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PD TRENDING AND TVA TEST READINGS ARE GOOD INDICATORS OF THE CONDITION OF AGED STATOR BAR INSULATION

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A dissertation submitted to the Faculty of Engineering and the Built Environment, University of Cape Town, in fulfilment of the requirements for the degree of Master of Science in Engineering in Electrical Engineering

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PLAGIARISM DECLARATION

I declare that the contents of this dissertation, submitted to the University of Cape Town for the degree of Master of Science in Engineering, are original and have not been submitted prior to this for an academic examination towards any qualification at this university or any other institution.

I know the meaning of plagiarism and declare that all the work in the document, save for that which is properly acknowledged, is my own.

Signed:

Mark Anthony Bruintjies

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LIST OF ABBREVIATIONS AND SYMBOLS

AC	Alternating current
DC	Direct current
DEV	Discharge extinction voltage
DF	Dissipation factor
DIV	Discharge inception voltage
HV	High voltage
IEEE	Institute of electrical and electronics engineers
IR	Insulation resistance
NDE	Non drive end
NQN	Total partial discharge activity
PD	Partial discharge
PDA	Partial discharge analyser
PDSL	Partial discharge site location
PF	Power factor
PHA	Pulse height analyser
PI	Polarisation index
PPA	Pulse phase analysis
PRPD	Phase resolved partial discharge patterns
PRPDA	Phase resolved partial discharge analysis
Q _m	Peak PD magnitude
RFCT	Radio frequency current transformer
Tan δ	Tan delta
TVA	Tennessee valley authority
VPI	Vacuum pressure impregnation
Ω	Ohms

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CHAPTER 1

Seeing an opportunity

1.1. Background to the problem

Keeping generators available on-line is a major factor in achieving maximum productivity in power generation.

During operation, generator components are continuously exposed to thermal, electrical, mechanical and environmental stresses. The complex interactions of these stresses degrade the components resulting in a reduction of useful life.

An integral part of satisfactory operation of high voltage (HV) electrical rotating plant relies upon the integrity of the electrical HV insulation of both the rotor and stator. The combined effect of the above mentioned stresses results in ageing of the insulation, which if not detected, results in premature failure in service. Deterioration of the stator bar insulation is a leading factor for determining the serviceability of hydro generators. Unexpected and expected stator bar failure can result in forced outages and costly emergency repairs. This research will deal with the deterioration of stator bar insulation in air-cooled hydro generators only.

As mitigation to prevent unexpected and expected stator bar failure, many power producers initiated condition monitoring programs on their generators. A condition monitoring program is a program of scheduled tests, monitoring the actual condition of the stator bar insulation. A typical condition monitoring program is comprehensive. It includes on and off line identifying, quantifying and locating techniques (Smith, 1996).

Eskom's hydro generator section started a condition monitoring program on their generators in 1997. After considerable research it was decided to install partial discharge (PD) monitoring equipment. The purpose was to monitor the actual condition of the insulation of the stator windings.

PD monitoring equipment was installed at Vanderkloof Hydro Power Station (2x 133 MVA) and Gariep Hydro Power Station (4x 100MVA) in September 1997 and September 1998 respectively. These typical hydro peaking plants were supplied and installed in 1974.

1.2. Construction of stator bar

The basic construction of a stator bar consists of copper strands, strand insulation, turn insulation, (not applicable to Roebel bars), groundwall insulation, semiconductive coating and silicon carbide coating as illustrated in Figure 1.1. The typical insulation of a stator bar as per figure 1.1 would be made of epoxy mica. The stator bar dimensions of a 122 MVA (13.2 kV) would typically be 20 X 74 mm with 48 strands and 3 mm thick groundwall insulation material. The electric field across the insulation would depend on the actual stator bar voltage. The electric field of a stator bar with phase-to-ground potential difference would have an electric field of approximately 2.5 kV/mm across the groundwall insulation.

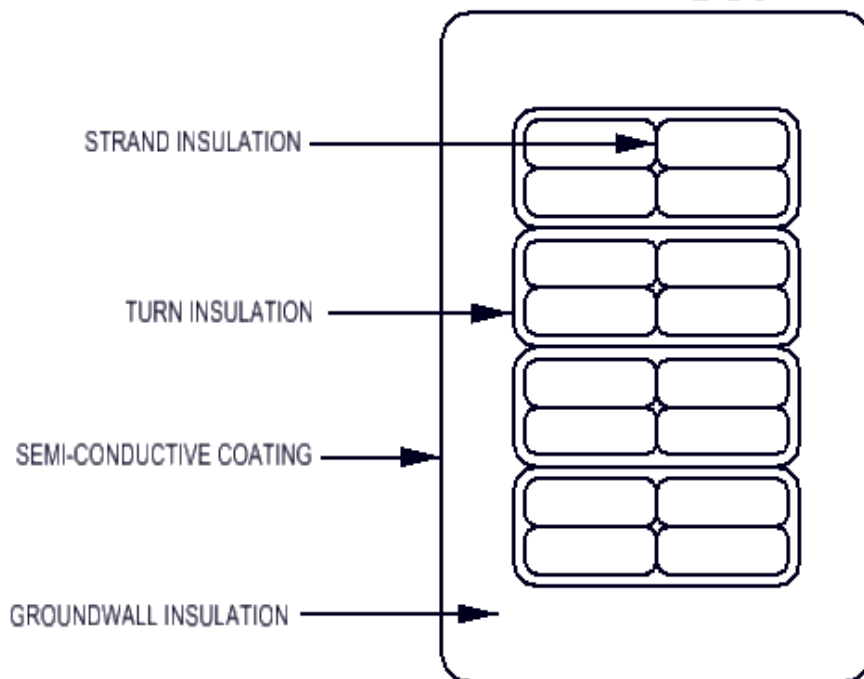


Figure 1.1: Construction of stator bar

In a Roebel bar the individual strands get transposed, commonly either 360 or 540 degrees, down the slot of the core. This allows each strand to occupy all strand positions in the slot. The strand will exit at the same position relative to it's entry point.

Typical insulation materials are (McDermid, 1993):

- Strand insulation: Glass and sometimes upgraded to mica based tape.
- Turn insulation: Mica based tape with glass fiber backing and thermosetting resins.
- Groundwall insulation: Mica paper with glass fiber backing and thermosetting synthetic epoxy resin.

Other important insulation materials are the slot semi-conductive coating and the endwinding silicon carbide coating.

The purposes of the respective insulations are as follow:

- Strand insulation: To lower the skin effect and stray current losses by reducing the cross sectional area of the copper conductors.
- Turn insulation: To prevent shorts between turns in a stator bar. When a turn is shorted it appears as the secondary winding of an auto-transformer. Consequently, a high circulating current will flow in the shorted turn, causing it to overheat. This will eventually lead to a stator earth fault caused by the melted copper burning through the groundwall insulation (Stone et al, 2004).
- Groundwall insulation: To prevent electrical contact between copper strands and the earthed core.
- Semi-conductive coating: Prevents discharges between the stator bar and the core.
- Silicon carbide coating: Grounding of stator bar in endwinding region.

There are basically four manufacturing processes being utilised for form-wound stators (Stone et al, 2004). They are:

- Vacuum pressure impregnation (VPI) of individual coils and bars.
- Global VPI of complete stators.
- Hydraulic moulding of individual coils and bars using resin-rich tapes.
- Hydraulic curing of individual coils and bars using resin-rich tapes.

1.3. Failure mechanisms present in generator stator windings

The following are some of the typical failure mechanisms in air-cooled generator stator windings (Stone et al, 2004).

- Thermal deterioration
- Load cycling
- Improper impregnation
- Loose windings in slot
- Electrical slot discharge
- Endwinding electrical tracking
- Semi-conductive coating deterioration
- Semi-conductive/grading coating overlap deterioration
- Insufficient spacing between stator bars
- Endwinding vibration

In many generators some of the failure mechanisms, which are discussed in chapter 2, are present simultaneously or some can be the reason for others starting, for example slot discharges can lead to loose stator bars.

1.4. Condition monitoring

For decades, time-based, or preventive, maintenance has provided power plant staff with marginal data, data without the actual thermal, electrical, mechanical and environmental stresses present, to assess the state of the stator winding insulation, while requiring lengthy unit outages and personnel resources. Alternatively, condition-based or predictive maintenance can produce a timely and reliable evaluation of the stator winding insulation with minimal outage and less labour. Power producers often foresee saving valuable resources by switching from time-based testing and maintenance procedures for examining the stator winding insulation condition of its hydro generators, to condition based maintenance.

Worldwide experience of condition monitoring application on hydro generators, operating voltage 6kV-18kV, has shown that, provided the condition monitoring application is applied correctly, uses proven test methods and analysis of results is carried out comprehensively, there are positive economic benefits (Stone and Warren, 2004). Personnel having the relevant level of knowledge and experience of HV test technology, plant design and plant operational experience should do the result analysis and interpretation (Smith, 1996).

The condition monitoring equipment installed allows for the establishment of a trend of some failure mechanisms of a generator. Also, it allows comparisons of tests results with identical or similar generators.

Power producers implement condition monitoring programs and based on condition monitoring results and analysis, promote a strategy of preventative and proactive maintenance to ensure plant health (Smith, 1996).

Typical available on-line condition monitoring applied to hydro generators presently:

- Air gap monitoring
- Stator core, bar and endwinding vibration
- Magnetic field balance
- Rotor pole temperatures
- PD
- Stator bar, rotor winding and core temperatures
- Rotor-stator concentricity and circularity
- Rotor mechanical balance
- Stator thermal expansion and frame displacement

Due to overall cost and retrofit constraints, Eskom decided that the installation of Iris PD couplers, coupled with the Iris PDA test method, was the best technical and economical solution at that time.

Iris PD couplers are 80pF epoxy mica capacitive couplers. These couplers block the 50 Hz power signal and pass the high frequency PD signals. These couplers are manufactured to close electrical tolerances and are corona free to voltages well beyond the machine operating voltage.

1.5. Partial discharge as condition monitoring tool

PD are small electrical discharges, which often occur in deteriorating insulation of HV equipment. These discharges occur in air pockets (voids) within the insulation, or at the surface of the insulation.

PD measurements are increasingly used as a valuable aid to assess the condition of stator winding insulation systems (Green et al, 2007). The presence of PD is one of the most reliable indicators of manufacturing defects and the on-going deterioration process of an electrical insulation system. The trending of PD activity over time is one of the most powerful methods of determining the condition of the HV insulation system of hydro generator stator windings (Stone et al, 2002).

Systems that have been developed for on-line PD detecting tests are utilising the following instruments:

- Capacitor couplers
- Radio frequency current transformers (RFCT)
- Rogowski coils

As stated before, after considerable research, Eskom decided on installing capacitor couplers.

1.5.1. Types of off-line confirming and quantifying tests

- Power (dissipation) factor tip-up test

All insulation has a dielectric loss which can be measured with a power factor (PF) or dissipation factor (DF) test, also known as $\tan \delta$. This is an indirect way of determining whether PD is present in HV windings. At low voltages these failure mechanisms are not present. At HV PD will occur if there are voids present in the insulation. PD discharges consume energy which consists of energy needed to produce light, sound and heat. The more delaminated the insulation the higher the PD levels, which will consequently increase the energy produced. This in turn will increase the PF and DF levels above the normal level, due to the dielectric losses and PD as an additional loss component, as the power supply must also supply this energy. The PF or DF is usually measured at two voltage levels, one at 0.2 times rated line-to-ground and the other at rated line-to ground voltage, giving PF_{HV} and PF_{LV} . The measured PF tip-up is:

tip-up= $PF_{HV} - PF_{LV}$. (Stone et al, 2004)

- Off-line PD test

This is essentially a comparison test and does not always correlate with the on-line results. The reasons being that the machine is not under operating conditions that is, no electro-mechanical forces present, windings will be at lower temperatures. The entire winding is energised to line-to-ground voltage hence PD might occur in some bars close to the neutral.

During the test the voltage is gradually raised to line-to-ground voltage. The first recorded value will be the voltage at which PD is first detected called the discharge inception voltage (DIV). At rated voltage the peak magnitude of PD pulse (Q_m) at 10 pps will be recorded. The voltage is then gradually decreased until no PD is measured. This voltage is then recorded as the discharge extinction voltage (DEV). These values are trended over a period of time to indicate the rate, if any, of insulation deterioration. (Stone et al, 2004)

1.5.2. Dismantled locating test

This test is carried out with some rotor poles removed to permit accurate location of the discharges in the winding, for example the actual slot where discharges are occurring.

1.5.3. Type of location test

- TVA probe (Tennessee Valley Authority)

This test is conducted by energising the stator winding to phase-to-ground potential and running a probe over the complete length of each slot and recording the discharge activity in mA as indicated by a handheld commercially available peak pulse meter. The TVA probe is tuned to respond to MHz range of signals, the frequency where PD pulses attenuate as they propagate away from the discharge site (Smith, 1970; Sedding and Stone, 1989).

After considerable research Eskom decided on the TVA test to indicate possible problematic areas off-line, as indicated by the on-line PD test.

1.6. PD monitoring at Vanderkloof (VDK) and Gariep Hydro Power Stations

From the initial PD readings taken, at VDK and Gariep Hydro Power Stations in 1997 and 1998 respectively, it could be seen that the PD levels of all the units were high, it being in the 90th percentile of the worldwide database analysed by Stone and Warren (2004).

PD readings have been taken at the above mentioned stations at intervals of 1450 running hours over a period of 6 and 12 years respectively. From these analyses it was ascertained that the Vanderkloof Hydro Power Station generators were at high risks of insulation failure. The area of concern was that the PD readings and the TVA probe tests clearly indicated that the stator winding insulation was deteriorating.

With the exception of some fluctuations due to variations in operating conditions, the PD activity has increased gradually over the years. Analysis of the test results, at VDK Hydro Power Station, indicated that combinations of various failure mechanisms are experienced in the different phases. Table 1 .1 listed below will show this.

Table 1.1: Failure mechanisms observed in various phases of VDK Units

Unit 1		Unit 2	
Phase	Failure mechanisms	Phase	Failure mechanisms
Red	Slot & endwinding discharge, cross coupling	Red	Slot & endwinding discharge
White	Slot & endwinding discharge	White	Slot discharge
Blue	Slot & endwinding discharge, cross coupling, semiconductive grading	Blue	Slot & endwinding discharge, cross coupling

1.7. Off-line verification of on-line PD readings

TVA probe tests were done on both the VDK Hydro Power Station Units and on Units 3 & 4 at Gariep Hydro Power Station prior to the rewinds at VDK Hydro Power Station.

From Eskom TVA testing experience over the years, table 1.2 is used as a TVA test guideline for analysis of epoxy-mica insulation.

Table 1.2: TVA probe readings test guideline

TVA probe reading (mA)	Interpretation
< 10	Typical of sound insulation
> 50	Small voids
> 100	Medium voids present which is a concern
> 300	Large voids present which is a major concern

The TVA test results for the two stations are recorded in table 1.3:

Table 1.3: TVA probe readings test readings

Unit	No of slots	Range of TVA reading (mA)	% of slots in range (%)
VDK # 1	432	100 - 300	2.8
VDK # 2	432	100 - 300	5.5
Gariiep # 3	396	100 - 150	1.26
Gariiep # 4	396	100 - 220	0.25

Given the high PD values (Stone and Warren, 2004) and the risks of failure associated with stator bar failure, it was decided to rewind Unit 2 and Unit 1 at VDK Hydro Power Station in 2003 and 2004 respectively.

During the rewind of Unit 2, twenty-eight (3%) of the generator's stator bars were selected as spares for the other running unit which was to be rewound the following year. The selection criteria for these bars were that their TVA recordings were low and that they had operated at the neutral end of the generator. After the rewind of Unit 1, these spare bars were HV tested up to 28kV DC and three (3) of these bars failed at 20 kV DC.

1.8. Scope of research project

The above occurrence led to this researcher seeking a better understanding of the PD condition monitoring program's test results and trending over a period of approximate 12 years. Also, is there any correlation between the TVA probe test results and breakdown voltage levels? An opportunity to research this came about when Eskom decided to rewind the units at Gariiep Hydro Power Station.

The research was done on the stator bars of two 100 MVA hydro generators rated at 13.2 kV. The stator bar insulation class is type B and the insulation for both slot and endwinding is mica tape impregnated with resin. The generators are air-cooled.

The scope was formalised as a hypothesis:

TVA probe test results and trending of PD levels are good indicators of the condition of aged stator bar insulation in hydro generators.

1.9. Research questions

Information giving answers to the following research questions will allow the validity of the hypothesis to be tested.

- How is PD used as a condition monitoring tool?
- What other tests can show the actual condition of the insulation?
- Can HV breakdown test show the actual condition of the insulation?
- What factors can influence PD?
- Are trends or absolute values of PD more significant?
- Is stator bar position in the generator significant?
- Is there correlation between diagnostics tests and breakdown voltage?
- Can PD be used as a key decision making tool?

CHAPTER 2

Literature research

2.1. Introduction

Numerous papers were identified as relevant to the research questions. These are discussed here. Most of the papers are from the late nineties to 2009. However, there are a few relevant papers from the fifties, seventies and eighties.

2.2. Some failure mechanisms present in generator stator windings

The following are some typical failure mechanisms in generator stator windings (Stone et al, 2004):

- **Thermal deterioration**

This failure mechanism is essentially an oxidation chemical reaction over period of time. At high temperatures the chemical bonds within the organic parts of the insulation break due to thermally induced vibration of the chemical bonds. The origin of the thermally induced vibration is the oscillating polar molecules of the insulation material. The energy for this vibration comes from the applied electric field across the groundwall insulation. Hence, an increase in dielectric loss. This leads to loss of mechanical strength due to long term overheating, resulting in delamination. The insulation layers debond, resulting in conductor vibration and PD due to strand/turn shorts. Overheating is due to overload, defective cooling, frequent inrush currents, unbalanced phase voltages and poor design. Depending on the actual temperature, this type of failure can take decades.

- **Load cycling**

Due to rapid load cycles during generator operation relating specifically to peaking duty and pumped storage schemes, the differential expansion between the copper and groundwall cause a loss of bond between copper and groundwall and/or cracking at slot ends. This leads from strand and turn shorts to groundwall failure at slot ends. This is typical of peaking plants. The rate of failure depends on the rate of load change and the operating temperature.

- **Improper impregnation**

Bad impregnation during manufacturing causes voids (air pockets) within the groundwall. PD will occur in these voids. The PD attacks the epoxy or polyester, leading to strand or turn shorts.

- **Loose windings in slot**

Stator bars are subjected to high magnetically induced mechanical forces at twice the power frequency. If the stator bars are not secured tightly in the slots, they will start to vibrate. The insulation system will move axially relatively to the core. This movement will result in an abrasion of the groundwall which will eventually result in insulation breakdown. The coils become loose due to shrinkage in the first year after installation, or due to ripple spring failure, loose wedges and endwinding vibration. Time to failure could be as short as two years in epoxy windings.

- **Electrical slot discharge**

Poorly made semi-conductive coatings (especially if paint) becomes non-conductive by oxidation of the carbon particles at elevated temperatures. This failure of the semi-conductive layer leads to PD activity between the stator bar and core, which will eventually decompose the epoxy or polyester insulation.

- **Endwinding electrical tracking**

The insulation material is under electrical stress. A moisture film on a polluted area of the insulation material will conduct leakage current which will flow between parts with a voltage differential. This leakage current will heat non-uniformly and distort the stress distribution over the surface. Areas of high resistivity will form and nearly the full surface voltage will appear across these areas causing flashovers.

The flashovers will continue until a gap occurs between the resistive area and the surface voltage. When this occurs, the temperature of the flashover may be sufficient to decompose the insulation material, releasing free carbon. Resistive areas, flashover and free carbon will proceed until a continuous conducting path, called tracking, forms between live parts where the flashovers occur (Kurtz, 1987).

The permanent phase-to-phase or phase-to-ground deterioration is due to partly conductive pollution in endwindings. Conductive contamination from moisture or oil mixed with dust or dirt also provides excellent paths for tracking. Electric (carbon) tracks form across blocking or along endwindings which will enable currents to flow over the insulation surfaces and eventually through the groundwall. This will degrade the groundwall insulation and will lead to eventual groundwall failure.

- **Semi-conductive coating deterioration**

This failure mechanism involves the deterioration of the semi-conductive coating on stator bars in the absence of stator bar vibration. During this failure process the semi-conductive coating becomes non-conductive by oxidation of the carbon particles and in some localised areas even non-existent. In stator bars operating at HV, PD will occur between the stator bar and the core. The PD will attack the groundwall insulation and degrade it. The end result would be a ground fault due to groundwall insulation failure. Failure may take decades.

- **Semi-conductive/grading coating interface deterioration**

The silicon carbide coating extends from the semi-conductive coating just outside of the slot, along the stator bar, into the endwinding. The silicon carbide coating must be electrically connected to ground by an overlap of the silicon carbide coating and the semi-conductive coating. It is the electrical connection inherent in the overlap that degrades. If the overlap region becomes non-conductive, then the silicon carbide coating is no longer grounded. The silicon carbide coating "floats" and rise to the voltage level of the copper inside the stator bar, due to the capacitive coupling effect. The semi-conductive coating will then be at ground level (grounded by the core) and the silicon carbide coating will be at a phase-ground (assuming it to be line side stator bar) level.

These two coatings will then be separated by a small airgap (the overlap region). Consequently, the air gap breaks down, resulting in discharges over the surface of the coil between the two different coatings. Failure may take decades.

- **Insufficient spacing between stator bars**

With the stator bars too close to each other, high electric stresses will be present. The air will breakdown, creating PD. PD can lead to groundwall puncture between adjacent stator bars or endcaps in the endwinding. This can result in phase-to-phase faults over several years. The closer the stator bars the faster the rate of failure.

- **Endwinding vibration**

If the endwinding support is inadequate, the stator bars will start vibrating. This vibration in the radial and circumferential directions will pivot at the stator slot exit leading to fatigue cracking just outside of the slot. The cracked insulation will lead to a phase-to-ground fault. Another mechanism that will enable endwinding insulation failure will be loose endwinding blocking and bracing. This will allow the stator bars to vibrate relative to each other. The stator bars will rub against each other and the support structures in the endwinding. As the support structure is normally made of hard material, this will abrade the insulation and will eventually cause a phase-to-ground fault.

2.3. Utilising partial discharge as a condition monitoring tool

Advanced monitoring systems now make it possible to conduct thorough on-line generator inspections. The major benefit of on-line monitoring is the fact that the actual generator condition is revealed under actual operating conditions. The key to on-line generator inspections is an understanding of fundamental generator problems.

Kurtz and Lyles (1979) give a brief historical review of PD problems encountered, a description of diagnostic tests and repair procedures on windings with slot discharge or mechanical abrasion insulation damage. Recent advances in the diagnostic test equipment and repair techniques show these methods to be outdated.

Stone et al (2008) review, using PD measurements, the failure mechanisms of three types of slot discharges and vibration sparking. Attempts are made to indicate how each process can be detected and distinguished before actual stator winding failure has occurred. Guidance on possible repair options (short of a rewind) is also presented.

Having previous PD data available enable users to make better informed decisions should an incident occur on a generator. Having this information in conjunction with electrical tests and monitoring assist with the assessment of the generator's actual condition and refurbishment effectiveness. Howarth and Smith (2003) discuss the dry-out procedure of a deluge incident by comparing pre and post incident PD test values as an indication of the actual state of health.

Duarte and Warren (2003) discuss power factor/capacitance and PD tests with regards to monitoring, applications, interpretation and limitations. Case studies of each technology and comparisons are also included.

Lyles et al (1988) have created a database spanning decades of on-line PD monitoring measurements. Their experience has shown that PD monitoring has successfully identified the following discharges: semi-conducting coating, internal groundwall delamination (voids), loose or tight stator windings and copper stack to groundwall interface delamination.

Warren et al (2000) compiled statistical analysis of PD results collected over a few decades. In particular, means of overcoming the limitations imposed by the comparative nature of PD testing are presented. In addition, better ways of identifying PD that may originate in the endwindings or on the circuit ring buses connections are discussed. Goodeve and Stone (2007) deduced from objective analysis that higher design stresses used over the past decade may result in more rapid deterioration of insulation systems. The conclusion is made that newer machines and rewinds do not necessarily have more reliable insulation. Stone and Wu (2009) have done some investigation on premature deterioration and failure of generator stator bars and found some evidence correlating with this conclusion.

Shunyuan and Chow (2007) show that stator winding insulation problems can be identified through analysis of the PD pattern, polarity predominance, pulse phase analysis (PPA) and trends, in correlation with visual inspection and HV test results. This was proved by some case studies on generators with known failure mechanisms.

2.4. What other tests can show the actual condition of stator bar insulation?

Stone et al (1992) subjected solid insulation to repetitive voltage surges. The results of the testing and the implications for HV equipment are discussed. They concluded that epoxy insulation can gradually age under the action of repetitive voltage surges. The aging mechanism is quicker under positive surges.

Lamarre et al (2004) conducted dissection test on service aged stator bars to assess to what degree non-invasive diagnostic tests results correspond to the actual state of the stator bar insulation. The tests did confirm problems, some serious, that are detected or suspected by diagnostic testing. However, it was also concluded that although diagnostic methods may point at problems that are considered serious (for example slot PD, internal PD, high $\tan\delta$), dissection may instead put their importance into perspective. Dissection illustrates that the problems measured by diagnostic methods could only be at an early stage of development or in a phase of slow deterioration or the failure mechanism has stopped completely. An important observation was that some of the failure mechanisms identified during dissection, were completely overlooked by diagnostic methods.

Goodeve et al (2005) discuss the importance of giving greater attention to detail in the manufacture and installation processes of stator windings. This is essential since competitive pressures have forced both suppliers and users to seek new and innovative ways to produce stator windings. It is stressed that a comprehensive plan involving supplier qualification, capability and quality assurance testing is essential to maximise the probability of a long service life.

Gupta and Culbert (1992) attempt to assess the condition of stator bar insulation without earlier diagnostic test results and limited information about the insulation systems. Their approach was to compare the diagnostic test results between phases of the same machine and between different machines with similar insulation systems. They concluded that from this method a limited assessment of the stator insulation condition is possible.

Stone (2005) summarizes the purpose of each current IEEE recommended test method (pertaining to insulation testing), provides some theory about the tests, discusses pass/fail criteria where appropriate and outlines the differences from past versions of the IEEE standard, practice or guide.

2.5. Can HV breakdown test levels predict the remaining life time of windings?

Mandal (2005) reviews various life models under individual stresses and their combinations along with the statistical methods for estimation of residual life of stator winding insulation. He also reviews the various non-destructive tests and diagnostic parameters, which is helpful in assessing the health of the insulation. He also investigates HV breakdown and withstand tests to correlate them to the predicted residual life of the insulation.

Kazuhiro et al (1987) utilise comparisons of various capacity generators, withstand tests, operating voltages and operating history to estimate aging and life estimation of generator insulation.

In order to estimate the remaining life of the bars of a hydro power plant generator, Naghashan (2004) tested one new and four old stator bars of a generator under combined electrical, thermal and mechanical aging stresses. PD quantity (total integrated charge of the bars in cooling-down period) before and during the aging is used for the life assessment prediction.

The time to breakdown of the old stator bars could be calculated from results obtained by accelerated aging stresses of the new stator bar. However, the stresses applied for accelerated aging on the new bar must closely resemble the actual operating stresses of the generator.

2.6. What factors can influence partial discharge measurements?

Over the years, results have been collected that indicate humidity may also be a factor that needs to be monitored. Stone et al (2002) have verified by way of simple laboratory experiments the existence of the effect of humidity on stator windings. In one case study and a laboratory experiment, a very strong inverse correlation between surface PD activity and humidity has been found. However many test specimens are needed to quantify the effect. Users of on-line testing need to record the humidity at the time of testing in order to address the possible impact because of humidity. Stone et al (2002) illustrate that PD is affected by machine operating conditions.

They present critical values of PD, which indicate significant risk of severe winding problems, for different types of air-cooled and hydrogen-cooled machines.

Bartnikas and Morin (2004) discuss in detail the experimental simultaneous aging data obtained on the stator bars at rated temperature and twice the rated voltage, and compare these results with those obtained at a conductor temperature of 165 °C but still at twice the rated voltage. The experimental results demonstrate that with moderately increased electrical stress, even tests up to 1500 thermal load cycles are insufficient to provide meaningful statistical failure data.

Bartnikas and Morin (2006) analyse the diagnostic test results obtained on new stator bars that have been aged simultaneously under multi-stress conditions in a three-phase stator model. The aging rates were examined in two groups of bars. Group 1, consisted of bars that have been load-cycled for a total of 1500 cycles, the duration of each cycle approximately 5.5 h, with the electrical stress as the prime acceleration aging factor (with other stresses maintained as in-service). Group 2 consisted of bars that were aged with all three stresses (electrical, mechanical, and thermal) as simultaneous acceleration factors. The duration of the load cycle remained between approximately 5 and 5.5 h. However, the current loading was increased by 10%. The first failure due to the development of intense discharges and sparkover at the bar's end was found to occur after 733 load cycles and it was decided to terminate the accelerated aging test after 1049 load cycles.

It's concluded that the multi-stress accelerated electrical aging tests on stator bar specimens installed in a three-phase model stator and subjected to simultaneous electrical, thermal, and mechanical stresses have demonstrated that useful life test data may be obtained by elevating the stress factors only moderately above the values encountered under operating conditions.

Smith et al (1998) compare the effectiveness in detecting PD using the following techniques: Rogowski Coil, Radio Frequency Current Transformer (RFCT) and Permanent Capacitor Couplers. Paolitti and Golubev (1999) review various implementation and measurement techniques that have evolved in the industry. Wang et al (2003) discuss the importance of sensors collecting PD data reliably and accurately with HV ceramic capacitors.

McDermid et al (2006) investigated the response of capacitive couplers in a generating unit to various sources of PD. They found that certain instruments coupled to these couplers can discriminate correctly between machine PD and power system noise.

Stone and Warren (2004) present the statistical analysis of PD results in a database and shows that voltage class, hydrogen pressure (where used), manufacturer, type of PD sensor and instrumentation are critical to interpreting test results; whereas machine type, insulation type and age of the winding are less important. They present critical values of PD, which indicate significant risk of severe winding problems.

Stone and Warren (2006) review methods that can reduce the risk of false indications of stator winding problems. Four objective methods that separate PD from noise are described and the differences of PD activity as a function of winding age, insulation type and machine manufacturer are presented.

Allahbakhshi et al (2009) introduced a new ultra-wide-band measuring system that can help to detect measure and record the waveform of PD pulses. The background noise reduction and pulse refinement ability of this system is very helpful and effective. Also it can be used effectively to suppress and filter external pulses. This advantage makes the ultra-wide-band systems a proper on-line measuring system for HV equipment. The measuring results on a hydro generator showed this system has valuable potential to be used in generators for on-line measurement.

Hudon et al (2008) studied the influence of different parameters affecting the intensity and behaviour of slot PD. Two laboratory experiments were set up in order to investigate the influence of different parameters on slot PD activity. The goal of the first experiment was to establish the relative importance of temperature and gap size on slot PD. The second experiment was used to determine how multi stresses, for example electrical, thermal and mechanical, influence the discharge mechanisms of stator bars affected by slot PD. Finally, the results obtained in the laboratory were confirmed when compared with actual field measurements on a generator.

Zhu et al (2000) analyse the reasons for not relying on an absolute PD magnitude to assess the insulation condition of rotating machines. Some of the factors which affect the diagnosis of stator insulation problems include the following: PD types and locations, PD calibration problems in rotating machines, bandwidth of the PD detector and differences among machines and PD measurements. They describe how these factors influence the assessment of stator insulation condition. PD trend analysis is recommended as the best way to identify machine insulation problems and is well demonstrated by some case studies. Stone (1998) discuss the complexities involved with PD calibration.

2.7. The effect of stator bar location on partial discharge?

Morin et al (1995) carried out statistical analysis on the results obtained with diagnostic tests on stator bars aged 7 and 22 years respectively. The results suggest that some deterioration of the stator bars have taken place under service conditions. The diagnostic tests comprised of voltage breakdown, PD inception voltage, average maximum apparent charge, total apparent charge, $\tan\delta$ and $\tan\delta$ tip-up. The deterioration of the stator bars is principally supported by the voltage breakdown, PD inception voltage and average maximum apparent charge test results.

All three parameters exhibit a perceptible systematic change with operating time. Regarding the inter-parameter correlations, no systematic tendencies are observed, although in some particular cases, such as that between the maximum apparent charge and breakdown voltages, correlations are obtained between the neutral end and 8 kV line end bar specimens aged in-service for 22 years. The statistical analysis would have been more conclusive had larger numbers of test specimens been available for the diagnostic tests.

2.8. Is there correlation between diagnostics tests and breakdown voltage?

Stone et al (1988) subjected stator windings to a wide variety of diagnostic and destructive tests. Diagnostic tests included Insulation Resistance (IR), Polarisation Index (PI), capacitance, dissipation factor tip-up, PD magnitude and discharge inception voltage. The destructive tests included breaking down individual coils with either AC, DC, or impulse voltages. No correlation was found between the diagnostic tests and the breakdown voltage.

They concluded that too few machines were tested to derive at any quantitative relationship between diagnostic tests and breakdown voltage. They also stated that it is unlikely that sufficient data will ever be collected for a quantitative relationship to be developed, especially when a relationship would be necessary for every different insulation system and operating environment.

However, they did collect considerable statistical data on the relationship between diagnostic tests on individual coils and the breakdown voltages of those coils. They state further that no group of tests on individual coils, nor once-off diagnostic tests, seem to be able to predict breakdown voltages. However, AC and DC diagnostic testing of stator windings give useful information on the relative condition of the winding insulation. The information from such diagnostic tests is most useful when results are taken over time, so that a historical trend can be established.

2.9. Can partial discharge test be used as a key decision making tool?

Investigations to improve current diagnostic techniques used to evaluate the condition of insulation systems are on-going. Contin et al (2000) developed a new measuring system. This measuring system allows the digital acquisition of PD pulse signals, operates at a sampling rate high enough to avoid frequency aliasing and provides an amount of PD pulses which enables PD stochastic analysis.

In addition to the traditional PD pulse height and phase analysis, PD pulse shape processing is also available. The first results of PD measurements performed on different types of complete stator bars, with and without defects, are reported to show the system performance.

If different PD phenomena are simultaneously active or PD sources are differently located, it can produce pulse sequences with different PD pulse shapes. These features can be used conveniently for separation between different simultaneously active PD phenomena. If separation is performed successfully, the original PD pulse sequence can be split in more sub-sequences, each one relevant to a well-defined PD phenomenon. Therefore, identification of failure mechanisms is facilitated.

The PD site location (PDSL) system was developed to provide a follow up diagnostic test once PD condition monitoring equipment indicates a potentially significant insulation problem is emerging. Simpson et al (1995) conducted dissection test to correlate the results with those obtained from on-line PD measurements. The on-line PD measurements were obtained utilising an RF slot probe, partial discharge analyser type H (PDA-H) detector and PDSL system. Good correlation was found between all methods with the PDSL system achieving high accuracy in identifying individual high discharging coil sides. The dissected coil sides showed deterioration of the inter-strand insulation and insulation/copper stack interface which was consistent with the negative pulse predominance characteristics of the on-line PDA and PDSL measurements. This research work suggests the PDSL accuracy in PD site location may be such as to enable accurate identification of high magnitude discharging coils which are at risk of failure. This diagnostic technique may have the potential for providing vital information to determine deferral of maintenance or refurbishment intervention of generators and thereby reducing life cycle costs.

Tychsen (1989) describes a power producer's initial experiences with PD technology. The age of this plant, the lack of reliable stator winding condition diagnostic methods and visual evidence of insulation deterioration during major overhauls made it imperative for the utility to invest in on-line PD condition monitoring equipment. Despite a limited set of measurements, on-line PD data has enabled the power producer to implement significant improvement and maintenance strategies in the fleet of generators.

Hudon and Rehder (1995) investigated discharge pattern evolution as a function of electrical aging for internal PD and external corona activity. From phase resolved PD analyses (PRPDA) and spectrum analyses two types of characteristic discharges patterns have been identified. Other factors such as the characteristic resonant frequencies of the system and the signal attenuation with propagation frequency will strongly depend on the machine size, bar length and winding design. Results indicate that the internal discharge spectrum will generally differ from external corona. It is believed that if multiple sources are present they most probably do not evolve at the same rate and represent different levels of risk. One level of discharge may be acceptable for one type of discharge while it would be considered critical for another one.

Fruth and Niemeyer (1992) experimented with a digital PD measuring concept which was designed to acquire not only conventional PD charge magnitudes but also statistical characteristics of PD signals which contain most significant information on insulation defects. The potential of combining the new measurement concept with a physical interpretation was demonstrated by measurements on artificial defects in laboratory experiments as well as on real HV insulation systems.

Hudon et al (1996) found that slot discharges and other simulated defects generated characteristic Phase Resolved PD Patterns (PRPD) easily distinguishable from internal discharge patterns. The severity of the defects created was not evaluated but it was found that PRPD recognition was a useful identification tool. They state that all discharge types cannot be treated equally, and probably don't degrade the insulation at the same rate. Both, acceptable levels and rate of change could very well be different for each type of defect.

Stone (2005) describes technical problems associated with factory PD tests on complete windings and proposes a method by which machine purchasers could insert a scientifically justifiable factory PD test requirement in a new or rewound stator specification. He also reviews the reasons for specifying both meaningful, yet not unreasonably difficult PD levels to pass, for a new machine.

While a variety of quality control tests are important in the production of stator bars and coils, there is merit in making selections for voltage endurance test (Ward et al, 1987) based on PD screening tests, instead of by a random selection process. McDermid and Bromley (1992) conducted tests to illustrate the relationship between PD and voltage endurance time. They concluded that, based on the PD screening test results, stator bars or coils can then be assigned to the line, middle or neutral thirds of the winding. A decision can even be made whether these bars or coils should be excluded, depending upon the test results and the specified voltage endurance requirements.

Bélec et al (2008) present results of a case study of on-line PD measurements from both the PDA and the PRPD techniques on a generator. Identification of slot discharge activity in the PRPD patterns in this generator triggered a more detailed diagnostic. In-situ off-line measurement of the electrical contact between individual bars and stator core was performed on selected bars in order to confirm the presence and extent of a semi-conductive coating problem.

In this particular case it was concluded that the slot discharges were localized and the short-term failure risk was low. This conclusion was confirmed by PRPD, contact coefficient measurements and visual inspection.

2.10. Conclusion

The papers clearly confirm that on-line PD is a reliable and proven tool for measuring the actual condition of stator windings insulation under actual operating conditions. On-line PD measurements can identify failure mechanisms in generators. However, PD can only detect these failure mechanisms but cannot predict when actual failure will occur. Having historic PD data available enables users to make better informed decisions regarding the actual condition of generators and affects planning maintenance and refurbishment decisions.

Other diagnostic test, for example IR or PI, can also disclose meaningful information regarding the relative condition of the insulation. It can be extremely helpful in making comparisons between phases and different machines with similar insulation systems.

However, as discovered from the literature research, a once-off set of diagnostic tests cannot accurately predict the condition of the insulation. The information from diagnostic tests is most useful when results are taken over time, to enable the establishment of a historic trend.

Dissection or invasive tests conducted on aged bars provided a very good correlation with the actual condition as determined by on-line PD and diagnostic tests. The dissection test provides a method of putting the diagnosed suspected failure mechanisms into perspective. It is also important to note that some of the failure mechanisms identified during dissection, were completely overlooked by diagnostic methods.

Destructive tests, which included breakdown voltage, cannot be used to predict the remaining life of stator insulation as the diagnostic tests do not correlate with the breakdown voltages. Obviously the test specimens cannot be re-used as they have been damaged during the test. It can be stated that the remaining life of stator winding insulation cannot be predicted on the basis of diagnostic tests alone but that diagnostic tests are most useful to indicate the trend in insulation aging.

As trending of PD is a powerful tool, it is extremely important to ensure that the test method (McDermid and Bromley, 1999) and certain operating parameters remain constant during testing. It has been proved that PD is affected by generator operating conditions. The important operating conditions that should remain constant are voltage, temperature, loading and to a lesser extent humidity (Stone et al, 2002)

Some of the factors which affect the diagnosis of stator insulation problems are PD types and locations, PD calibration problems, bandwidth of the PD detector and differences among generators. Critical values of PD, which indicate significant risk of severe winding problems, can change with changing operating conditions. Reviewed methods that can reduce the risk of false indications of stator winding problems are also available. Methods for separating PD from noise and differences of PD activity as a function of winding age, insulation type and machine manufacturer are well documented.

No correlation between diagnostic test and breakdown voltage was found. The researchers are also of the opinion that it is unlikely that a quantitative relationship would be found, as a relationship for every different insulation system and operating environment would be necessary.

The PD monitoring technique has been identified to reliably identify the different failure mechanisms in generators. All discharge types cannot be treated equally and the rate of degradation of different failure mechanisms are completely different. Hence, different repair or refurbish strategies would be implemented. Power producers utilise this vital information to implement maintenance and refurbishment strategies.

PD tests can even be utilised as one of the control test during manufacturing of stator bars. Instead of making the conventional random stator bar selection for voltage endurance testing, this selection can now be based on PD screening tests.

CHAPTER 3

Partial discharge testing

As revealed in the literature review, PD can be a powerful diagnostic tool. PD can be either a source or a symptom of stator bar insulation systems deterioration in HV generators (Johnson and Warren, 1951). PD testing can be utilised to detect and monitor certain failure mechanisms in generators (Contin et al, 2000).

3.1. Partial discharge testing

As stated earlier, Eskom decided to install PD couplers to detect and monitor PD, utilising the Iris PDA method.

PD on-line testing is done utilising the Iris test method and instrumentation as prescribed by Eskom generation. The testing is done as per Eskom Guideline GGG 0826. All the relevant sections are extracted in Appendix A.

3.2. Partial discharge locations

Figures 3.1 and 3.2 show typical PD discharge locations in hydro generator stator bars (Eskom Guideline GGG 0826, 1999)

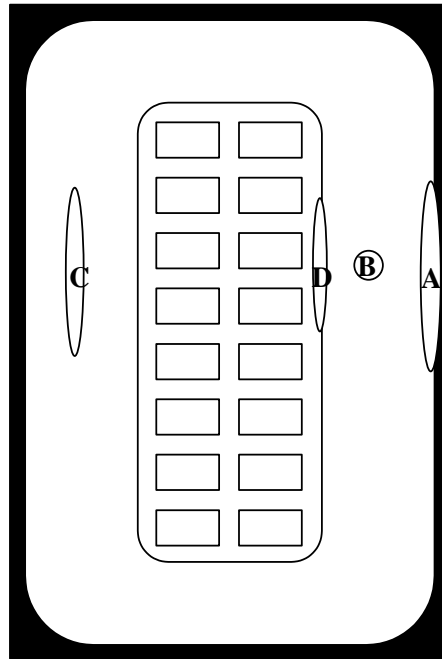


Figure 3.1: PD locations in stator bar
A: Void between the main insulation and the slot wall
B: Void in the main insulation
C: Delamination between the layers of insulation
D: Delamination between the winding stack and the

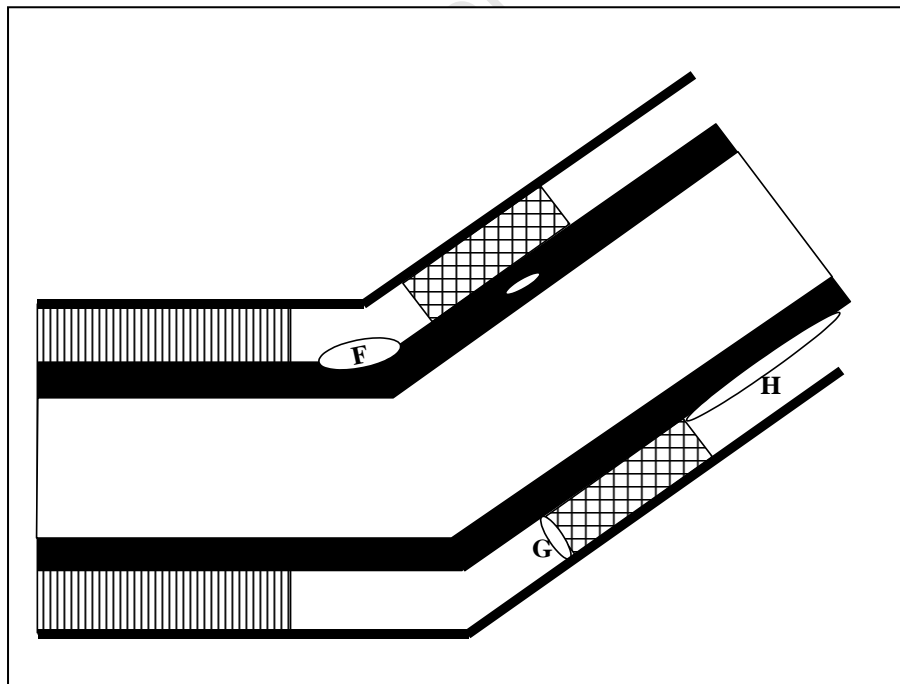


Figure 3.2: PD locations in endwinding region
F: Delamination of the insulation at the elbow
G: Tracking between bars
H: Surface tracking

3.3. Partial discharge interpretation

Interpretation of PD test results are described in IEEE 1434-2000 in Sections 11.1-11.5 with excellent reference papers in A.5.

3.4. Iris PDA test method

As stated earlier, Eskom decided to utilise the Iris PDA test method to detect and monitor PD activity in the hydro generators.

3.4.1. Monitoring hardware equipment

In order to detect pulses caused by PD the PDA test requires the installation of HV capacitive couplers, (coupler A and B) on the stator winding as shown in Figure 3.3. This figure shows the installation of couplers on one phase only. The other two phases are connected in the same manner with inputs to the PDA. These retrofitted capacitors block the 50 Hz signals, yet allowing the very high frequency (~47 MHz) of PD pulses to be conducted to the measuring apparatus (PDA).

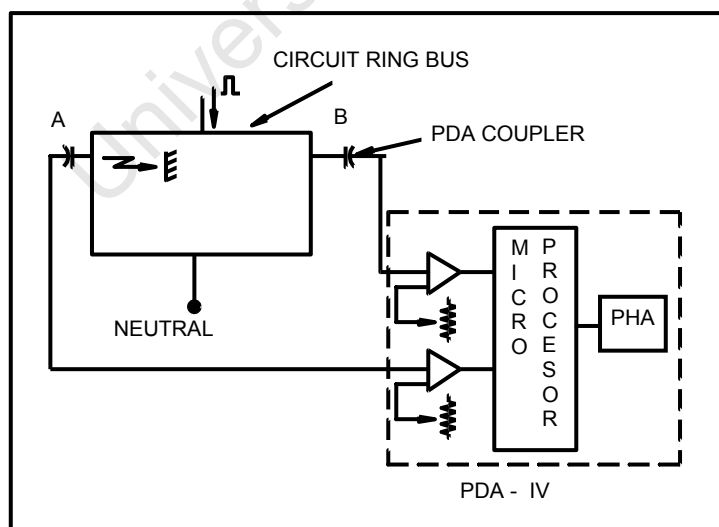


Figure 3.3: Location of couplers

In any PD measurement noise suppression is of vital importance. When testing HV rotating machines, electrical noise (interference) can come from many sources e.g. static exciter, service transformer, and arcing brushgear.

Although much of this interference has a different frequency content than PD, some types of noise do appear to have a similar character as PD pulses. To measure PD on an operating winding, a method had to be found to distinguish between noise and winding PD signals.

The principle feature of the PDA test is its ability to reject electrical interference from the power system, which often dominates the PD signals in on-line tests. The interference is reduced by forming a bridge-like circuit from two capacitive couplers. By relying on the very high frequency of the PD pulse and the fact that it takes time for electrical pulses to travel along the generator's circuit ring bus, common-mode electrical noise from the power system is eliminated (Gaouda et al, 2008). Typical travelling times for PD pulses are 0.3 m/ns in copper and 0.2 m/ns in co-axial cable.

The PDA determines and logs the polarity, number and magnitude of pulses picked up by the permanent couplers. The instrument is portable and can be used to test a large number of machines equipped with retrofitted permanent coupling capacitors.

The attenuation and differential amplification circuitry, which eliminates external noise, is incorporated into the PDA. The remainder of the PDA circuitry consists of a dual polarity pulse height analyser, which can respond to 5ns rising pulses. The pulse height analyser determines the number of PD pulses per second and their magnitude. Circuits are also present to eliminate false counting from pulse ringing and reflections. The operation of the PDA is controlled by a microprocessor. Test results are normally acquired, filed and displayed via an IBM compatible computer, connected via Ethernet, and a dedicated software controller. The software package being used to collect data is called PD-Lite and the software package used for analysing this data is called PD-View.

3.4.2. PDA test software (PD view)

The software (PD-View) produces two types of plots, as shown in Figures 3.4 and 3.5, for each PD test. The first type of plot, Figure 3.4, is two-dimensional (2-D), where the number of PD per second versus PD magnitude is displayed. The greater the number of pulses per second, the more widespread is the deterioration in the winding insulation. The higher the PD pulses magnitudes, the more severe is the deterioration. Both positive and negative PD activities are plotted.

The second type of plot, Figure 3.5, is three-dimensional (3-D). These plots show the number (y-scale) and magnitude (z-scale) of the PD versus the AC phase angle (x-scale). Experience has indicated that such pulse phase analysis can be used to identify whether multiple deterioration mechanisms are occurring, and what these mechanisms are.

The PDA-IV summarises each plot with two quantities: the peak PD magnitude (Q_m) and the total PD activity (NQN). The Q_m is defined as the magnitude corresponding to a PD repetition rate of 10 pulses per second. Q_m relates to how severe the deterioration is in the worst spot of the winding, while the NQN is proportional to the total amount of deterioration. The NQN and Q_m values are calculated for both the positive and negative PD by the PDA-IV instrument. From experience the following is used as a guideline for analysis of epoxy-mica insulation:

Q_m	<100 mV, good
Q_m	>500 mV, bad

The trending of PD over time is one of the most powerful methods of determining the condition of the HV insulation system of generator stator windings (Stone et al, 2002).

As trending of PD is a powerful tool in determining the condition of insulation, it is extremely important that certain operating parameters remain constant during testing. The important operating conditions that should remain constant are voltage, temperature, loading and to a lesser extent humidity. The trend of on-line PD data collected over 8 years, at Gariep Hydro Power Station, will be displayed.

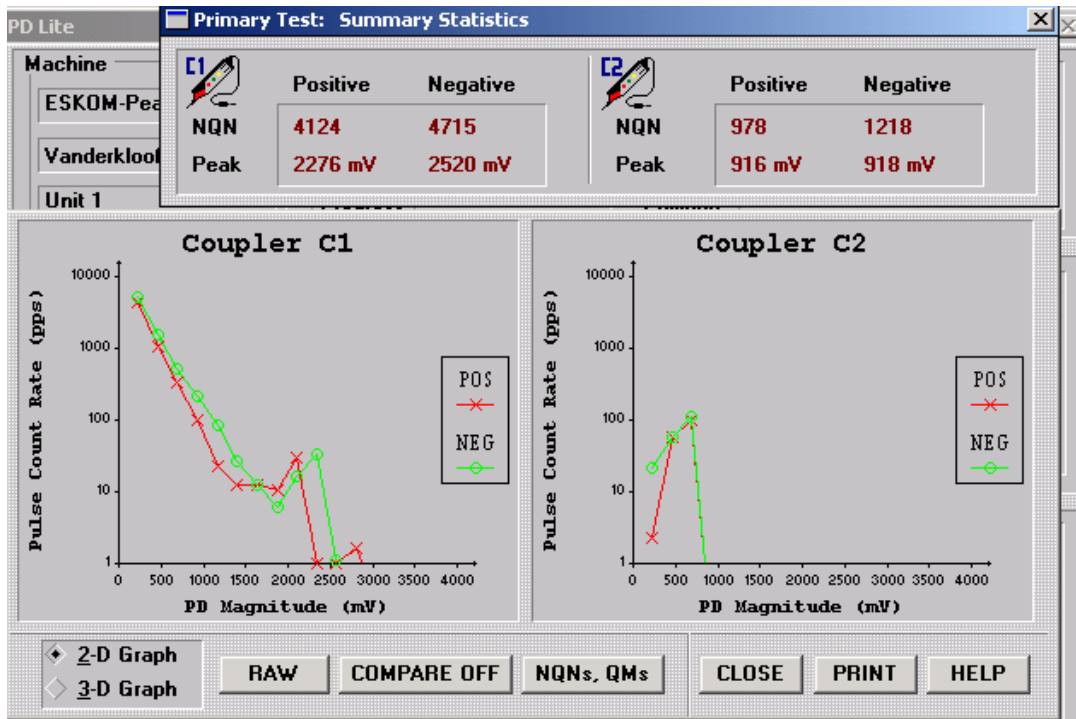


Figure 3.4: Typical 2-D Plot

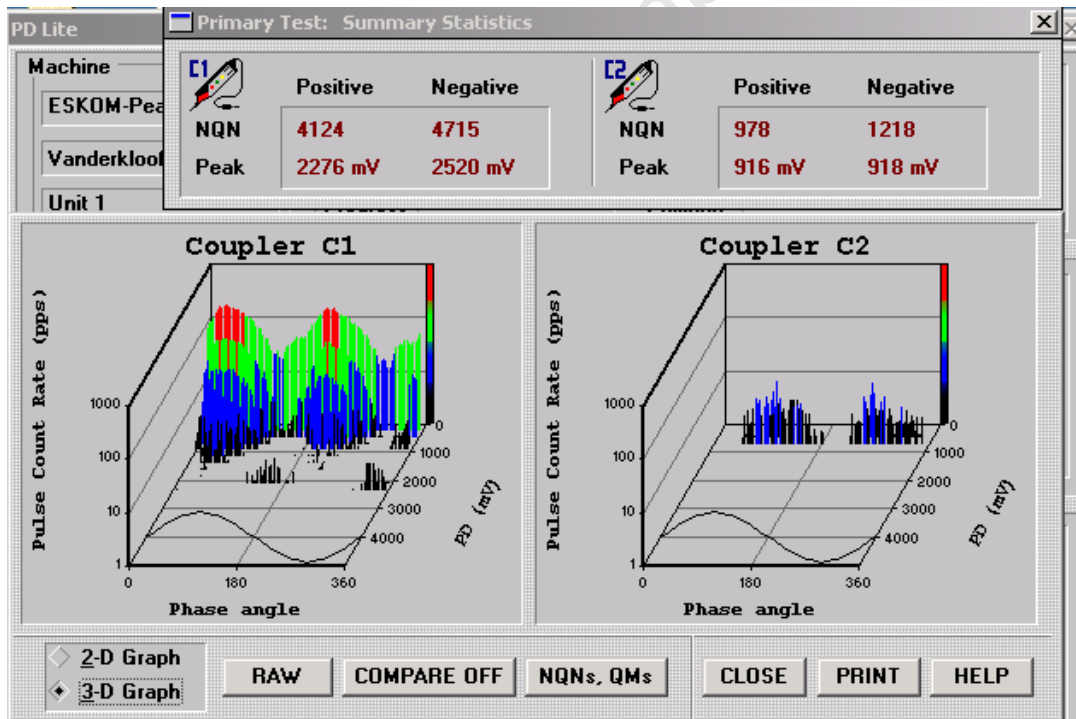


Figure 3.5: Typical 3-D Plot

3.5. Typical partial discharge test set-up

In order to detect pulses caused by PD the PDA test requires the installation of HV capacitive couplers (80pF) on the stator winding. The other side of the couplers, conducting the high frequency PD pulses, is connected to co-axial cables. These cables are routed via cable trays to the termination box. Inside the termination box the co-axial cables get connected to BNC connectors. The PVA-IV test instrument then gets connected to these to perform PD on-line tests.

The PDA-IV instrument determines the magnitudes, rates and polarities of voltage pulses created by PD. Additional parameters such as NQNs and peak pulse magnitudes are also calculated. The instrument comes equipped with user selectable RS232, USB, or Ethernet (TCP/IP) communication ports. An external computer is used to control data acquisition, display, and store PD test results quickly and conveniently. The software package being used to collect data is called PD-Lite and the software package used for analysing this data is called PD-View

Figures 3.6- 3.11 show an installed capacitive coupler and a typical test set.

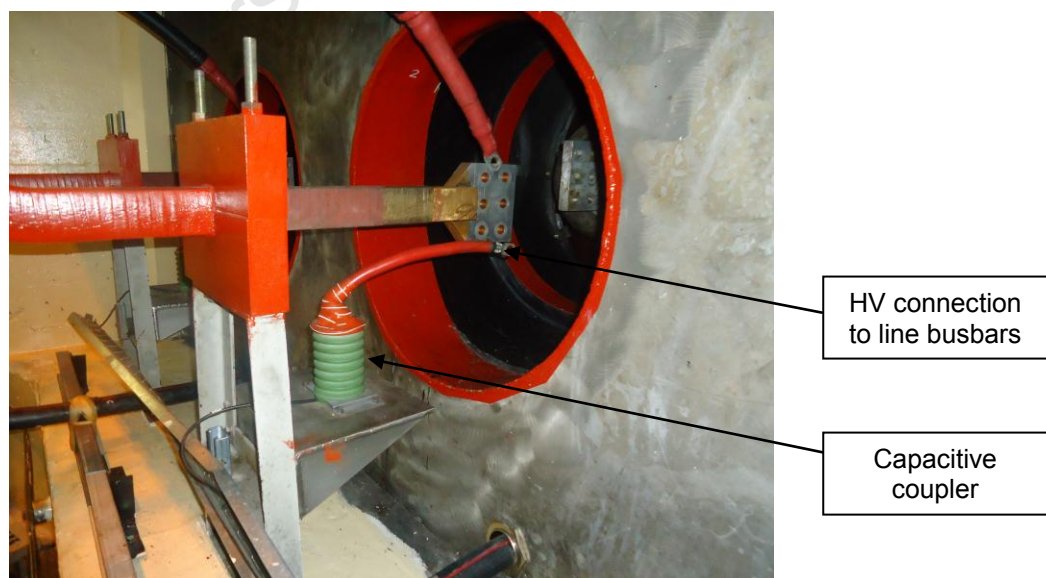


Figure 3.6: Capacitive coupler with HV connection



Figure 3.7: Capacitive coupler with co-axial connection for transfer of high frequency of PD signal

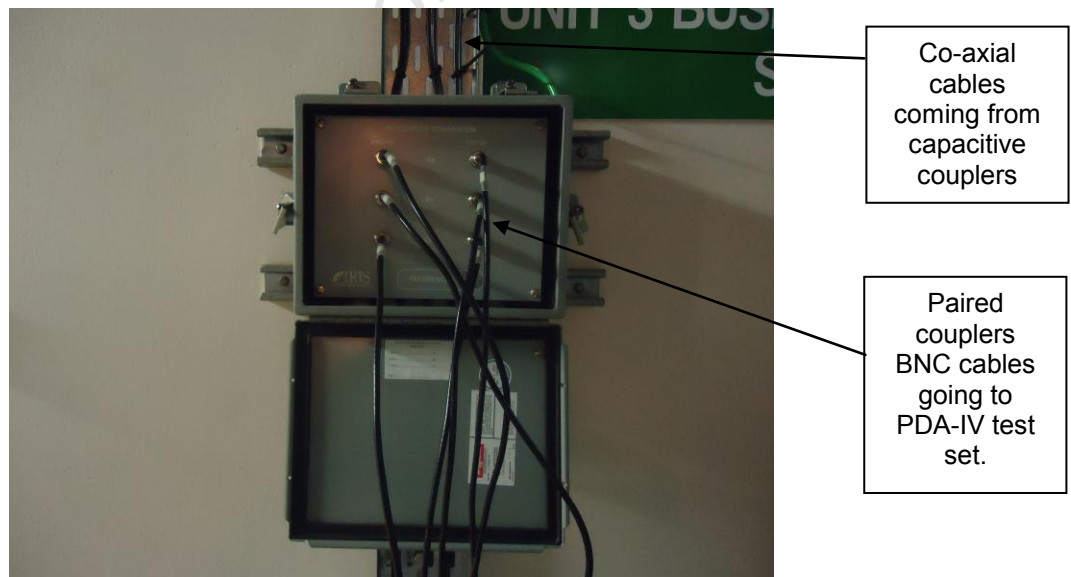


Figure 3.8: Termination box



Paired
couplers BNC
cables coming
from
termination
box.

Figure 3.9: PDA-IV test set



Figure 3.10: PDA-IV test setup showing Ethernet connection to software interface



Figure 3.11: Typical PD data collection test setup

CHAPTER 4

High voltage direct current insulation testing

4.1. Expected correlation between PD and breakdown voltage

As will be seen later from the trends of one of the Gariep Hydro Power Station generators, Figures 6.1-6.3, there is a steady increase of positive PD (Q_{m+}) measured over a period of approximately 8 years. The negative PD (Q_{m-}) values of the red and white phases start decreasing between 2006 and 2007. The blue phase negative PD (Q_{m-}) value starts decreasing between 2002 and 2003. Decreasing of PD even just prior to insulation failure is not uncommon (Bartnikas 1979), but is not yet understood. With no significant polarity predominance evident in the red and white phases, over the first couple of years, analysis showed that the PD was occurring within the groundwall according to Lyles et al (1988). With the blue phase having a negative PD (Q_{m-}) predominance, the PD was probably occurring at the copper and groundwall interface (Lyles et al, 1988). The interpretation is consistent with the guideline subsequently produced by Shunyuan and Chow (2007).

With the above background and the fact that a larger overvoltage, across the void, produces a larger pulse amplitude with a shorter rise time (Bartnikas and Novak, 1995), it was expected to find some correlation between the PD results and breakdown voltage.

4.2. HV direct current insulation test

The windings will first have to be declared suitable for HV testing according to IEEE 43-2000. This standard provides a basis for interpreting IR test results to estimate stator bar suitability for an overvoltage test. Sections 5,6,8,11 &12 are applicable.

The test set-up regarding instrumentation and connections are done in accordance with IEEE 95-2002 Section 5.

The test procedure for proof testing and controlled overvoltage as per IEEE 95-2002 is described in Sections 6 and 7 respectively.

Three (3) alternative HV DC test methods are available, that is, uniform-time step, graded-time step and ramped voltage. The ramped voltage test method will be utilised thereby minimizing any human interference. The test is more accurate, repeatable and better controlled compared to the other test methods (IEEE standard 95-2002). Unfortunately the ramped voltage test method could only be applied to the 30 kV and 23 kV (rms 0.1 Hz) test. The 50 kV test was done utilising the uniform-time step (voltage increments) method.

University of Cape Town

CHAPTER 5

Generator history

5.1. Generator history

The stator bars that were used as test specimens came from Gariiep Hydro Power Station generators Units 3 and 4. The units were commissioned in 1974 and 1976 respectively. The generators are used in a peaking operating regime with typical morning and evening start for a generating period of about three hours. Every stop-start and start-stop action is classified as a mode change. This parameter is important as stopping and starting of generators could also affect stator bar insulation degradation. Unfortunately, history regarding the operation of the generators is limited. The available information is displayed in table 5.1:

Table 5.1 Generator operating and design data

Unit	Year Commissioned	Generating hours (1995 to Dec 2009)	Mode changes (1994 to Dec 2009)
3	1974	53 841	8 542
4	1976	31 104	6 759
Design Data			
Rated Output	100 MVA		
Rated Voltage	13 200 V		
Rated Current	4 374 A		
Power Factor (Lagging)	0.9		
Phase rotation	Red-white-blue (Clockwise)		
Efficiency at rated output	98.12%		
Rotation (viewed from NDE)	Counter-clockwise		
Rated frequency	50 Hz		
Number of poles	44		
Number of phases	3		
Rated speed	136.4 rpm		

Runaway speed under 69 m head (No load)	296 rpm
Rotor	
Insulation class	B
Rated Voltage	440 V
Rated Current	940 A
Stator winding	
Insulation class	B
Type of winding	wave
Connection	star
Total conductors	792
Conductors per slot	2
Bar insulation, slot section	Mica tape impregnated with resin
Bar insulation, overhang section	Mica tape impregnated with resin
Cooling	
Type of cooling	Closed air circuit
Number of coolers	8
Cooling medium	air
Quantity of cooling water at 30°C required	80 l/s
Heat exchanged (8 coolers)	1660 kW

5.2. PD monitoring history

PD detecting and monitoring equipment was installed in September 1998 on the units at Gariep Hydro Power Station. PD readings have been taken over a period of approximately 12 years at intervals of 1450 running hours. It must be admitted that the test results were fluctuating over the first few years (approximately 4 years) due to engineers still training and the operating parameters not being kept similar for trending purposes. Hence, the trends in Figures 6.1-6.3 starting at around 2002 only. These trend results will be discussed in the following chapter.

The analyses over the years, of the 2-D and 3-D plots similar to Figures 3.4 and 3.5, have shown both slot and endwinding discharges to be present (Shunyuan and Chow, 2007). The test data show classic slot discharges present at 45 (negative PD) and 225 (positive PD) degree on the AC cycle waveform (Shunyuan and Chow, 2007). It is also showing endwinding discharges at 15/75/195/255/-105/-165 degrees (Shunyuan and Chow, 2007).. The possible failure mechanisms for the two units are shown in Table 5.2

Table 5.2: Failure mechanisms detected in various phases of Gariep Units

Unit 3		Unit 4	
Phase	Failure mechanisms detected	Phase	Failure mechanisms detected
Red	Slot & endwinding discharge, cross coupling	Red	Slot & endwinding discharge, cross coupling
White	Slot & endwinding discharge, cross coupling	White	Slot & endwinding discharge, cross coupling
Blue	Slot & endwinding discharge, cross coupling	Blue	Slot & endwinding discharge

5.3. TVA probe testing

TVA probe testing was done on Gariep Units 4 and 3 in 2000 and 2004 respectively. The overall test results are shown in table 5.3:

Table 5.3: TVA probe readings test readings

Unit	No of slots	Range of TVA reading (mA)	% of slots in range (%)
Gariep # 3	396	100 - 150	1.26
Gariep # 4	396	100 - 220	0.25

These test results will be discussed in detail in the following chapter.

CHAPTER 6

Partial discharge and TVA test results

6.1. Partial discharge testing history

PD testing was done on the Gariiep Hydro Power Station generators, Units 3 and 4, since 1998 using the Iris testing procedure and equipment. The testing and analyses were done in-house by Eskom engineers who attended an overseas training seminar with Iris to obtain the necessary skills. The parameters recorded during these tests were stator bar temperature, generator voltage and generator loading, both real and reactive power. For simplicity this research is only discussing trends of the Q_{m+} and Q_{m-} values recorded over the years. These two PD quantities were chosen as any significant change in PD would be easily detected by trending these quantities. These trends can be seen in Figures 6.1-6.3. The sudden decrease in PD value in 2010 was due to the fact that the generator was refurbished with a total stator bar replacement during that year.

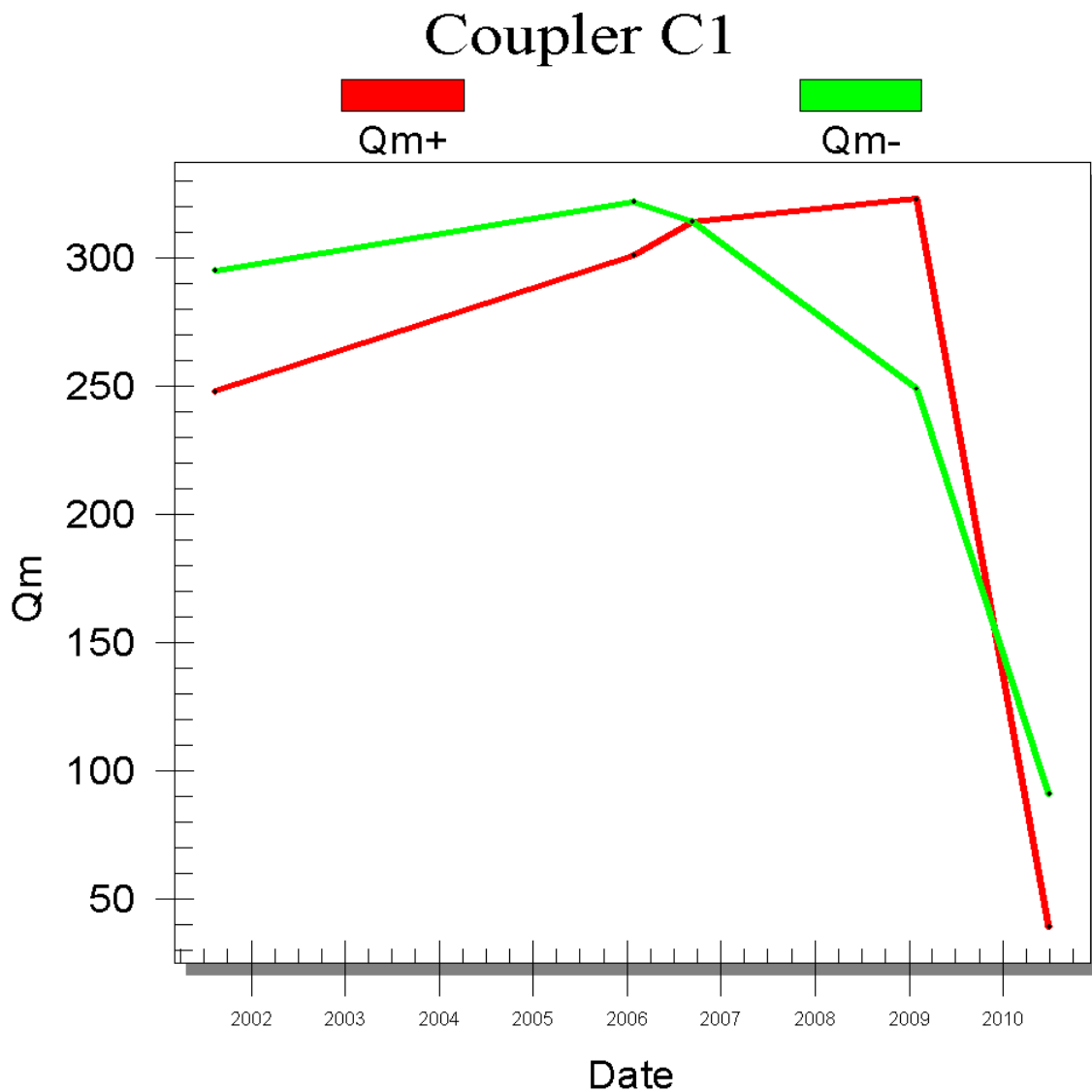


Figure 6.1: Gariep Unit 4 Red phase trend

As can be seen from the above figure, there is a steady increase in both positive PD (Q_{m+}) and negative PD (Q_{m-}) values with no significant polarity predominance until around 2006. This is an indication that the PD activity is occurring within the groundwall (Shunyuan and Chow, 2007). After 2006 there is a decrease in Q_{m-} and a steady increase in Q_{m+} , meaning that the failure mechanism could be driven by slot discharges (Shunyuan and Chow, 2007). This was one of the failure mechanisms identified from the 2-D and 3-D plot analyses as listed in Table 5.2. On the other hand, the failure mechanism could have been driven by the Q_{m-} as PD can possibly decrease just before insulation failure (Bartnikas, 1979).

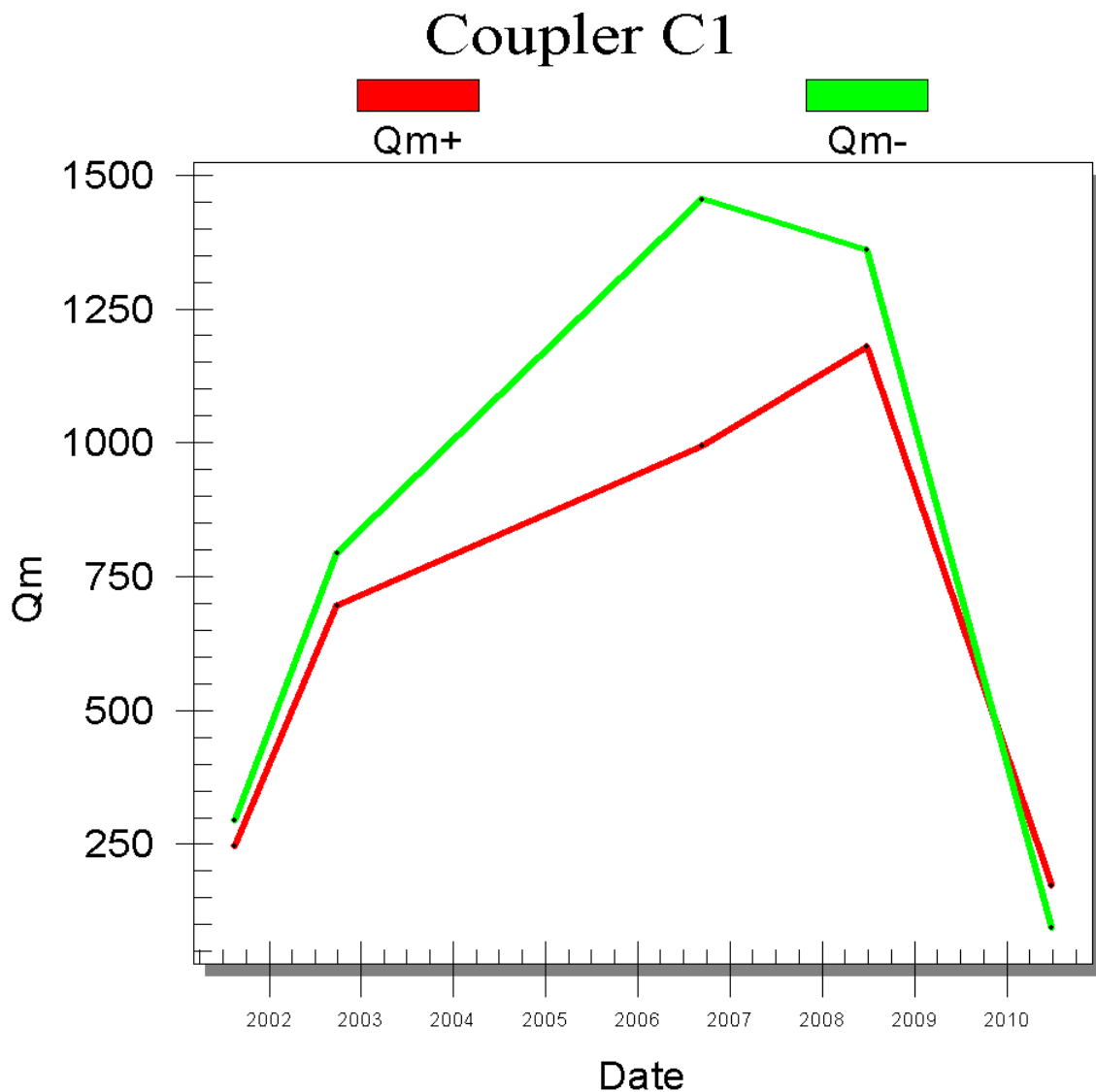


Figure 6.2: Gariep Unit 4 White phase trend

Figure 6.2 shows an increase in both positive PD (Q_{m+}) and negative PD (Q_{m-}). Initially until somewhere in 2002 there is no polarity pre- dominance. Hence the PD activity is occurring within the groundwall (Shunyuan and Chow, 2007). From about 2003 to 2006 there is a significant increase in PD with Q_{m-} predominance. This is an indication that the PD is occurring at the copper and groundwall interface (Shunyuan and Chow, 2007). This could indicate a failure of bonds between the copper and groundwall insulation (Stone et al, 2004). After 2006 there is a decrease in Q_{m-} and a steady increase in Q_{m+} , meaning that the failure mechanism could be driven by slot discharges (Shunyuan and Chow, 2007). This was one of the failure mechanisms identified from the 2-D and 3-D plot analyses as listed in Table 5.2. Again, the failure mechanism could have been driven by the Q_{m-} as PD can possibly decrease just before insulation failure (Bartnikas, 1979).

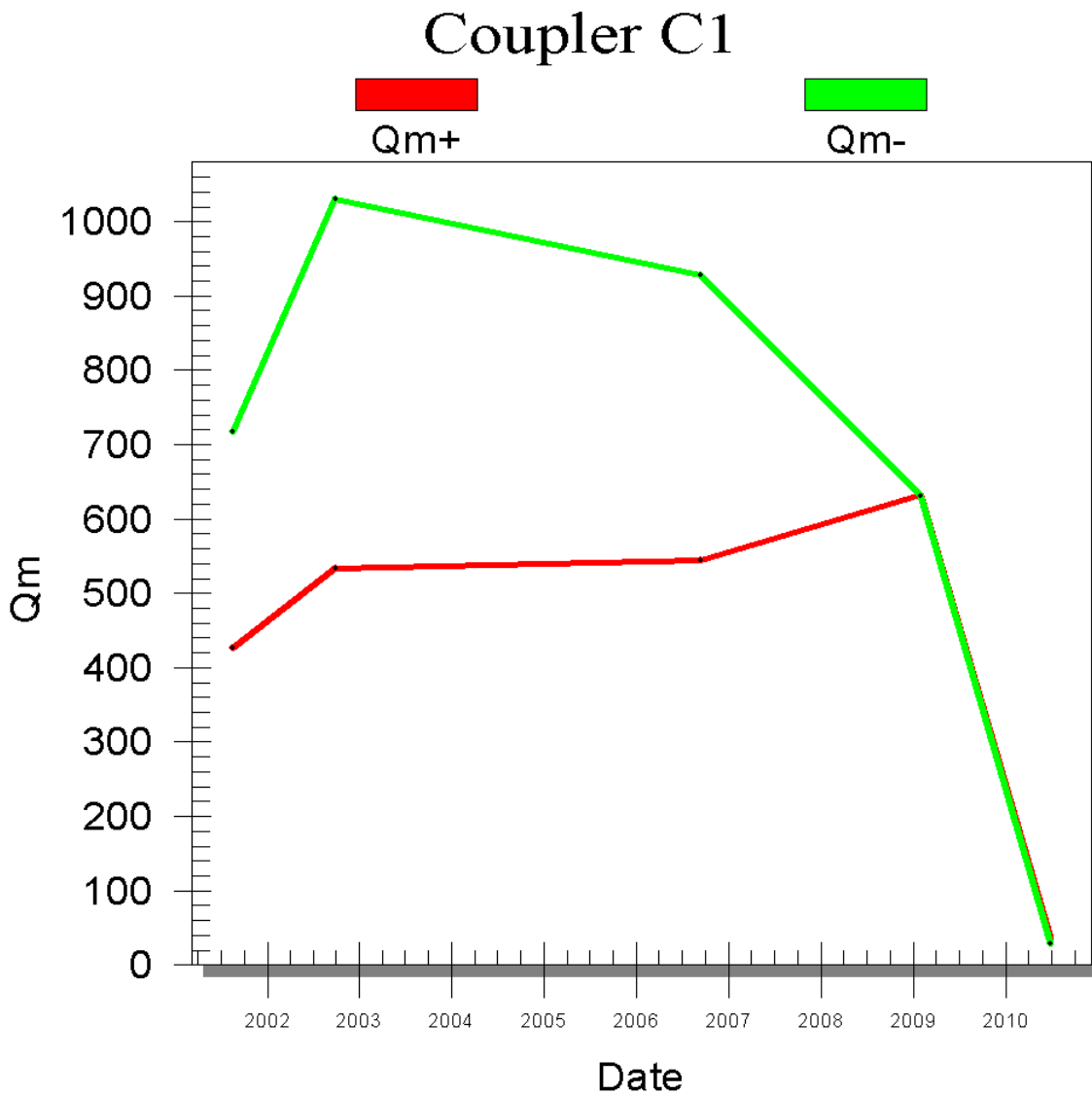


Figure 6.3: Gariep Unit 4 Blue phase trend

Figure 6.3 shows an increase in both positive PD (Qm+) and negative PD (Qm-) with Qm- predominance. Hence, PD is occurring at the copper and groundwall interface (Shunyuan and Chow, 2007). Even with a decrease of Qm- and steady increase of Qm+ between 2003 and 2006, the pre-dominant failure mechanism may still be driven by the Qm-. In other words, the PD is still occurring at the copper and groundwall interface due to the significant Qm- predominance, almost double the Qm+ value (Iris PD seminar, 2000). After 2006 there is a decrease in Qm- and an increase in Qm+ with PD levels becoming approximately equal. This indicates that the pre-dominant PD failure mechanism has moved to within the groundwall insulation. This could also indicate that pre-dominant PD failure mechanism could change over the lifespan of a generator without any repair intervention. Alternatively, the failure mechanism could, once again, have been driven by the Qm- as PD can possibly decrease just before insulation failure (Bartnikas, 1979).

Unit 4 at Gariep Hydro Power Station was rewound in 2010 therefore the decrease in PD values.

A better understanding of the actual failure mechanism present would possibly be explained after dissecting some stator bars (Gupta and Culbert, 1992).

6.2. TVA probe testing

TVA probe tests were done on Gariep Unit 4 and Unit 3 in 2000 and 2004 respectively. Unit 4 and Unit 3 were tested by Rotek Engineering and Technology Services International respectively.

The profiles from Figures 6.4- 6.9 reveal the discharge activity in the slots as presented in table 6.1:

Table 6.1: TVA probe readings test readings

Unit	No of slots	Range of TVA reading (mA)	% of slots in range (%)
Gariep # 3	396	< 10	1.77
Gariep # 3	396	10 - 50	89.89
Gariep # 3	396	50 - 100	7.07
Gariep # 3	396	100 - 300	1.26
Gariep # 4	396	< 10	7.07
Gariep # 4	396	10 - 50	75.51
Gariep # 4	396	50 - 100	17.17
Gariep # 4	396	100 - 300	0.25

Taking cognizance of table 1.2, it would appear that Unit 3 is at risk of a few specific bars failing whereas Unit 4 is showing a higher risk of overall insulation deterioration.

A number of stator bars from these generators were selected for HV testing, which will be discussed in the following chapter.

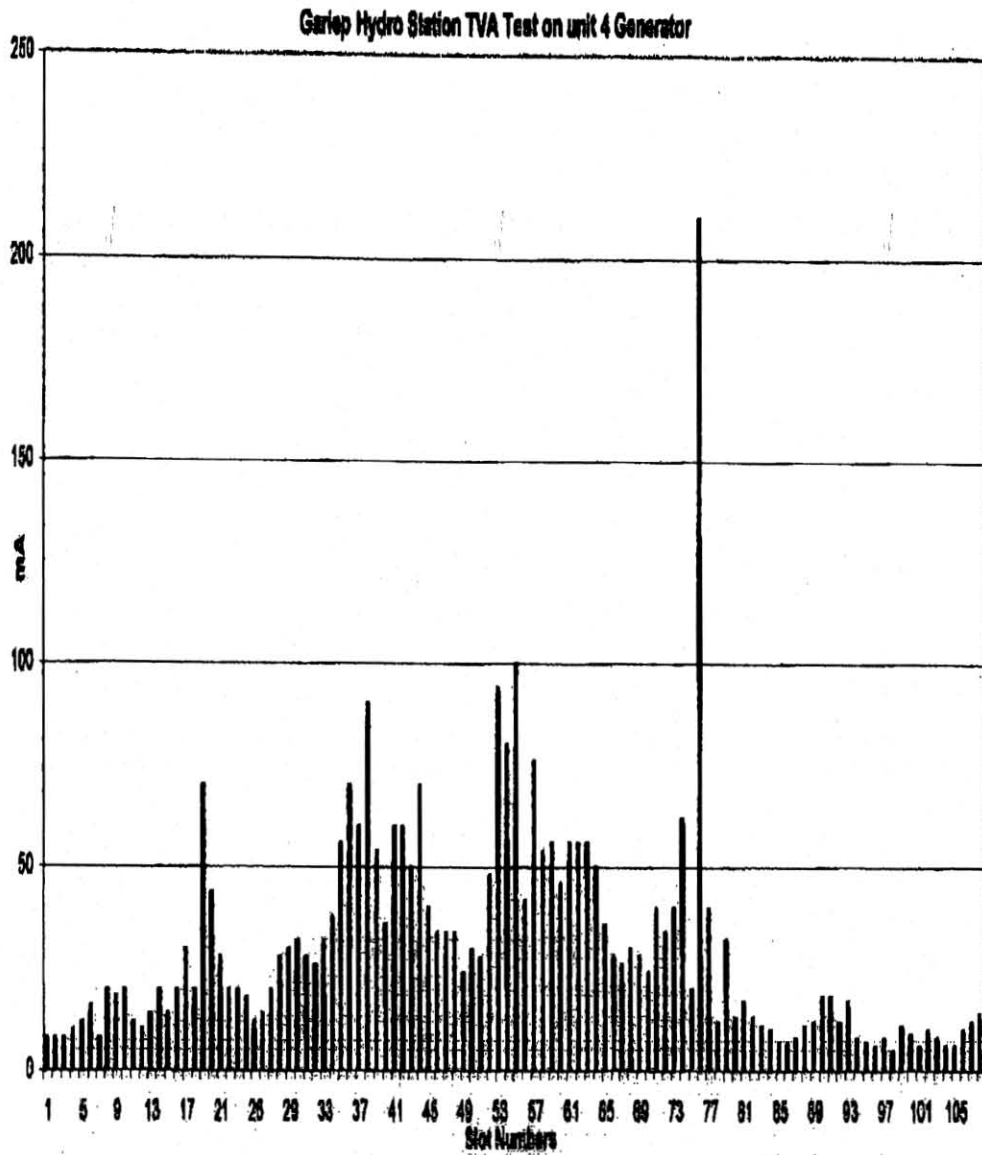


Figure 6.4: Gariep Unit 4 TVA probe profile for slots 105-108

22-JUN-2004 14:07

0116294612

98%

P.13

22-JUN-2004

14:08

TRM

GENERATOR SERVICES

10 60213143121

P.13

Gariep Hydro Station TVA Test on unit 4 Generator

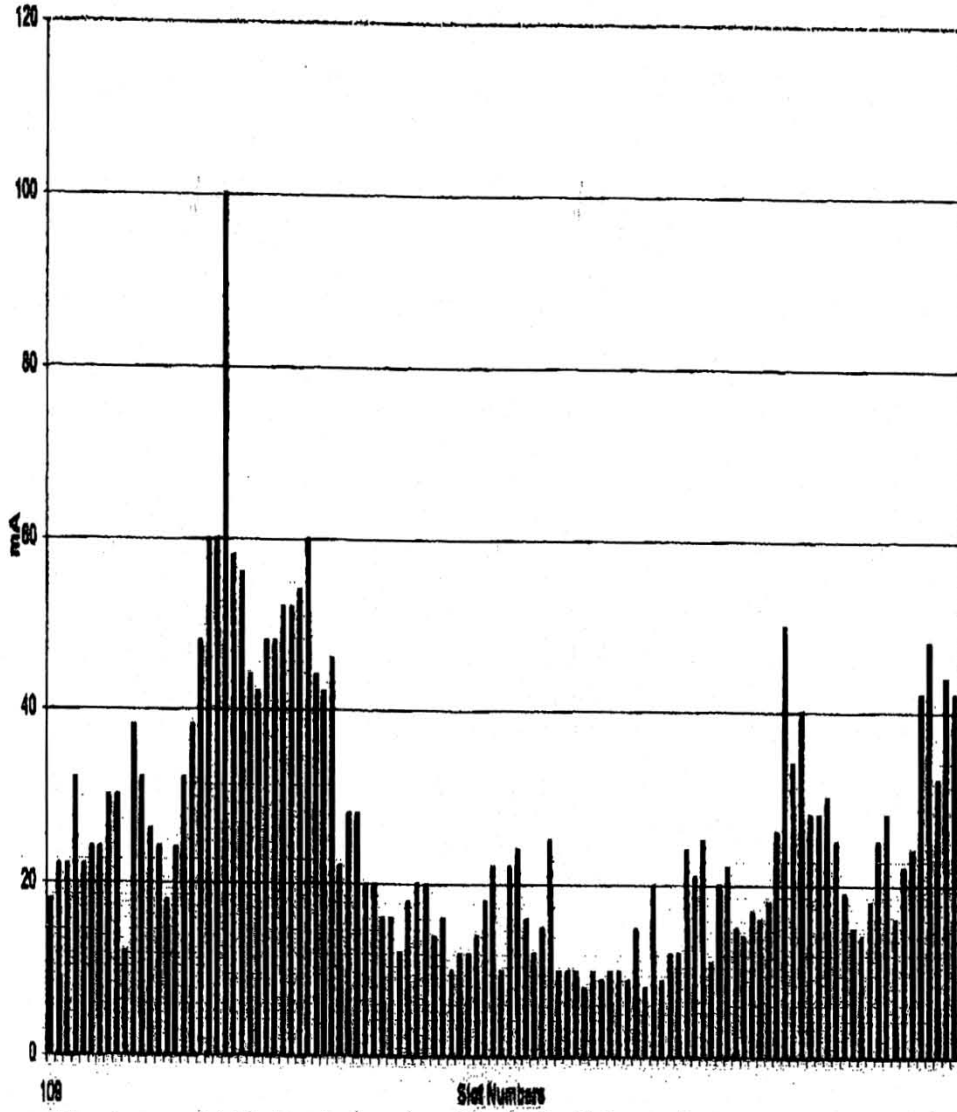


Figure 6.5: Gariep Unit 4 TVA probe profile for slots 109-217

22-JUN-2004 14:07

0116294612

98%

P.15

22-JUN-2004 14:06 IEEE GENCO INC SERVICES IU SERVICE CENTER P.15

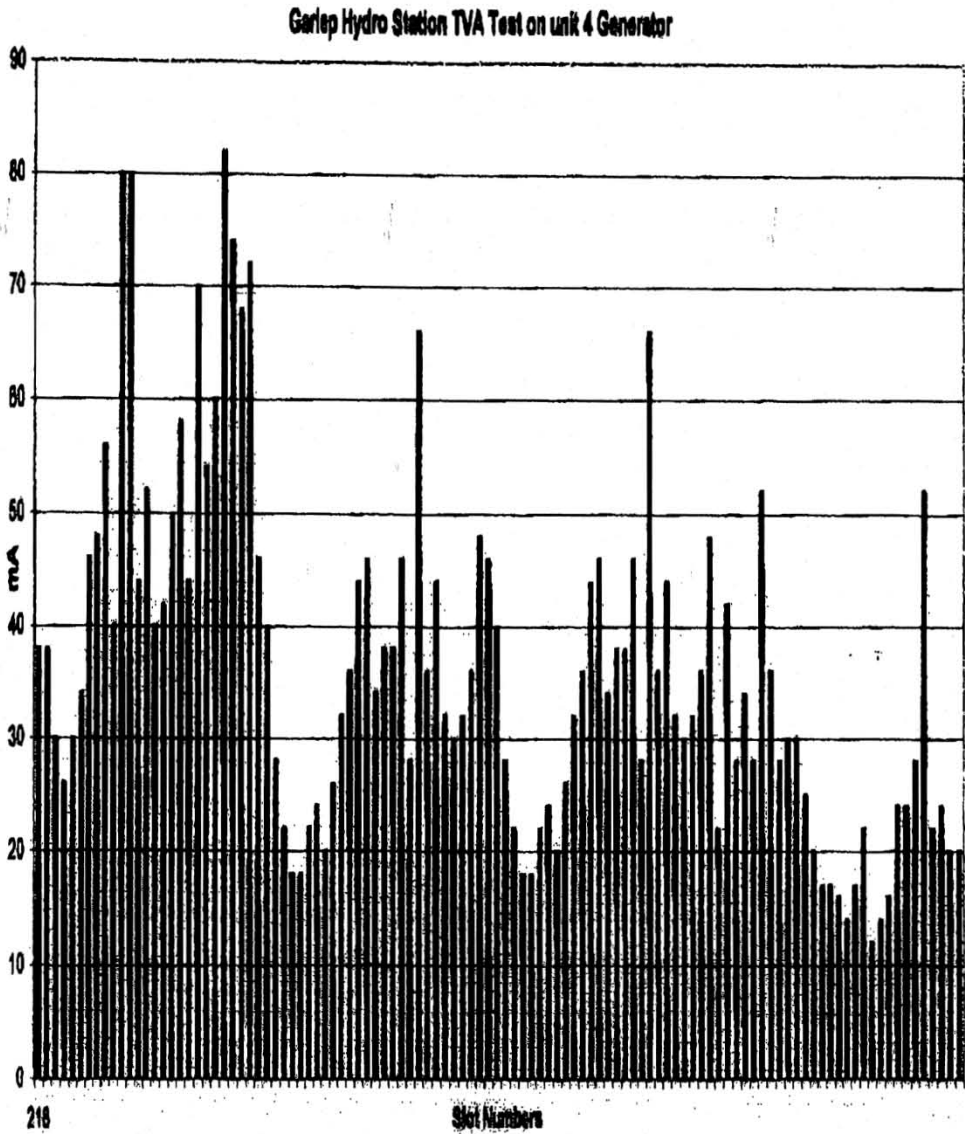


Figure 6.6: Gariep Unit 4 TVA probe profile for slots 218-326

22-JUN-2004 14:08

0116294612

97%

TOTAL P.16
P.16

22-JUN-2004 14:08 TUE GENZIN-UCS SHS-1-CHS
0116294612 97% 000004381 P.16

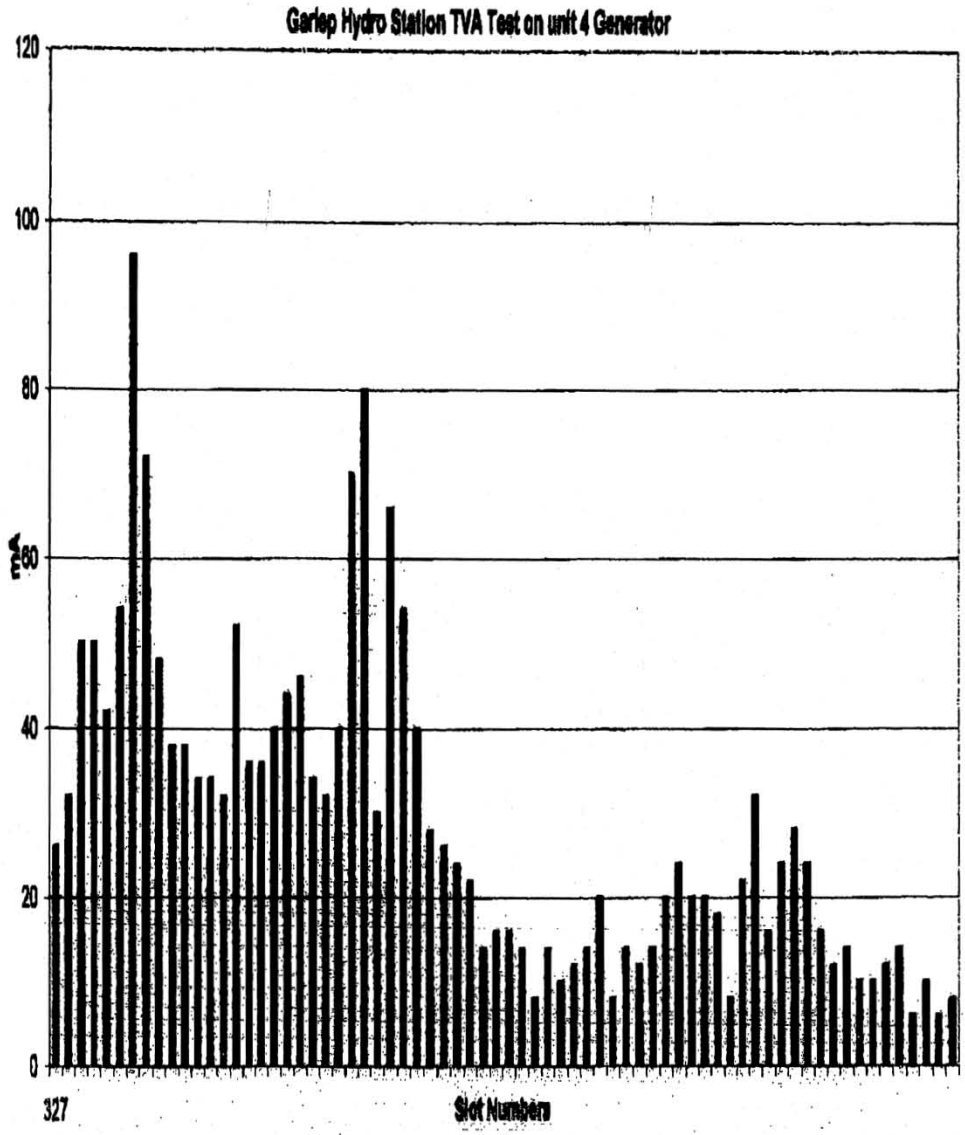


Figure 6.7: Gariep Unit 4 TVA probe profile for slots 327-396

PD trending and TVA test readings are good indicators of the condition of stator bar insulation

TVA Profiles:

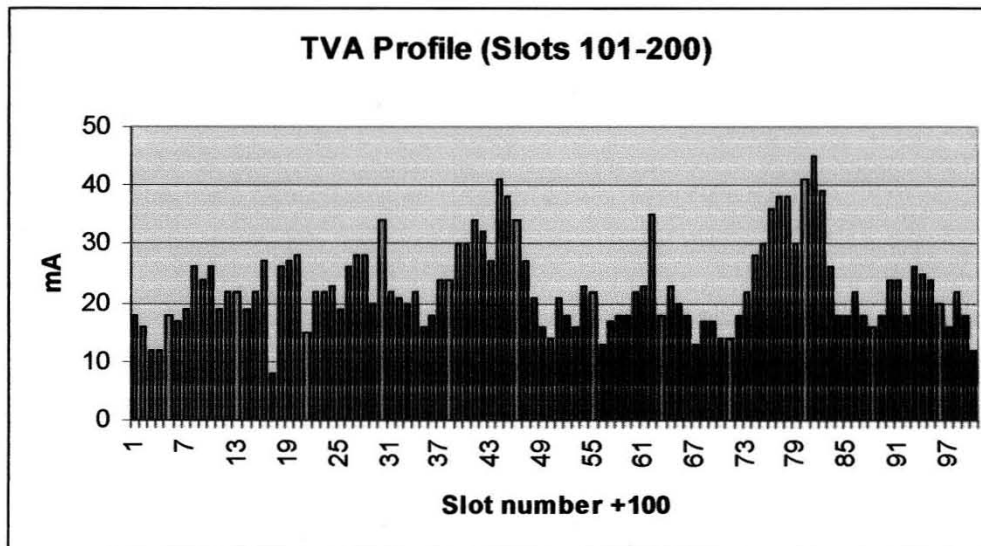
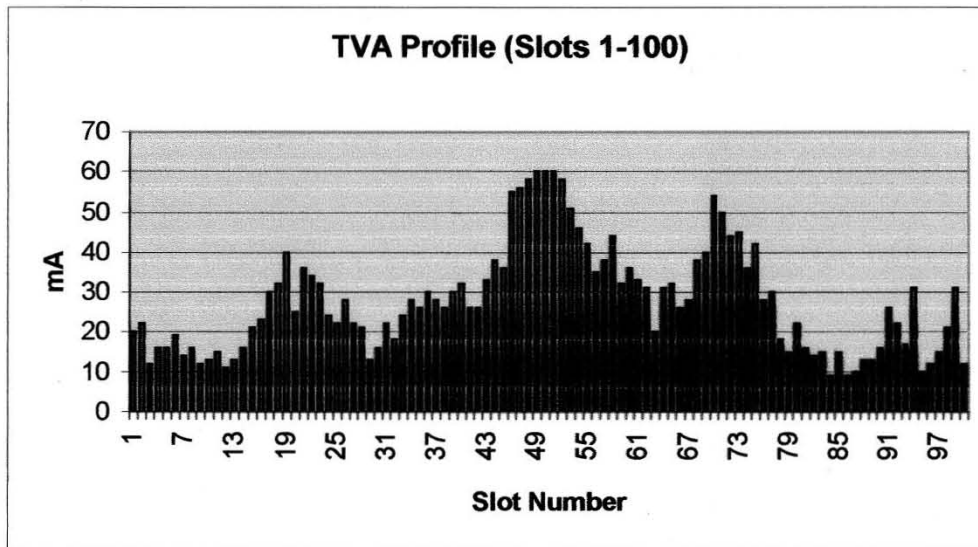
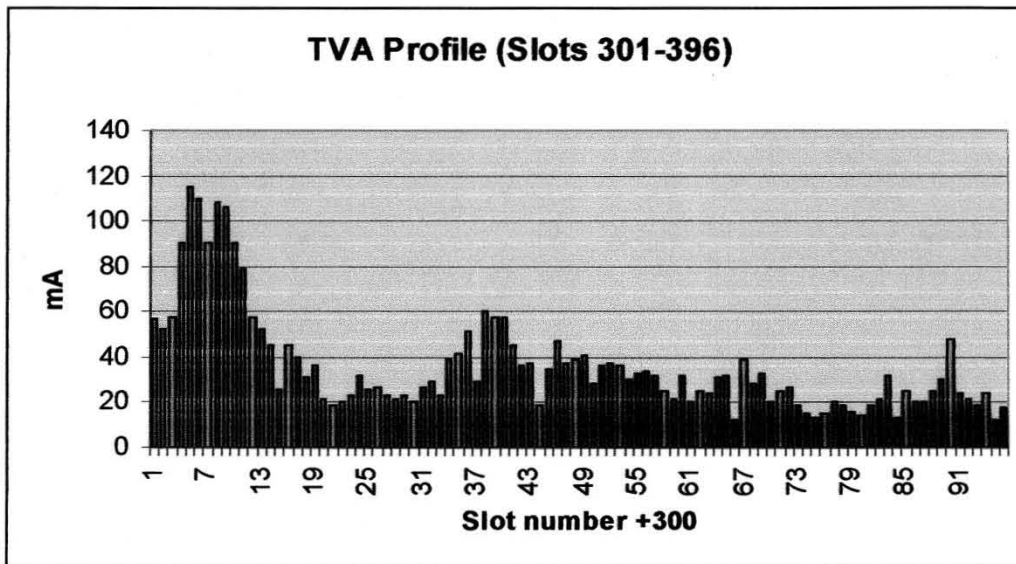
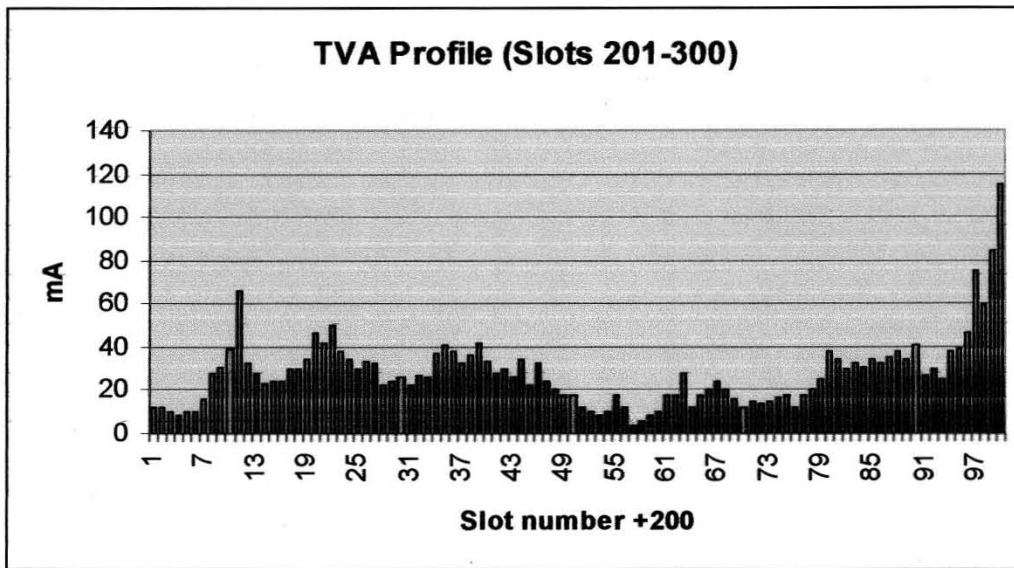


Figure 6.8: Gariep Unit 3 TVA probe profiles for slots 1-200

TVA Profiles (cont.):



Report no: TSI/EL/04/023
6.3. Expected test results

Figure 6.9: Gariep Unit 3 TVA probe profiles for slots 201-396

Due to the increasing trend of high PD values over the trending period in conjunction with high TVA probe values, it was expected that some of the stator bars would fail the breakdown voltage test. It was anticipated that some of the stator bars with high operating voltage values in combination with stator bars with the higher TVA reading ($>100\text{mA}$) would fail during the 30kV (DC) test and those with the lower TVA test results ($<100\text{mA}$) would fail during the 50 kV (DC) test given the age of the stator bars (commissioned in 1974 and 1976) and being utilised in a peaking station.

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CHAPTER 7

HV testing and results

7.1. Stator bar selection

The selected bars, as shown in Tables 7.1 and 7.2, were chosen from the TVA test results as described in the previous chapter. The selection criteria set down were to have stator bars of low (less than 20mA), medium (between 20mA- 100mA) and high (more than 100mA) TVA probe readings, as well as stator bars of various operating voltages.

Table 7.1 Test stator bars for Gariep Unit 3

Stator bar no	Phase	Operating voltage (V)	TVA probe value (mA)
86	B	461	9
12	B	7621	11
1	W	2655	20
71	R	7101	50
49	B	2771	60
297	W	5715	75
311	B	635	79
299	W	635	84
304	R	3060	90
310	B	3175	90
309	B	5715	106
308	W	2078	108
306	W	7159	110
305	R	5600	115
300	B	6928	115

Table 7.2

Test stator bars for Gariep Unit 4

Stator bar no	Phase	Operating voltage (V)	TVA probe value (mA)
2	W	115	8
6	R	7621	16
355	B	4734	40
20	W	230	44
229	B	3926	80
228	B	6466	80
260	R	1616	84
259	R	4156	90
38	W	346	90
268	R	3290	94
333	W	5484	96
130	B	4330	100
76	B	4676	210

7.2. Test equipment

The following test equipment was used during the voltage breakdown test:

BAUR PGK50 HV test set

HV Diagnostics HVA30 HV test system

The technical data of these test sets can be found in Appendix B.

From the limited technical data available in Appendix B, it cannot be deduced that the test equipment is fully compliant to IEEE 95 requirements. However, the given technical data complies with most of the testing requirements as stated in IEEE 95. Therefore, it is assumed for the purposes of this research that the test equipment fulfills the requirements of IEEE 95.

7.3. Test set-up

A typical test set-up and the actual test set-up are illustrated in Figures 7.1 and 7.2 respectively.

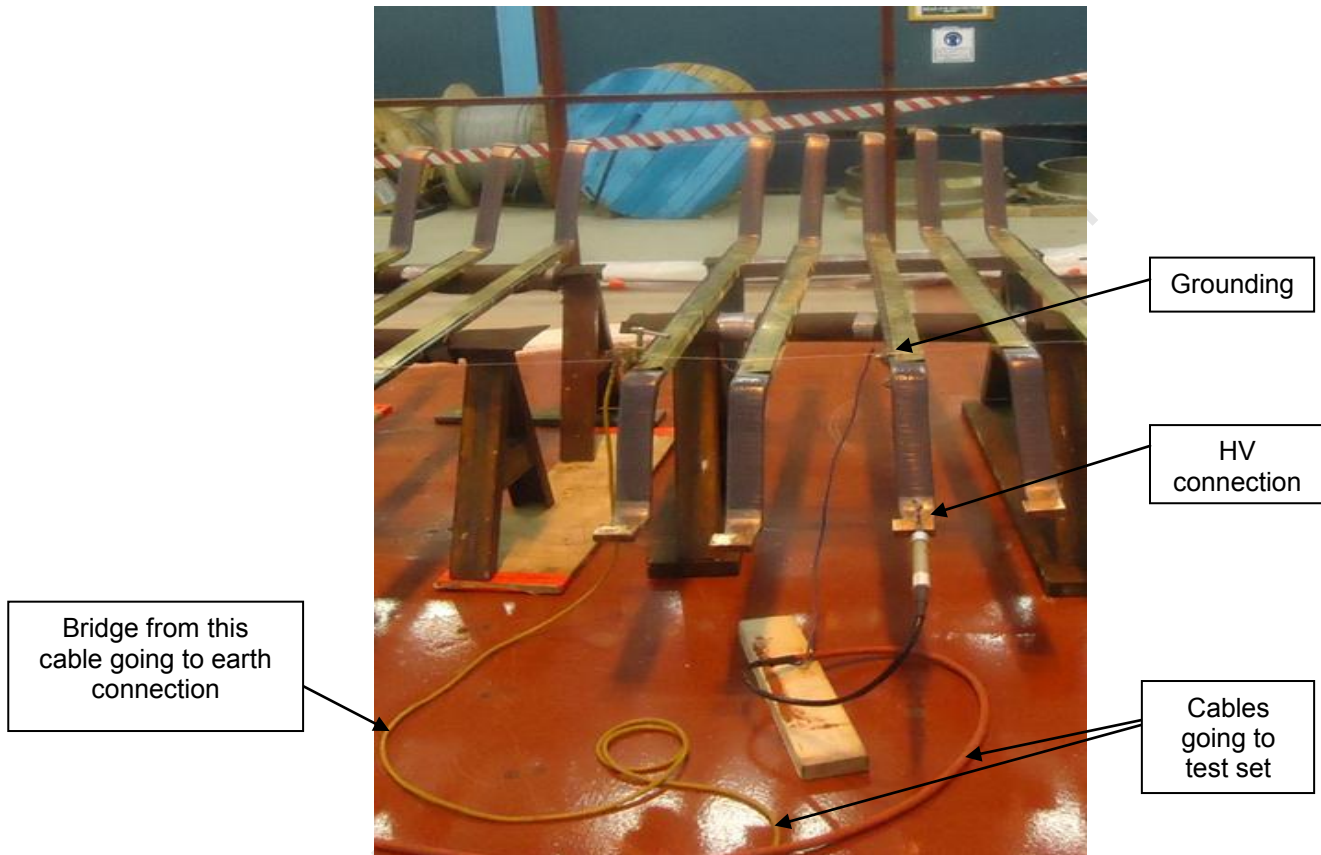


Figure 7.1: Typical HV test set-up

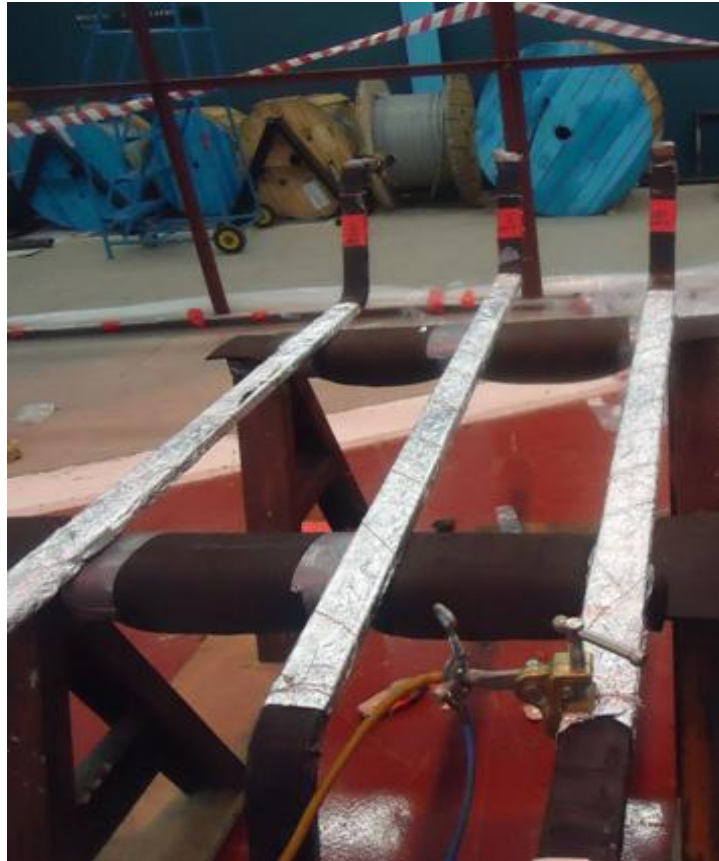


Figure 7.2: Test set-up for test specimens as per Figure 7.1

7.4. Field testing

HV testing was done on the test stator bars between 1-2 December 2011. Fifteen (15) and thirteen (13) stator bars, as per Tables 7.1 and 7.2, of Unit 3 and Unit 4 were tested respectively. Each bar was subjected to 30 kV (DC), 50 kV (DC) and 23 kV (rms 0.1 Hz) respectively. All the stator bars were tested at room temperature.

7.4.1. Actual test results

During the 30 kV (DC) and 23 kV (rms 0.1 Hz) the following parameters were recorded:

Stator bar capacitance

Stator bar insulation resistance (IR)

Leakage current

Insulation resistance @ 5 kV (DC)

Humidity

Ambient temperature

A complete list of the test results can be found in Appendix C. The initial outcome of the tests appeared to be completely random as regards to expected outcomes.

During the 50 kV (DC) test all of the above parameters except stator bar capacitance and resistance were recorded as the test equipment used did not have the capability to measure the mentioned parameters.

All the stator bars passed the 30 kV (DC) test. This was not surprising as all the IR values were a very good margin above the specification (IEEE 43-2000). We should take cognisance that high IR values indicate that the winding is dry and free of any cracks and it does not necessarily imply that the insulation of the stator bars is in very good condition. However, the breakdown voltage test results were contrary to the expectation that the bars with high TVA values and high operating voltage readings would fail. This can be seen from the various voltage and TVA probe values in Tables 7.1 and 7.2. The variations in the test parameters can be seen in the test results in Appendix C.

Once again, during the 23 kV (rms 0.1 Hz) test all stator bars passed even though there were variations amongst the test parameters. However, it was established that the insulation resistance values of Bars 130 and 76 in Unit 4 were significantly lower than all the other readings. This can be seen from Tables 7.3 and 7.4.

Table 7.3 IR test values stator bars for Gariep Unit 3 @ 23 kV (rms 0.1 Hz)

Stator bar no	Phase	Operating voltage (V)	TVA probe value (mA)	Insulation Resistance (GΩ)
86	B	461	9	3.3
12	B	7621	11	4.2
1	W	2655	20	3.3
71	R	7101	50	4.3
49	B	2771	60	4.2
297	W	5715	75	4.4
311	B	635	79	3.3
299	W	635	84	4.2
304	R	3060	90	4.3
310	B	3175	90	3.4
309	B	5715	106	4.2
308	W	2078	108	3.1
306	W	7159	110	4.4
305	R	5600	115	4.3
300	B	6928	115	4.2

Table 7.4 IR test values stator bars for Gariep Unit 4 @ 23 kV (rms 0.1 Hz)

(Bold figures apply to failed stator bars)

Stator bar no	Phase	Operating voltage (V)	TVA probe value (mA)	Insulation Resistance (GΩ)
2	W	115	8	4.1
6	R	7621	16	2.1
355	B	4734	40	4.4
20	W	230	44	4.2
229	B	3926	80	3.0
228	B	6466	80	4.1
260	R	1616	84	3.2
259	R	4156	90	3.2
38	W	346	90	4.2

268	R	3290	94	3.9
333	W	5484	96	2.5
130	B	4330	100	0.586
76	B	4676	210	0.787

During the 50 kV (DC) all the stator bars except Stator Bars 6, 76 and 130 of Unit 4 passed. These bars failed at voltages of 42 kV, 50 kV and 40 kV respectively. These bars are highlighted in Table 7.4. From the stator bar physical dimensions it seems as if all three bars have failed in the stress grading region. This could not be confirmed as there is no accurate drawing available giving the stress grading dimensions as this is considered to be OEM propriety information.

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CHAPTER 8

Discussion of test results

8.1. Discussion of results

After analysing various graphs and comparing different parameters, the following was observed.

There is no direct correlation between TVA probe measurements and voltage breakdown values. Figure 8.1 suggest that it is rather a combination of the TVA probe value and the operating voltage of the stator bar that will contribute as a failure mechanism. However, the test values for Stator Bar 12 seem to suggest otherwise.

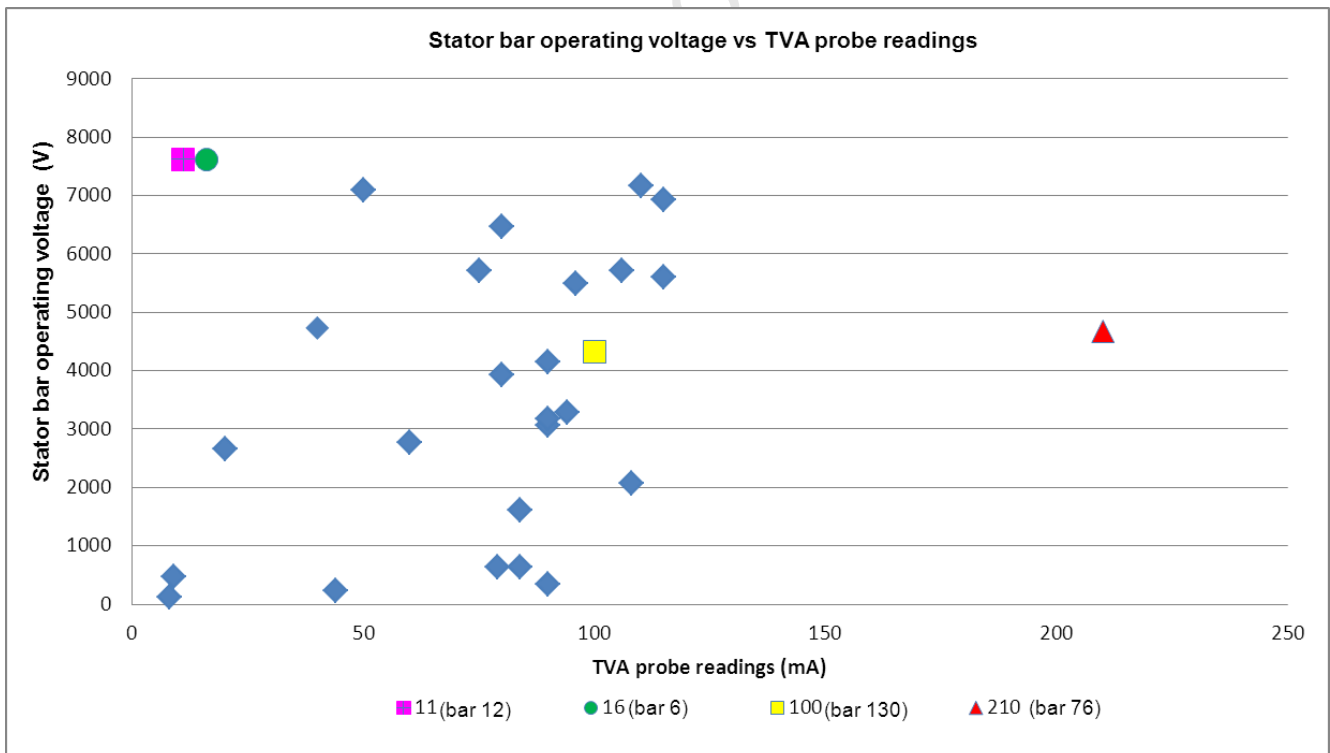


Figure 8.1: Stator bar operating voltage vs TVA probe readings

Comparing the stator bar operating voltage value to the leakage current presents a picture of a “window of leakage currents” between the values of 48 (μA) and 57 (μA). Stator Bars 76 (6.5 μA) and 130 (104 μA) are completely outside of this window. Stator Bar 6 (53 μA) is lying within this window and its failure can be attributed to the fact that it is operating at a higher voltage than Stator Bars 76 and 130; 7621V compared to 4676V and 4330V respectively. Once again Stator Bar 12 seems to contradict this. The same scenario presents itself for the operating voltage compared to the stator bar capacitance. All the bars are clustered between 3.2 (nF) and 3.9 (nF), except Stator Bars 76 and 130 at 2.9 (nF) and 6.7(nF) respectively.

This can be seen in Figures 8.2 and 8.3.

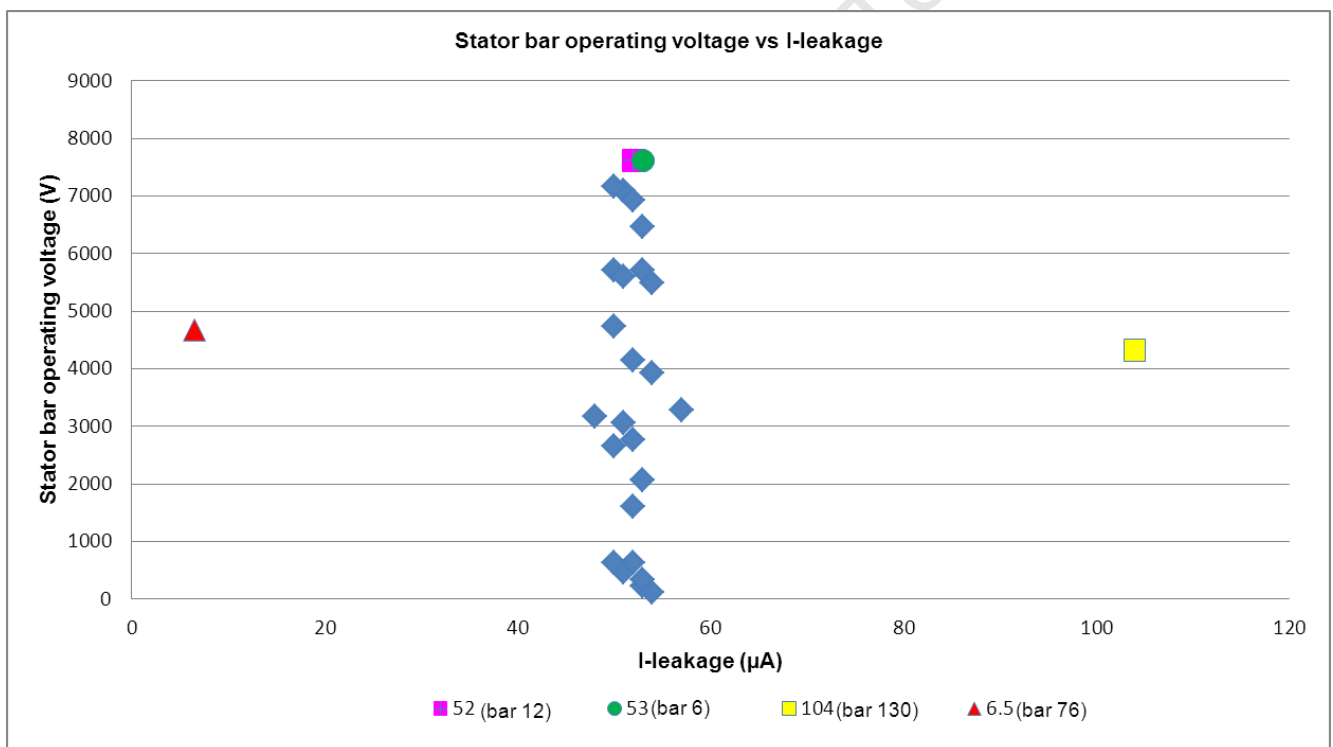


Figure 8.2: Stator bar operating voltage vs I-leakage

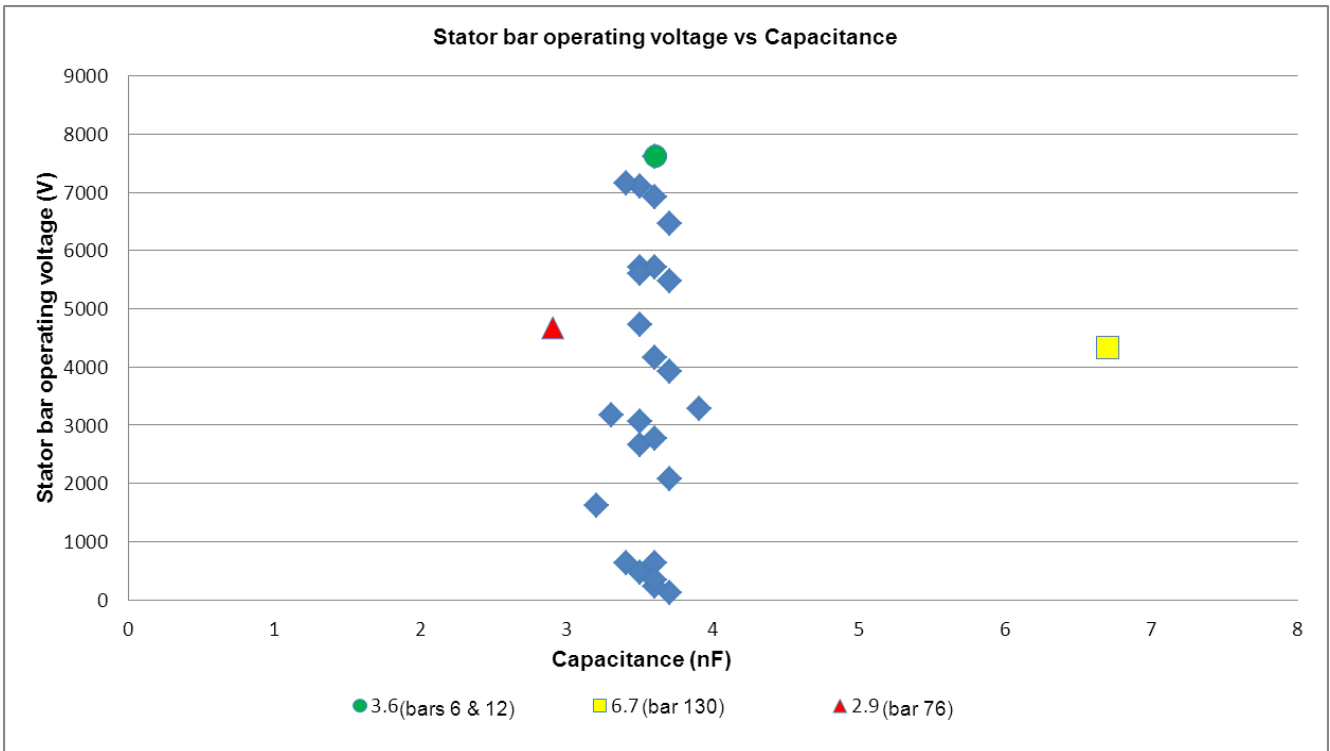


Figure 8.3: Stator bar operating voltage vs capacitance

Comparing the stator bar insulation resistance @ 23 kV with operating voltage (bar position), TVA probe and IR (@ 5kV), the three (3) stator bars that failed had the lowest insulation resistance values. This shows that irrespective of the operating voltage, TVA probe value or IR (@ 5 kV) value the failure mechanism appears to be driven by the low bar insulation resistance @ 23 kV. It appears that the cut-off point is some value lower than 2.5 GΩ. This is demonstrated in Figures 8.4, 8.5 and 8.6. There is however no direct relationship between the breakdown voltage, operating voltage, insulation resistance @ 23 kV and TVA probe readings of these bars. Table 8.1 illustrates this.

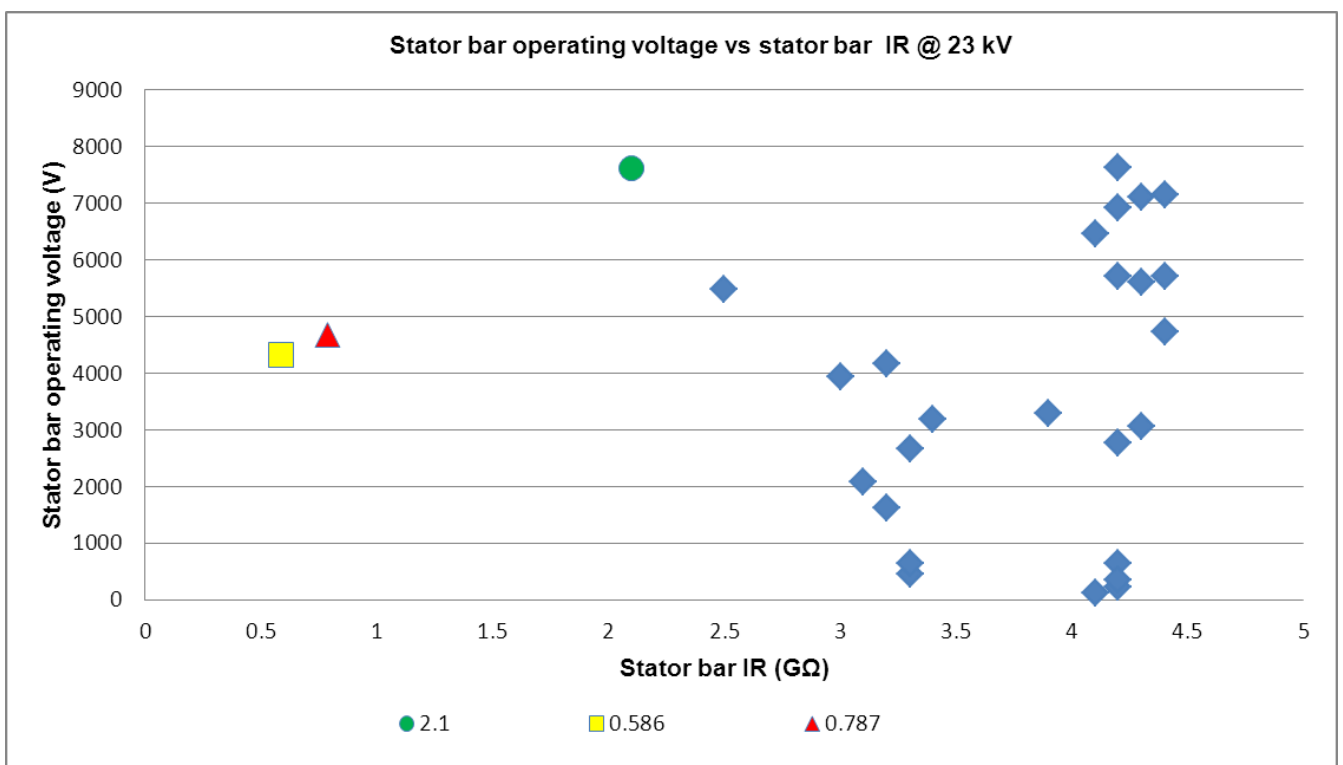


Figure 8.4: Stator bar operating voltage vs Stator bar IR @ 23 kV

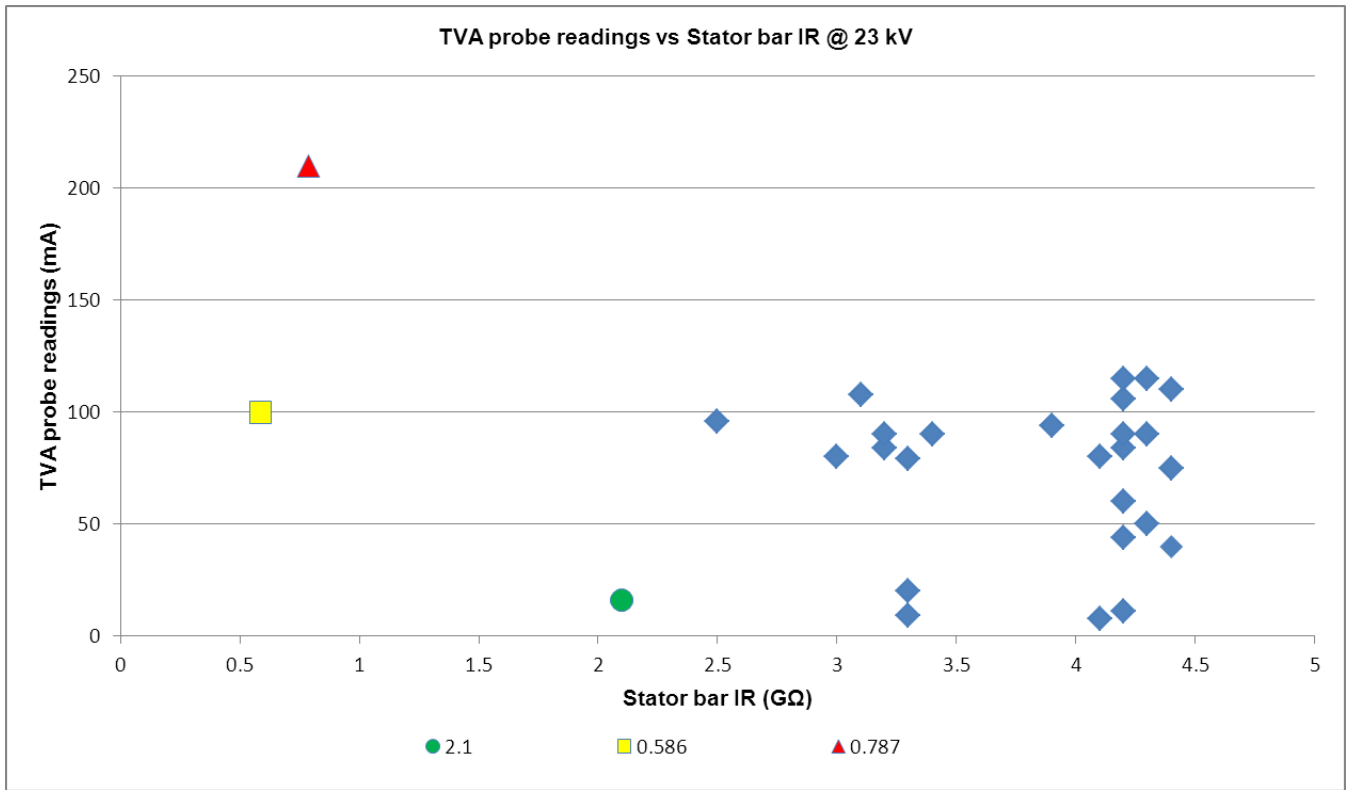


Figure 8.5: TVA probe readings vs Stator bar IR @ 23 kV

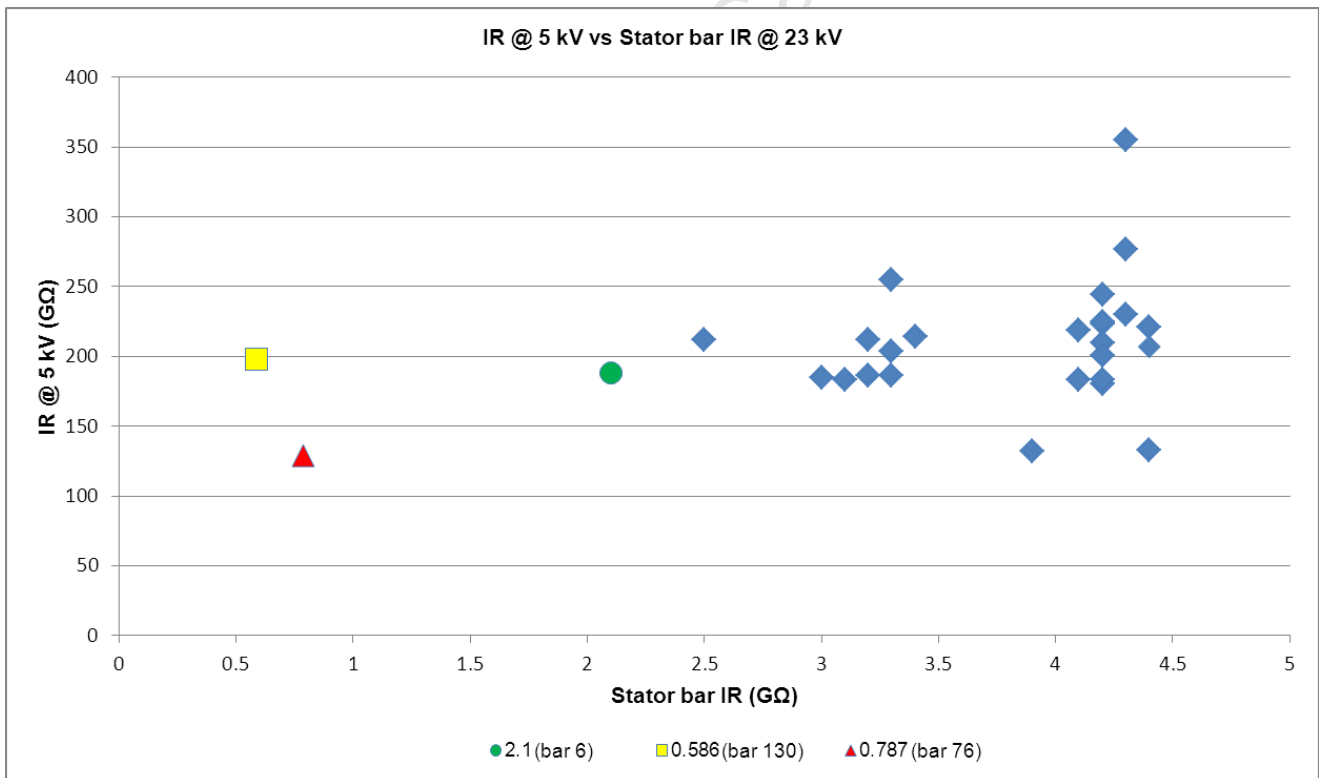


Figure 8.6: IR @ 5 kV vs Stator bar IR @ 23 kV

Table 8.1 No correlation between breakdown voltage and other parameters

Breakdown voltage (kV)	IR @ 23 kV (GΩ)	TVA probe readings (mA)	Operating voltage (kV)	Failed stator bar no	Phase
40	0.586	100	4.33	130	B
42	2.1	16	7.62	6	R
50	0.787	210	4.67	76	B

Further analysis of the graphs show an inverse relationship between the voltage breakdown and the following stator bar parameters: capacitance, I leakage and IR @ 5 kV. This can be seen from Figures 8.7, 8.8, 8.9 and Table 8.2.

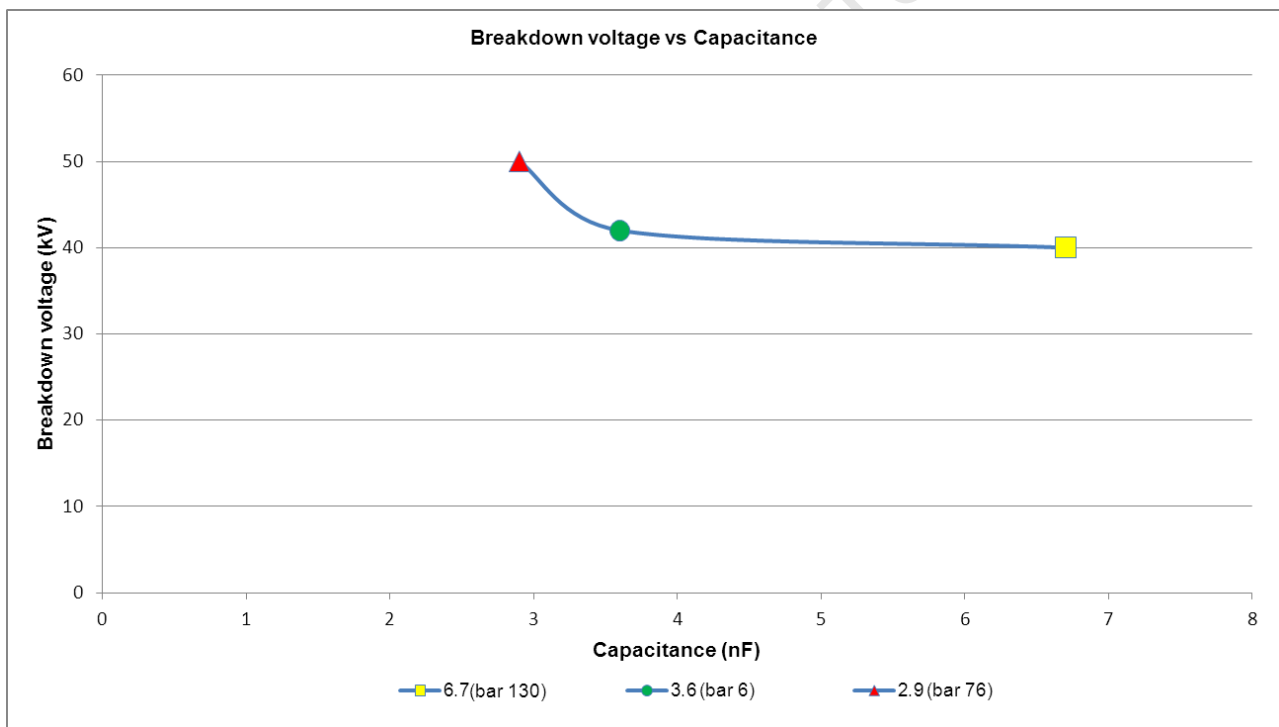


Figure 8.7: Breakdown voltage vs Capacitance

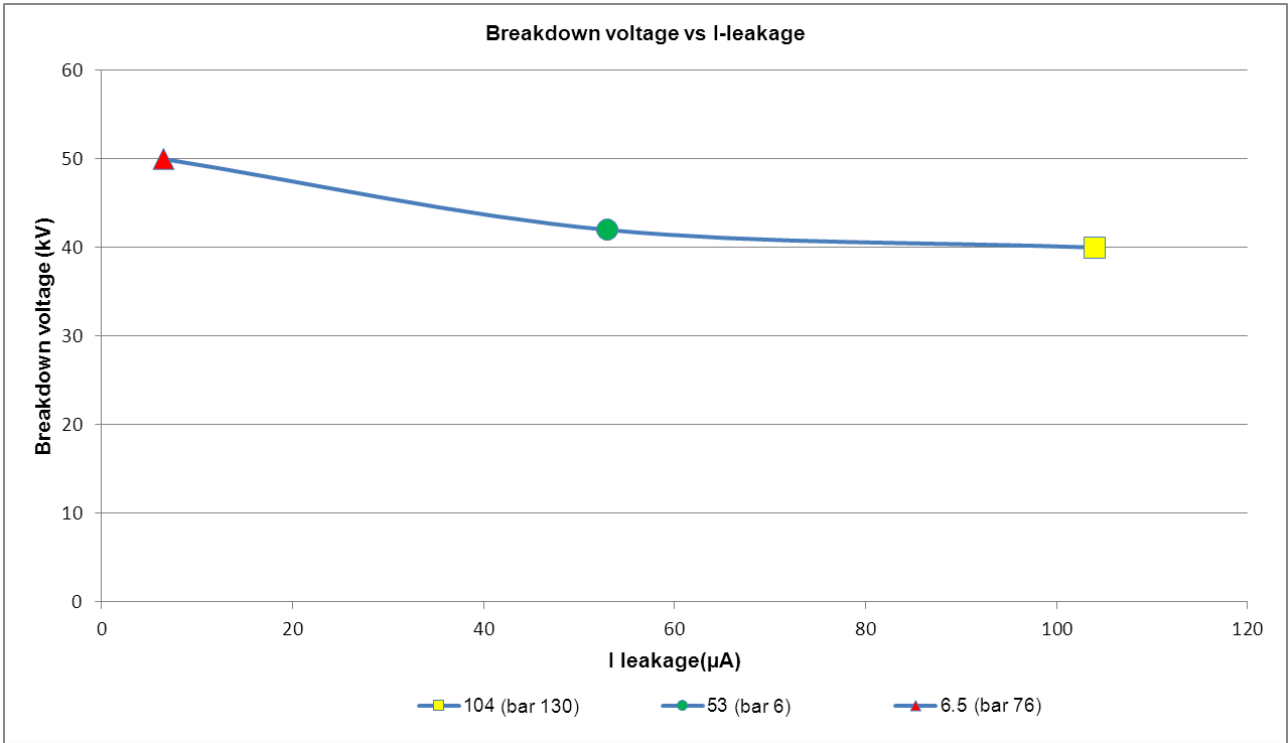


Figure 8.8: Breakdown voltage vs I-leakage

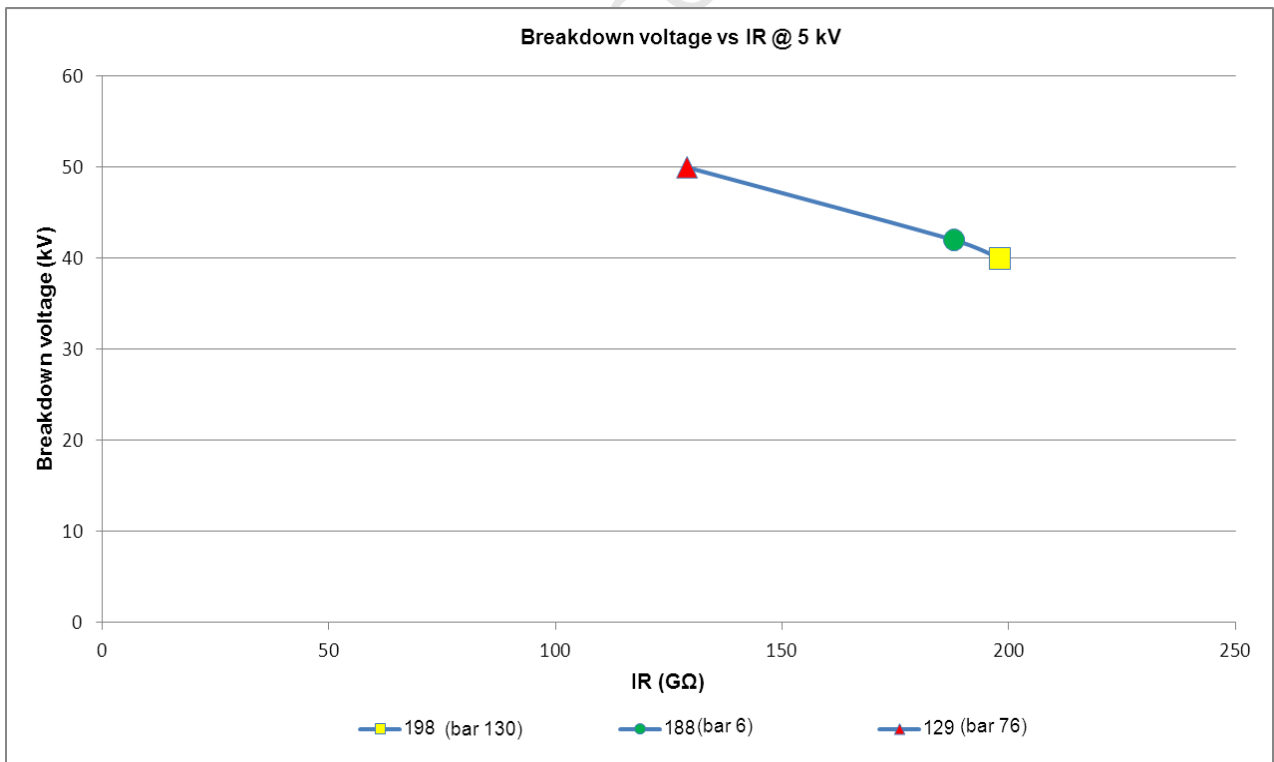


Figure 8.9: Breakdown voltage vs IR @ 5 kV

Table 8.2 Correlation of voltage breakdown and other parameters

Breakdown voltage (kV)	IR @ 5 kV	Capacitance	I leakage	Operating voltage (kV)	Failed stator bar no
40	198	6.7	104	4.33	130
42	188	3.6	53	7.62	6
50	129	2.9	6.5	4.67	76

There seems to be no correlation between breakdown voltage and stator bar operating voltage inside the generator. Table 8.1 shows that there is no direct correlation between these two parameters. Looking further at Tables 7.1 and 7.2 it seems that no significant electrical aging had occurred, as 36% of the test specimens are operating at a level higher than the lowest (4330V) failed bar. If any significant electrical aging had occurred these stator bars would have failed and they might even have failed at a lower voltage.

8.2. Conclusion

Diagnostic tests like PD and TVA probe testing alone are not very accurate indicators of the actual condition of stator bar insulation in hydro machines. PD may not be the actual failure mechanism but its presence could contribute towards the degradation process. The above mentioned tests should be used in conjunction with various other diagnostic tests to enable the user to make a more informed decision regarding the actual condition of the insulation.

The 30 kV DC and to a certain extent the 50kV DC tests show relatively good results of the various parameters. Contrasting to this, the 23 kV rms (0.1 Hz) test was showing some differences in various parameters in the stator bars that eventually failed. Hence the AC test seems to be a more sensitive test.

The destructive breakdown voltage test cannot be used to predict the remaining life of stator insulation as the diagnostic tests do not correlate with the breakdown voltages. It can be stated that the remaining life of stator winding insulation cannot be predicted on the basis of diagnostic tests alone but that diagnostic tests are most useful to indicate the trend in insulation aging.

It should also be noted that the test were done with bars removed from the generator at room temperature. Thus some of the actual conditions may have a varying affect, for example temperature, vibration, slot coatings or loading.

The diagnostic test (IR @ 5 kV) shows correlation with the voltage breakdown test. Although there seem to be some correlation between the breakdown voltage and IR @ 5 KV values, it should be stressed that the test sample was extremely small. A bigger test sample could possibly give a better or even different view regarding correlation.

It should be acknowledged that the IR test could be insensitive to voids and delamination which are likely to result in PD under high AC stress. However, the value of the IR test in assessing the condition of materials when gross cracks, moisture, etc are present has been proven for decades.

It appears that no specific group of diagnostic tests can predict breakdown voltage levels. It is recommended to have a test strategy to perform all types of diagnostic tests, since each test can give a slightly different view of the stator bar insulation condition and thus the tests are complementary.

The aging process does not seem to be significant as a failure mechanism, as the breakdown voltages are relatively high. The reasoning behind this is that the stator bars are relatively aged, more than 30 years old and operating in a peaking operating environment. It must once again be stressed that the test sample used is very limited, 1.7% of the actual stator bars in the generator, and that a small quantity (10.7%) of this sample actually failed. A more representative test sample may give better insight into this behaviour.

CHAPTER 9

9.1. Discussion

This dissertation set out to answer the research questions in order to validate the hypothesis. The questions have been examined and the following section shall examine the implications of the investigation for the validating of the hypothesis.

Hypothesis

TVA probe test results and trending of PD levels are good indicators of the condition of aged stator bar insulation in hydro generators.

Research questions

- How is PD used as a condition monitoring tool?
- What other tests can show the actual condition of the insulation?
- Can HV breakdown test show the actual condition of the insulation?
- What factors can influence PD?
- Are trends or absolute values of PD more significant?
- Is stator bar position in the generator significant?
- Is there correlation between diagnostics tests and breakdown voltage?
- Can PD be used as a key decision making tool?

How is PD used as a condition monitoring tool?

By utilising strategic condition based maintenance, power producers save valuable resources. This enables power producers to do preventative and pro-active maintenance. World wide experience has shown that by applying condition monitoring programs correctly, the correct analysis of the results can have positive economic benefits.

PD has been identified as a tool to identify manufacturing defects and continuing failure mechanisms of stator bar insulation. By trending the PD values over a period of time, the user could detect that certain failure mechanisms were present (Goodeve and Stone, 2007). It has been proven over the years that PD monitoring is a reliable condition monitoring tool by analysing databases with numerous results (Warren et al, 2000). The major benefit of on-line monitoring is the fact that the actual generator condition is revealed under actual operating conditions for example temperature, stresses etc.

Having PD data available enables users to make better informed decisions regarding the actual condition of stator bar insulation and planning refurbishment effectiveness.

The above information is validated by the literature review. However, from a research perspective it was found that although PD is giving vital information regarding the condition of the insulation, as well as failure mechanisms, the trending over time gives questionable results especially regarding the decrease in Qm- activity in all the phases.

What other tests can show the actual condition of the insulation?

Other diagnostic tests for example IR, PI and PF tip-up have been used for decades by maintenance personnel to determine the condition of insulation in generators. The vital information gathered from these tests was used for trending rather than providing objective estimates of remaining life (Kurtz and Lyles, 1979).

The limitation of some of these tests must be recognised: for example the PF tip-up test is done off-line with the measured PF and capacitance an average value of the tested phase. It is thus difficult to determine whether high test values are from the complete phase or only from certain stator bars within the phase.

Diagnostic test may be better indicators of remaining life when insulation is close to failure. Diagnostic measurements might then be relatively insensitive life indicators for bars which still have significant life remaining (Stone et al, 1988).

It is advisable to perform all possible diagnostic tests as no single diagnostic test or group of tests can accurately reveal the condition of the stator bar insulation. These tests results may produce valuable information when put into perspective with past test data, incident history, operating history, etc.

It should also be acknowledged that some test could be ineffective for detecting aging in the stator bar insulation, for example IR and PI tests would not be adding much value in evaluating deterioration caused by slot discharge. It is therefore imperative to have sufficient knowledge to know what outputs to expect from the specified diagnostic tests. This requires a considerable level of expertise.

Can HV breakdown test show the actual condition of the insulation?

No direct correlation was found between TVA diagnostic test and the breakdown voltage. From the TVA test results it can be seen that a once-off test cannot predict breakdown voltages. The test results do not show a clear correlation between the TVA test and breakdown voltage. That is, stator bars with the worst results from this diagnostic test did not have the lowest breakdown voltage.

It can be stated that voltage breakdown values of stator bar insulation cannot be predicted on the basis of diagnostic tests alone, but that diagnostic tests are most useful to indicate the trend in insulation aging.

What factors can influence PD?

Trending PD over time is a very reliable method of monitoring the actual condition of stator bar insulation. However, to enable reliable trending, certain operating parameters need to be similar, or as close as possible, as they are affecting PD.

These parameters are operating load, voltage, temperature, humidity and gas pressure (Stone et al, 2002). This will enable the user to make direct comparisons between phases and even generators, with similar insulation systems, of similar capacity. Taking readings in conditions of significant ambient variability influences the PD activity and its measurement. This has effectively been shown in the variations in the readings taken by inexperienced personnel in the earlier part of the Eskom database collection, in relation to the readings taken between 1998 and 2002.

Are trends or absolute values of PD more significant?

According to the literature PD trend analysis is recommended as the best way to identify machine insulation problems. Analysing Figures 6.1-6.3 seems to confirm this recommendation as there are significant differences in the Qm+ and Qm- values. Although the Qm- values are showing a decrease, the Qm+ values are showing a steady increase over the years. The significance of these trends show that even though no stator bar from the white phase has failed, the Qm+ of this phase, is almost double and quadruple the values of blue and red phases respectively. Yet the stator bars from these phases failed at different voltage levels as per Table 8.1. Hence, it seems as if the trends are more significant than the absolute values. This finding is in line with what is stated by Stone et al (2004) as identified in literature review.

Is stator bar position (operating voltage) in the generator significant?

The literature review is inconclusive regarding this parameter specifically referring to the small sample being tested.

There seems to be no correlation between breakdown voltage and stator bar operating voltage inside the generator. Table 8.2 shows that there is no direct correlation between these two parameters. Analysing Tables 7.1 and 7.2 show that all stator bars, except Stator Bars 6, 76 and 130, operating at various levels between neutral side and line side have passed the breakdown voltage test. It is also significant that 36% of the test specimens are operating at a level higher than the lowest (4330V) failed bar.

Is there correlation between diagnostics tests and breakdown voltage?

Numerous attempts have been made in the past to relate PD intensity to insulation life. These attempts ended in failure because it was not possible to establish a PD intensity level or threshold that could foretell insulation failure (Bartnikas 1979). Even just prior to insulation failure, the PD pulse intensity may alternatively increase, remain constant, or even decrease (Bartnikas 1979).

The once-off TVA probe test was not able predict the breakdown voltages. No significant electrical aging appears to have occurred, given the age and operating regime of these stator bars. If any significant electrical aging had occurred these test specimens would have failed, and might even have failed at a lower voltage.

The test results as shown in Table 8.1 show no correlation between breakdown voltage and TVA probe readings. However, Table 8.2 shows a correlation between breakdown voltage and IR @ 5 kV.

Can PD be used as a key decision making tool?

PD can possibly identify potential failure mechanisms. Of the failure mechanisms listed in Table 5.2 there was visual evidence of slot discharges on the removed stator bars. This degree of evidence will enable power producers to implement different repair strategies for different identified failure mechanisms and also influence decision making regarding refurbishment.

PD can also be used as quality control test during stator bar manufacturing (McDermid and Bromley, 1992).

9.2. Validity of hypothesis

Although there was some correlation between IR @ 5 kV, I-leakage, capacitance and breakdown voltage, it should once again be stressed that the test sample was extremely small. A bigger test sample could possibly give a better, or even a different correlation.

The test results do not show a clear correlation between diagnostic test of PD, TVA test and breakdown voltage. That is, the stator bars with the worst results from this diagnostic test (TVA) did not have the lowest breakdown voltage.

From the test results and literature it is clear that much more research is required before objective, reliable predictions regarding the actual condition of stator bar insulation can be made.

It is therefore concluded that the hypothesis is not valid.

9.3. Future actions

It is clear from the research that having a PD trend over a long period gives the user some indication of stator bar insulation deterioration and the possible failure mechanisms present. To give some insight into these possible failure mechanisms, correlation should be sought with physical inspections, for example remove a stator bar and inspect for actual slot discharges.

To better understand failure mechanisms and the actual condition of the insulation, it is suggested that TVA test results, collected over the years, should be trended. The information from the TVA test could be much more informative if the TVA testing is done just before stator bar removal.

Also, consider doing the TVA test at a voltage level just above the inception voltage, thereby not exposing all the stator bars to inception voltages. This would then give a more realistic picture of the actual discharges during operation as this reflects the reality inside the generator during operation.

It could be anticipated that the stator bars showing discharge activity would show increased activity during the period where the voltage is raised during generator operation.

Eskom should re-evaluate the TVA probe guideline values as a stator bar with supposedly small voids (Bar 6) had actually failed. These values can obviously only be tested by doing more breakdown voltage test on stator bars with known TVA probe test values. Hence, more stator bars should be made available to interrogate these guideline values.

The failed stator bars should be dissected and the insulation should be analysed to determine the exact failure mechanism. An example of what could be identified would be evidence of weak adhesion between layers of insulation which would result in delamination of the insulation or even debonding next the copper insulation interface.

Researchers could possibly find more comprehensive results when doing a proper AC voltage endurance test which could possibly be more informative for less advanced deterioration of insulation.

There seems to be some evidence that AC hipot testing (unfortunately this test set-up was limited to a 0.1 Hz signal only) may be more searching to identify insulation weaknesses in stator bars than DC hipot testing. This should be investigated further as most of the stator bar testing is done with DC techniques and the AC test seems to be a more sensitive test for insulation defects.

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APPENDIX A

Eskom PD Measuring Guideline GGG 0826

Iris On-line testing

Digital instrumentation is used to gather process and display PD information. The instrumentation is attached to permanently mounted coupling capacitors via connections housed in a terminal box. Two sets of coupling capacitors are used on each phase. The first set is mounted at the phase output terminals of the machine. The second set is mounted at least two meters away from the first set toward the generator transformer. A capacitive/resistive divider is used to detect the signal and pass it to a switching matrix. A block diagram of the on-line detection method is shown in Figure 5.

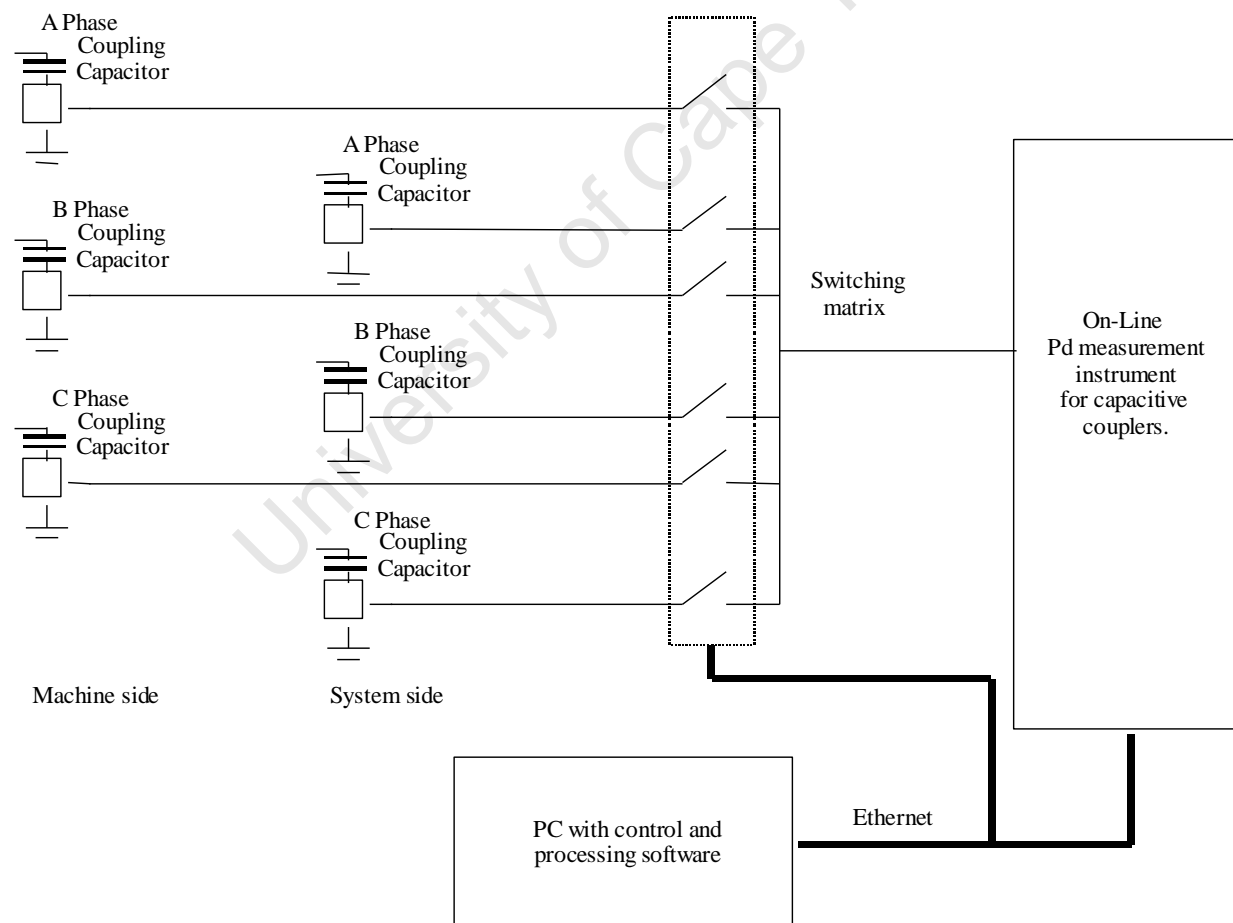
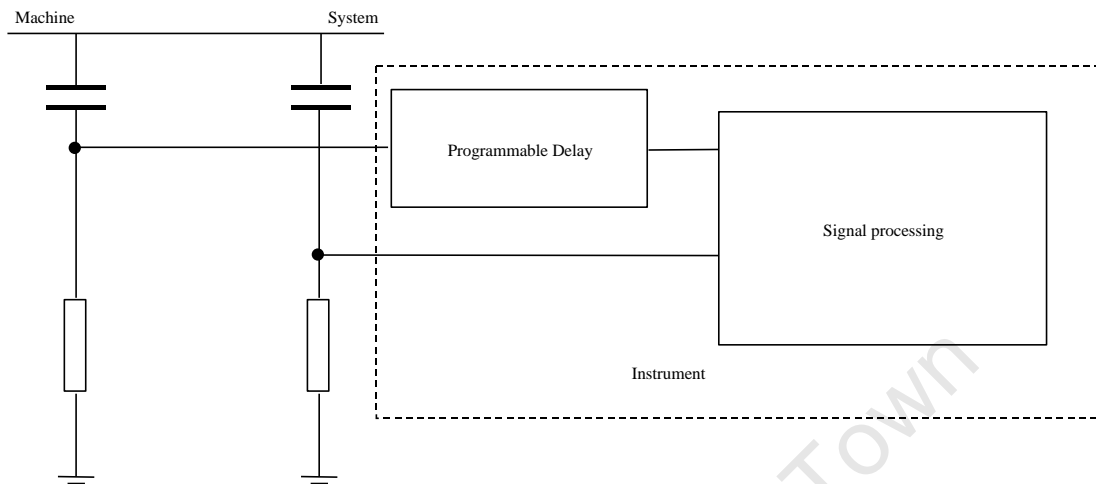
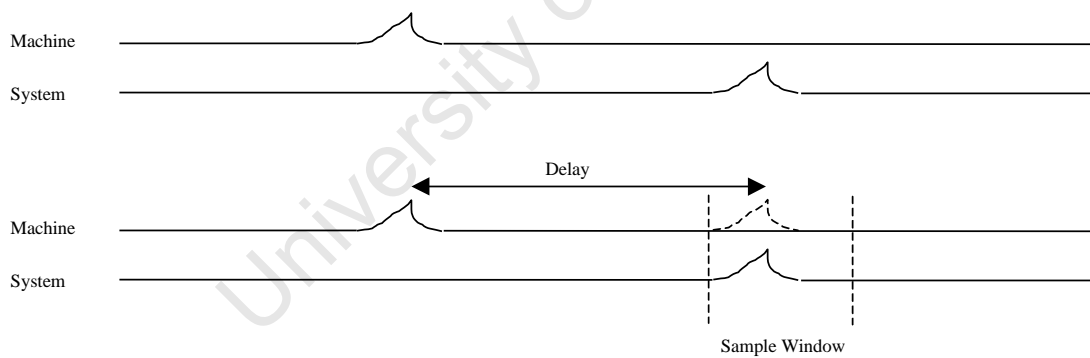


Figure 5. Block diagram of the on-line PD detection instrument

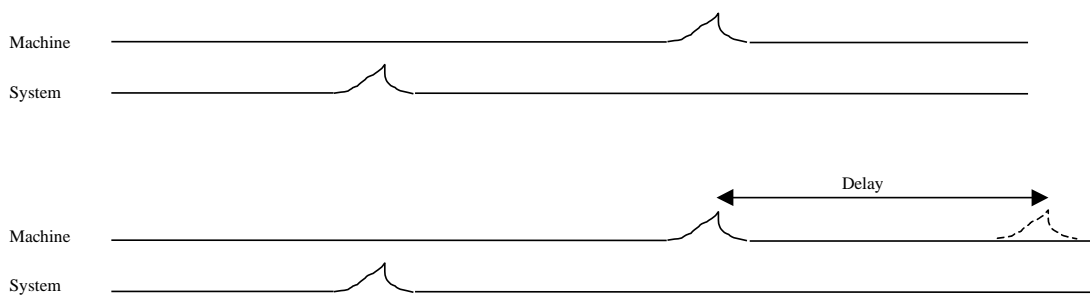
Once the switching matrix has selected the appropriate phase the signals are passed to the noise discrimination electronics. A programmable delay line, as illustrated below, delays the signal from the machine side:



If the signal origin is from within the machine the two detected signals will fall into the same sample window as illustrated below:



If the signal origin is from the system the two detected signals will not be congruent as illustrated below:



By using this technique signals from the machine can be discriminated from system noise.

The instrumentation performs the data processing at the same time as it takes the measurement. The PDs on the positive and negative sections of the mains cycle are separated, and displayed on a graph.

As a result of the method of detection, the analysis equipment detects all electrical discharges within the machine. This technique also detects non-discharge type phenomena such as coil to stator sparking and core back burning to be detected. This can be an advantage, as it gives an indication that there is a problem in the machine, but can be a disadvantage if the non-discharge phenomena masks or mimics the discharges.

The measured results depend on the insulation type, and would need to be compared with the results from similar windings. However an absolute reading of 400 mV or more is considered reason for concern.

APPENDIX B

Test equipment data



1.6 Technical Data – PGK 50 and PGK 80

Power supply	230 V, 50/60 Hz	Optional: 110 / 115 / 120 / 127 / 220 / 240 V		
Rated power	600 VA			
Installed load	PGK 50	1610 VA	PGK 80	PGK 80 1380 VA
Rated output voltage		50 kV DC neg.		80 kV DC neg.
Rated output current		2 mA		0.8 mA
Short circuit output current		25 mA		20 mA
Accuracy	±2.5%			
Timer	0 – 30 min			
Discharge device	for a maximum discharge energy of 1 discharge per 15 minutes, T _a = 20°C, max. 8000 WS			
Voltage measuring range				
I	PGK 50:	0 – 50 kV	PGK 80:	0 – 80 kV
II		0 – 10 kV		0 – 16 kV
Current measuring range				
Smallest readable current	1 µA / 10 µA / 100 µA / 1 mA / 10 mA / 100 mA 20 nA			
Relative humidity				
Ambient temperature	not condensing Working: 0°C ... +45°C Storage: -20°C ... +60°C			
Dimensions (WxHxD)				
Weight	500 x 285 x 460 mm 25 kg			
Conforms to CE standard				
	Low voltage directive 73/23/EEC EN 61010-1, VDE 0104, EMC directive 89/336/EEC with Modification 91/263/EEC, 92/31/EEC, VDE 0843 part 2, IEC 801-2/VDE 0843 part 4, IEC 801-4, VDE 0875 part 11, EN 55 011			

Technical Data

Input Voltage	110-230 V 50 / 60 Hz (400 VA)
Output Voltage	Sinusoidal: 0-33 kV peak, Symmetrical, 23kV rms DC: + 0-30 kV Squarewave: 30kV Accuracy: $\pm 1\%$ Resolution: 0,1kV
Output Current	0-15mA (Resolution 1 μ A) Accuracy: $\pm 1\%$
Resistance Range	0.1 M Ω ...5 G Ω
Output Frequency	0.01...0.1 Hz in steps of 0.01 Hz (default 0.1Hz) – auto frequency selection
Output Load	0.5 μ F @ 0.1Hz @ 23kV RMS (Approx 1,500m / 5,000ft of cable)* 1.0 μ F @ 0.05Hz @ 23kV RMS (Approx 3,000m / 10,000ft of cable)* 2.5 μ F @ 0.02Hz @ 23kV RMS (Approx 8,000m / 25,000ft of cable)* 12.0 μ F maximum Capacitance
	* Based on a typical cable: 100pF/ft or 300pF/m
Output Modes	AC (VLF) Symmetrical and load independent across full range DC (plus or negative polarity) Burn / Fault Condition or Fault Trip Mode Jacket / Sheath Testing
Safety	50Hz 12kV Feedback Protection
Memory	50 Test Records Stored in non-volatile built in memory
Metering	Voltage and Current (True RMS and/or peak) Capacitance, Resistance, Time, Flashover Voltage
Duty	Continuous! No thermal limitation for operating time.
HV Cable	4.5m (15') with Alligator clamps on end (other options available on request)
Computer Interface	RS232 connection (Software Included), USB Flash Drive
Temperature	Storage: -25°C to +70°C Operating: -5°C to +45°C
Dimensions (L X H X W)	430 x 360 x 250mm / 17" x 14" x 10"
Weight	19,5 kg / 43 lbs

Part Number	Description
SH 0201	Standard HVA30
SH 0207	TD 30 Tan Delta Accessory
SH 0220	PD 30 Partial Discharge Accessory
GH 0202	Battery Charger with Integrated Charger
GH 0501	Special Lead 50kV / 4m / Dolphin MC Clamp
VKR 0002	Transport Case
GH 0505	Protective Gear
GH 0601	Vacuum Bottle upgrade (DC)

APPENDIX C

Field test data

Stator bar no	Test voltage (kV)	Capacitance (nF)	Insulation Resistance @ 30/23 kV (GΩ)	I leakage (μA)	Amb Temp (°C)	IR @ 5kV (GΩ)	TVA (mA)	Bar voltage inside machine	phase
unit 3									
86	30	2.4	1.9	16	22.3	186	9	461	B
86	50			20	23.1	186	9	461	B
86	23	3.5	3.3	51	23.5	186	9	461	B
12	30	2.7	1.6	19	19.8	210	11	7621	B
12	50			2	20.8	210	11	7621	B
12	23	3.6	4.2	52	21.0	210	11	7621	B
1	30	2.5	1.8	17	22.6	255	20	2655	W
1	50			22	20.8	255	20	2655	W
1	23	3.5	3.3	50	21.0	255	20	2655	W
71	30	2.6	1.8	16	20.3	355	50	7101	R
71	50			10	20.8	355	50	7101	R
71	23	3.5	4.3	51	21.0	355	50	7101	R
49	30	2.6	1.6	18	20.3	244	60	2771	B
49	50			20	20.8	244	60	2771	B
49	23	3.6	4.2	52	21.6	244	60	2771	B
297	30	2.6	1.6	19	24.2	133	75	5715	W
297	50			18	21.0	133	75	5715	W
297	23	3.5	4.4	50	21.6	133	75	5715	W
311	30	2.5	1.9	16	20.3	204	79	635	B
311	50			19	20.8	204	79	635	B
311	23	3.4	3.3	50	21.0	204	79	635	B
299	30	2.7	1.5	20	20.3	223	84	635	W
299	50			16	20.8	223	84	635	W
299	23	3.6	4.2	52	21.0	223	84	635	W

304	30	2.5	1.8	17	20.3	277	90	3060	R
304	50			7.8	20.8	277	90	3060	R
304	23	3.5	4.3	51	21.0	277	90	3060	R
310	30	2.3	1.9	15	20.3	214	90	3175	B
310	50			15	20.3	214	90	3175	B
310	23	3.3	3.4	48	21.0	214	90	3175	B
309	30	2.8	1.6	19	19.8	201	106	5715	B
309	50			6.2	20.8	201	106	5715	B
309	23	3.6	4.2	53	21.0	201	106	5715	B
308	30	2.6	1.6	19	20.3	183	108	2078	W
308	50			22	20.8	183	108	2078	W
308	23	3.7	3.1	53	21.0	183	108	2078	W
306	30	2.6	2.1	14	22.3	221	110	7159	W
306	50			12	23.1	221	110	7159	W
306	23	3.4	4.4	50	23.5	221	110	7159	W
305	30	2.7	1.8	17	22.3	230	115	5600	R
305	50			8.4	23.1	230	115	5600	R
305	23	3.5	4.3	51	23.5	230	115	5600	R
300	30	2,7	1.5	20	23.1	225	115	6928	B
300	50			25	20.8	225	115	6928	B
300	23	3.6	4.2	52	21.6	225	115	6928	B
unit 4									
2	30	2.8	1.6	19	23.8	183	8	115	W
2	50			28	23.8	183	8	115	W
2	23	3.7	4.1	54	24.0	183	8	115	W
6	30	2.7	1.5	20	23.8	188	16	7621	R
6	50			0.8	23.8	188	16	7621	R
6	23	3.6	2.1	53	24.0	188	16	7621	R
355	30	2.6	2.7	11	22.3	207	40	4734	B
355	50			10	23.1	207	40	4734	B
355	23	3.5	4.4	50	23.5	207	40	4734	B
20	30	2.8	1.8	17	23.1	180	44	230	W
20	50			17	23.1	180	44	230	W
20	23	3.6	4.2	53	23.5	180	44	230	W
229	30	2.8	1.8	17	23.1	185	80	3926	B
229	50			7.2	23.1	185	80	3926	B

229	23	3.7	3	54	23.5	185	80	3926	B
228	30	2.7	1.7	17	23.8	219	80	6466	B
228	50			16	24.0	219	80	6466	B
228	23	3.7	4.1	53	24.0	219	80	6466	B
260	30	2.3	2.1	15	22.3	186	84	1616	R
260	50			9.8	23.1	186	84	1616	R
260	23	3.2	3.2	52	23.5	186	84	1616	R
259	30	2.5	1.7	18	23.8	212	90	4156	R
259	50			8	24.0	212	90	4156	R
259	23	3.6	3.2	52	24.0	212	90	4156	R
38	30	2.7	1.7	18	22.3	183	90	346	W
38	50			10.5	23.1	183	90	346	W
38	23	3.6	4.2	53	23.5	183	90	346	W
268	30	2.8	1.6	19	23.8	132	94	3290	R
268	50			12	23.8	132	94	3290	R
268	23	3.9	3.9	57	24.0	132	94	3290	R
333	30	2.8	2.1	14	23.1	212	96	5484	W
333	50			30	23.1	212	96	5484	W
333	23	3.7	2.5	54	23.5	212	96	5484	W
130	30	2.7	1.5	20	23.8	198	100	4330	B
130	50			20	23.8	198	100	4330	B
130	23	6.7	0.586	104	24.0	198	100	4330	B
76	30	2.9	1.6	19	23.8	129	210	4676	B
76	50			8	24.0	129	210	4676	B
76	23	2.9	0.787	6.5	24.0	129	210	4676	B