tan delta and so did not alert to the degrading insulation, but the instantaneous data records had captured the varying relative tan delta. This variation may have been caused by a stream of bubbles introducing partial discharge and resistive leakage currents in the insulation body of the CT. These resistive leakage currents were in parallel with the original capacitive leakage currents, resulting in the varying relative tan delta measurements. This indicated that the HVIEWS system was tracking the changes in the state of the insulation.

The HVIEWS system produced similar results for the 3 failures.

As the HVIEWS system produced consistent results for the back energisation failure induced mode, the second failure mode was introduced to see if consistency could again be achieved.

The second failure mode was introduced by damaging layers of the insulation, as described in chapter 6 concerning failure 4, thereby changing the capabilities of the insulation. Figure 6.13 indicates that immediately the CT was energised, the relative tan delta jumped to 6%, indicating a change in the leakage current flowing through the insulation. This change is due to the resistive circuit caused by the holes in parallel with the capacitive circuit of the insulation. Again the HVIEWS system tracked the change in the degrading insulation, showing consistency with the first 3 failures. The rapid tan delta variations took place over 6 hours prior to failure, with a variation of relative tan delta of up to 11%.

The relative tan delta of this unit showed a number of jumps from 6% to 15% then settled back down to 9.5%. These jumps in the relative tan delta may be due to low power partial discharges taking place in the holes, in the damaged insulation, then the holes could have squeezed closed, cutting off the discharge. As the leakage current was high, this probably continued to cause local overheating of the insulation until failure took place.

The time period during which large variations in the relative tan delta took place, averaged out at 1H13 with the shortest time taken, being 51 minutes. If system operators were warned 30 minutes prior to the need to isolate plant from service, this would be enough time to carry out a planned shut down. The HVIEWS rate of change alarm system could timeously warn system operators to safely shut down the faulty CT.

The incidents experienced with the HVIEWS system in various operational substations indicated the following results as part of the overall assessment.
At Illovo the unit was unnecessarily removed from service and sent for testing, because of a faulty surge arrestor, which is placed in the circuit in parallel with the monitoring system. This introduced a resistive path in parallel with the monitored capacitive leakage current and resulted in varying tan delta measurements.

The Duvha Power station incident, was again the introduction of a parallel resistive leakage current, distorting the tan delta measurements, this was again due to a faulty component (insulation of CT from ground) in parallel with the measuring devices. Laboratory tests indicated that the introduction of saline water, creating a parallel resistive leakage current path, resulted in the variation of the measured tan delta.

Figure 7.3 indicates an increasing variation in the Duvha relative tan delta measurement in the early morning of every day as the moisture in the air condensed and bridged the insulation, as the heat of the day increased and the moisture dried up, the tan delta measurement decreased.

The Illovo and Duvha incidents and the laboratory testing indicates that moisture, rain, pollution, failing insulation or any other item, interfering with the integrity of the measuring circuit, results in a varying tan delta reading similar to that experienced when insulation of the CT degrades. This results in confusion for operators and the unnecessary isolation of plant. Field experience of the HVIEWS system indicated that the system performed poorly under rain or high humidity conditions due to the water introducing a parallel resistive path for the leakage current to follow. This failing in the system requires addressing.

The HVIEWS system at Hendrina had not been in service for sufficient time to collect enough data to set up a trend. Analysis and manipulation of recorded instantaneous data, showed that the relative tan delta of the blue phase bushing was varying. The variation took place over a period of 17 days with the relative tan delta reaching 6%. This varying tan delta can be traced to the variation in the leakage current, indicating a degradation of the insulation. The blue phase bushing failed.

The HVIEWS relative on line tan delta monitoring system cannot supply absolute values of tan delta, but only compares one CT to the next one in the monitored loop. An absolute value can be obtained if a pure gas capacitor is introduced into each loop for comparison to the other CT's. This research has indicated that absolute tan delta values are not necessary to determine the condition of the insulation, but the relative tan delta measurement is a good indication of degrading insulation.

From the results obtained on the first three failures, the HVIEWS system was modified to alarm for any relative tan delta measurement, varying by more than 1% between any two consecutive readings. This modification to the software, successfully detected the degrading insulation during the fourth failure.

From the results obtained during the four failures, anytime the relative tan delta exceeded 3% during a bona fide failure process, the CT carried on to failure.

A recommendation to the system operators would be to switch out any plant where the relative tan delta exceeds the following conditions:

- An increase in relative tan delta of 1% or more between any two consecutive readings,
- Any relative tan delta measurement exceeding 3%.

Of course this would mean that any variation in relative tan delta, not related to a bone fide failure, but possibly related to environmental interference, would result in the switch out of healthy plant. Until the nuisance interference of environmental influences is solved, it would be safer to switch out plant exceeding the above criteria, this plant should be further off line tested, to verify a failure.

Future research to enable the successful operation of on-line, relative tan delta monitoring system should include:

- Mechanisms to eliminate all the external, environmental influences which can effect the accuracy of the relative tan delta measurements, these to include the insulation failure of the measured unit to ground, as well as the ingress of water.
- Increased operational experience with active systems on energised networks, in order to develop enough confidence in the monitoring system to automatically switch out circuits, which indicate increasing tan delta measurements (similar to protection systems).
- Lifecycle costing of the monitoring system. As the CT's have an expected life of 30 years, and the monitoring systems are micro processor based with a probable life span of 8 years, the monitoring system will be replaced 4 times in the life of the CT. This must be considered during the lifecycle costing of the system.

CHAPTER 9
CONCLUSIONS

An investigation into the ability of an on-line relative tan delta system to detect incipient failure of oil/paper insulation and hence to send an alarm signal such that the equipment may be de-energised, prior to catastrophic failure, required the construction of a special test station in which the investigation could be undertaken. The following major conclusions may be reached:

- The design of the test station proved satisfactory for the task undertaken. Catastrophic failures occurred where the effects of the explosions were contained safely and with minimal impact on the system, particularly after the installation of the current limiting reactor.
- Back-energisation of the CT's resulted in a far more rapid failure mode than was expected or predicted.
- The on-line system used in the research detected these rapid deterioration modes. Software modifications ensured that the system would alarm for such fast failure modes.
- The back-energisation technique utilised in the research caused a large degree of overheating in the secondary windings of the CT which then resulted in what is most likely not a failure mode experienced in practice. It is, however, an effective means of failing these particular CT's rapidly and enabled conclusions to be drawn on the on-line system.
- Laboratory work confirmed that the CT secondary cores were overheating.
- Comparisons between the relative on-line tan delta technique and the 2 off-line techniques conclude that the 2 off-line techniques correlated but the only correlation between the on-line and off-line techniques, if the climatic interference is ignored, is that an increase in on-line relative tan delta indicates failing insulation, which is the same indication an increase in the off-line absolute tan delta provides. The measured values have no correlation nor are they repeatable.
- A second failure mode was investigated by causing gross damage to the insulation. This also caused a rapid failure mode that was detected by the on-line system.

- Such fast failures were not suspected but the data from a transformer bushing failure on a unit in service indicated that such a rapid failure mode does occur and needs to be detected.
- The failure modes observed in this research resulted in typical changes of relative tan delta values of 0.5% - 4% per hour. Such large changes in relative tan delta would indicate incipient failure and hence an effective limit of relative tan delta value changes may be set from this work.
- Evidence of partial discharge activity was found in one case where total destruction of the CT did not occur.

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APPENDICES

Appendix 1

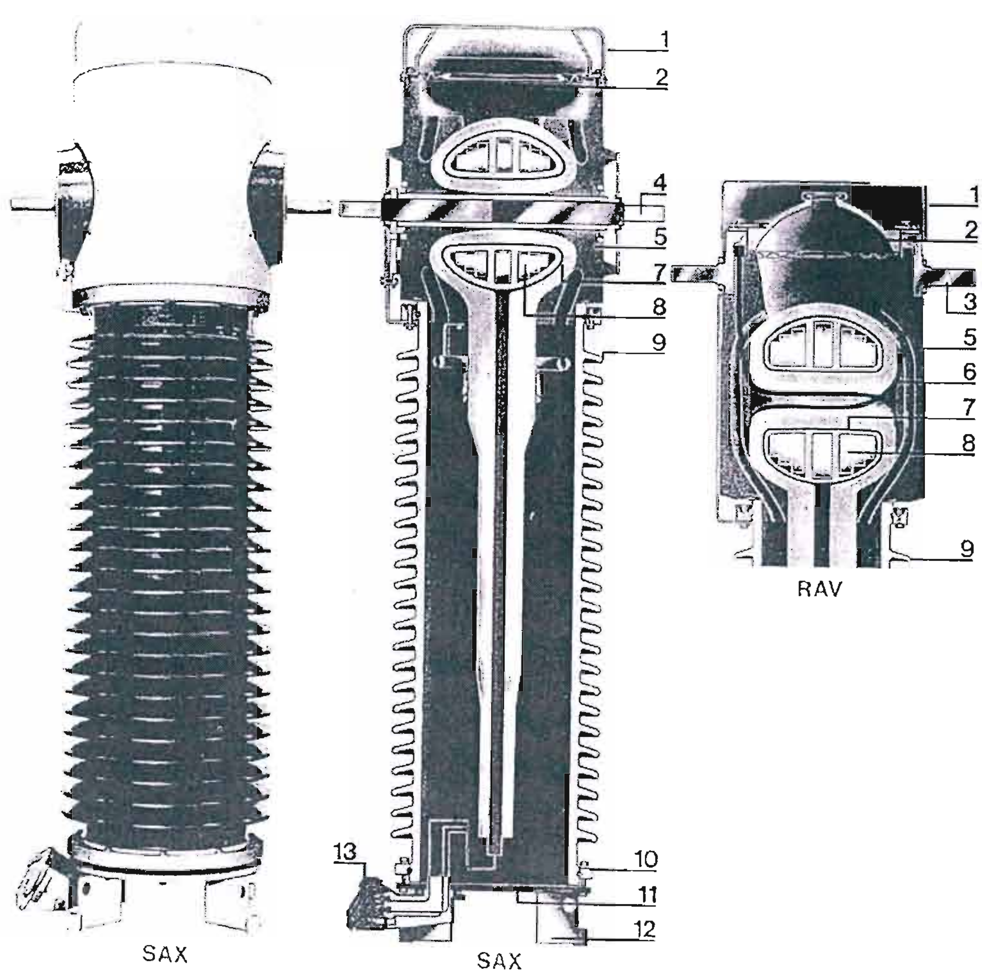
Diagrams and explanation of the Balteau CT and a transformer bushing taken from manufacturer's information.

hermetic

Balteau

Current Transformers

1. Aluminium hood.
2. Diaphragm allowing thermal expansion of oil.
3. Primary terminals and reconnectable primary device.
4. Bar type primary with terminals (SAX).
5. Main parts moulded in epoxy resin.
6. Primary winding (RAV).
7. Metallic shell enclosing the core(s) with HV insulation, oil impregnated paper.
8. Core(s) and secondary winding(s).
9. Long creepage distance porcelain.
10. Porcelain clamping device with spiral spring.
11. Hot galvanised steel base.
12. Fixing legs and lifting holes.
13. Aluminium moulded terminal box with secondary terminals in epoxy resin casting.

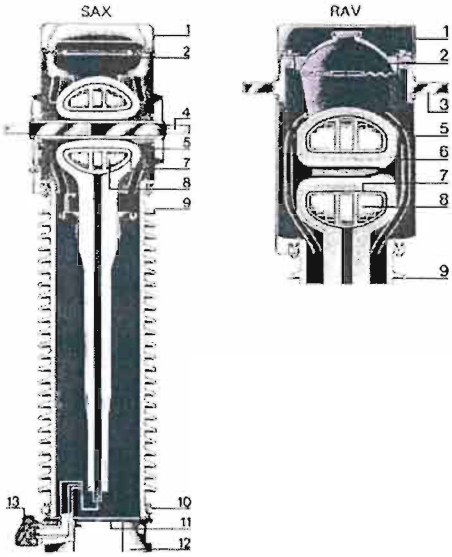


Current Transformers for High Voltage Outdoor Stations 123–245 kV

Hermetic Series of High Rating Current Transformers
Types SAX, RAV

High Rating Current Transformers with Hermetic Sealing for Outdoor Service

SAX and RAV Hermetic current transformers as compared to the SEV and SEX types, have their active part located above the porcelain insulator. This arrangement allows the current transformer rating to be increased without having to enlarge the diameter of the porcelain insulator.
The primary side of the SAX current transformer can be executed as a bar primary, or as a wound primary (SAX 245) for primary currents of up to 3000 A (x 1,2), whilst RAV current transformers are provided with a primary winding allowing up to three transformation ratios by means of primary change-over connections.



1. Aluminium-alloy head casing.
2. Membrane for thermal expansion of oil.
3. Primary terminals and primary change-over arrangements (RAV).
4. Primary bushing with terminal studs (SAX).
5. Active part moulded in epoxy resin.
6. Primary winding (RAV).
7. Ring-shaped light metal shell enclosing the secondary windings and cores. The high voltage insulation consisting of several layers of oil impregnated paper is wound around this shell.
8. Secondary winding and cores.
9. Outdoor fog-type porcelain insulators with long creepage distance.
10. Fixing of porcelain with flange and pressure distributing spring.
11. Hot-dip galvanized current transformer steel base.
12. Current transformer base with lifting eyes.
13. Cast aluminium terminal box with secondary terminals cast in epoxy resin.

Design Features

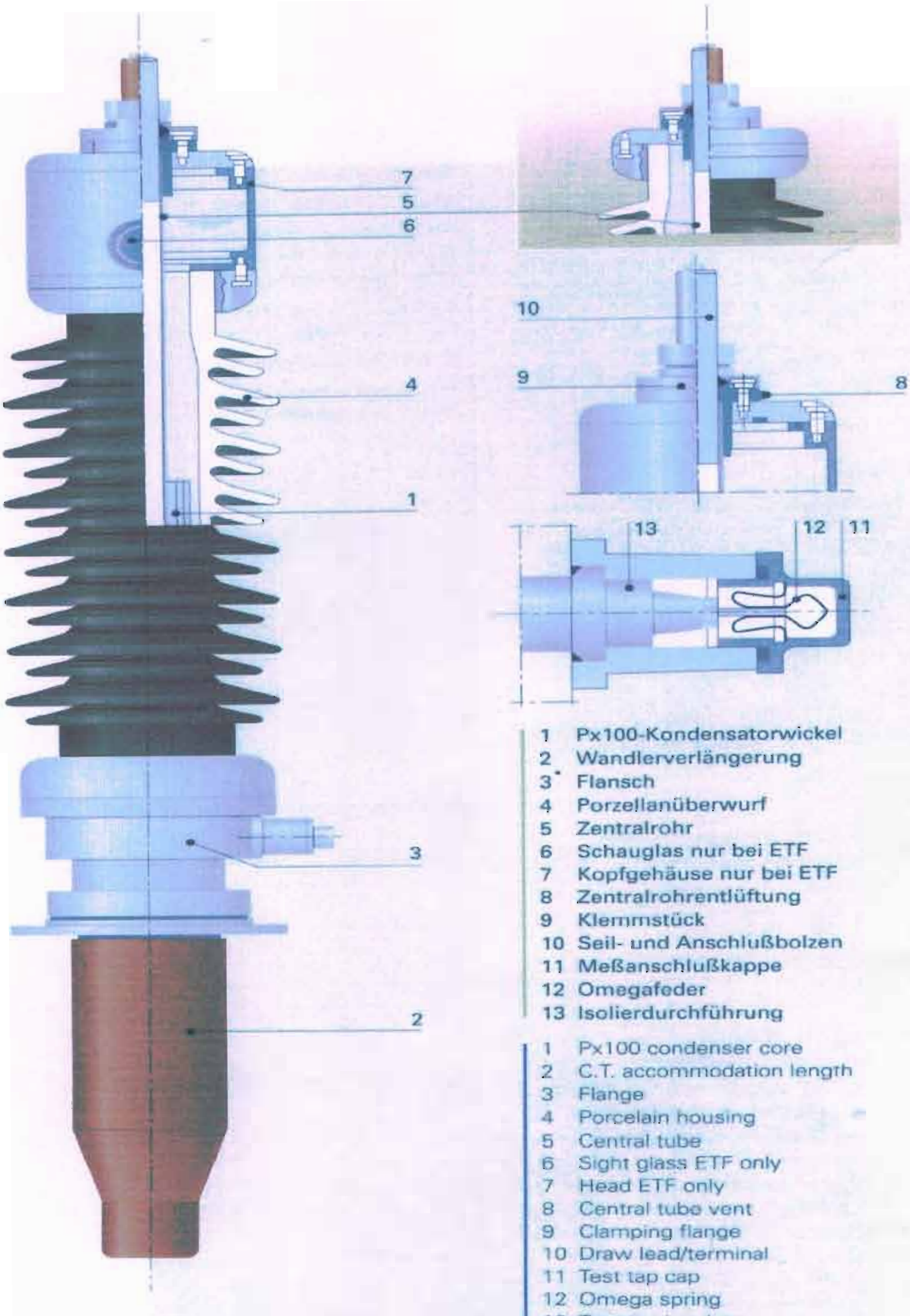
The active part of SAX and RAV current transformers is moulded in epoxy resin to provide a compact unit which is accommodated in the current transformer head above the porcelain insulator. The epoxy resin is not subjected to electrical stresses. Due to its excellent mechanical strength, it, however, provides perfect cohesion of the active part under dynamic short circuit fault stresses. Furthermore, the thermal conductivity of cast resin is utilized to conduct heat away from the primary conductors.
The iron cores of the active part are ring-shaped. They are enclosed, together with their secondary windings, in a ring-shaped light metal shell. The high voltage insulation consists of several layers of insulating paper of high dielectric quality. This insulation is wound around the shell, and coated with a conductive screening at the top section of the current transformer. The shell at earth potential and the screening at high voltage form two equipotential surfaces. With the high voltage insulation situated in between them, they constitute a condenser. On request, the resulting capacitance can be utilized for the connection of a low potential tap to provide voltage indication. This capacitive potential tap can also be used to feed a signal circuit. For such designs, the current transformer is provided with a second terminal box. Cable end boxes, or a sealing plate can be fitted to the secondary terminal boxes. The sealing plate can be supplied with glands or with steel pipe threads.
In types RAV and SAX 245, the primary winding is uniformly wound around the insulated shell. The primary conductor in a SAX type of current transformer is a bushing conductor. Both types ensure regular distribution of magnetic flux and exclude local saturation of the core. This design method thus allows high overcurrent factors.
Owing to a well-tried clamping arrangement, the porcelain insulator and the metal parts are connected to one another. The required forces are evenly distributed by the use of a spiral spring.

Hermetic Sealing

SAX and RAV type current transformers are hermetically sealed. A synthetic rubber membrane totally segregates the oil from ambient air. Owing to its wavy shape, this membrane expands with an increase in volume of oil, preventing as such the slightest overpressure in the apparatus. Before impregnation, both apparatus and oil are dried and degassed under a technical vacuum of 0.01 mm Hg.

Minimum of Maintenance

SAX and RAV current transformers require no maintenance on their metal parts as the latter are very carefully protected against corrosion. The base and trolley are manufactured from hot-dip galvanized steel. In addition, the head casing, fixing flanges and terminal box are manufactured from light metal and protected by anodized oxidation. The top casing of the current transformers is made up of «Skin-Plate» (aluminium with PVC coating), while all the bolts are manufactured from a corrosion-resistant alloy.
The terminal boxes fitted at the base of the current transformer are protected against rain, insect penetration and moisture condensation. The secondary terminals consist of brass glands which are moulded in a synthetic resin. They are provided with strong, embossed labels.
Owing to the relatively long creepage distance of the porcelain insulators (2.5 cm/kV), SAX and RAV current transformers can be inserted in industrial areas where the air is heavily polluted, or the atmosphere is salt-laden. They only require occasional maintenance (cleaning of the porcelain insulator).
As the temperature-rise of instrument transformers is very small under normal operating conditions, there is practically no ageing of oil. The oil, therefore, maintains its original characteristics with respect to dielectric breakdown strength (300–350 kV/cm). The RAV and SAX instrument transformer design eliminates any need for drawing oil samples (for analysis). Drain taps and filling-plugs have therefore not been included. They can, however, be fitted, if required. It is, moreover, possible to inspect the position of the compensating membrane on a membrane position indicator (supplied on request at an extra charge).



1 Px100-Kondensatorwickel
2 Wandlerverlängerung
3 Flansch
4 Porzellanüberwurf
5 Zentralrohr
6 Schauglas nur bei ETF
7 Kopfgehäuse nur bei ETF
8 Zentralrohrentlüftung
9 Klemmstück
10 Seil- und Anschlußbolzen
11 Meßanschlußkappe
12 Omegafeder
13 Isolierdurchführung

1 Px100 condenser core
2 C.T. accommodation length
3 Flange
4 Porcelain housing
5 Central tube
6 Sight glass ETF only
7 Head ETF only
8 Central tube vent
9 Clamping flange
10 Draw lead/terminal
11 Test tap cap
12 Omega spring
13 Test tap insulator

Meßanschluß-Prinzip:
Bei angeschraubter Meßanschlußkappe ist der Stift der Isolierdurchführung über die Omegafeder geerdet. Für Meßzwecke 4 mm Federbuchse aufstecken und in diese Laborstecker einführen.

Test tap principle:
The pin of the test tap insulator is earthed over the omega spring inside the screwed-on cap. For testing purpose, a 4 mm spring socket must be slipped over the pin and then a 4 mm plug can be inserted into the spring socket.

Appendix 2

Operating Principle of CSD (extract from Operating manual for The new loss tangent bridge was developed at Central Electricity Research Laboratories and is manufactured under licence in Northern Ireland. by CSD).

Figure 2.1 below shows schematically the general features of the bridge circuit. The oscillator generates an 80Hz sinewave. This signal is amplified by the power amplifier and stepped up by the voltage transformer to 600Vrms. The excitation voltage is used to drive both arms of the bridge circuit. One arm contains the sample being measured and a fixed winding on the ration transformer, the other arm contains the standard capacitor and a variable winding on the ratio transformer. The bridge circuit is balanced by varying the resistance in the standard arm to equalize the phases of the currents in the two arms, and by varying the number of turns in the variable winding to balance the current turns of the two windings. At balance the flux produced in the core of the ratio transformer by one winding is cancelled by the flux produced by the other. With no flux link in the transformer core, the windings have a low impedance, this low impedance appears in parallel with any capacitance to earth so that errors caused by capacitance are small. Capacitance across the voltage transformer also has little effect on the measurement as it effects both arms of the bridge equally.

If the bridge arms are not balanced, the currents in the windings will not cancel and a net flux will be induced in the core of the transformer. This flux is detected by the third winding on the core, the detector winding. The voltage across this winding is amplified and filtered, to attenuate interference at power frequency. Phase sensitive detection is used, both to provide a very narrow bandwidth filter and to discriminate for the phase out of balance signal. Two separate channels are provided to independently measure the loss tangent balance and the capacitance balance. Additional low pass filters after the phase sensitive detectors have a varying bandwidth, which depends on the amplitude of the signal. Large out of balance signals, such as are experienced during course balancing of the bridge are filtered out least and so experience a shorter delay than small out of balance signals which require more filtering to achieve a balance null.

Both isolated and earthed samples can be accurately measured using the sample earth switch in the required position.

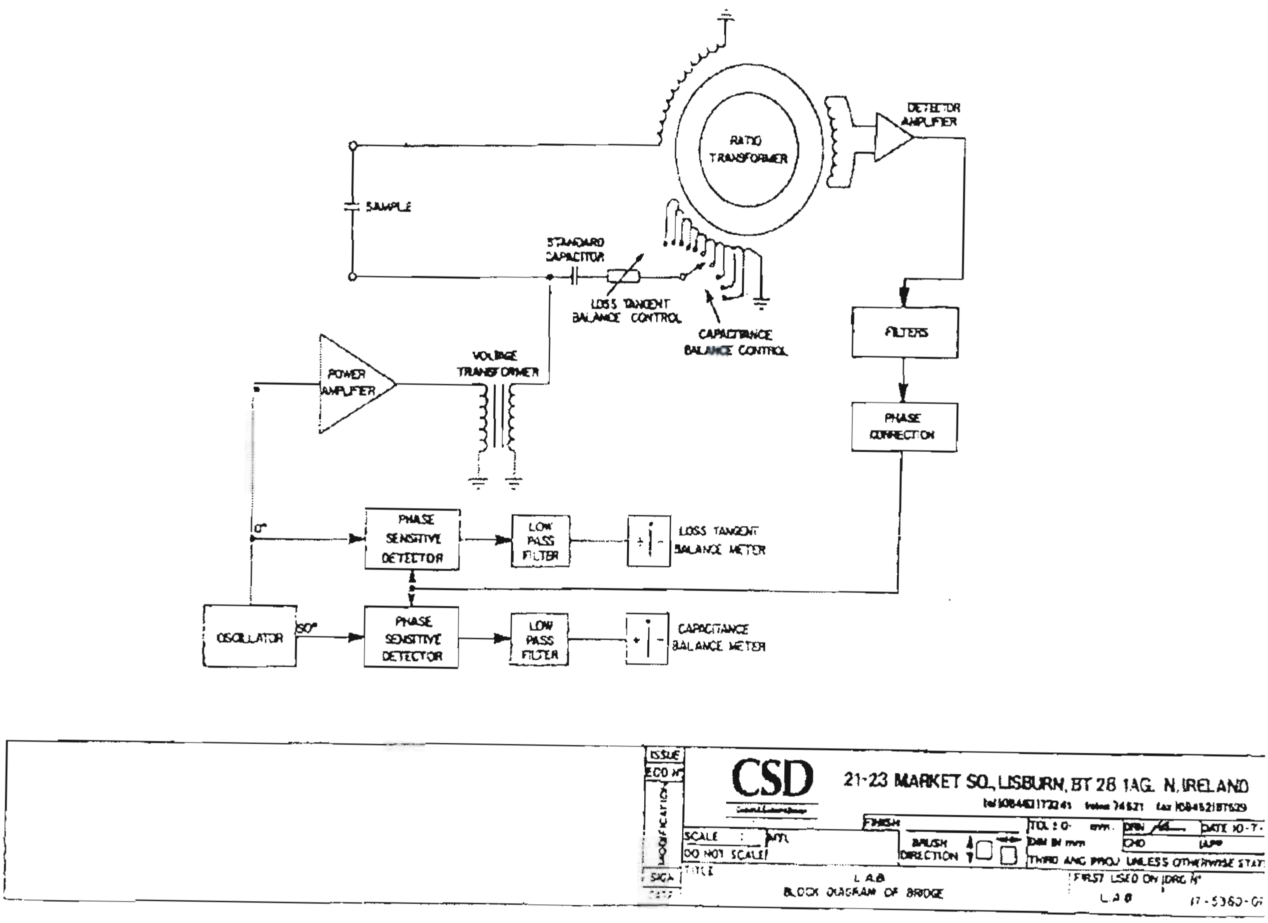


Figure 2.1 Block diagram of CSD loss tangent test set.

Appendix 3

Environmental Impact Assessment of the Tugela Test Site

This report serves as a assessment towards the activities that would take place at Tugela substation during the construction, operation and decommissioning of the Current Transformer (CT) test site, pointing out the various impacts and counter measure that would be implemented to ensure no adverse affects are caused to the environment.

5.3.2.1Background information

The Transmission network has an average of 6-8 violent C T failures and 1 or 2 transformer bushing failures a year, resulting in destruction of plant, outages to customers and even danger to staff. A local RSA designed product bought out by Rainbow Technologies and installed in some 7 Transmission substations, with 3 more to go, monitors the leakage current flowing through the insulation and trends this current with all the other devices in the substation. Any device showing a deviation is removed from service, as the indication is that the insulating is failing. In theory all this is very simple but in practice the device has not been monitored to destruction, in order to set the limits on this Rainbow device to ensure optimal use of our plant

Transmission in conjunction with Technical Research Institute (T R I) have motivated a project to install a test center to test bushings and C T's and age the insulating to the point of destruction in order to set limits on the useful monitoring system.

The site selected for this test site was the Tugela substation on the Bloukrans one 275kV feeder at Tugela.The intention was to build an explosion proof test site next the line and install up to 10 C T's and 3 bushings to be monitored by a Rainbow Tan Delta test set and to accelerate the aging to destruction. The line will be kept in service until a point of failure on one of the C T's is reached. The explosion will be contained in the designed structure as well as any oil spills.

5.3.2.2 Substation layout

Tugela substation is situated on the road between Bergville and Geluksburg and is ±18 Km from Bergville. The substation has 2 x 275 / 132 transformers fed from Bloukrans and Danskraal substations.

5.3.2.3 Water

The water table at the substation is ± 38 meters deep.

The substation water supply is from a borehole on the site.

The closest spruit is ± 1 Km towards the northern side of the substation. The spruit runs from West to East (Hlantchan).

5.3.2.4 Land

The land around the substation is mainly used for agricultural purposes Maize during the summer months and cattle grazing during winter months.

5.3.2.5 Vegetation

The natural vegetation in and around the substation is veld grass with no known endangered species.

Trees growing in the area are thorn trees and planted black wattle.

5.3.2.6 Wildlife

(a)Birds

Birds detected in the area are Guinea fowls, Crows, Rock Pigeons, Cape Sparrow and Cattle Egret.

(b)Animals

Animals such as Rabbit and Porcupine are moving in and on site during night times.

5.3.2.7 Local Community

The substation is situated in a rural farm land area with the farmer closest to the substation ± 1 Km.

Farm workers live ± 2 Km from the substation.

The Bergville / Geluksburg gravel road passes next to the substation on the Eastern boundary.

5.3.2.8. Proposed site layout

The bunded and walled area around the C T platform is designed in such a way that should the C T explode, the walls will prevent oil and porcelain pieces scattering, it

will confine it to the inside, oil will run within the bunded area into a oil trap, from where it will be pumped into drums and removed to Mkondeni workshop.
The C T's are each within their own wall preventing one C T damaging those next to it. Storage area for spare C T's will be in the demarcated area inside the substation. Oil will be stored in a bunded oil store and be used for refilling of C T's.

5.3.2.9 *The impact on the various systems if a C T explodes*

Water

The impact an explosion should have on the surface and underground water would be minimum. No oil would be spilled outside of the design area.
See emergency plan should any spillage occur outside of the bunded area.

Land

Construction Phase

Site will be built on planned future expansion area that became redundant.
Drainage will form part of the existing system on the site. No excavations during construction phase will take place.
No waste will be dumped on site during construction on or around the property. Waste will be removed to waste site at Bergville Municipality.
Contractors will ensure that any disturbed land is rehabilitated before leaving the site.

Operational Phase

The land will be maintained and managed in accordance with Transmissions Environmental Management System based on SABS /ISO 14001 to ensure all risks are identified and managed proactively.
If oil should spill during explosions into area outside the designed area see E P P for action to be taken.

Decommissioning Phase

The decommissioning of the site will be done after completion of the tests.
The area will be brought back to the state it was before the site was build.
Removal of waste will be in line with statutory requirements and Company Policy.

Vegetation

Construction Phase

Grass inside substation will be affected during construction due to vehicles and construction equipment moving to the test site.
Affected area will be rehabilitated after completion of construction.

Operation Phase

No impact on vegetation should occur during this phase, should any vegetation impact occur (oil pollution) the area will be remedied and rehabilitated to its natural state.

Firebreak will be maintained around the property to ensure that fires should it occur are confined to the site.

See EPP for action should any spill occur.

Wildlife

If a C T explodes the noise would cause all wildlife inside the station to fly or run away.

As far as it is known no endangered species have been detected in or around the substation.

Situation will be monitored after each explosion to determine its impact on wildlife.

Local Community

If the C T explodes the affect it will have is that of noise (a bang) to the farmer Mr. C J Uys living ± 800 meters from the substation, and or the public that could be walking passed the substation at the time of the explosion.

This situation was discussed with Mr. C J Uys, and he has no objections towards this site being built inside the substation.

The directions of the wind is mostly from a West direction which means that it blows from the farmers residence towards the substation and it could cause the noise to be less than normal.

Employees

The substation is not manned on a daily basis and 1 to 2 employees might be on site during the day, depending on the work required at the substation.

As the test site will be in a walled area the possibility of porcelain pieces flying around is limited.

Noise would be the only affect for that second the C T explodes.

The test site will also have a lockout system implemented to ensure that employees do not enter the site when it is live and or under test conditions.

5.3 2.10 Conclusion

Taking into account all facts, designs, possible impacts and the preventative measures in place to prevent or remediate affected spilled areas no negative impact to the environment should take place.

Situations will however be monitored and if additional measures are required to prevent and rehabilitate affected areas it would be implemented.

It is suggested that no full Environmental Impact Assessment is carried out for this project.

Liebrandt P

Appendix 4

Fault and Load Studies for Tugela Test Station.

1.1 Load flow studies undertaken with various system contingencies.

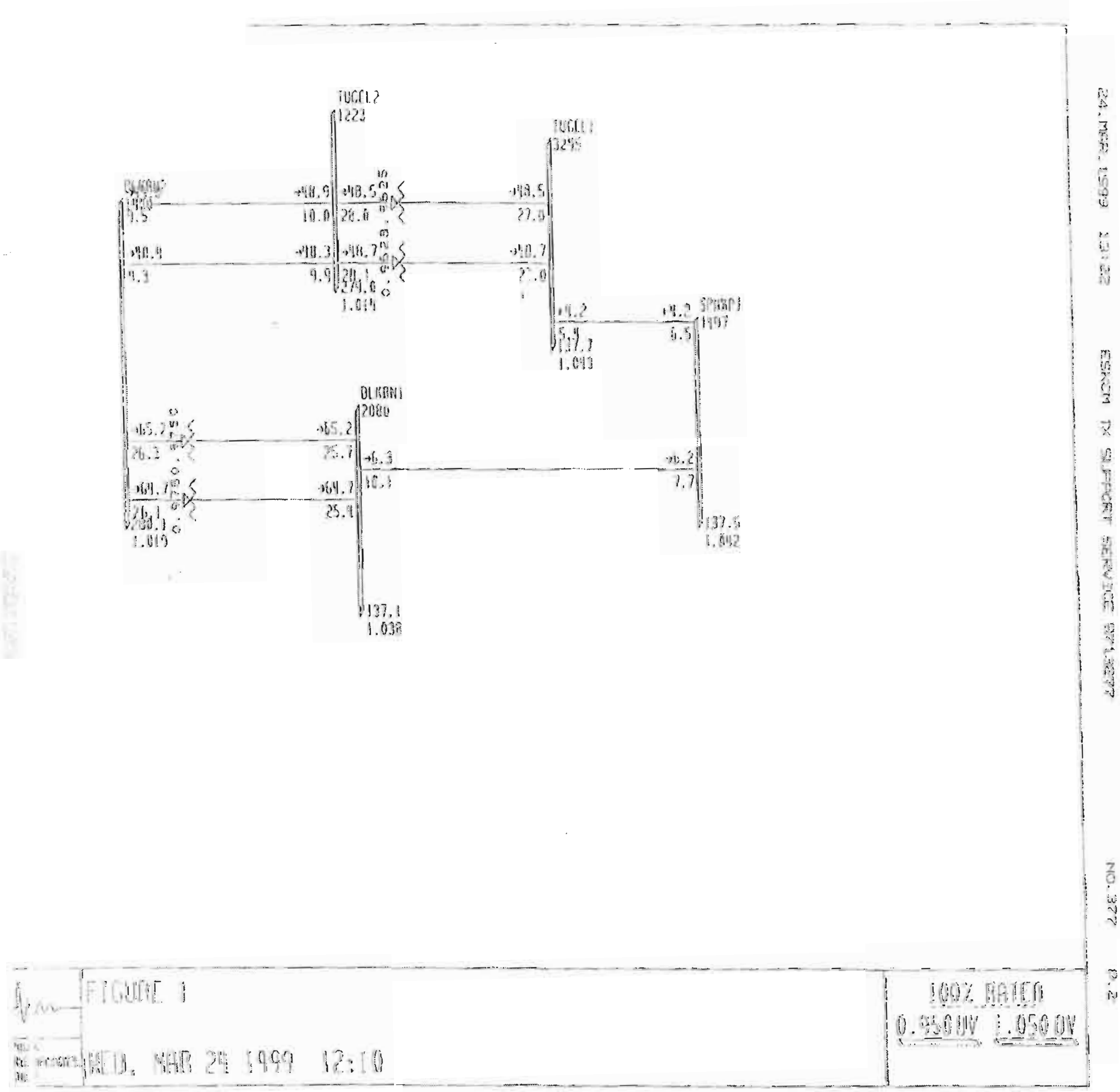


Figure 4.1 Load flow study at Tugela Substation with all infeeds in service

Note; MW's load indicated above each line, % loading indicated below line

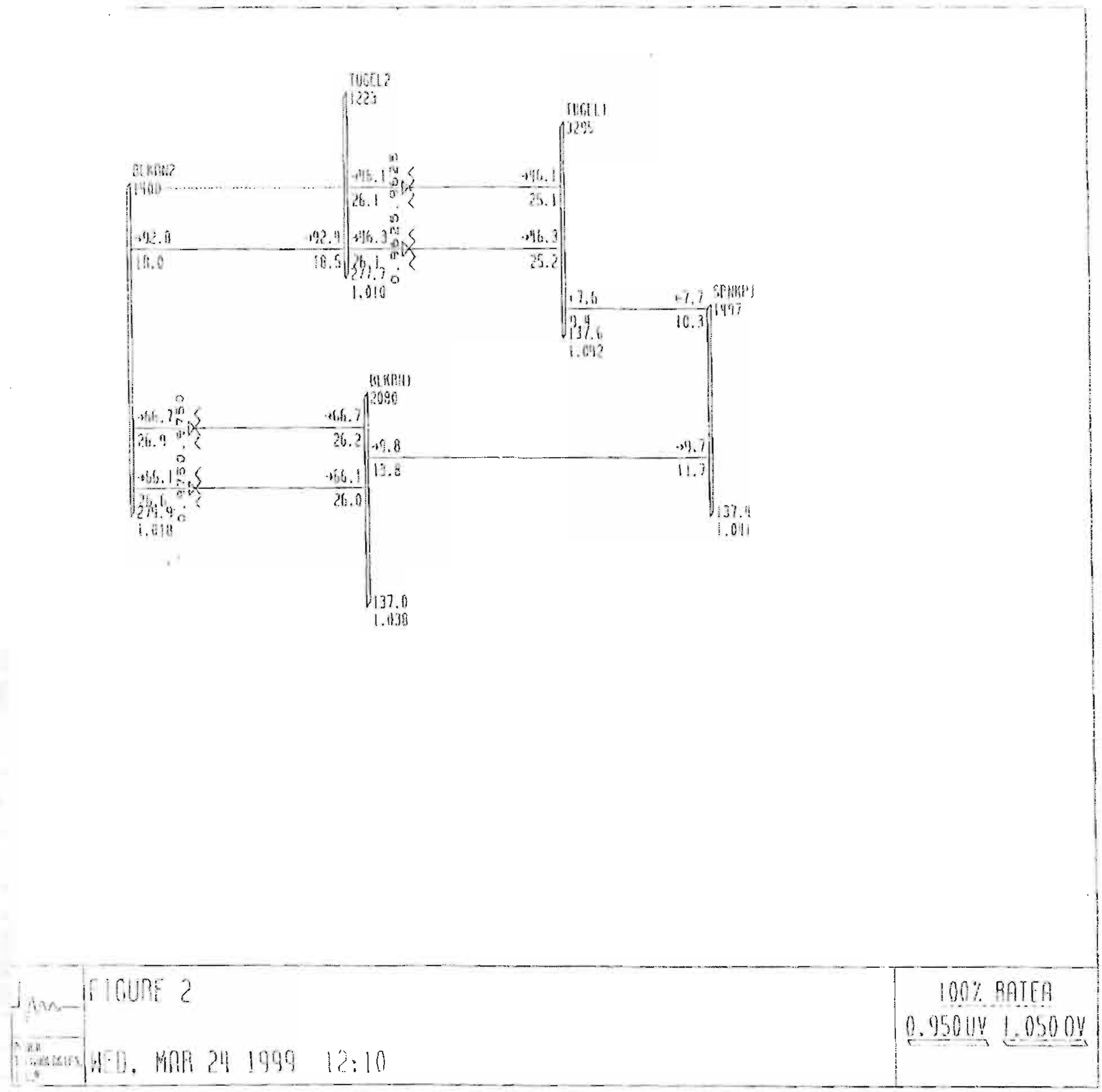


Figure 4.2 Load flow study at Tugela Substation with one 275kV infeed out of service
Note; MW's load indicated above each line, % loading indicated below line

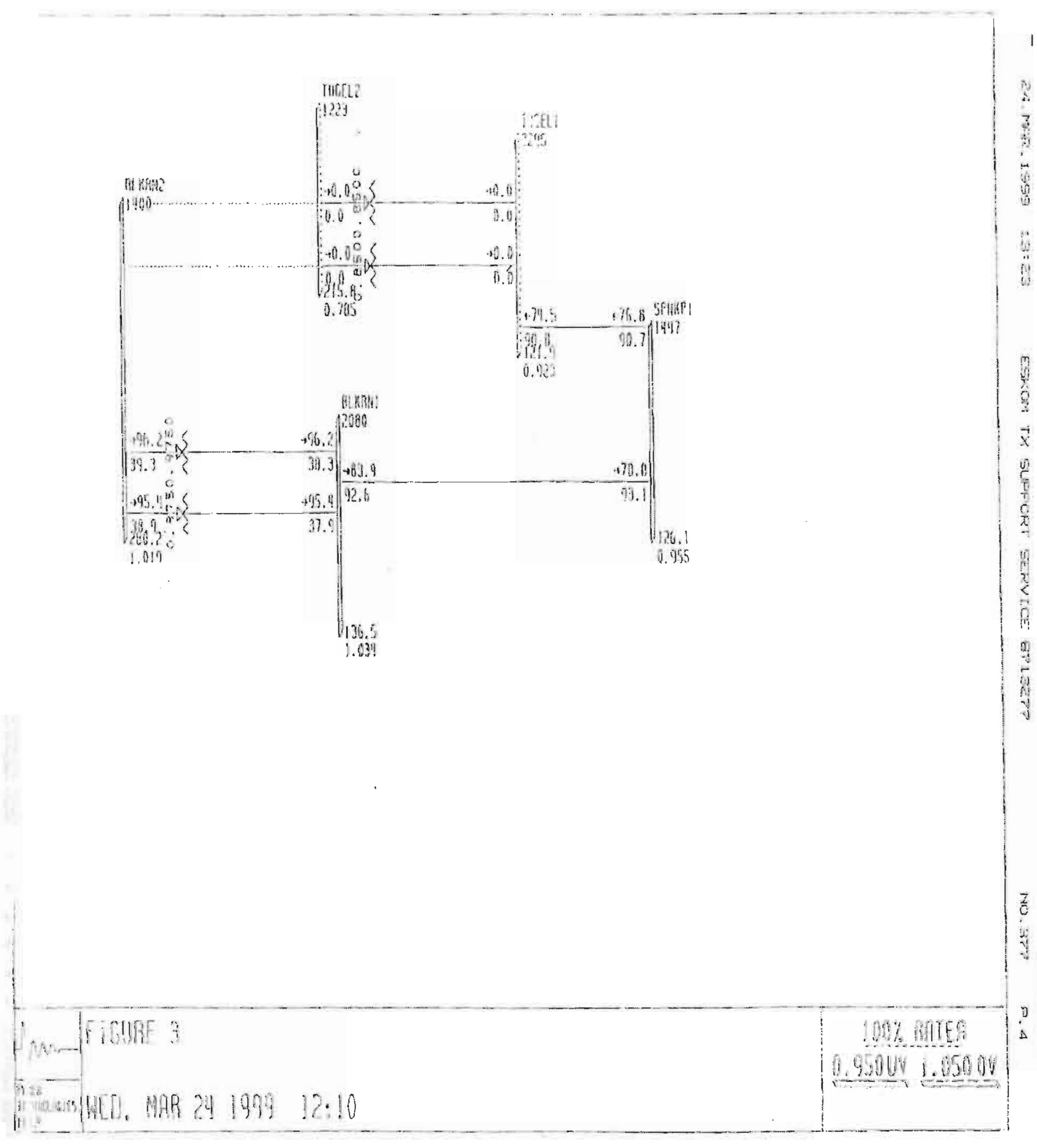


Figure 4.3 Load flow study at Tugela Substation with both 275kV infeeds out of service

Note; MW's load indicated above each line, % loading indicated below line

Fault flow studies undertaken with various system contingencies.

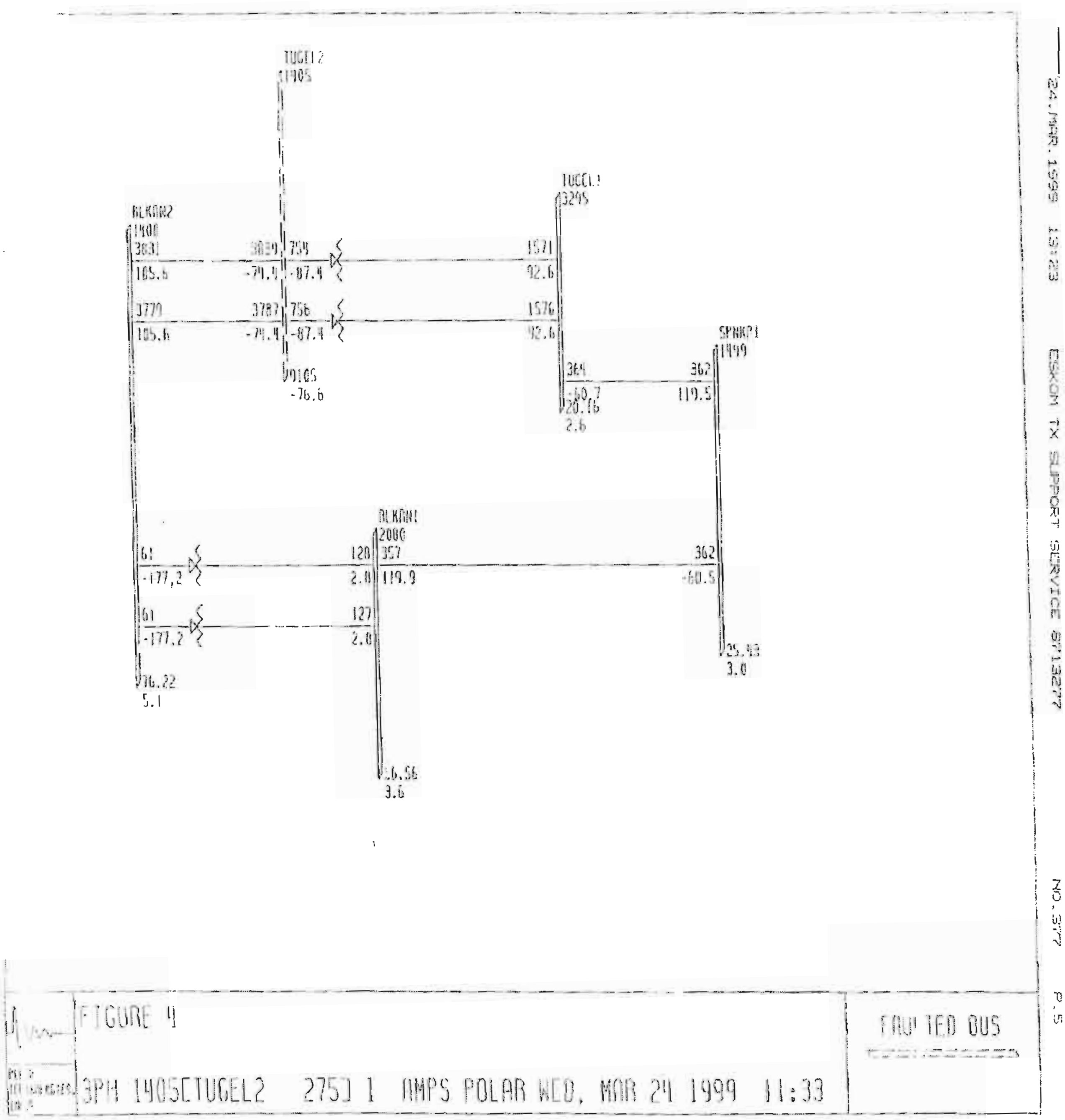


Figure 4.4 Fault study at Tugela Substation with all infeeds in service

Note; Fault current in Amperes indicated above each line, load angle indicated below line

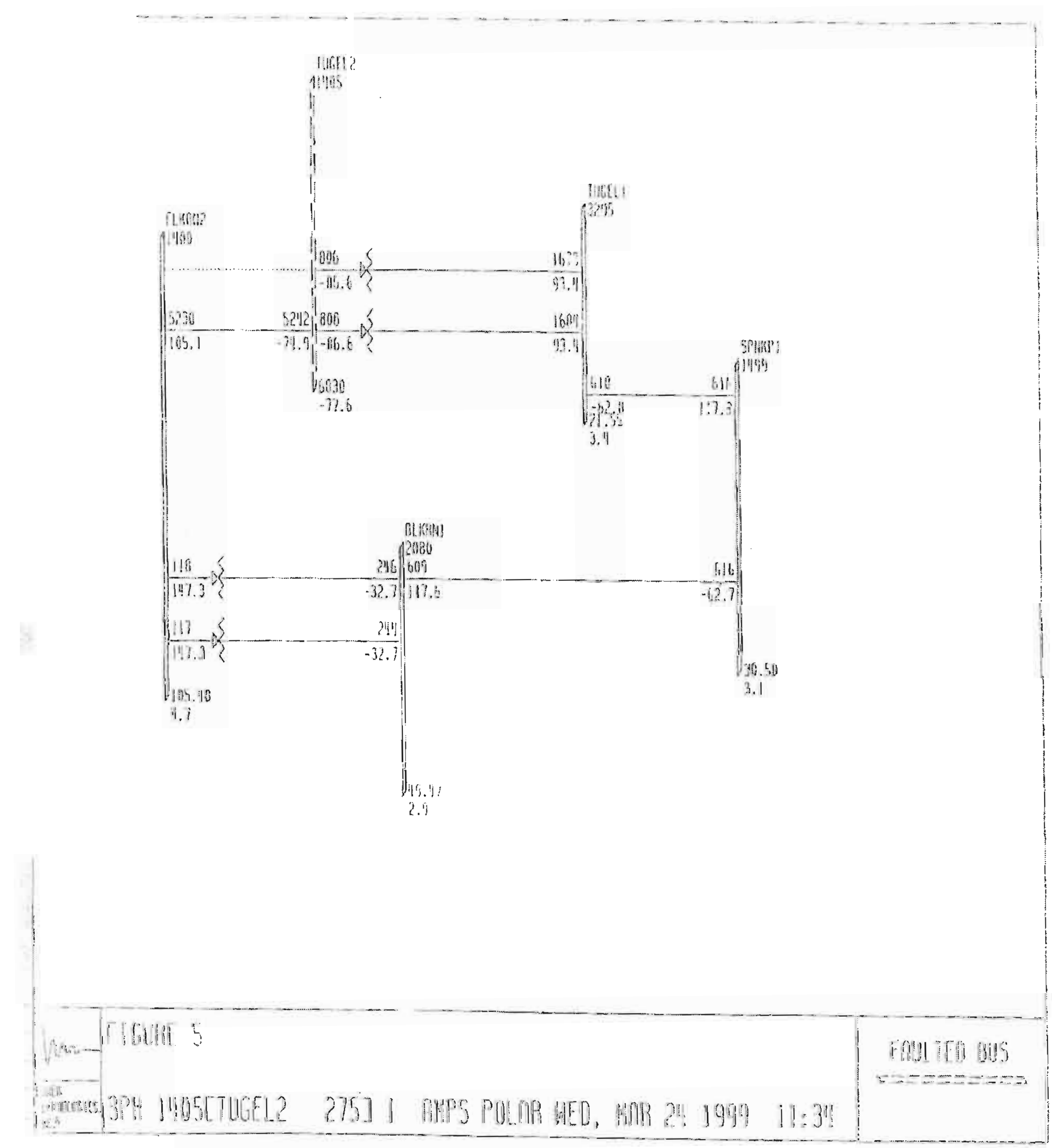


Figure 4.5 Fault study at Tugela Substation with one 275kV infeed out of service

Note; Fault current in Amperes indicated above each line, load angle indicated below line

From: "Teresa Carolin" <Teresa.Carolin@eskom.co.za>
To: <cormacr@eskom.co.za>
Date: Wed, Mar 24, 1999 1:00 PM
Subject: Tugela - Bloukrans

Hi Roger

The data I've used for lines in the area of study is taken from the distribution case. In this case the 132 kV path between Bloukraans and Tugela is open. When querying this we were told that this 132 kV path is normally open when both 275 kV lines are in service. I presume when you are carrying out these tests the 132 kV line will be closed, and I've have done the studies accordingly.

I have faxed you copies of the load flow scenarios of:

* both 275 kV Bloukrans - Tugela lines in service (FIGURE 1)
* one of the 275 kV lines out of service (FIGURE 2)
* both 275 kV lines out of service (FIGURE 3)

The values above the lines on these figures indicate the MW power flow and the value below the line indicates the % loading on the line.

I have then also sent you copies of the fault calculations. In this case the values indicate the amount of fault current flowing on the line when there is a 3 phase fault at Tugela 275 kV busbar. The value above the line is the magnitude of fault current (A) and that below the line is the angle. The values at the base of the Tugela busbar are the magnitude and angle of the total fault level. Again I've sent you the three scenarios of:

* both 275 kV lines in service (FIGURE 4)
* one of the 275 kV lines out of service (FIGURE 5)
* both 275 kV lines out of service (FIGURE 6)

To answer your specific questions:

When both Bloukrans - Tugela 275 kV lines are out, the 132 kV line is loaded up to 93% of its 75 degree thermal rating. Hence the load can be maintained. Following the loss of the second 275 kV line a voltage drop from 138 kV to 122 kV can be expected at the Tugela 132 kV busbar. With appropriate tapping of transformers at Bloukrans, this voltage can be increased to 126 kV.

The fault current on each Bloukrans - Tugela line when there is a fault at Tugela is presently 3.8 kA. When one of the lines is out, the overall fault level decreases, and the fault current on the other line increases to 5.2 kA.

If you have any questions or queries please contact either myself or Gavin Hurford (871-3542).

Regards
Teresa

Teresa Carolin
Transmission System Operations

Note 4.1 Note explaining the capability of the electrical system supply at Tugela substation.

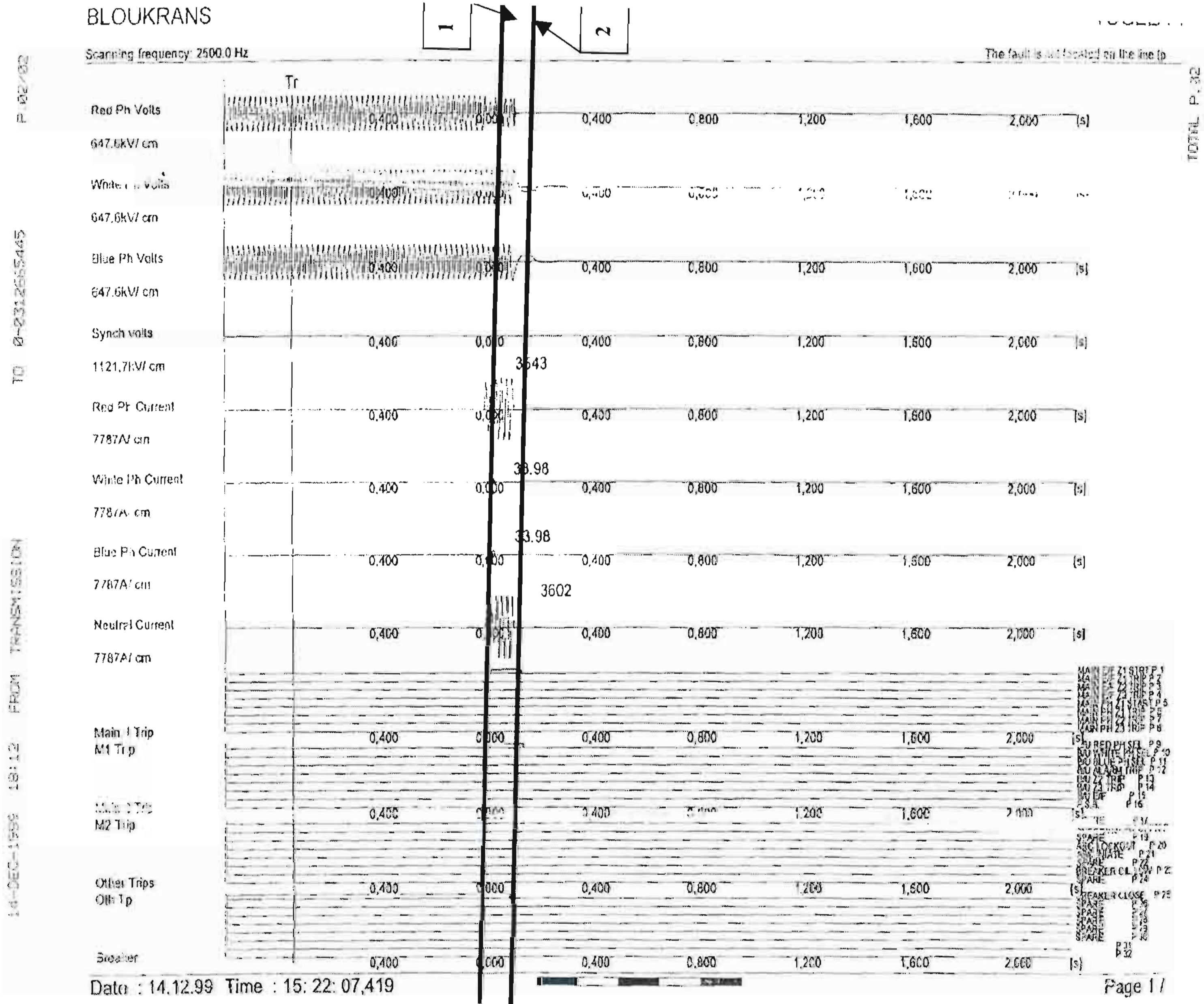


Figure 5.1. Siemens P531 recording taken at Bloukrans on the Tugela 275kV feeder, for a CT failure at Tugela test station on 14.12.99

Appendix 6

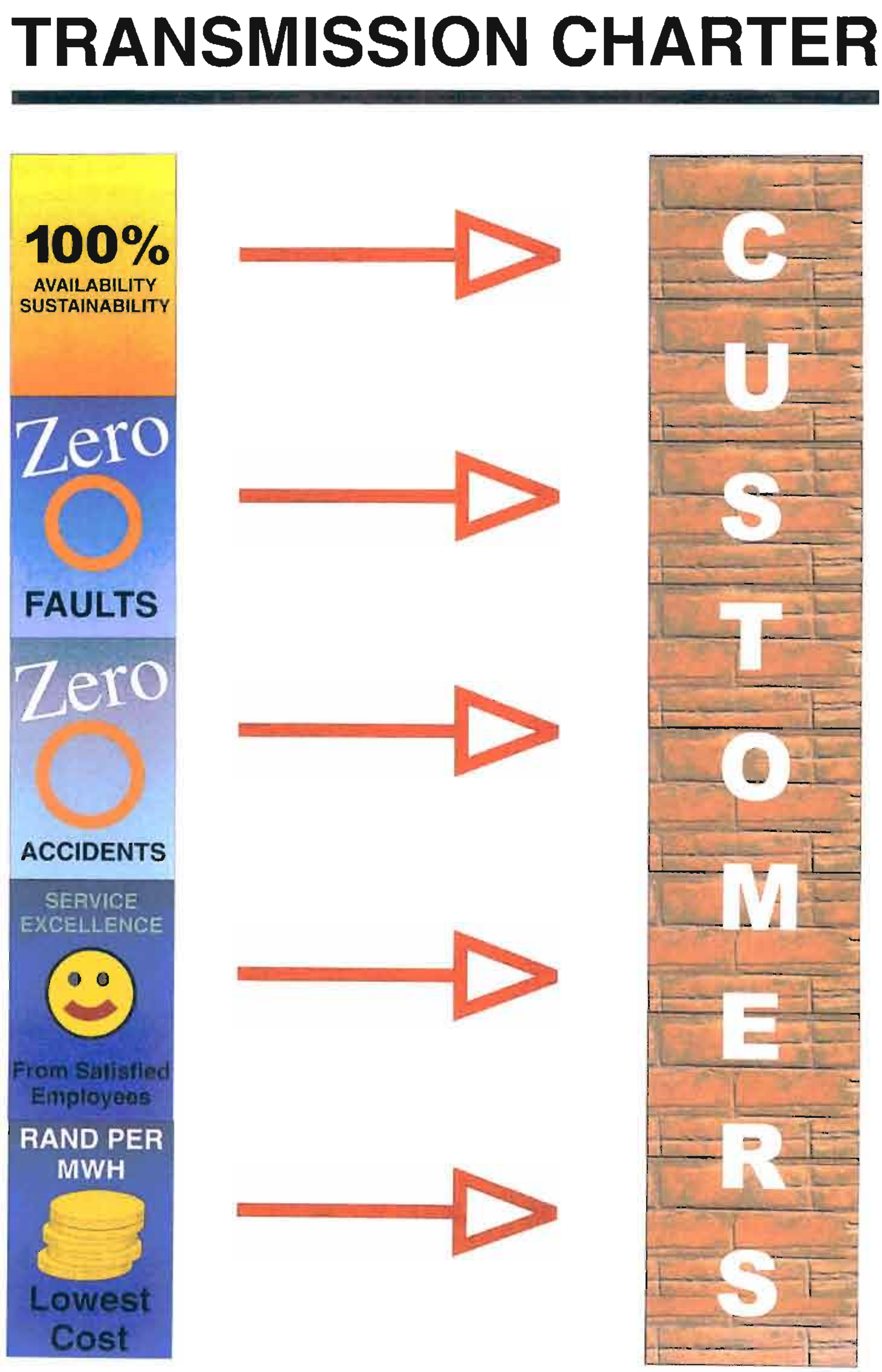


Figure 6.1 The Transmission Charter, which was the driving force behind the Transmission business

Appendix 7

Civil Diagrams of the Tugela test station

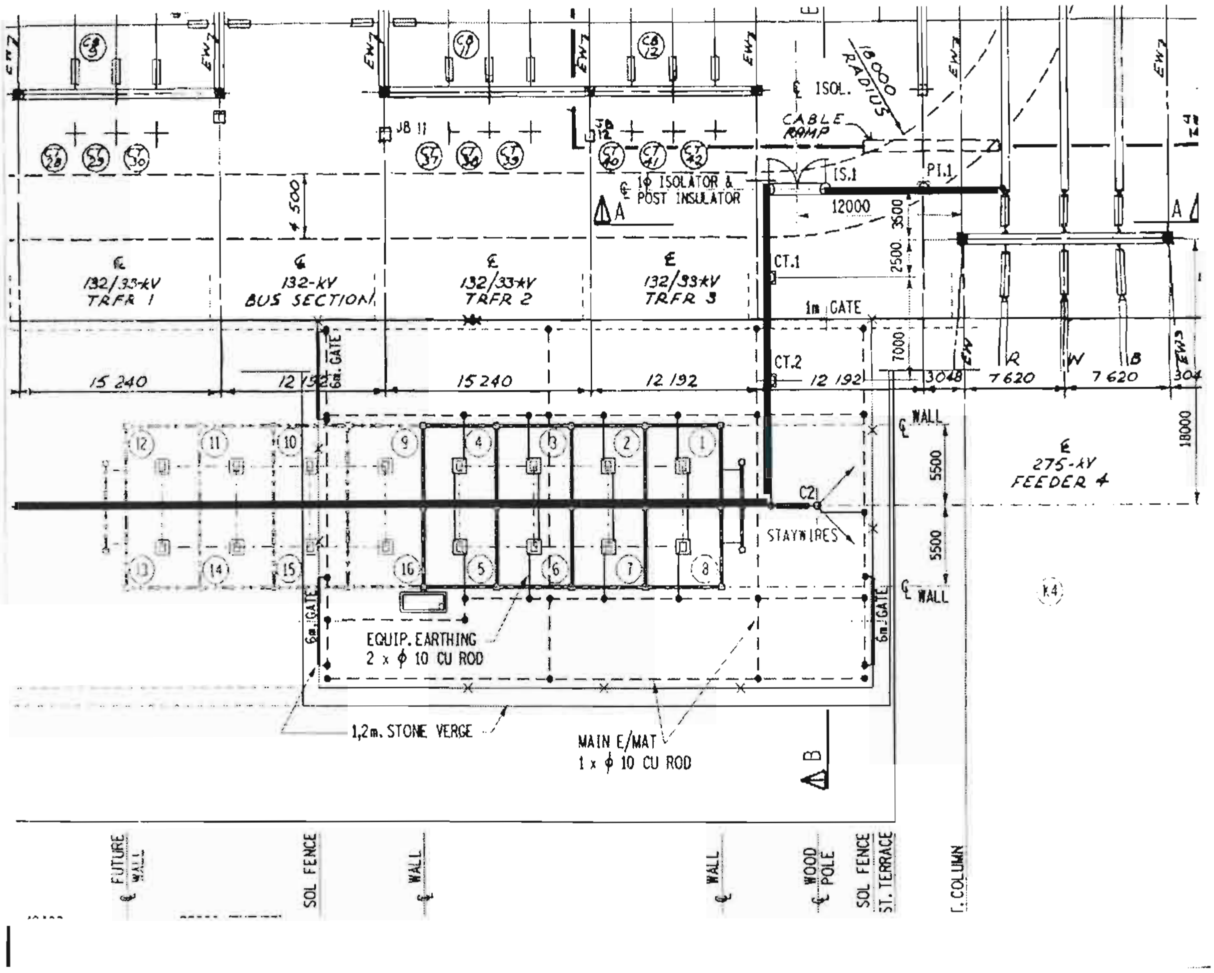


Figure 7.1 General Arrangement drawing showing the Tugela test Station

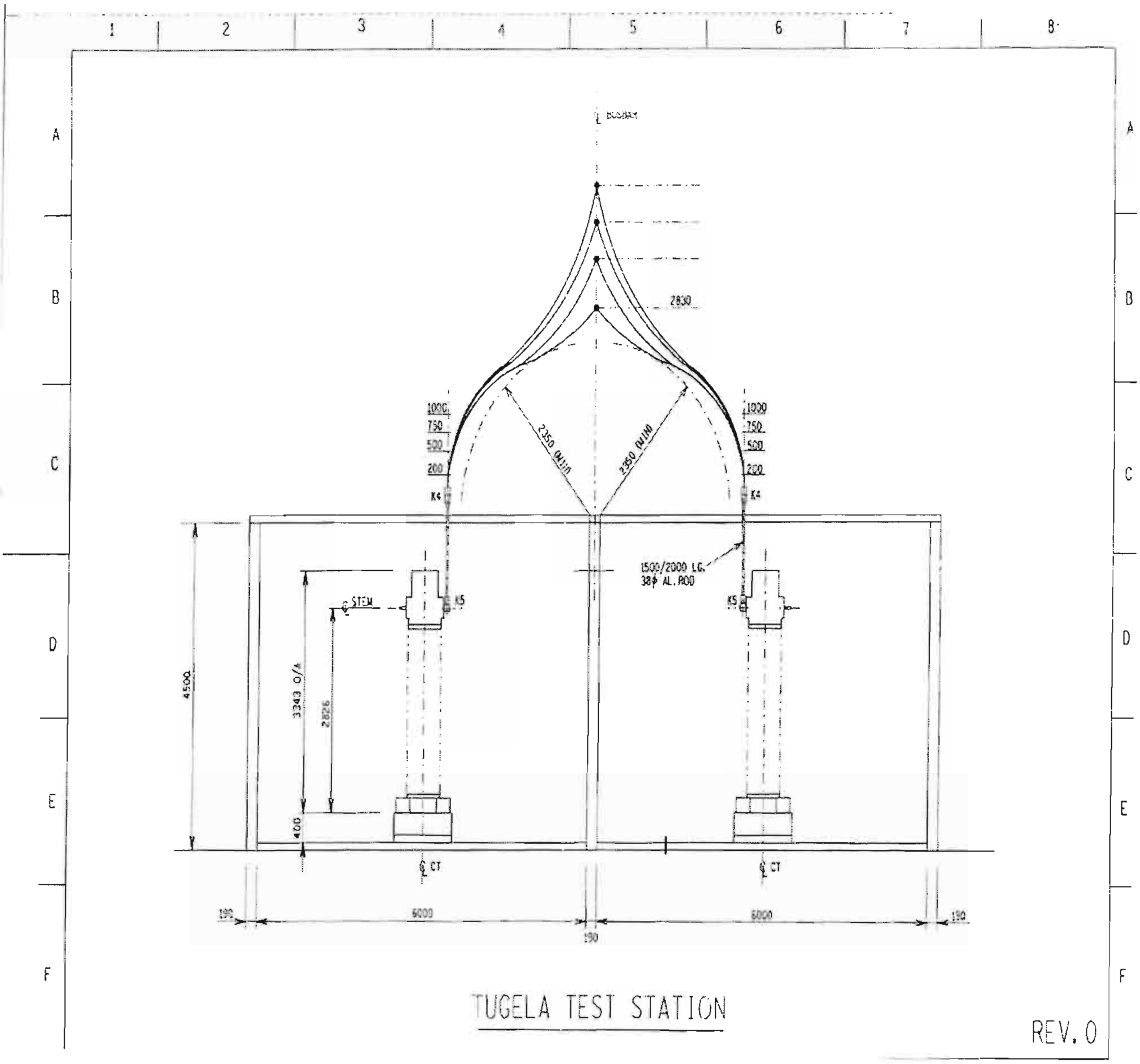


Figure 7.2 Drawing showing the layout and dimensions of the cubicles at Tugela test station.

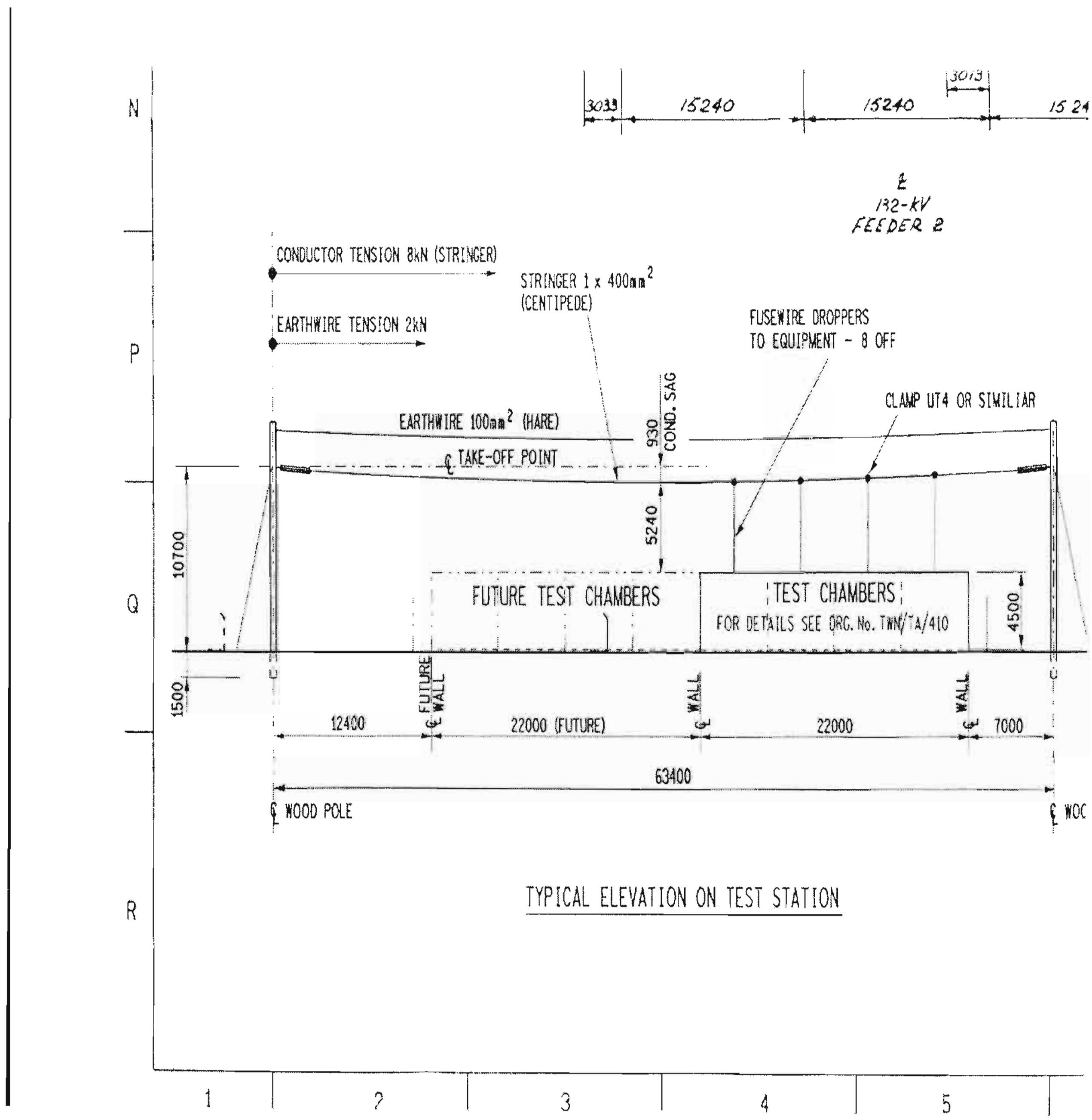
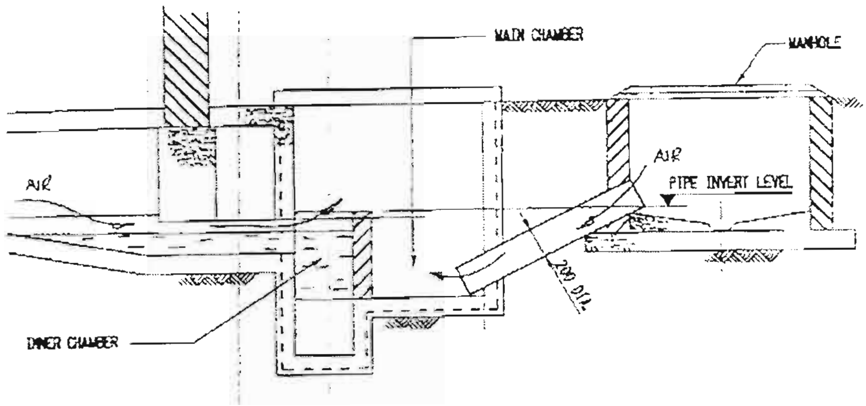


Figure 7.3 Design drawing of Tugela Test Station showing the side elevation

Appendix 8 The oil collection and fire extinguishing system at Tugela Test Station

<u>Scenario 1</u>(No water in the tank)
Oil will flow into the inner chamber. Since each CT contains a volume of oil ±400 litres the inner chamber will contain 300 litres of this oil. Depending on how much oil burns in the drain inside of the test chambers, and we remain with less than 300 litres of oil, the air trap will not be formed and the oil will continue burning inside the tank. See figure below.



Scenario 2 (Tank full of water)
The oil from the CT will flow into the tank. This oil will displace an amount of water equal to its volume. This water will then overflow into the subsoil drain through the connecting pipe. In this condition air supply into the tank will be sealed off and the fire will stop burning. See fig. below.

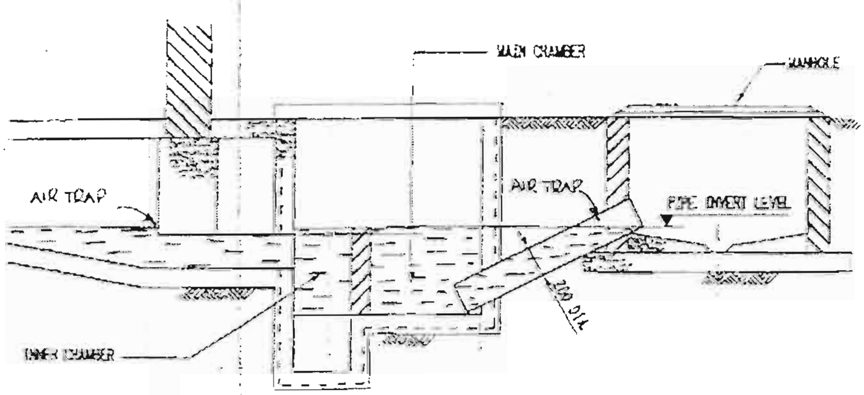


Figure 5.7. Diagram indicating how the oil sump will block off the oxygen and extinguish any fire in the oil.