

**Testing for relationship between diagnostic tests and
DC BDV of in-serviced aged stator bars of a hydro
generator**



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fulfilment of the requirements for the degree of Doctor of Philosophy in Engineering**

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Mark A. Bruintjies

Date: 2024/05/21

Dedicated in loving memory to my Godfather

Henry James Page

A colossus of a man with a heart much bigger than his frame size and
always willing to help his fellow human being.

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First of all, I would like to thank our Heavenly Father for giving me the strength, courage and endurance to complete this work. Without Him this would not have been possible.

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ABSTRACT

The effective management of assets currently presents a challenge to utilities. A cognisance and understanding of the actual condition of these assets will enable utilities to implement mitigation strategies and use these assets for the full duration of their lifespan. One of these assets could be hydro generators with the stator bars constituting one of the failing components.

Integral to the satisfactory operation of a high voltage (HV) electrical rotating plant is the integrity of the electrical high voltage insulation of both the rotor and stator. During operation, high voltage generator components (for example stator bars), are continuously and simultaneously subjected to electrical, thermal, mechanical and ambient (environment) stresses. Subsequently, the complex interactions of these stresses degrade and deteriorate the insulation material gradually, resulting in a reduction of valuable operative life, potential forced outages and costly emergency repairs.

Because both expected and unexpected stator bar in-service failures may lead to costly repairs, rotating machine users implement condition monitoring (CM), diagnostic tests and condition-based maintenance in order to mitigate risk.

The contribution was executed in the form of removing aged stator bars from a generator and subjecting the bars to various diagnostic and direct current (DC) HV tests, testing for correlation. The diagnostic tests included insulation resistance (IR), polarization index (PI), partial discharge (PD), tan delta (TD) and Tennessee Valley Authority (TVA) tests. The HV breakdown tests included very low frequency (VLF) and DC tests.

Despite using this wider range of tests than has been used before, the test results still confirm earlier reports that there are no clear correlations between the different diagnostic tests. There is also no clear relationship between the condition monitoring test results and physical breakdown of the insulation in the high voltage tests.

Hence, it was concluded that these diagnostic tests on their own could not predict incipient insulation failure and that currently the most value derived from these tests would be to use the results as trending parameters rather than absolute values to predict insulation failure.

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ABBREVIATIONS

AC	Alternating current
BDV	Breakdown voltage
C	Capacitance
Cigre	Conseil International des Grands Réseaux Electriques
CM	Condition monitoring
DC	Direct current
DDF	Dielectric Dissipation Factor
DF	Dissipation factor
DIV	Discharge inception voltage
DL	Discharge locating
DMA	Dynamic mechanical analysis
EPRI	Electric Power Research Institute
FDS	Frequency domain spectroscopy
FEA	Finite element analysis
HCM	Hybrid clustering method
Hipot	High potential
HV	High voltage
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IR	Insulation resistance
IREQ	Research Institute of Hydro-Quebec
MCSA	Motor current signature analysis
MICAA	Machine Insulation Condition Assessment Advisor
NEMA	National Electrical Manufacturers Association
NQN	Nomalised quantity number
PD	Partial discharge
PDA	Partial discharge analysis
PDC	Polarisation and depolarisation current
PDI	Partial discharge index
PDPHA	Partial discharge pulse height analysis
PDSL	Partial discharge site location
PI	Polarization index
PRPD	Phase resolved partial discharge
PRPDA	Phase resolved partial discharge analysis
QM	Peak PD magnitude
RF	Radio frequency
RH	Relative humidity
RR	Resin rich
SCO	Synchronous condenser operation
SEM	Scanning electron microscope
SiC	Silicon Carbide
TB	Technical brochure
TC	Thermal cycling
TD	Tan delta; Tan (δ)
TVA	Tennessee Valley Authority
VE	Voltage endurance
VLF	Very low frequency
V _{op}	Operating voltage
VPI	Vacuum pressure impregnation

1. INTRODUCTION

1.1. Background to the problem

The effective management of assets currently presents a challenge to utilities. A cognisance and understanding of the actual condition of these assets will enable utilities to implement mitigation strategies and utilise these assets for the full duration of their lifespan. One of these assets could be hydro generators with the stator bars constituting one of the failing components. Understanding and monitoring the failure mechanisms present in high voltage (HV) stator bars would enable the utility to implement mitigation strategies, and possibly postpone refurbishment of the stator bars, thereby increasing the possibility of achieving maximum productivity from the generator.

The lifetime expectancy of quality stator windings is generally expected to be 30 to 40 years if maintained and operated properly [1,2 3.] Lifetime expectancy is defined as the duration of reliable, economical and available operation of the electrical insulation system.

However, during operation the HV electrical insulation is subjected to electrical, thermal, ambient and mechanical stresses simultaneously [1]. Constant exposure to any of these or a combination thereof will result in insulation ageing [4]. The electrical and physical properties of the insulation are changing with the continued in-service ageing and continued degradation will lead to reduction of valuable operative life and eventual insulation failure.

Various factors, of which some are caused by ageing, can influence the insulation condition like thermal decomposition, oxidation, leakage currents, moisture absorption, electrical discharges and their chemical by-products, mechanical wear or abrasion and thermo-mechanical stresses.

Failure could be caused or initiated by a single, combination or all ageing stresses simultaneously. Stresses can either be constant, e.g. magnetically induced mechanical stress or transient, e.g. out-of-phase synchronisation. Consequently, the time to failure, due to ageing stresses, is affected by the rate of degradation of the insulation material.

Furthermore, a global survey (Cigre TB 392) [5] on hydro generator failures indicates that the most frequent failures (57%) are caused by insulation damage (see figure 1-1). Figure 1-2

shows the insulation failure root cause analysis which is dominated by ageing and thirdly by internal partial discharges, 31% and 22% respectively.

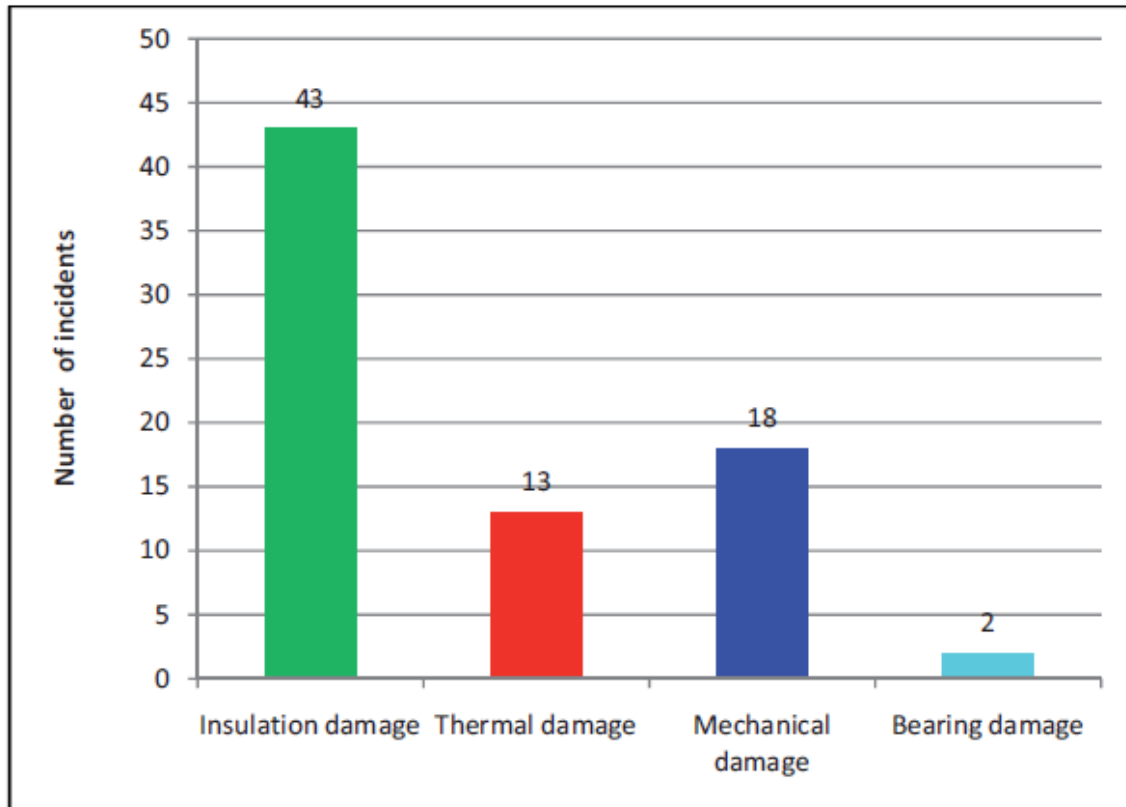


Figure 1-1: Hydro generators failures [5]

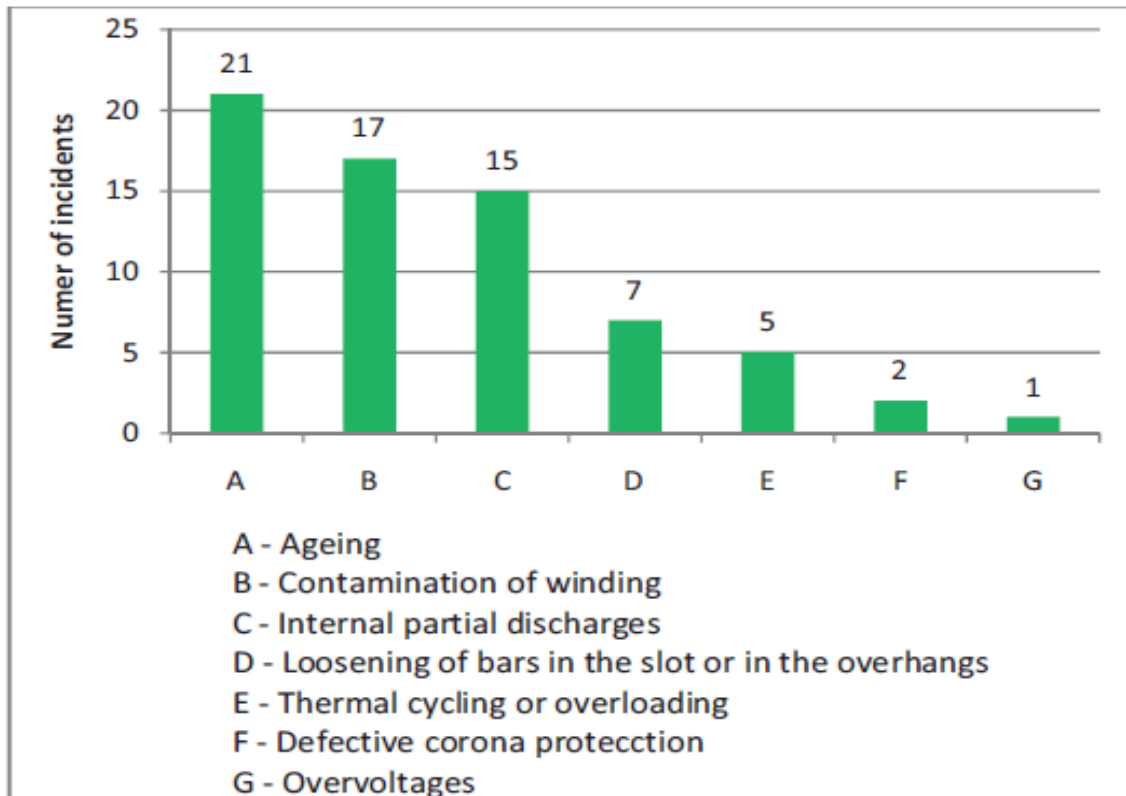


Figure 1-2: Insulation failure root cause analysis [5]

From figure 1-2 it can be deduced that the dominant root cause failure mechanism is ageing

Because both expected and unexpected stator bar in-service failures may lead to costly repairs, rotating machine users implement condition monitoring (CM), diagnostic tests and condition-based maintenance to mitigate risk. A typical CM programme is comprehensive and includes on-and-off-line identifying, quantifying and locating techniques [6].

Typical CM parameters in hydro generators are: air gap monitoring; stator core vibration, stator bar and endwinding vibration; magnetic field balance; partial discharge (PD); stator bar, rotor winding and core temperatures; rotor-stator concentricity and circularity; rotor mechanical balance; stator thermal expansion and frame displacement.

As the electrical and physical properties of the insulation material change with ageing it is reasoned that these changes might be measured to deliver a diagnostic of the insulation condition. Hence, it is reasoned that augmenting the CM parameters with conventional diagnostic tests would provide a more holistic view of the insulation condition. These tests could include: Insulation Resistance (IR); Polarization Index (PI); High Potential (hipot)

Alternating Current (AC) and Direct Current (DC) withstand tests; Dissipation Factor (DF); Tennessee Valley Authority (TVA) and Partial Discharge (PD).

However, due to the complex interactions of the above stresses, it is recognised that the interpretation of the diagnostic data is not straightforward, and many other properties of the machine are required to enable a reliable condition assessment. It is also acknowledged that the diagnostic techniques have some shortcomings.

1.2. Previous case study done at a utility

In 2003 and 2004 a utility conducted PD and TVA diagnostic tests on 30-year-old service aged stator bars. From these test results 26 stator bars (3%) were identified for breakdown voltage (BDV) testing. The test specimens identified had low, medium and high TVA values [6,7] and had operating voltages at the neutral or close to the neutral end connection.

The operating voltage (V_{op}) is the distribution of the induced voltages in individual bars throughout the entire stator winding. The specific generator stator winding design determines that a specified number of stator bars, connected in series, will result in the maximum stator voltage at the line side connection and zero voltage at the neutral side connection. Hence, individual stator bars in between the line side and neutral side will be of various voltages between these two values depending on the generator design. The stator winding is divided into three phases which is predominantly wye connected. The wye connection is used for the neutral grounding point and for the connection point of the relays used for generator protection.

Three (3) of the above-mentioned stator bars failed the 50 kV DC BDV test randomly, as described in 3.2.5.2, as there was no correlation between the voltage level and these diagnostic tests.

This occurrence led to further research into a better understanding of the results of the above-mentioned diagnostic test results, as well as further research into the correlation between these and BDV. This opportunity was presented with the refurbishment of two hydro generators in 2009. The TVA test was conducted with all the test specimens exposed to 7kV AC. From these test results a selection of stator bars with low, medium and high TVA readings were selected for BDV testing. Unfortunately, owing to time constraints, only a sample of 1,7% (28) of the stator bars could be tested of which three (3) stator bars failed.

The conclusion from the small sample was that TVA and PD testing alone are not accurate indicators of the actual condition of stator bar insulation in terms of their BDV even though these tests have been around for decades. This is consistent with Da Silva et al [8] who found a lack of correlation of PD readings and failure location as well as variability of PD results among laboratories. However, Stone et al [9] studied trending PD over time and concluded that doubling of PD magnitudes over a six-month period signifies a rapid rate of deterioration of the insulation,

The only way of objectively assessing the usefulness of a particular diagnostic test regarding the actual insulation condition is through destructive BDV testing and/or dissection of the insulation. Obviously, these approaches are not possible with test specimens that must be returned to the machine. An alternative is to subject test specimens to accelerated tests in laboratories. Experience has shown that although useful information can be acquired by these tests, the laboratory ageing cannot duplicate the complex machine stresses and the assessments of the efficacy of diagnostic tests based on laboratory aged insulation are suspect [5].

Using PD and TVA tests in conjunction with other diagnostic tests could possibly improve the accuracy of prediction to failure. To obtain a more holistic view of the actual condition, and failure mechanisms present of the stator bar insulation, it is considered advisable to conduct as many complementary diagnostic tests as possible from service aged test specimens.

Another opportunity to test service -aged bars arose when the decision was taken to replace all the stator bars on another hydro generator, one larger than the two tested in 2009. This research will provide more extensive diagnostic data on thirty (30) 34-year-old stator bars indicators of possible incipient faults and subsequently test the DC breakdown voltage strength.

It must be noted that the above referred DC breakdown voltage is a hipot DC test, which could possibly breakdown the insulation at an unknown value before reaching the limit of the test set (50 kV) and not a breakdown test where the voltage is continually increased according to a chosen procedure, until failure occurs.

1.3. Hypothesis

The following hypothesis will be tested; Traditional diagnostic tests of in-service aged stator bars can indicate incipient faults caused by ageing and can be verified by DC breakdown voltage.

1.4. Research questions

- To what extent can diagnostic tests directly predict imminent insulation failure in a hydrogenator stator.
- Are generator diagnostic tests results repeatable?
- Is the stator bar operating voltage in the generator significant with respect to ageing?
- What relationships can be identified between generator non- destructive diagnostic tests, DC BDV and the location of any DC high voltage failure?

1.5. Methodology

The methodology is based on an extensive literature research on ageing stresses, failure mechanisms, diagnostic testing standards and acceptance criteria for stator bars/coils globally. Collecting data from the various diagnostic test parameters and testing of sensitivities and combinations of the diagnostic test parameters to identify possible indication of DC high voltage insulation breakdown.

The approach of the research will be as follows:

- Conduct a literature review
- Description of diagnostic tests
- Conduct test protocols
- Analyse the test results
- Discussion of the test results
- Conclusion

1.6. Analysis not covered by this research

The research does not cover the following in the analysis:

- Neural networks - The data sample is too small for a neural network approach.
- Dissection of stator bars - Dissection and physical inspection would possibly provide more information regarding the exact failure mechanisms; that is, inter-strand failure, voids in groundwall insulation delamination, debonding from copper or even conversely well consolidated bars [10,11].
- Statistics Statistical analysis, for example, Weibull distribution could possibly yield more information [12,13].

1.7. Resources

The resources needed and available for the research include:

- In service-aged stator bars for testing
- Various test equipment for diagnostic testing

The following factors are limitations of the research project.

- The research was unfunded, in that no budget item has been establish for the unexpected testing.
- Only DC BDV testing was possible as no funds were available to transport an AC test set to the remote production site.
- Testing was done on a production site meaning time and space limitation to conduct testing.
- No funds were available for FEA software simulation packages.

1.8. Impact on utility

The utility has experienced several generator failures due to stator bar failures. This has led to high unplanned capital expenditure and, ultimately, hundreds of millions of rands in production losses.

Additionally, the utility is currently applying the utility industry standard of rewinding their generators every 30 years. Having reliable and accurate information regarding the actual condition and rate of degradation of the insulation material, would enable management to review this practice.

The intention of this research is to collect, correlate and interpret diagnostic test data intelligently.

This research would attempt to link particular diagnostic parameters to different failure mechanisms and thereby identify incipient fault conditions. This would possibly afford asset managers a better understanding of the actual degradation process or processes present, resulting in the capacity to define the risks involved and to prevent catastrophic failures. Consequently, planning for the most effective remedial intervention, that is, repair, refurbish or replacement as different environment and operating conditions could affect the insulation differently.

The results of this research are likely to be useful to other users of HV rotating plants.

The following chapter reviews existing literature describing the effectiveness of diagnostic tests in assessing the actual condition of insulation and whether there is correlation between these diagnostic tests and the DC breakdown voltage of the insulation.

2. LITERATURE RESEARCH ON HYDRO GENERATOR STATOR BARS

This chapter reviews existing literature describing the effectiveness of diagnostic tests in assessing the actual condition of insulation material as well as repeatability of the results. Any published information relating to correlation between diagnostic tests and BDV, as well as the location of insulation failures and repeatability of the results will be collected. Discrepancies between sources, and information about testing and interpretation will be noted.

The literature review is arranged according to the research questions identified in section 1.4.

2.1. Which tests can show the actual condition of stator bar insulation?

Rao [14] presents case studies of insulation condition assessment by various diagnostic tests (IR, PI, TD, PD). He concludes that each test has its own advantages and disadvantages, e.g. PD is more effective at detecting localised discharges than TD, but that all give unique information which should be analysed holistically taking cognisance of the machine operating conditions.

Yoshida and Umemoto [15] describe monitoring methods, deterioration judgement criteria and the development of diagnostic tests to determine serviceability of machines from a stator insulation health perspective. They were challenged and the limitations of the proposed tests were explained by Stone et al [16] on the basis that the statements were inferred from very limited test specimen quantities.

Hudon et al [17] describe how the Research Institute of Hydro-Quebec (IREQ) has developed an integrated diagnostic web based condition based maintenance system. The system has a three level diagnostic strategy: level 1- online-measurements; level 2- detailed on-line and off-line measurements (including physical inspections); and level 3- off-line measurements (including physical inspections, to which the understanding of fundamental generator problems is crucial) which entails significant dismantling [18]. All levels use specific diagnostic tools and the sequential level gets dictated by the results of the previous level.

Expert systems have been developed over the years to interpret several diagnostic test data. These systems have been developed to assist non-expert personnel to diagnose the condition of the machines thereby determining the risks to the machines from a wide range of inspections and tests. Various expert systems are described in the literature: Machine

Insulation Condition Assessment Advisor (MICAA) [19]; installed continuous on-line PD monitoring [20]; and the prediction of the remaining life of the insulation [21].

However, from previous experience it was found that the above systems are using limited inputs, predominantly traditional diagnostic tests, and at least one fundamental input that is the actual manufacturer of the equipment. Also, the suppliers express neither the size of the database being used nor the repeatability of the results. There is no mention of how many algorithms are being used and whether they make provision for the wide variety of manufacturing processes and materials.

The efficacy of the above systems is uncertain as during operation machines are exposed to very complex interactions of several operational stresses. Furthermore, multiple failures mechanisms can occur simultaneously producing a wide variety of unclear symptoms. Due to this, even experienced human experts can sometimes not arrive at a definitive diagnostic decision. It must also be understood that these systems are predominantly manufacturer specific as the 'knowledge base' database contains propriety information (materials used, design practice etc). Hence, very detailed information is required to be entered into these systems to obtain reasonable results. Also, the 'knowledge base' database could possibly be outdated with what is currently prevalent.

A crucial consideration regarding the reliability of insulation is that machine design and manufacturing processes have evolved significantly since 1970. Consequently, the previous specifications, which govern the diagnostic test procedures and interpretation, had to be reviewed and revised. Stone [22] provided a detailed review and recent changes of the following IEEE standards: 43, 56, 95, 286, 522, and 1434. He summarises the purpose of each standard, provides the pass/fail criteria (where applicable) and describes the differences from past versions. Stone [23] conducted a review on diagnostic and CM tests and found that significant improvements have been made in warning about developing insulation problems through the utilisation of traditional tests and monitors. These tests have improved reliability and are easier when using advanced technologies. New methods, such as dielectric spectroscopy; and polarisation and depolarisation current (PDC), have been introduced, but these have not yet been fully accepted by the industry.

No test is sensitive to all insulation failure mechanisms; hence, no single test is ideal and therefore the actual insulation condition cannot be determined by one specific test or only one measurement [24]. Various authors describe the following diagnostic tests: AC and DC hipot; HV DC voltage step and ramp tests; IR; PI; power factor and tip-up, voltage surge and PD.

However, the above-mentioned tests are not without their limitations, which Warren and Stone [24] discuss. Some of the quoted specifications have been updated over the last decade. For this reason, their quoted values are no longer valid.

Sedding and Stone [25] discuss the limitations of the TVA probe, as well as the evolutionary upgrade: the discharge locating (DL) probe. Brown [26] describes the TVA probe design and found satisfactory correlation between TVA probe measurements with off-line PD measurements. Sedding et al [27] investigate the effectiveness of using the DC ramp test to detect delamination in the groundwall insulation by testing stator bars of both low and high PD as indicated by the TVA probe tests. They conclude that the surface condition dominates the current readings and that it will be difficult to detect delamination in the groundwall under those conditions.

David and Lamarre [28] present theoretical considerations on the dielectric response of various types of generator winding insulation systems when subjected to DC testing for both ramp voltage test and PDC test. They conclude that changes in the insulation material can be precisely identified. However, they do caution about the effect of various winding technologies when interpreting the magnitude of absorption currents and the presence of Silicon Carbide (SiC) based stress grading tapes when measuring the IR.

David et al [29] describe a model of theoretical calculation of the dielectric response of stator winding insulation employing the DC ramp test. The current component of the I-V curve measured during this test is a summation of all contributing currents: that is capacitive, surface leakage, conductive and absorption. Their model enables the separation of individual contributions of the above. A satisfactory correlation was found between their calculated values of absorption and leakage currents when compared to those deducted from the PDC test.

Bhumiwat [30] employs PDC as an on-site non-destructive test to monitor the condition of the HV insulation of motors. Bhumiwat [31] applies this technique to illustrate field experiences by testing two identical stators with different insulation conditions. She demonstrates that although the frequency domain dielectric response cannot identify the failure mechanisms present, it will be the decision-making parameter for acceptable continued operation. The time domain measurements can identify failure mechanisms like conductive or surface contaminants. She concludes that the earlier the polarisation current separates from the depolarisation current, the quicker the rate of insulation deterioration.

Bhumawat [32] demonstrates with case studies that PI value alone is not a sound parameter to decide insulation dryness but that the product of IR and capacitance (C) provides a better measure of insulation dryness quality. She also demonstrates that a combination of PDC, Dielectric Dissipation Factor (DDF) and C ratio provide decisive crucial information regarding the failure mechanisms present in the insulation.

Although PD testing has been recognised as a valuable tool to monitor the condition of insulation materials in HV rotating machines, a testing specification with specifying limits, has not yet been developed [24]. It is, however, acknowledged that trending PD on machines is a reliable method of identifying stator insulation deterioration [9,33,34]. Documents published by CIGRE, IEEE and EPRI do not define acceptable PD levels.

PD data of 45 years of one utility have been reviewed by Sedding et al [35]. They discuss anomalies between on and off-line PD measurements. Warren et al [36] and Stone et al [37] employ PD to identify some failure mechanisms present during operation in generators, to provide guidelines for detecting these and also provide repair options.

Various PD measurement technologies and techniques are currently applied: electromagnetic waves [38] pulse height distribution, [39,40]; phase resolved partial discharge analysis (PRPDA) [41]; partial discharge site location (PDSL) [42] and partial discharge pulse height analysis (PDPHA) [43] all either complementing or confirming each other.

Various factors affect PD activity in machines: voltage, loading, temperature, pressure and humidity [44], PD types and location, bandwidth of detector and so on [45].

Goodeve and Stone [46] conclude from analysing a large database that machines manufactured and rewound over the last few years demonstrate more active PD activity than some older machines. This indicates that newer machines do not necessarily have superior insulation systems. Stone and Wu [47] concur with the above authors as they have discovered collaborating evidence when investigating the premature deterioration and failure of generator stator bars. Goodeve and Stone [46] recommend that in order to secure and maintain high reliability and longevity of machines, due diligence should be conducted during the following processes: specification, production and installation. McDermid and Bromley [48] recommend using PD as a screening test, for selecting stator bars for voltage endurance (VE) and thermal cycling (TC) tests, as a manufacturing quality control tool. They conclude that due diligence should also be applied during the monitoring phase over the equipment's full lifespan.

Mallikarjunappa and Mooching [49] present experimental data of PD analysis distinguishing between internal, slot and endwinding discharges on accelerated aged stator bars. There is unfortunately no clarity on both the method of the applied ageing stresses and on whether these are single, multi, sequential or simultaneously applied.

Stator bar insulation is exposed to different stresses in different areas. Lu et al [50] investigated the ageing extent in both the slot and endwinding sections. The diagnostic tests they applied were: PI; Dielectric loss at various voltages and temperatures; AC current measurement, PD and acoustic detection. Their test results from the above demonstrates that the worst readings occur within the endwinding, hence they concluded that the ageing extent is worst within the endwinding section compared to the slot section because of the higher stresses present.

Neti et al [51] introduce a concept of accelerated thermo-mechanical ageing of a motor. They apply the motor current signature analysis (MCSA) technique to monitor for any revelatory signs of the ageing process and/or failure mechanisms present that may result in imminent failure. Meaning a reasonable probability of happening.

Cherukupalli et al [52] review the test methods, conditions and the pass/fail criteria as specified in the voltage endurance specification IEEE 1553-2002 [53].

Previously, models have been developed for multi stress ageing, but the tests were conducted sequentially, thereby ignoring the interaction of various failure mechanisms acting simultaneously. Song et al [1] present an ageing test model of simultaneous multi-stresses that consist of mechanical vibration, thermal, electrical and winding thermal cycling. Through experimental tests, they concluded that the model was suited for the study of multi stress ageing of mica based insulation. They also concluded that the rate of change of the incremental loss tangent, incremental capacitance and partial discharge index (PDI) provide useful information regarding the ageing condition of the insulation and that the degree of insulation degradation can be estimated by using the AC current rapid increase index. The scanning electron microscope (SEM) analysis of some test specimens reveals that the applied multi-stresses can cause crack and delamination failures.

No single diagnostic, or set of once-off tests, can accurately determine the actual failure mechanisms present and actual insulation condition. Therefore, repair and refurbishment methods, driven by diagnostic tests results, should be applied differently for different failure mechanisms as the rate of failure differ significantly. However, stringent diagnostic tests can

be prescribed as quality control tests during the manufacturing process: that is, tests ought to be conducted during simultaneously applied multi stresses. Although diagnostic tests provide well informed insight into failing mechanisms present in insulation material, they cannot predict actual failure or remaining insulation life.

2.2. Are generator diagnostic test results repeatable?

Li and Chow [54] prove through case studies, on generators with known defects, that stator winding insulation failure mechanisms can be identified using diagnostic tests. They subjected the test specimens to the following tests: on-line and off-line PD, corona probe and DF. Some of their diagnostic test results were confirmed through visual inspection findings. Bélec et al [55] also present results from a case study through using PD measurements, applying both phase resolved partial discharge (PRPD) and other partial discharge analysis (PDA) methods. These test results showed that the semi-conductive (S/C) paint had eroded on some bars and the paint was reapplied by injecting S/C paint through the vent ducts.

Stone et al [44] tested for the effect of humidity on PD measurements and found an inverse correlation between surface PD and humidity during both laboratory and field tests [44]. However, the authors indeed acknowledge that their findings are based on a small test specimen.

Újvári et al [56] propose an algorithm for automated PD pattern recognition for turbo generators. They found satisfactory correlation between a previously defined referenced pattern and their system. They do, however, concede that a major limitation of their system is that it can only be used for a number of previously known failure mechanisms reference patterns, and unknown faults would therefore go undetected.

Comparison of discharges measured from both the generator terminals and in-front of individual slots were drawn by Hudon et al [57] on two hydro generators. They measured off-line PD discharges from the line side and compared those to measurements taken with a TVA probe from in-front of individual slots. The TVA measurements were also used as a detector for a PRPD acquisition system. The authors found that slot discharges could only be detected by both methods in one instance, and that the combination of the TVA/PRPD analysis could distinctively identify the source of the discharges.

Han and Song [58] validate their PD diagnosis based on a hybrid clustering method (HCM) through, using laboratory data from stator bars with artificial defects.

For continued and reliable operation of HV equipment, the insulation system should be properly designed and manufactured [59]. Many end-users stipulate stringent quality control and assurance functions IEEE 1310-2012, [60] for example during manufacturing to determine the insulation performance during cyclic and elevated temperature operation. Braun et al [59] describes a way to determine the effect of cyclic and elevated temperature into the behaviour of the resin component of insulation systems through the use of dynamic mechanical analysis (DMA). Stone et al [61] also uses TC to describe the failure mechanisms present during cyclic operation of machines. They test certain manufacturers' insulation systems in order to identify any shortcomings.

Wendel et al [62] subjected 40-year-old aged bars to the following diagnostic tests: loss factor; polarisation currents and PD. They found that all the selected bars had passed the required parameters, as had been stated within the appropriate specifications. However, the PD test was the most sensitive test to incipient failure mechanisms, and it would eventually lead to imminent failure. They conclude that although diagnostic tests cannot predict the remaining life of insulation material, they unquestionably provide information regarding failure mechanisms present, and provide insight into the operational reliability as well as failure probability.

Song et al [63] diagnosed stator bars being aged in three distinctive groups: thermal and electrical stresses; mechanical vibration and thermal cycling. These groups were then interchanged. They conclude that the ageing state of insulation can be correlated with the skewness of PD distributions and that the BDV has some relation to PD maximum magnitude.

Although [62;63] conclude positive outcomes there are some important factors to consider. Firstly, [62] does not declare PD values and [63] results came from laboratory aged bars. Hence, it was prudent to obtain actual test parameter values on a bigger sample size of in-service aged test bars and compare to these findings.

Traditionally, IR and PI have commonly been used to identify contaminated windings [64]. However, these tests cannot detect thermal deterioration of insulation abrasions [65]. Stone and Sasic [65] tested some specimens, with the age ranging from new to a few decades old, to determine whether the PDC could provide more diagnostic information regarding failure mechanisms present. They compared these test results with the following off-line tests: DF

tip-up, DC ramp and both low and high frequency PD tests. They conclude that the PDC test seem able to detect failing mechanisms associated with stress grading problems, but not thermal ageing. They do, however, stress that the comparison test results produced inconsistent results, and that further tests are required to determine the PDC test effectiveness confidently.

Sumereder et al [66] compare unconventional diagnostic test results with the following conventional tests: $\tan \delta$; IR and PD. They verify the dryness of a winding by analysing the dielectric response when subjected to PDC and frequency domain spectroscopy (FDS). They use an algorithm that applies PDC at low frequencies and FDS at high frequencies, with the resultant $\tan \delta$ value a function of frequency. Their results indicate that a more reliable parameter of the dryness would be $\tan \delta$ measured over a relevant frequency spectrum. They also acknowledge that for resin-impregnated insulation systems, more research is needed to determine the absolute effect of humidity.

Pinto [67] suggests an improved method to detect contaminated stator windings in the field by comparing $\tan \delta$ values with the estimated $\tan \delta$ and C variations with frequency, driven by the charging current. However, more analysed field data is required to determine the validity of this method.

Muhr et al [68] investigated the influence of temperature and relative humidity on the DF of both resin rich (RR) and vacuum pressure impregnation (VPI) insulation systems. They developed mathematical models and concluded that the temperature dependence was an exponential function for which the DF could be calculated with known system parameters. Contrary to this, the relative humidity (RH) is more complicated but shows significant influence from 53% and 59% for VPI and RR systems respectively. Unfortunately, no data other than the test objects had a RR/mica insulation system, was given. Unknown parameters are sample size, both in numbers and physical dimensions, technical specifications of the climate chamber etc. With all these unknown parameters it will be a challenge to verify their findings.

Da Silva et al [8] subjected laboratory aged Roebel bars to PD testing by different independent expert laboratories and repetitive testing at one of these laboratories. These bars had to be tested to the same nominal conditions, same specification, and instrumentation. The variables allowed were e.g practices of pre-conditioning, environment control, grounding method etc. They concluded that the variability found amongst the different laboratories reach high discrepancies and is therefore not a reliable parameter to indicate pass-fail criteria. When analysing the results of the repeated tests at one laboratory, they found that repeatability and

reproducibility results also had variations amongst different test operators. Hence, giving credence to their previous finding.

It is clear that some questions remain regarding the repeatability and reproducibility of diagnostic test results as these tests have limitations and can be influenced by various factors e.g., humidity, temperature, changing of materials etc. Also, most of the test results came from laboratory aged specimens with the researchers stressing that more information is needed from in-service aged specimens for a better understanding of the failure mechanisms.

2.3. Is the stator bar operating voltage in the generator significant with respect to ageing?

Statistical analysis was performed on diagnostic tests results from stator bars aged 7 years, 22 years and unaged respectively by Morin et al [13]. The bars were subjected to the following measured quantities: PD inception voltage; average maximum apparent charge; $\tan \delta$ and $\tan \delta$ tip-up; total apparent charge and BDV. When comparing the test results to those of the unaged bars, there were some indications that the insulation had deteriorated under service conditions. The following parameters exhibit change with operating hours: PD inception voltage; average maximum apparent charge and voltage breakdown which accords possible validity to the above suggestion. Some correlation could be found between the maximum apparent charge and BDV of the line side and neutral side bar. This is disputed by Stone et al [16] which found that breakdown voltage is not a function of stator bar operating position thereby stating that electrical stress is not the dominant ageing failure mechanism.

These are contrasting views and the test results of this research will provide more data regarding this aspect.

2.4. What relationship can be identified between generator diagnostics tests, DC BDV and the location of any DC high voltage failure

In order to determine any quantitative relationship between BDV and diagnostic tests, a database for every different operating environment as well as every unique insulation system needs to be created [16]. They subjected stator windings to the following diagnostic and destructive tests: IR; PI; C; DF tip-up; PD magnitude and discharge inception voltage; HV DC, HV AC and impulse voltages. No direct correlation between the BDV and diagnostic tests

could be determined. They conclude that it is not possible to predict BDV from both once-off or a group of diagnostic tests. They do, however, express that these diagnostic tests indeed provide insight into the relative condition of the state of the insulation material and would function as an aiding tool if trended as historical data. Bruintjies [69] found a possible inverse relationship between BDV and both leakage current and capacitance after subjecting aged stator bars to IR, PD and BDV testing. He acknowledges that this conclusion is drawn from a small sample of test specimens and recommends that this concept be pursued using a larger sample of test specimens.

Sumereder and Dolcic [70] investigated the residual voltage endurance of operationally aged, 44-year-old, stator bars. The bars were exposed to the following diagnostic tests: IR; PI; DDF and PD. They concluded that only the DDF was able to indicate the probability of imminent failure conclusively.

Da Silva et al [71] mapped the PD distribution along the entire length of laboratory aged stator bars to identify insulation critical areas that would later fail under electrical stress by BDV. The insulation breakdown locations were compared to the PD mappings and no correlation could be found between the two entities.

Audoli and Drommi [72] and Timperley [73] give a brief description of the different stresses present when testing with AC and DC and that the stresses are controlled by their dielectric constants, whereas, the DC stresses are resistive and controlled by the resistivities of the insulation materials. Both Alke [74] and [4] states that DC is more probing for endwinding defects based on some of their findings. EPRI 1014908 [75] gives a guide for hipot testing of windings in rotating machines covering: types of hipot testing; difference in AC and DC testing stresses and suggest that the two tests test for different type of weaknesses in different areas.

Gupta [76] test different groups with both AC and DC high voltage in-situ in an attempt to ascertain the superiority (or not) and conclude that AC is more probing than DC. He does not indicate the breakdown locations for either test.

Lu et al [50] conducted PI, tan delta PD and acoustic detection on a slot and endwinding section of an in-service aged bar. It is not clear whether only one or more bar sections were tested. Based on experimental test results, they conclude that from all diagnostic tests that the ageing extent of stator insulation of endwindings is more serious than that of the insulation in slots. This phenomenon is explained by the fact that the insulation of endwindings was subjected to stronger stresses than that of slot portions was. Evidence in support of the

observations was obtained through slitting the specimens and inspecting the cross section of them. As stated, the sample size is unknown, and it is assumed that the two sections came from one bar only. Hence, a one bar experiment.

Emery [77] produced results from experiments showing that the voltage reduction along the endwinding is significantly better for an AC supply compared to that of a DC supply meaning that the stress grading is more effective when exposed to an AC voltage.

Gupta and Culbert [10] investigate an in-service endwinding failure by comparing the diagnostic test results between different machines with similar insulation systems and between phases of the same machine. They found in one machine a phase that passed the AC hipot test failed the DC ramp test meaning the claim that AC is a more probing test than DC is refuted. They conclude that the known different stresses under AC and DC testing can be more complex for significantly deteriorated insulation therefore more research is required to clarify the relationship between DC and AC hipot testing.

Most of the literature shows that diagnostic tests were conducted on test specimens that were artificially aged in a laboratory setting to assess potential ageing effects.

Some researchers [13, 16] have tested service aged bars in-situ and in a laboratory respectively. They attempted to find a correlation between these diagnostic test results and HV breakdown tests. Morin et al [13] used AC HV tests while Stone et al [16] used AC, DC and impulse voltages. There is contention in industry around AC and DC testing as it is implied that they detect different deficiencies in different areas of stator bars and that further experimental studies would provide more detail regarding breakdown location, failure mechanisms, etc.

2.5. Conclusion

A group of repeated diagnostic tests, if trended and analysed correctly by skilled operators, might provide valuable information regarding a holistic view of the relative condition of the insulation. However, diagnostic tests cannot predict actual time to failure or remaining life of insulation but can be significant trending tools.

Although it is believed that traditional diagnostic tests are proven to be reliable and acceptable, it is also clear that they are not without a few shortcomings; that is missing some failure

mechanisms. However, invasive or dissection tests, are still providing test personnel with relatively satisfactory correlations with diagnostic tests and putting the test results into perspective regarding significance of failure mechanisms present and rate of failure. However, the conclusions from above come from test specimens that were mostly aged by accelerated ageing in a laboratory environment. Hence, a need for data to be collected from in-service aged test specimens.

Newer diagnostic tests and techniques have recently been proposed. However, these have not yet been fully accepted by industry as more research and application tests need to be conducted.

To date, researchers have not discovered a proven correlation between diagnostic tests and BDV and are of the opinion that it is highly unlikely for a quantitative relationship to be discovered, as a relationship for every unique insulation system and operating environment would need to be established.

It is clear that some questions remain regarding the repeatability and reproducibility of diagnostic test results. However, asset managers in industry use the data provided by diagnostic tests to plan for future business strategies that is planning for plant maintenance, refurbishments, replacement of equipment or deferment of these. Also, the results of diagnostic tests are deemed extremely important as quality assurance tools during the manufacturing and installation processes. Hence, the reliability, repeatability and accuracy of this data is of the utmost importance.

Therefore industry requires better clarity or consensus on how to use this important information. For example, more emphasis on trending the data rather than relying solely on individual data points, could significantly enhance the level of confidence and applicability of diagnostic tests within industry.

The following chapter describes the diagnostic tests (applied for testing insulation integrity), the test parameters, and some limitations associated with of the parameters. This will then lead to a diagnostic methodology of possible correlation between the various test parameters amongst each other and insulation breakdown.

3. ASSESSMENT OF DIAGNOSTIC TESTS OF HYDRO GENERATOR STATOR BARS

This chapter describes the diagnostic tests applied in this research, the parameters used for assessment and their limitations. Understanding the purpose and protocols is important for doing the test properly, to obtain valid data, and in interpreting the results.

3.1. The role of diagnostic tests in detecting insulation material failure

In the majority of instances, integrity of the insulation material determines the expected lifespan of HV machines. It is notable copper conductors and core steel are superior to the insulation material (from a mechanical strength and melting temperature perspective).

Insulation damage is the dominant failure mechanism in hydro generator failures (see figure 1-1). The insulation material deterioration and eventual breakdown could be triggered by any of, or a combination of, thermal, electrical, mechanical or ambient stresses.

The epoxy/mica insulation material used to insulate stator bars comprises approximately (55-65% by weight) of mica insulation, (25-30%) resin and glass fabric and (10-15 %) other support materials [3,78,79]. The ratios depend on the manufacture's insulation system design.

Thermal ageing occurs in insulation material exposed to operating temperatures for prolonged periods. Thermal ageing is essentially an oxidation chemical reaction over a prolonged period caused by heat in the organic materials e.g., binders. The chemical bonds within the organic parts of the insulation occasionally break due to the thermally induced vibration of the bonds. Over a prolonged period, this reaction precipitates brittle and mechanically weakened insulation material [2].

In the case of epoxy materials, thermal stresses alters the bonds and breaks the molecular structure. This ageing process results in loss of insulating material and subsequent deterioration of the electrical and mechanical properties [80].

Hence, to achieve satisfactory service life, insulation materials must conform to various IEC, IEEE and NEMA MG1 standards, which are used for both maintenance and manufacturing tests.

Historically, the insulation defects, or some of them, have been detected and trended by diagnostic tests. These diagnostic tests are described and prescribed in the standards. Diagnostic test results, if properly interpreted, provide information about the future serviceability of components, in this case stator bars [14 ,81].

3.2. Description of test parameters

3.2.1. Polarization index (PI)

IR and PI tests are commonly used diagnostic tests to detect contamination, moisture and cracks in the insulation. The IR test is the measurement of the resistance of the insulation between the copper conductors and the grounded component usually the frame in the case of generators. This is achieved by supplying the copper conductors with a high voltage, well-regulated DC supply and measuring the resistance with a “megohmmeter” commonly known as “megger testers”. Since the purpose is to block the current flow between copper and the core, this resistance should ideally be infinite. Hence, the lower the IR value, the higher the probability of insulation material deficiencies.

In the present work the test specimens were first tested for insulation dryness and contamination as per IEEE 43-2013 [82] before being exposed to diagnostic testing that is, PD, TVA, and TD.

When the DC test voltage is applied the following, test currents are present over time: capacitive, conductive, absorption and surface leakage and decay as per figure 3-1.

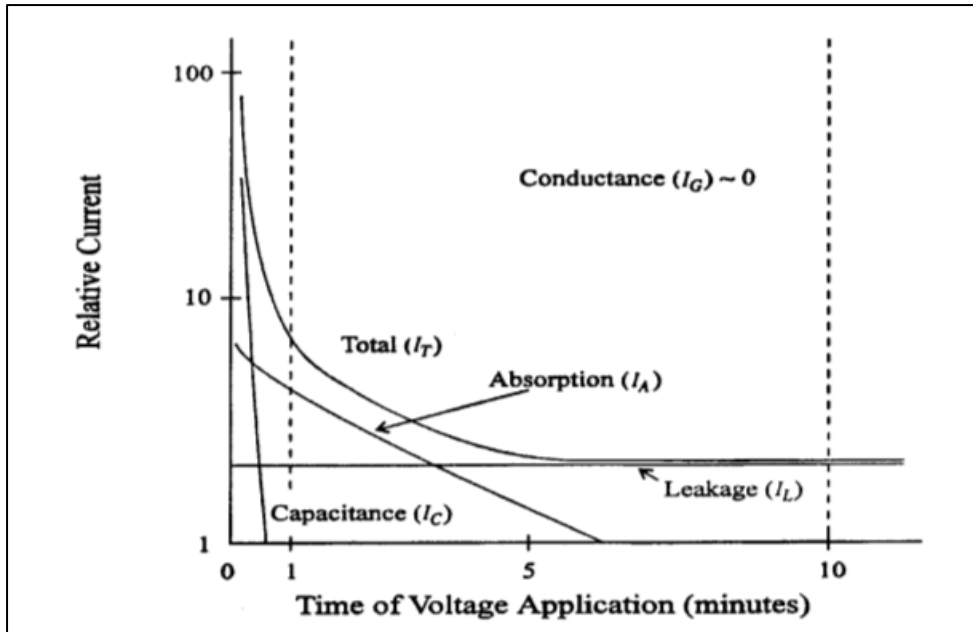


Figure 3-1: Currents present during IR testing [82]

3.2.1.1. Current descriptions

Capacitive Current (I_C): When the DC voltage is initially applied, a high charging current flows and decays exponentially depending on the capacitance of the insulation material and the instrumental resistance in series. The first IR reading is taken after 1 minute after applying the DC voltage to negate any distorted influence from this current.

Conductive current (I_G): This current flows due to the migration of electrons and ions across the groundwall insulation material and depends on the type of insulation. This current should ideally be zero and only flows due to contamination caused by pinholes, cuts or cracks. With healthy modern epoxy-mica insulation this current is normally zero as electrons and ions cannot penetrate this insulation material.

Absorption current (I_A): Many insulation materials contain polar molecules which have an internal electric field due to the distribution of electrons within the molecule. This current flows due to the re-alignment of polar molecules in the applied DC electric field and depends on the type and condition of the insulation material. The current stops after all molecules are aligned. This is the one component of the absorption current called the polarization current. As figure 3-1 shows, the absorption current is initially high and monotonously decays with time. Other

than molecular realignment, absorption currents may arise in high voltage laminated insulation due to electron trapping at interfaces [22].

Surface leakage current (I_L): It can be seen from figure 3-1 that this is a constant DC current caused by partly conductive contaminants (oil, dirt, chemicals, etc) on the surface of the stator bars/coils and is dependent on the amount of conductive material as well as temperature. A large leakage current (I_L) is indicative of deterioration caused by contamination which could lead to electrical tracking.

The total current (I_T) is the sum of all these current components.

With the initial DC voltage application all the currents are present and charge the insulation material. The I_G is ideally zero in modern insulation systems (with no deficiencies). The I_C decays exponentially rapidly and the I_A decays over a longer period until the polar molecule re-arrangement process is completed. Hence, leaving I_L as the only current present and thereby giving an indication as to the degree of contamination present via the IR reading (figure 3-1).

However, IR is geometry (size, shape, spacing, effective insulation area and thickness) [83] and temperature dependent, as illustrated by correction factors in [82], and therefore considered as an unreliable trending parameter.

The PI parameter, an IR 10 minute to 1 minute ratio reading, was developed to make IR interpretation less temperature sensitive [22].

$$PI = IR_{10} / IR_1 \quad [82]$$

Industry experience over decades shows that if I_L or I_G are much larger than I_A , the PI ratio would be in the region of 1 and the possibility of electrical tracking exists. Conversely, a PI ratio higher than 2 indicates a low probability of electrical tracking.[22]

3.2.2. Partial discharge (PD)

Electric breakdown strength is an important characteristic of insulation material. The electric breakdown is not solely dependent on the applied voltage but rather on the strength of the electric field it is exposed to. The electric stress in a parallel geometry is expressed as

$$E=V/d \quad (\text{kV/mm}) \quad [2]$$

where E is the electric stress, V is the voltage across the copper and the insulation material and d the distance between the copper and the outside of the stator bar/coil, that is the insulation thickness. If V is increased gradually, electric breakdown will eventually occur. The electric strength can then be calculated using the above equation [2].

Each material has a defined electric breakdown strength. For air at room temperature, atmospheric pressure (100 kpa) and low humidity, the electric strength is 3 kV/mm. The breakdown strength for solid insulating materials is normally much higher than air [84].

Electric breakdown can occur within air pockets (voids) within insulation material. Voids can be caused by deterioration of the insulation material during operation or introduced during manufacturing. A high enough electric field across an air pocket ($E > 3 \text{ kV/mm}$), will breakdown the air through a process called ionisation, causing a spark. This spark is called a partial discharge. The lowest voltage at which continuous PD pulses are detected is called the discharge inception voltage (DIV). The PD spark is called partial as it is only occurring in the air pocket while the rest of the insulation can withstand the applied voltage. However, continuous discharges will deteriorate the insulation material to the extent where it will erode the groundwall resulting in a fault condition for the machine.

PD cause rapid current pulses to travel in stator windings. One method applied in measuring these pulses is via HV capacitors, typically 80-1000 pF. These capacitors present high impedances to the power frequency and low impedance to the high frequency PD pulse currents. This allows the high frequency pulses to be detected by PD measuring instruments.

PD discharges occur on the surface of endwindings, within the slots and within voids inside the insulation material of HV bars/coils. PD is a symptom of other failure mechanisms caused by thermal, electrical, ambient and mechanical stresses. However, PD itself can contribute to insulation ageing by eroding the organic material of the insulation.

Unlike, the tan delta tip-up measurement (3.2.4) that is sensitive to the total PD activity, the PD test measures both large and smaller pulses. The void size drives the magnitude of the PD pulses [22]. Hence, the pulse analysis is concentrated on the larger pulses as failure is more likely to occur at the more deteriorated areas. This research does not focus on the theory of PD degradation of the insulation as this has been extensively covered by others.

PD tests plot two quantities: namely, peak PD magnitude (Q_m) and normalised quantity number (NQN). Q_m is defined as the magnitude of pulses corresponding to the PD repetition rate of 10 pulses per second [7], which represents the severity of deterioration, of the worst location, in the insulation material. NQN is defined as the normalised quantity number which is proportional to the overall deterioration of the insulation material [11]. For the sake of aligning with the PRPD plots (Appendix D), Q_m will be referred to as Q_{Peak} for the remainder of the document.

Because a variety of factors (driven by different failure mechanisms) affect the detection of PD pulses, the most value derived from this test is to use the results as a trending and comparison tool; that is, doubling of PD values over a six-month period indicates insulation material deterioration [7].

It is accepted that PD measurements can provide information regarding the quality/condition of the insulation material. However, because numerous variables are involved (that is, the particulars of insulation systems, the testing protocols and so on), it is complicated to set absolute limits [7].

IEEE 1434-2014 [7] is augmented by SANS 60034-27-2007 [85], IEEE 1799-2012 [86] and IEC 60270-2000 [87].

3.2.3. Tennessee valley authority (TVA)

PD activity, due to electromagnetic disturbances [7] is detected in the insulation material by the TVA probe (peak pulse meter) due to its sensitivity to radio frequency (RF) energy. The larger the discharges or closer the probe, the larger the discharge response.

The TVA limitations (directionality and quantitative measurements for comparison) of the initial probe have been improved by a modern version called the Corona probe (Qualitrol). However, the industry still refers to the test as the TVA test. As such, the Corona probe used in this research will also be referred to as the TVA test.

Field experience [6] indicates the following:

- Less than 10 mA – good insulation
- Greater than 50 mA – small voids
- Greater than 100 mA – medium voids
- Greater than 300 mA – large voids

IEEE 1434- 2014 [7] acceptable values:

- Asphalt mica <100mA
- Polyester mica < 30 mA
- Epoxy mica < 20 mA

CIGRE TB 581-2014 [88]

- 20-120 mA : possible aged insulation; operation with medium risk
- >120 mA : possible faults developing; operation with high risk

However, when the TVA probe values (maximum amplitude) are combined with a PRPD acquisition system, the diagnostic capabilities are further enhanced, and several defects can be recognised [57].

Corroboration of TVA and off-line PD is sometimes possible, but not always as the results depend on the quantity of discharges. [57]

3.2.4. Tan delta (TD; Tan δ)

The ideal stator winding/coil insulation is essentially a high voltage lossless capacitor. However, the ideal winding/coil does not exist, and practical insulation materials have some inherent loss factors, called dielectric losses.

Dielectric losses consist of the following: solid losses (dielectric absorption and conductivity), and ionisation losses. The sum of these is called the total dielectric losses which is measured during the Tan delta tip-up test. Figure 3-2 shows that these losses can be plotted as a function of applied voltage [89].

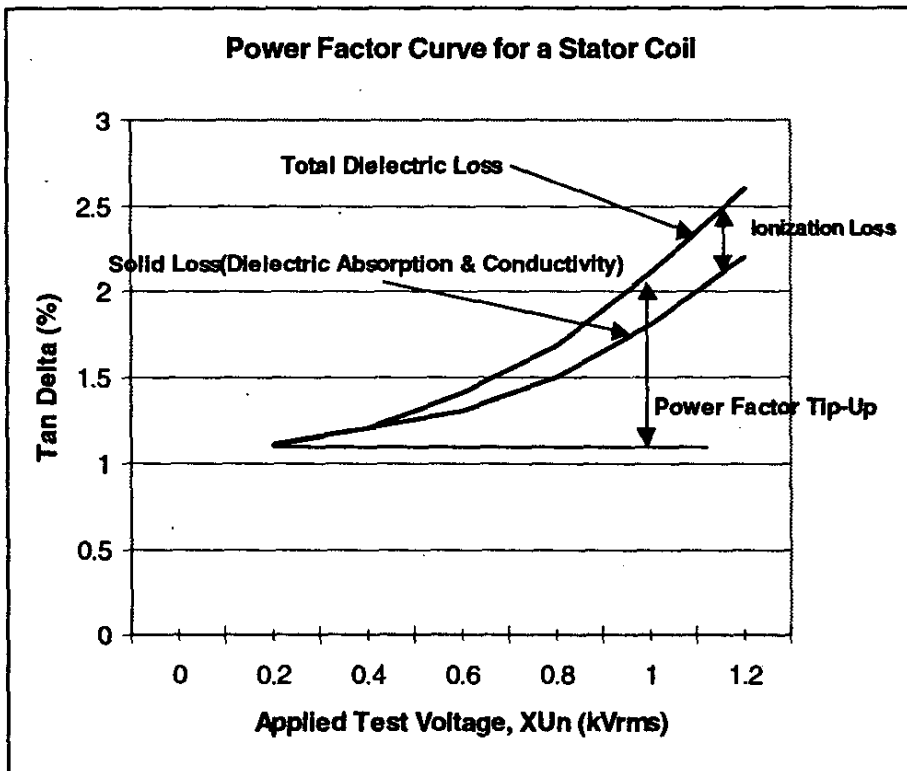


Figure 3-2: Tan delta tip-up as a function of voltage [89]

The tan delta tip-up value, in percent or per unit, is calculated by subtracting the value of tan delta factor measured at the selected lower test voltage from that measured at the selected higher test voltage.

Tan δ tip-up is measured in steps of 20% applied U_n , where U_n is rated line-to-ground voltage. IEC 60034-27-3 [90] defines tan delta tip-up factor as $0.6U_n$ minus Tan δ reading recorded at $0.2U_n$.

with an acceptance value of 5×10^{-3} (0.5%).

Capacitance tip-up test is deemed a complementary test to the tan delta test as the capacitance values are recorded during the tan delta test and is defined as:

$$\Delta C = \frac{C_{HV} - C_{LV}}{C_{LV}} \quad [2]$$

When voids exist within the insulation material structure, gaseous discharges will occur within these voids at high enough voltages (breakdown voltage). These discharges intensify with an increase of applied voltage and produce higher levels of localised sound, light and heat. These

internal discharges (ionised losses) can occur at many locations within the winding/coil insulation structure. The ionisation loss factor is shown in figure 3-2.

The complete gas space does not discharge immediately at breakdown voltage, but only a fraction of it [91]. Areas with previously charged deposits, from the previous cycle will discharge first. Several factors influence the inception voltage of these discharges over the AC cycle (e.g., different void depths). Numerous discharges are occurring in sequence during each cycle, predominantly on the increasing voltage part of each half cycle [91].

The higher the $\Delta \tan \delta$ value, the more widespread the PD activity. Hence, the higher the $\Delta \tan \delta$ value, the higher the energy consumed by PD.

According to Dakin [91] both the capacitance and TD of insulation material increase with an increase in voltage. As shown in figure 5-5 there is a significant increase in both around the $0.6 \times U_n$ value. This is where the PD inception voltage is reached, see 5.3, and where the TD rises steeply [92].

3.2.5. High voltage withstand tests (HV)

The following are voltage withstand tests meaning that the insulation should not breakdown when a specific level of voltage is applied across the insulation for a specific time period. When the insulation passes these tests, it is accepted that the insulation will not fail during operation. Hence, the insulation would withstand the normal electrical stresses for the expected lifespan of operation. Contrary to this, if the insulation fails these tests it is not fit for future operation.

3.2.5.1. Very low frequency (VLF) tests

This test is described in IEEE 433- 2009 [93]. This is not a diagnostic test but rather a pass or fail offline test. The voltage stress distribution at low frequencies, (as low as 0.1 Hz), was found to be similar to those at the rated frequencies in the insulation material of machines used in the HV environment [94,95].

The AC breakdown process can be ascribed to PD induced heating and to the continued deterioration because of the repeated discharges or thermal losses associated with the dielectric losses [93].

3.2.5.2. Direct current (DC) high potential tests

DC high potential tests are described in IEEE 95 -2002 [96]. This is an off-line test indicating insulation defects that could lead to imminent in-service insulation failure. The voltage drop across the components depends on the components' resistivity. Hence, the lower the resistance, the lower the voltages drop. The DC high potential test is seen as a controlled off-line over voltage test of maximum voltage being applied to a stator under a phase-to-ground fault. Meaning the component will pass a surge caused by a system fault [22]

The options available for DC HV testing include the conventional DC hipot test and the controlled DC overvoltage test. The controlled overvoltage test has three (3) alternative HV DC test methods available, that is, uniform-time voltage step, graded-time voltage step and ramped voltage [75]. The ramped voltage (1 kV/min) test method will be used for the 30 kV DC and 23 kV (rms 0.1 Hz, VLF) tests, thereby minimising any human interference. The test is more accurate, repeatable and better controlled compared with the other two test methods [96]. The 50 kV hipot (1 minute) test was done using the conventional controlled DC overvoltage hipot method by manually increasing the voltage in a series of 1 kV/min steps [96; section 7.6.1].

The above specifications were complemented with IEEE 62.2-2004 (section 7) [97] IEEE 492-1999 (Section 8) [98].

It can be concluded that the DC hipot is not a very informative diagnostic test but rather (from a delamination, pinholes or cracks perspective) a go-no-go test for the condition of the insulation material.

It must also be stated that the stress distribution within the insulation material is different than during a normal AC operation due to the electric field being determined by the insulation material resistance instead of capacitance as is the case during normal operation [82].

3.3. Limitation of some test parameters

3.3.1. Insulation resistance (IR) and Polarization index (PI) values

Bhumawat [32] presents case studies demonstrating that the PI value on its own is not an accurate indicator of insulation dryness. She states that PI is sensitive to contaminants but not to polarisation failure mechanisms, that is, insulation failure caused by thermal and electrical ageing. She concludes that the insulation Capacitance Ratio, DDF and PDC shape present the most decisive and efficient assessment of failure mechanisms present in insulation materials.

3.3.2. Partial discharge (PD) Q_{Peak} readings

Q_{Peak} readings are a quantitative comparison value only and can provide an indication of the level of deterioration by trending over a period.

More insight into the failure mechanism(/s) present can be determined by measuring the pulse count and on which half cycle the PD is occurring. From this information the location of the PD activity can be determined. That is: positive PD predominance meaning activity on the surface of the bars; negative PD predominance meaning activity at the copper and insulation interface; and no PD predominance meaning activity within the insulation material [2,54]. PD pulse patterns can also indicate the failure mechanism(/s) present [7].

Current technology cannot record PD patterns and unequivocally calculate the source of the failure mechanism [7].

3.3.3. Direct current (DC) tests

More detailed analysis would have been possible if the current vs voltage values were trended during the ramp-up, this is because the capacitive current remains the same and can be ignored in the analysis. The current was not recorded during this test. This way, current instability can be detected more easily and could possibly enable delamination detection. The linearity of current-voltage curve, with no curve breakaway, is indicative of healthy insulation [96]. However, bars have failed before without prior warning, that is, no breakaway current curve [10,27].

3.4. Summary

It is envisaged that the interrogation of the results of these non-destructive diagnostic tests will provide one or more indicators of imminent insulation failure and to be verified by DC HV breakdown test.

The next course of action is to identify suitable test specimens and test them according to the diagnostic tests described earlier in this chapter.

The following chapter describes the generator from which the test specimens were collected, as introduced in chapter 1.2, and the test protocols for collecting the data.

4. GENERATOR DATA AND TEST PROTOCOLS

This research explores whether a relationship exists between a particular parameter, or a combination of parameters, and insulation failure of aged stator bars being exposed to all stresses simultaneously during operation.

This chapter provides the history of the test specimens, as well as the operating regime in which they were used. The test protocols are also described and illustrated in this chapter.

For this research in-situ IR, PI (table B-1) and TVA (figure 5-1) tests were conducted on an assembled generator with 34-year-old stator bars. From these tests results (figure 5-1;180 stator bars), 30 stator bars (table 5-1) out of a total of 180, with low, medium and high TVA values, were selected to be removed and individually subjected to the previously described diagnostic tests. As can be seen, some bar numbers are missing in the table, as, initially 60 bars were numbered to be removed for testing. Regrettably, 30 of these were damaged due to various reasons, and the initial numbering was retained as specimen numbers.

It must be stated that even though the bars were found tight in the stator core slots, the visual inspection found some evidence of degradation of the semi-conductive paint (semicon) in the slot section on some stator bars. This is indicative of a loss of electrical contact between the stator bar and grounded core that could lead to slot discharges. The intent of the research was to test the integrity of the groundwall insulation of the in-service aged stator bars. Hence, to only detect the PD activity present in the aged groundwall insulation material, it was decided to repair the semicon and stress grading coatings with the originally specified SiC based paint. Thereby, nullifying the effect that could possibly be caused by the damaged semicon stress grading paints, on the PD test reading. Also, by repairing these paints, it was also expected that there will be no effect on the leakage currents owing to the influence of endwinding environmental materials (oil, dust etc).

4.1. Generator history

The machine is coupled to a reversible hydraulic turbine and operates as a generator when the unit is in generation mode and as a motor when the unit is in pump mode. The generator-motor (G/M) is also designed for Synchronous Condenser Operation (SCO) when it is used for voltage and power factor regulation of the transmission line system.

The machine was commissioned in 1982 and is operated in a peaking operating regime with typical morning and evening start for generating, within a Class B temperature rise environment. Every stop-start and start-stop action is classified as a mode change. This parameter is important as the stopping and starting of generators could also affect stator bar insulation degradation. Unfortunately, accurate history regarding both the operation and diagnostic data of the generator are limited. In fact, the utility had only done IR and PI readings on some occasions. As these parameters are influenced by environmental factors such as temperature, humidity etc, it would not add value to compare the test values with the historic values. The available information is displayed in table 4.1:

Table 4-1: Generator operating and design data

Year Commissioned	Operating hours until October 2016		
	Generating	Pump	SCO
1982	62328	90719	73503
Design Data			
Rated Output	281.5 MVA		
Rated Voltage	11000 V		
Rated Current	14775/15215 A		

Operational electrical stress of stator bars: 2.45kV/mm

4.2. Test protocols

4.2.1. Tests on assembled machine

The following tests were conducted on the assembled generator:

IR and PI at 5 kV DC (table B-1)

TVA at 7 kV AC (figure 5-1)

4.2.1.1. Insulation resistance (IR) and Polarization index (PI) tests

These tests were conducted in accordance with [82]. The IR and PI readings were taken after one minute and 10 minutes, respectively, with 5 kV DC being applied to the bars.



Figure 4-1: Megger, used for measuring IR and PI

4.2.1.2. Tennessee valley authority (TVA) test readings inside assembled machine

IEEE 1434-2014 [7] was used to conduct these tests. The test bars were energised to 7.0 kV AC. The probe readings were taken along the slot and the highest value was recorded.



Figure 4-2: Top left and bottom: Taking in-situ TVA readings
Top right: Typical power supply indicators

4.2.2. Tests on individual bars

The 30 removed bars (table 5-1) were subjected unguarded to the following diagnostic tests and sequencing:

- IR and PI before PD, TVA and TD tests (5 kV DC); (table C-1)
- PD and TVA (6.4.0 kV AC); (table C-2)
- TD (6.4 kV AC); (table C-2 and C-3)
- IR and PI before HV tests (5 kV DC); (table C-4)
- HV {23 kV (VLF); 30 kV (DC); 50 kV (DC) }; (table C-5)
- IR and PI after HV tests (5 kV DC); (table C-6)

The above diagnostic test and sequencing were used to determine whether there were any indications of imminent insulation material failure and whether there was any relationship between the failure and any of the diagnostic test parameters, or a combination thereof.

In theory, it is expected that the insulation material of bars with high PD, TVA and TD values, or a combination thereof, will have deteriorated due to ageing to the extent that the bars will fail HV tests.

All the respective diagnostic test parameters were recorded in the appendices A-D and analysed in chapter 5.

4.2.2.1. Preparation of test specimens

The bars were clamped in earthed plates to simulate the earthed core. The bars were then suspended on insulated stands and directly connected to the respective test sets for the respective tests, as per the above sequence.

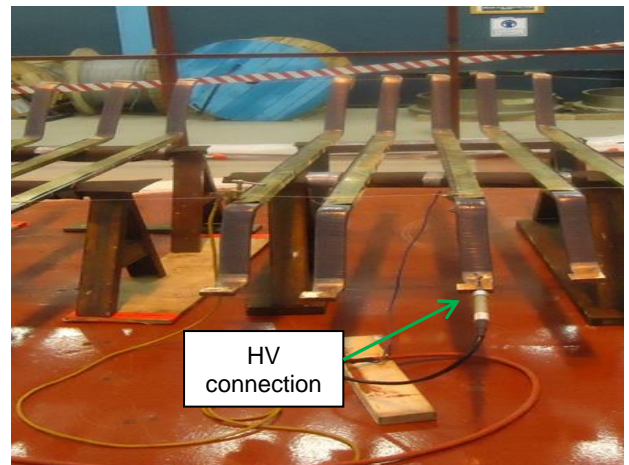
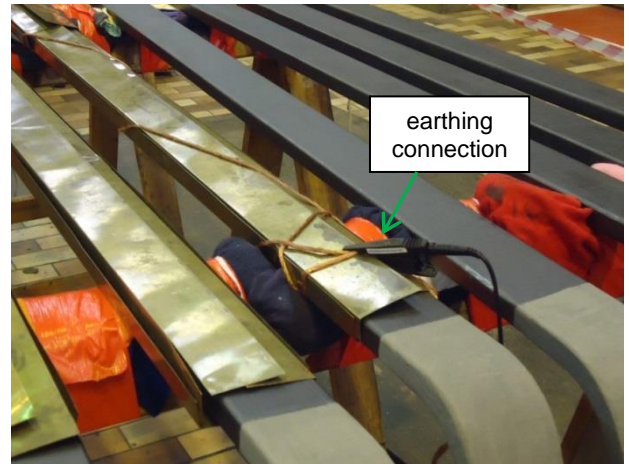


Figure 4-3: Test specimens showing typical connection points for tests.

4.2.2.2. Insulation resistance (IR) and Polarization index (PI) testing before Partial discharge (PD), Tennessee valley authority (TVA) and Tan delta (TD) tests

The first of the test, the IR and PI, as sequenced in 4.2.2 were conducted in accordance with [82]. The IR and PI readings were taken after one minute and 10 minutes, respectively, with 5 kV DC being applied to the bars.

4.2.2.3. Partial discharge (PD) test configuration

The PD testing was conducted in accordance with [7,85,86,87].

The voltage was raised to U phase to ground (6.4 kV), was stabilised for a few minutes and then the PD parameters (Q_{Peak} , Q_{Avg} , DIV) were captured.

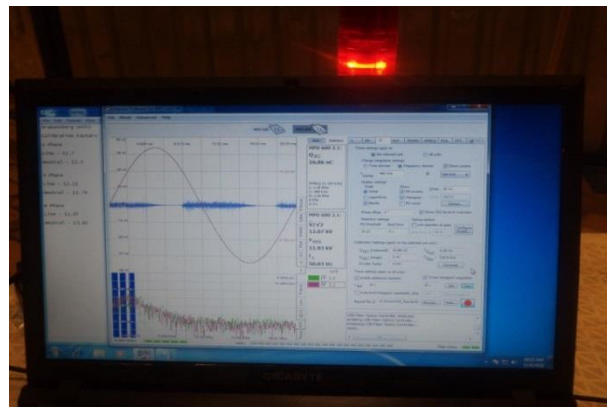
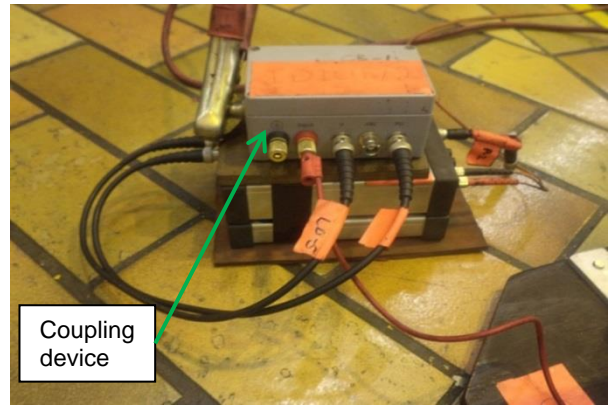
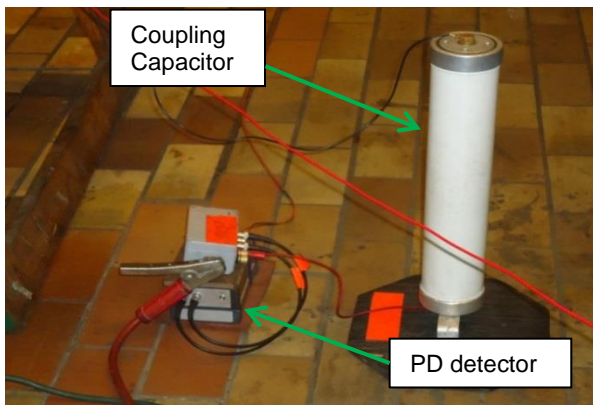


Figure 4-4: PD test configuration showing test equipment and a typical result screen.

4.2.2.4. Tennessee valley authority (TVA) testing

IEEE 1434-2014[7] was used to conduct these tests. The test bars were energised to 6.4 kV AC. The probe readings were taken along the length of the surface of the stator bar and the highest value was recorded.

4.2.2.5. Tan delta (TD) testing

These tests were conducted in accordance with [90,99]. The voltage was gradually increased in steps of 0.2 Un until 6.4 kV AC, and back down to 0 V. Readings of TD, capacitance and current were recorded at the ascending and descending 0.2 Un steps.

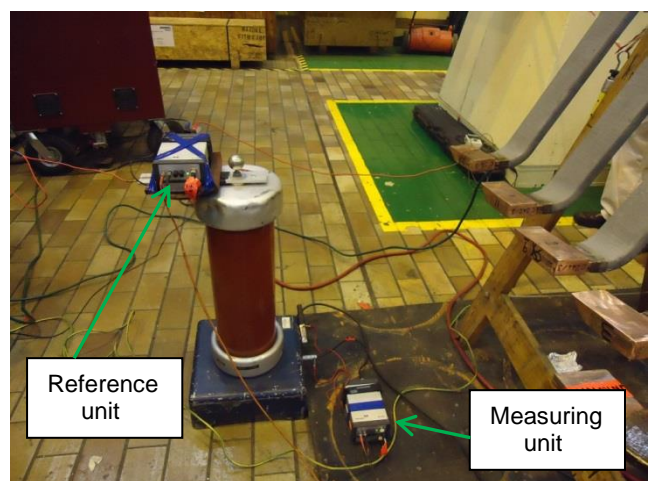
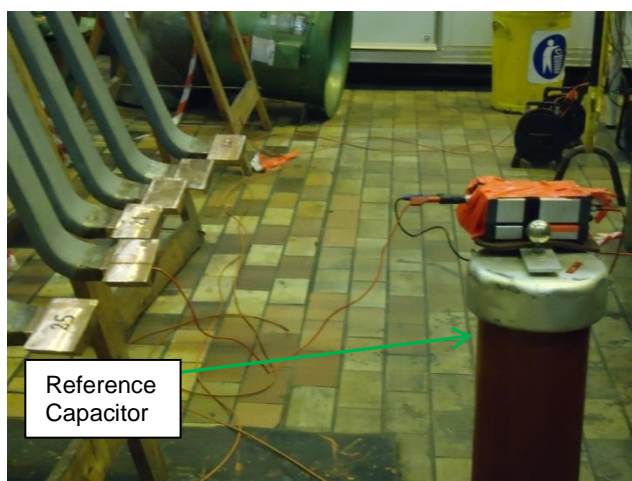
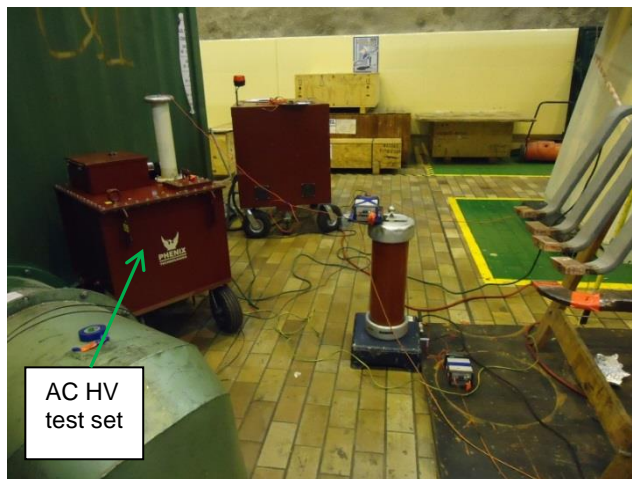


Figure 4-5: TD test configuration showing test equipment

4.2.2.6. Insulation resistance (IR) and Polarization index (PI) testing before High voltage (HV) testing

These tests were conducted in accordance with [82]. The IR and PI readings were taken after one minute and 10 minutes, respectively, with 5 kV DC being applied to the bars.

4.2.2.7. High voltage (HV) Testing

The test configuration in respect to instrumentation, connections, proof testing and controlled overvoltage was done in accordance with IEEE 4-2013 Sections 5-7 [100] and IEEE 95-2002 Sections 5-7 [96].

The bars were tested according to IEEE 433-2009 (VLF) [57/93] and IEEE 95-2002 (DC) [96] respectively.

The bars were first tested at 23 kV (VLF) and thereafter at 30 and 50 kV DC respectively.

Figure 4-6 shows the test circuit as per [96 figure1]

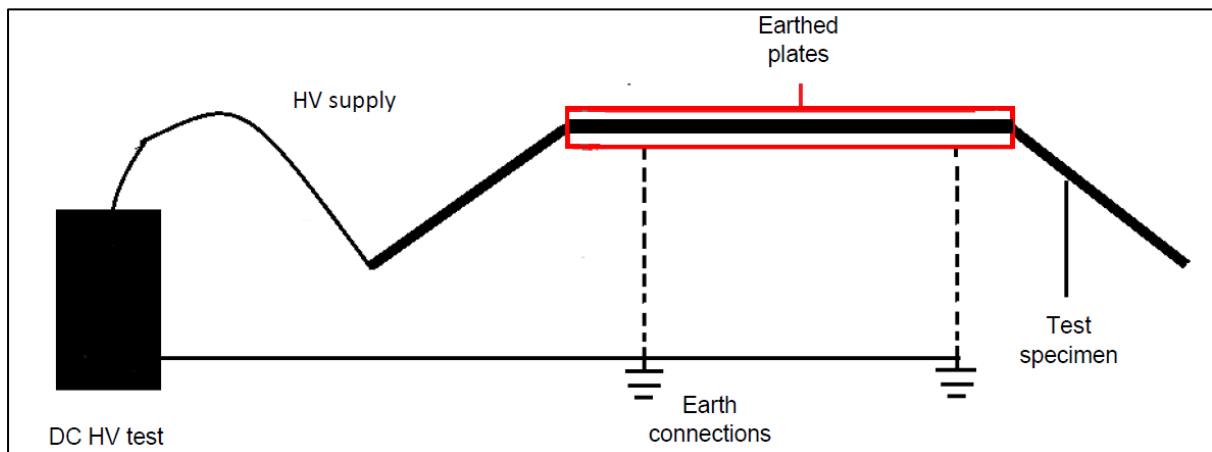
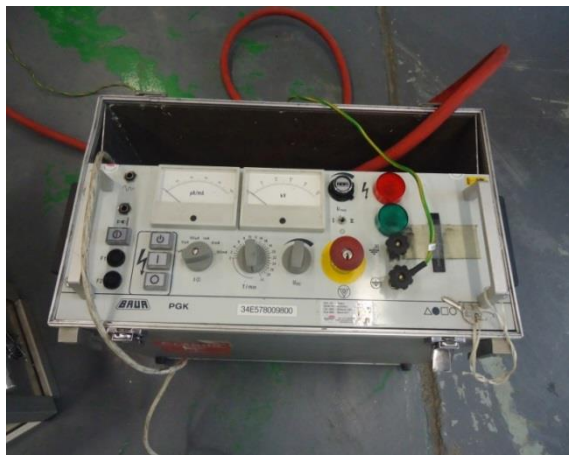
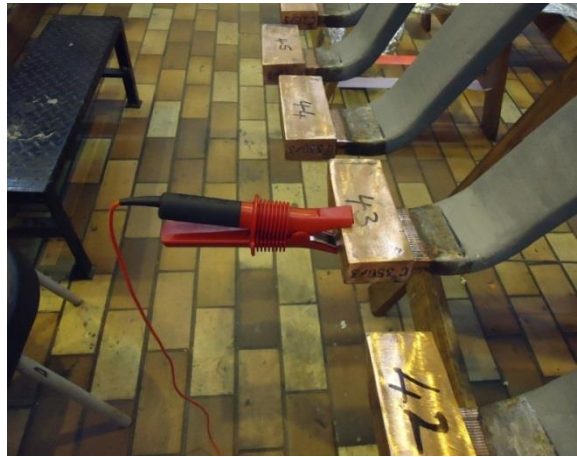


Figure 4-6: HV test circuit [96]



Insulation failure

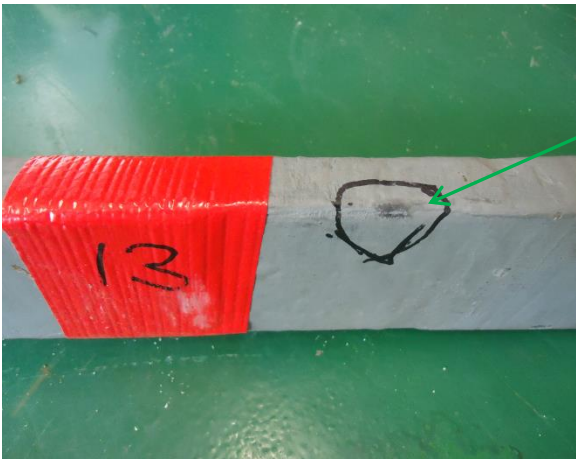


Figure 4-7: HV test configuration with 50 kV test set and fault location of some failed bars

4.2.2.8. Insulation resistance (IR) and Polarization index (PI) testing after High voltage (HV) testing

These tests were conducted in accordance with [82]. The IR and PI readings were taken after one minute and 10 minutes, respectively, with 5 kV DC being applied to the bars.

For the above tests (4.2.1.1- 4.2.2.8) the following were also used as additional specifications:

IEEE 492-1999 [98] and IEEE 62.2-2004 [97] (not for TD and VLF).

4.3. Test equipment

The following test equipment was used for testing:

Table 4-2: Test equipment

Test equipment	Test
Fluke 1555 (Megger)	IR and PI
Iris power Corona Probe (PPM-97)	TVA
Omicron MPD 600	PD
Omicron MI 600	TD
HV Diagnostics HVA30	VLF and 30 kV DC
Baur PGK50 HV test set	50 kV DC

4.4. Summary

Traditionally, diagnostic tests have been used to monitor the relative condition of insulation material in generators. Currently, maintenance personnel trend these test results and any significant deviations warrant further investigations, be it physical inspections or further on-line or off-line diagnostic tests.

Although researchers have made various unsuccessful attempts to estimate insulation failure subjectively using predominantly artificially aged test specimens, the test results from the diagnostic and breakdown tests described earlier in this chapter, conducted on in-service aged stator bars, would contribute to possible correlation of the diagnostic parameters and/or objective prediction of insulation failure.

The data of the test results will be analysed in the following chapters.

5. ANALYSIS OF TEST RESULTS

Chapter 4 described the technical data and operating regime of the selected test specimens. It also illustrated and described the following:

- Test protocols for both the assembled machine and individual stator bars
- Preparation of test specimens
- Tests set-up
- Test equipment

The analyses of the test results are presented in this chapter. The methodology applied was to analyse the in-situ TVA test results (figure 5-1) and select test specimens, with low, medium and high TVA values. It must however be noted that these test values should not be considered as absolutely accurate as the entire generator was energised at 7 kV during this test. Hence, the test values could be influenced from adjacent stator bars. As stated earlier, some test specimens were damaged during removal and the final test specimen selection was made as per table 5-1. These are all top (air gap) bars. These bars were then subjected to the tests as described in section 4.2.2.

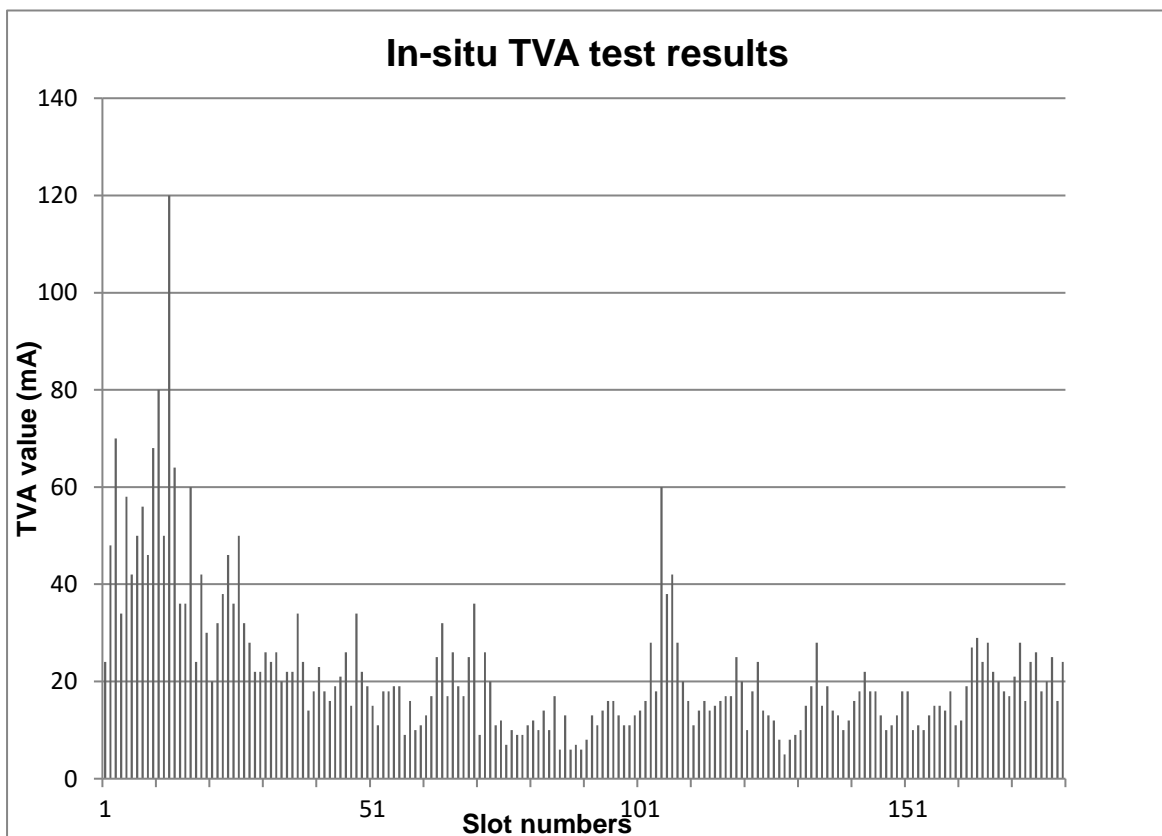


Figure 5-1: In-situ TVA test results

Table 5-1: Selected test specimens

Bar no	Operating V (kV)	TVA value
1	6.35	15
2	1.90	26
3	5.93	16
5	4.66	29
6	3.81	27
13	0.64	09
14	1.06	06
15	3.81	06
17	6.35	08
18	5.50	60
19	2.33	48
20	1.48	70
21	0.64	34
22	2.75	46
24	1.06	80
25	3.81	120
28	2.33	60
30	0.64	42
33	2.75	46
34	1.90	36
37	5.08	34
39	4.66	10
40	0.64	32
41	1.06	09
42	3.81	20
43	2.33	10
49	4.66	25
52	0.64	20
53	2.33	42
55	4.66	22

It was envisaged that the test results would indicate a parameter, or combination of parameters, that could predict imminent insulation failure.

It was expected that the stator bars with the more severely deteriorated insulation material would have the higher PD, TVA and $\Delta \text{Tan } \delta$ values, or a combination thereof. If these bars were operating (in-situ) at the higher voltages, it is expected they would be failing the HV tests, as these bars are constantly exposed to the higher electrical stresses and the insulation material would therefore be more deteriorated.

The outcome after completing the tests as per section 4.2.2, was the following bars: 3, 13, 14, 15, 18, 25, and 49 failing the 50 kV DC hipot test. When analysing the operating voltages of

these failed bars (table 5-1) an initial deduction can be made the failure is not driven by the operating voltage as the failed bars are almost over the full operating voltage spectrum, that is from neutral side to almost line side voltages. Hence, the ageing is not driven by electrical stress. This will be further investigated during the analysis.

5.1. Insulation resistance (IR) profiles before partial discharge (PD), Tennessee Valley Authority (TVA) and Tan delta (TD) testing

As stated earlier before exposing the test specimens to the various test voltages, the specimens, first had to be tested for suitability from an insulation dryness and contamination perspective. This was done by conducting the IR and PI tests as per [82].

Figure 5-2 shows the IR profiles of the passed bars and, depending on the groupings, they all, except for bars 30 and 53, demonstrate similar profiles with variances in amplitude. The profiles of the bars that would eventually fail the 50 kV DC test are not shown in figure 5-2.

Figure 5-2 clearly shows that the IR value of a bar does not consistently serve as a definitive indicator of impending insulation failure. as there are bars on the lower scale, Bars 53, 28, 22 and 33, with 10 minute IR values of 14.4 GΩ, 77.3 GΩ, 83.5 GΩ and 90.4 GΩ respectively, and bars on the upper scale, Bars 41 and 2, with values of 741 GΩ and 764 GΩ respectively, all passing the HV tests.

This is further demonstrated in figure 5-3 when comparing the profiles (red profiles) of the bars that would eventually fail the 50 kV DC test :3, 13, 14, 15, 18, 25 and 49 to that of the passed bars, from figure 5-2, with similar profiles. This is clearly demonstrated with the following profiles: Bars 2 and 14 & 18; 24 and 3; 34 and 49; 1 and 15; 21 and 13; 20 and 25.

This demonstrates that the IR value is not a parameter accurately describing insulation deterioration or imminent failure. The test results concur with [32] in stating that high IR values do not indicate no risk of failure during operation.

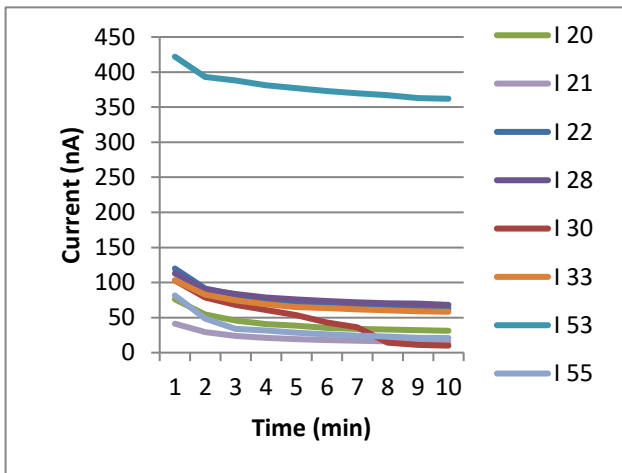
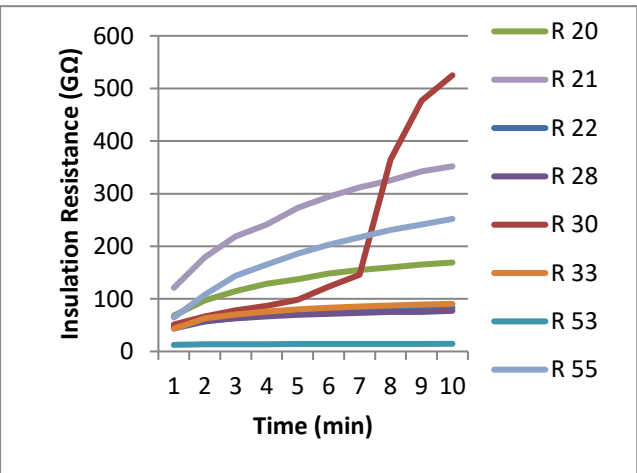
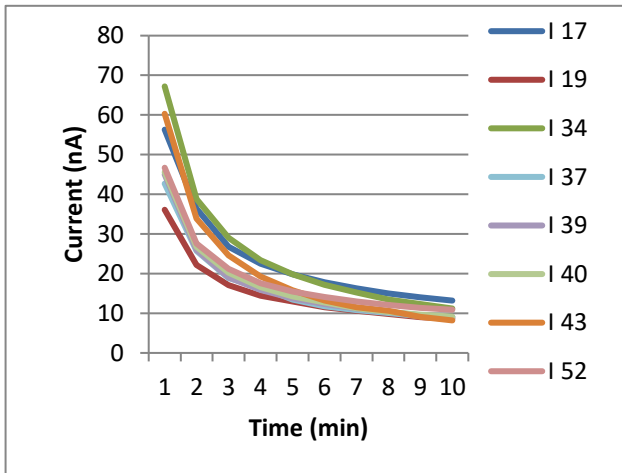
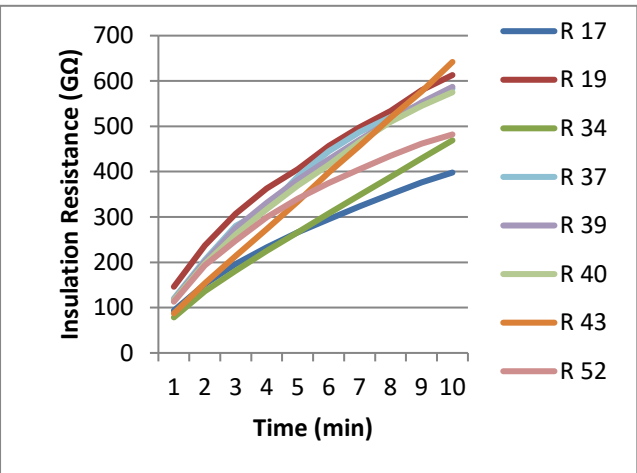
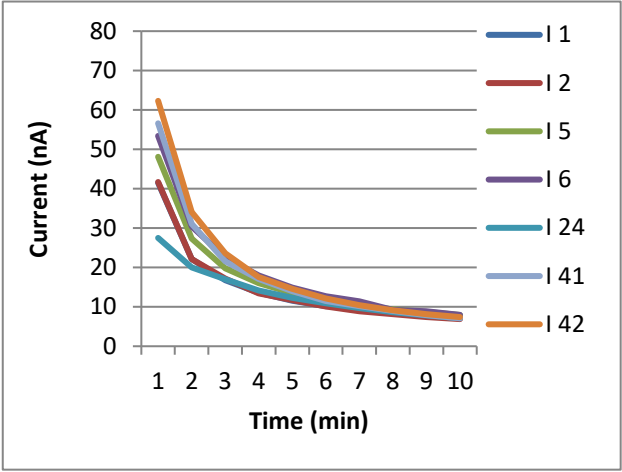
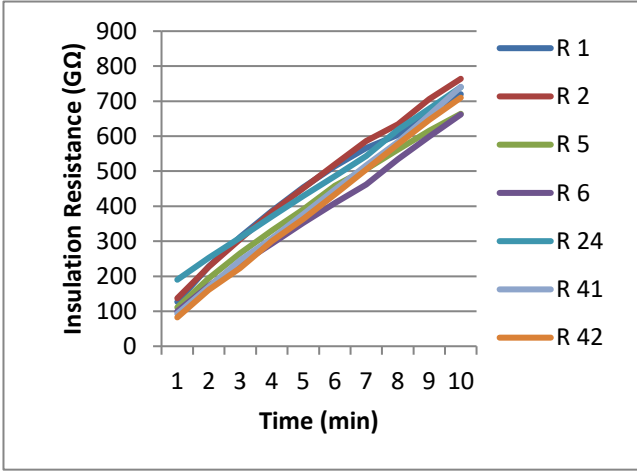


Figure 5-2: Passed bars IR profiles

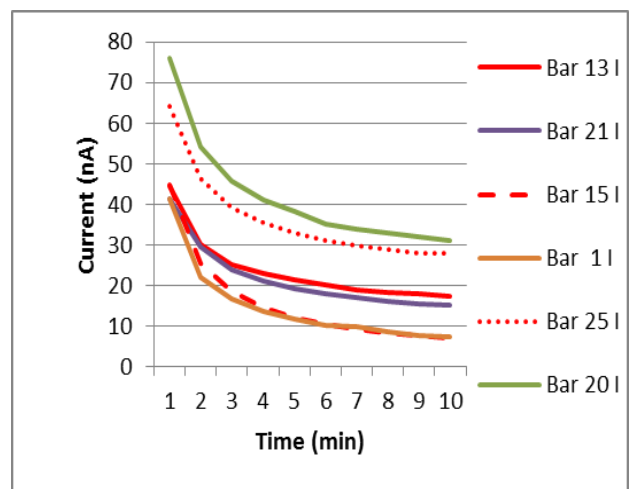
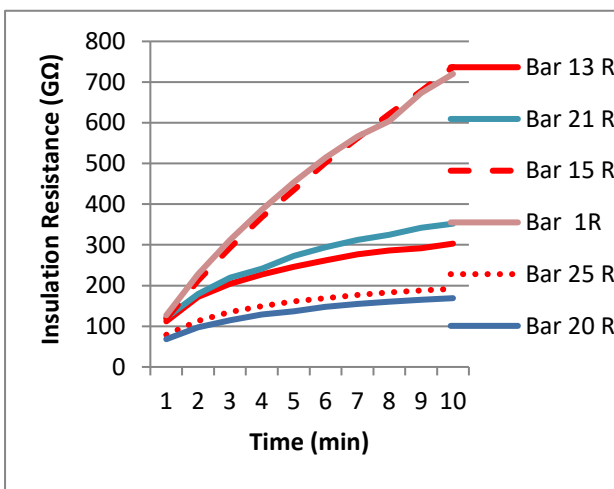
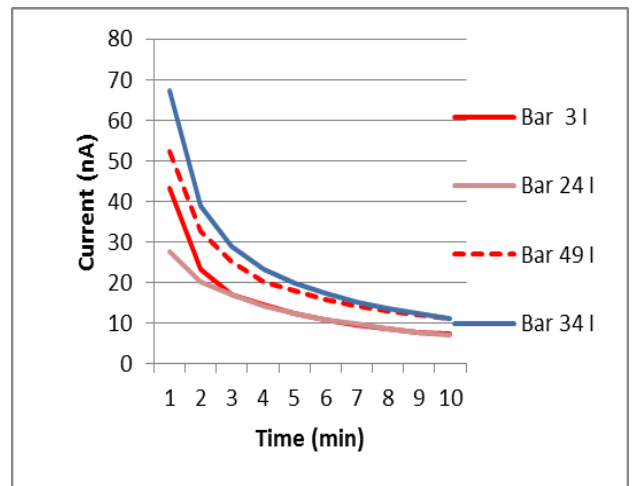
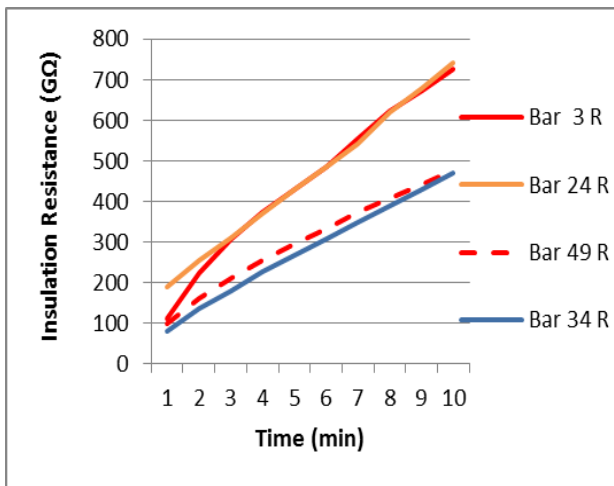
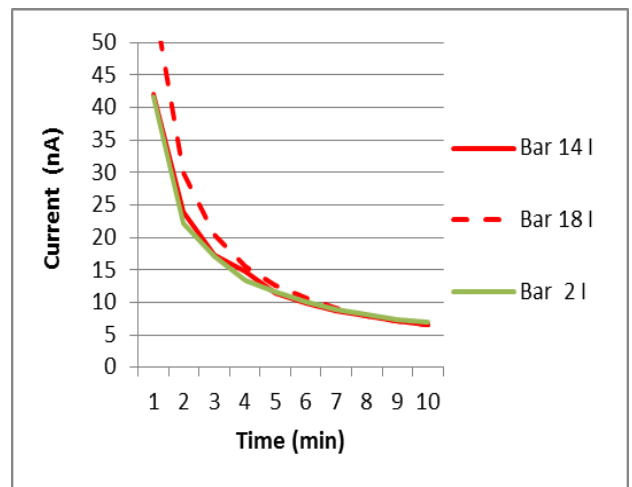
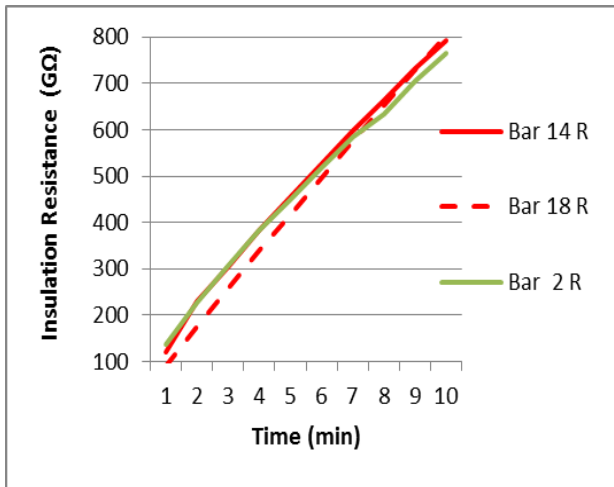


Figure 5-3: Combination of passed and failed bars IR profiles

5.2. Insulation resistance (IR) profiles before and after high voltage (HV) testing

To determine whether the HV test itself had any effect on the insulation material, it was decided to compare the 'before' and 'after' HV tests IR profiles of the test specimens. The same specimens as those used in figure 5-3 were used, as these specimens show similar profiles to the bars that passed the HV tests and those that eventually failed.

Figure 5-4 displays the IR profile comparison of the IR values 'before' and 'after' both the VLF and HV tests. It once again can be seen that the failed bars (red profiles) have IR values between the higher and lower values of the passed bars. What is also noted though is that all passed bars show a lower IR (1 minute and 10 minute) reading value after the HV tests when compared to their before HV tests values. This is expected to be due to the residual polarized charge still present because the time interval between the two tests (HV test and IR test afterwards) was found to not be not long enough for the bars to be completely discharged even though the time interval was consistent of four times the voltage application time [82]. An alternative approach would have been to use an external source to drive depolarisation. Neither this equipment, nor the time for longer discharge periods, were available as the testing was in an operating environment with limited time allowed for testing.

There are, naturally no 'after' HV tests profiles to display for the failed bars.

However, even though the failed bars had IR and PI values above the specified [82] values after the diagnostic tests (IR and PI values before HV testing in table C-4), they nevertheless failed the 50 kV DC test.

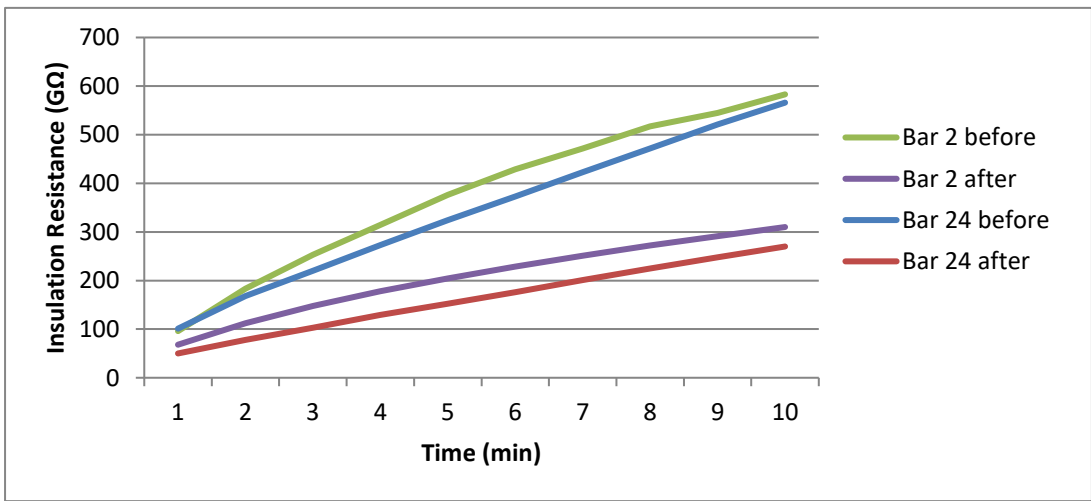
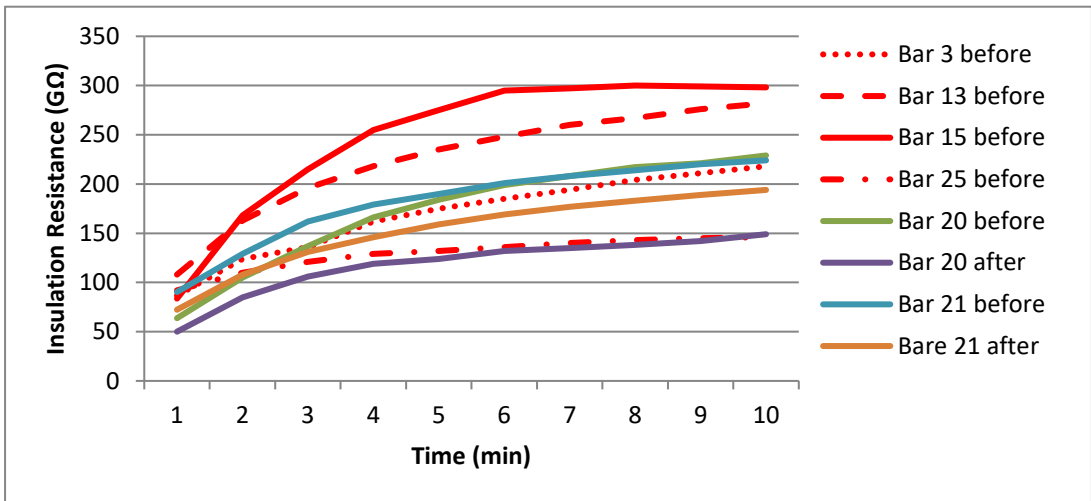
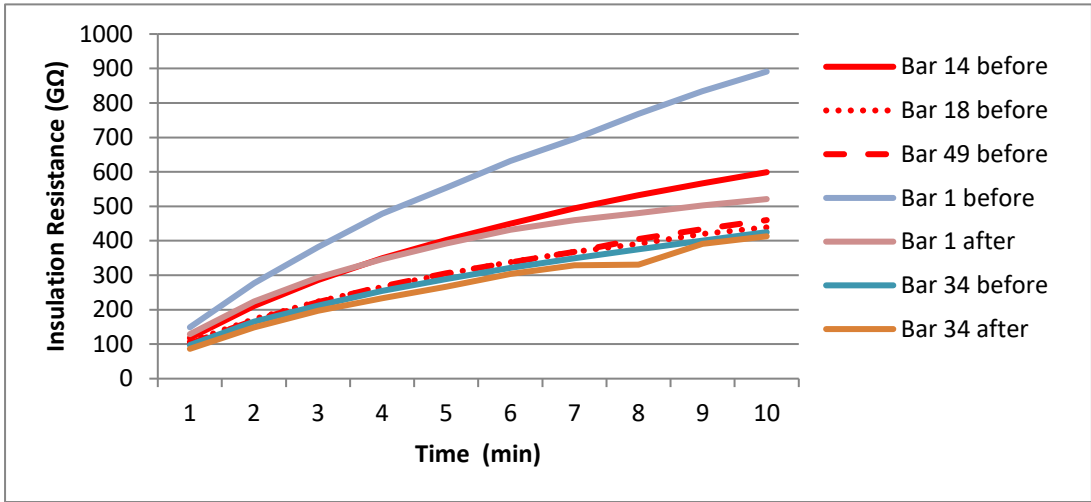


Figure 5-4: Comparing IR profiles "before" and "after" HV tests

5.3. Tan delta (TD) profiles

According to Dakin [91] both the capacitance and TD of insulation material increase with an increase in voltage. This is evident in figure 5-5 where there are significant increases in both around the $0.6 \times U_n$ value. This coincides with the start of the DIV [92] that was found for all bars to be between 2.5-3.8 kV ($0.4-0.6 U_n$) with the readings taken at atmospheric pressure of around 90 kPa. Hence, it is expected that the stator bars with the higher $\Delta \tan \delta$ have the more deteriorated insulation material and would eventually fail the HV tests.

Figure 5-5 also shows the TD profiles of the passed bars (6.10 -13.02) all below the defined acceptance limit of 20 [90]. Again, the bars that would eventually fail (red profiles) the 50 kV DC test are not shown. Instead, these are shown (red profiles) in figure 5-6, with values of (8.18- 9.20) where they are compared with similar profiles of bars that passed the 50 kV DC test.

Figure 5-6 shows very similar profiles for Bars 5 & 3; 40 & 18, 25; 22 & 13; 30 & 15. Once again, this indicates that this test parameter is not a reliable and consistent indicator of imminent insulation failures. It shows that individual data points are inconsistent in predicting bar failure as bars with similar values and profiles both pass and fail the HV test. It points to TD could possibly be more predictive of bar failure if applied as a trending parameter.

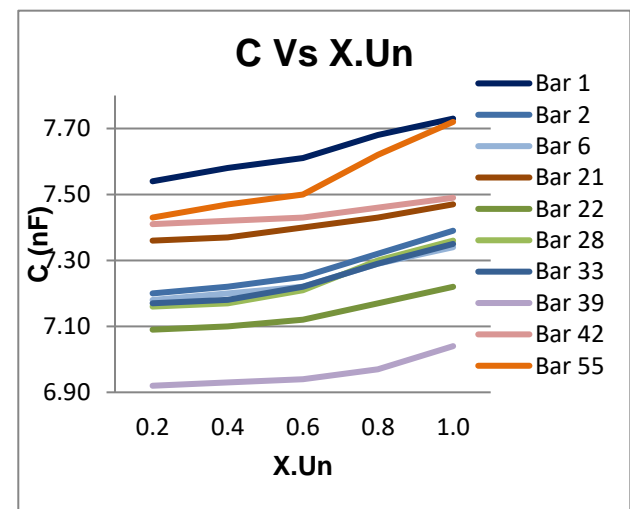
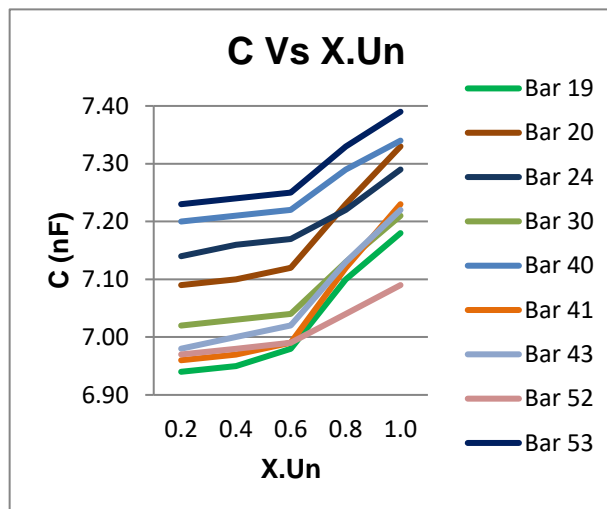
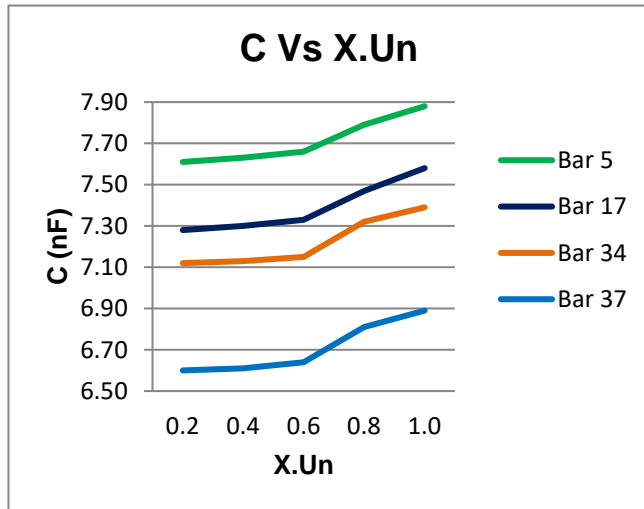
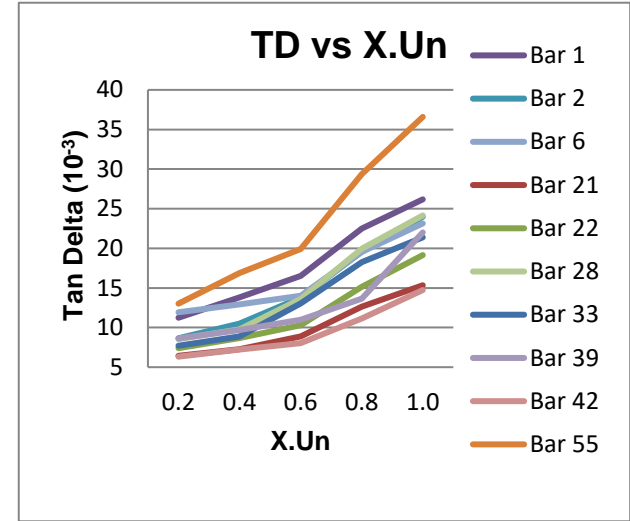
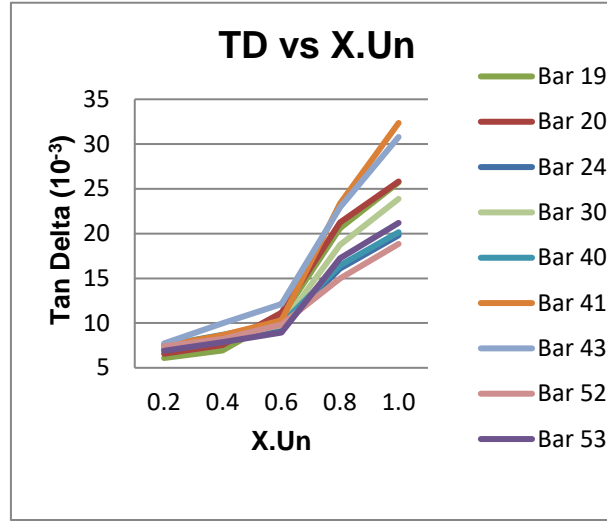
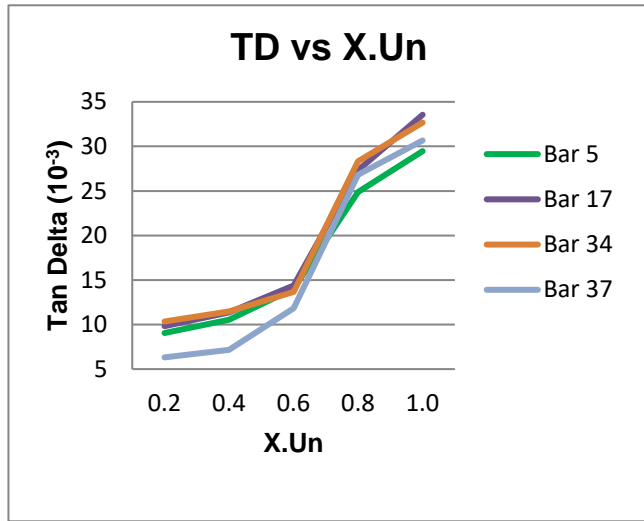


Figure 5-5: Passed bars TD profiles

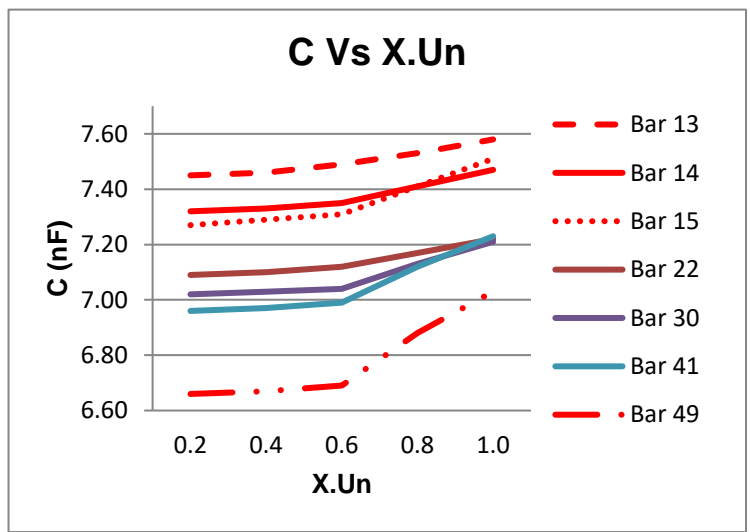
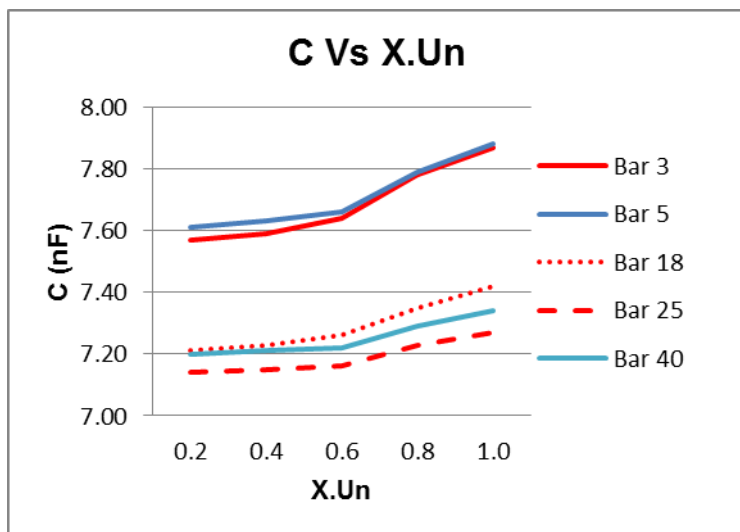
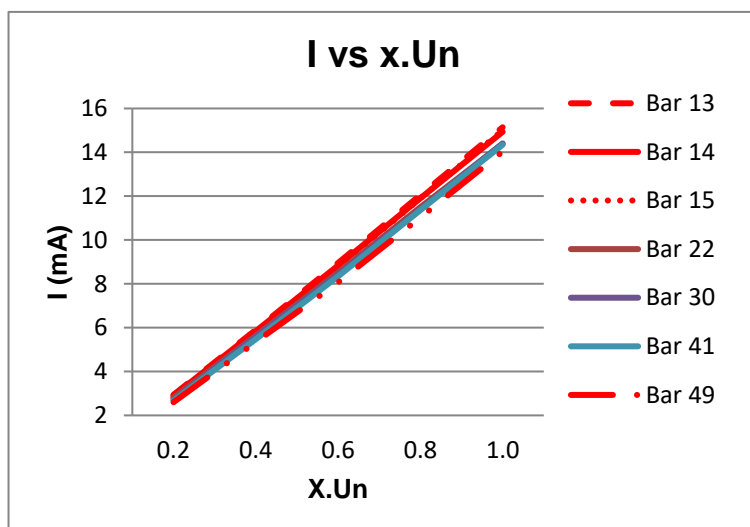
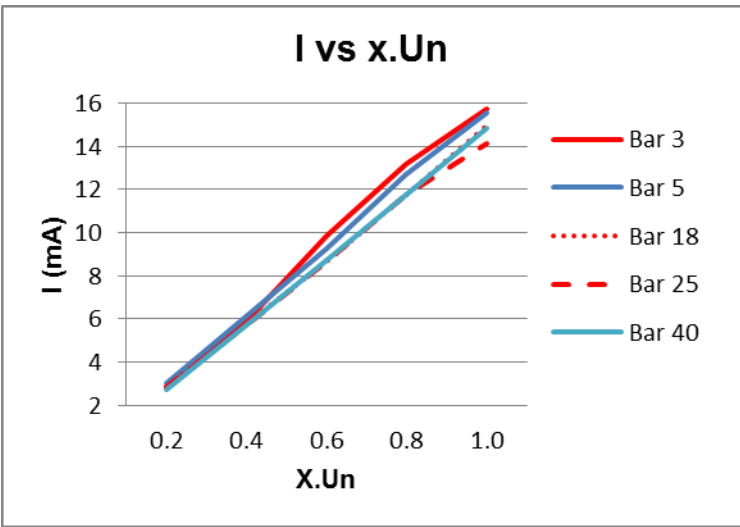
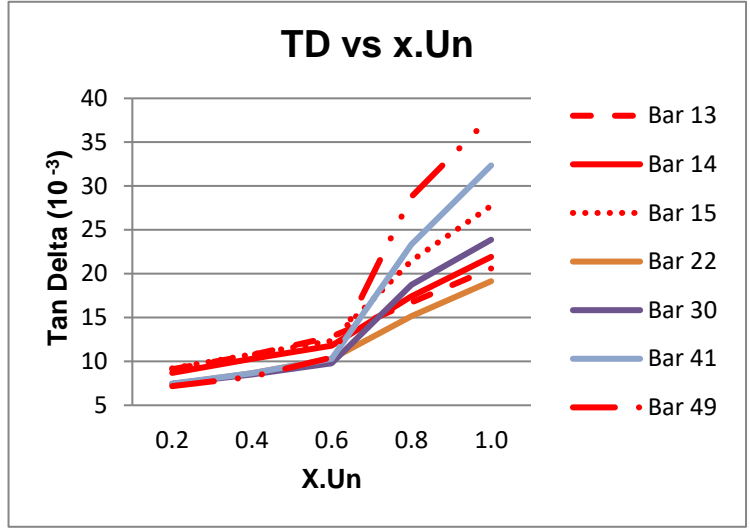
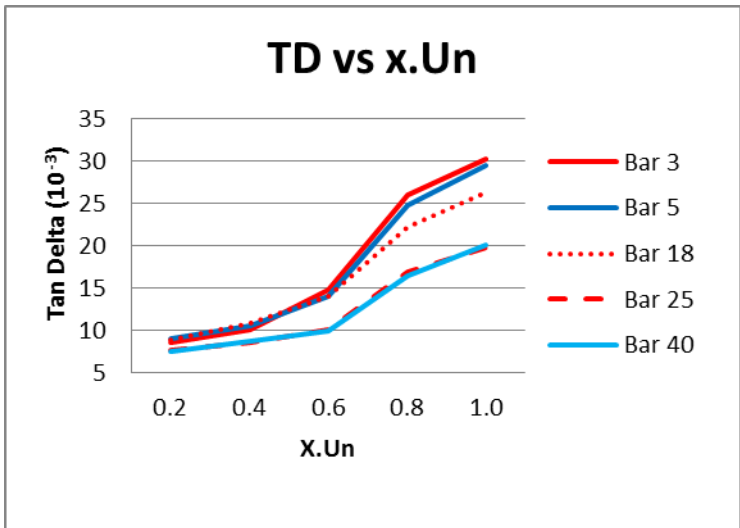


Figure 5-6: Combination of passed and failed bars TD profiles

5.4. Individual test parameters

When analysing the individual values of the PD, TVA and TD tests as per the Appendix A (table A-1) the following are found:

5.4.1. Partial discharge (PD) test

- The test values range of all test specimens as per Appendix C (table C-2): 23.58– 251.9 nC.
- The range of the 7 (23.3% of test specimens) failed bars: 23.58– 118.4 nC.
- 20 (66.6% of test specimens) of the passed bars fall within the range of the failed bars (23.58– 118.4 nC).
- Meaning, only 3 bars (10% of test specimens) fall outside of the failed bars' range.

5.4.2. Tennessee valley authority (TVA)

- The test values range of all test specimens as per Appendix C (table C-2): 15 – 240 mA.
- The range of the 7 (23.3% of test specimens) failed bars: 30 – 102 mA.
- 18 (60.0% of test specimens) of the passed bars fall within the range of the failed bars (30 – 102 mA).
- Meaning, only 5 bars (16.7% of test specimens) fall outside of the failed bars' range.

5.4.3. Tan delta ($\Delta \text{Tan } \delta$)

- The test values range of all test specimens as per Appendix C (table C-2): 0.084 – 0.308 %. These are all below the defined acceptance limit of 0.5% [90]
- The range of the 7 (23.3% of test specimens) failed bars: 0.115 – 0.308 %
- 19 (63.3% of test specimens) of the passed bars fall within the range of the failed bars (0.115-0.308 %).
- Meaning, only 4 bars (13.3% of test specimens) fall outside the failed bars' range.

From the above, it can be deduct that although 23 % of the test specimens failed within certain ranges, from a PD, TVA and $\Delta \text{Tan } \delta$ perspective, 43.3%, 60.0% and 63.3% of the passed bars, respectively, fall within the failed bars' failure ranges. This indicates that, individually, these parameters are not reliable indicators of pending insulation failure.

5.5. Combinations of test parameters

It can be seen from the above that no relationship exists between the individual diagnostic tests and the failed bars as bars that passed these tests either fall within the ranges of the failed bars or display the same profiles. Hence, there was a need for analysis of more complex relationships to test for any relationship between the test parameters. Table 5-2 below shows the correlation coefficient factors or lack thereof between the various diagnostic tests, their associated respective parameters, and operating voltage.

Table 5-2: Correlation coefficient of diagnostic tests to each other and operating voltage

	$\Delta C/C_o$	$\Delta \text{Tan } \delta$	Vop	TVA	Q_{Avg}	Q_{Peak}	DIV	C_H
$\Delta \text{Tan } \delta$	0.98							
Vop	0.41	0.38						
TVA	0.08	0.10	0.19					
Q_{Avg}	-0.05	0.03	-0.21	0.66				
Q_{Peak}	-0.14	-0.05	-0.12	0.74	0.97			
DIV	-0.12	-0.13	-0.33	-0.17	0.16	0.09		
C_H	-0.02	-0.06	0.30	-0.30	-0.41	-0.37	-0.47	
C_L	-0.31	-0.35	0.16	-0.31	-0.38	-0.32	-0.41	0.95

The following figures will show some the correlation, to a certain extent, and non-correlation of some of the parameters in table 5-2.

5.5.1. $\Delta \text{Tan } \delta$ vs $\Delta \text{C/Co}$

Figure 5-7 and table 5-2 show a high degree of correlation between $\Delta \text{C/Co}$ and $\Delta \text{Tan } \delta$. This is to be expected as both are measuring the content of voids in the insulation. The expectation is that the higher the values, the more deteriorated the insulation and thus more prone to failure [90,16]. This is the case with bar 49 but not with some of the other failed bars 13,14 and 25 as these are of the lower range while bars 17 and 37, with higher values than the failed bars (other than bar 49) passed the HV test. This is contrasting to expectations as other than bar 49, bars 17 and 37 have the highest readings from both $\Delta \text{C/Co}$ and $\Delta \text{Tan } \delta$ perspective. Also, bars 22, 24, 40, and 52 with similar values to bars 13,14 and 25 have also passed the HV test meaning that these parameters are not indicative of bars to be identified for imminent failure.

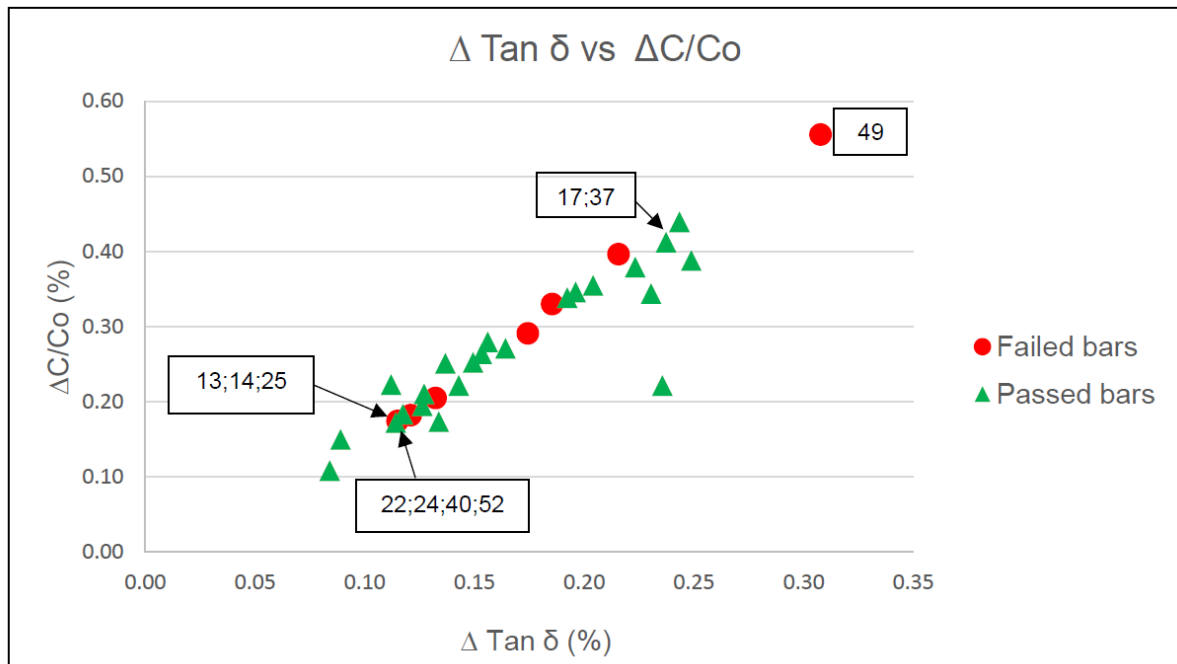


Figure 5-7: $\Delta \text{Tan } \delta$ vs $\Delta \text{C/Co}$

5.5.2. Q_{Peak} vs TVA

Table 5-2 and figure 5-8 also show a degree of correlation between Q_{Peak} and TVA values. Again, this is expected as both values are measuring partial discharges. However, a closer correlation would have been expected. The lack of a higher correlation could possibly be attributed to the instruments taking measurements at different frequencies and that the TVA measurements are not electronically stored measurements but read by the operator. It should also be considered that these readings are read from an analogue meter making the accuracy more operator dependent.

Bar 39 measured the highest values but passed the HV test. Again, against expectations. The fact that Q_{Peak} is the measurement of PD at the most deteriorated part of the bar, and that bar 39 which is almost double in value for both Q_{Peak} and TVA compared to the other bars, did pass is an indication that these parameters are not good indicators of imminent insulation failure [81]. This is contrasting to the failures of bars 13 and 25 which are at the lower spectrum for both Q_{Peak} and TVA. In fact, the figure shows some failed and passed bars showing very similar readings and thereby affirming the previous statement.

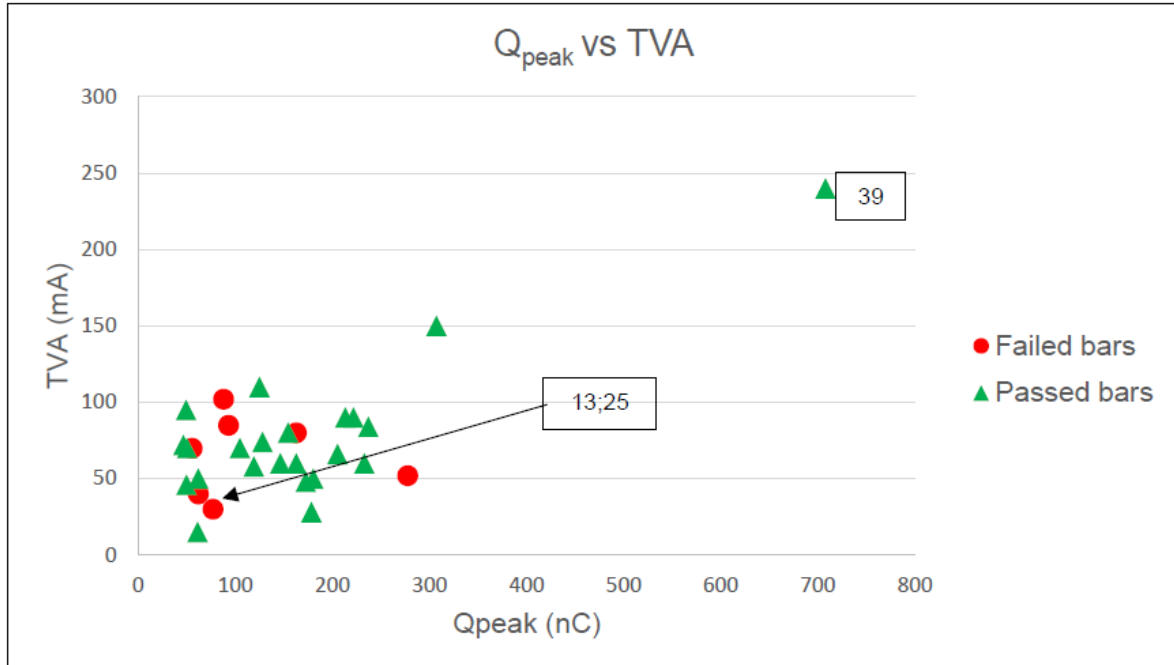


Figure 5-8: Q_{Peak} Vs TVA

5.5.3. Vop vs $\Delta C/Co$

Table 5-2 and figure 5-9 show there is no strong correlation between Vop and $\Delta C/Co$. It is also clear that the insulation failure mechanisms are not driven by the bar operating voltage as the failed bars are presented over a wide range of the operating voltage spectrum. The same can be said for the failed bars with respect to capacitance tip-up expect for bar 49 which is having the highest capacitance tip-up value.

Also, the failure mechanism is not voltage driven as two of the failed bars 13 and 14 failed at the lower voltage spectrum and two passed bars 1 and 17 are at a higher voltage than any of the failed bars.

Also, two of the failed bars 13 and 14 are at the lower spectrum for both voltage and capacitance tip-up and have very similar values to two of the passed bars 21 and 24. Hence, proving that ageing was not driven by electrical stress.

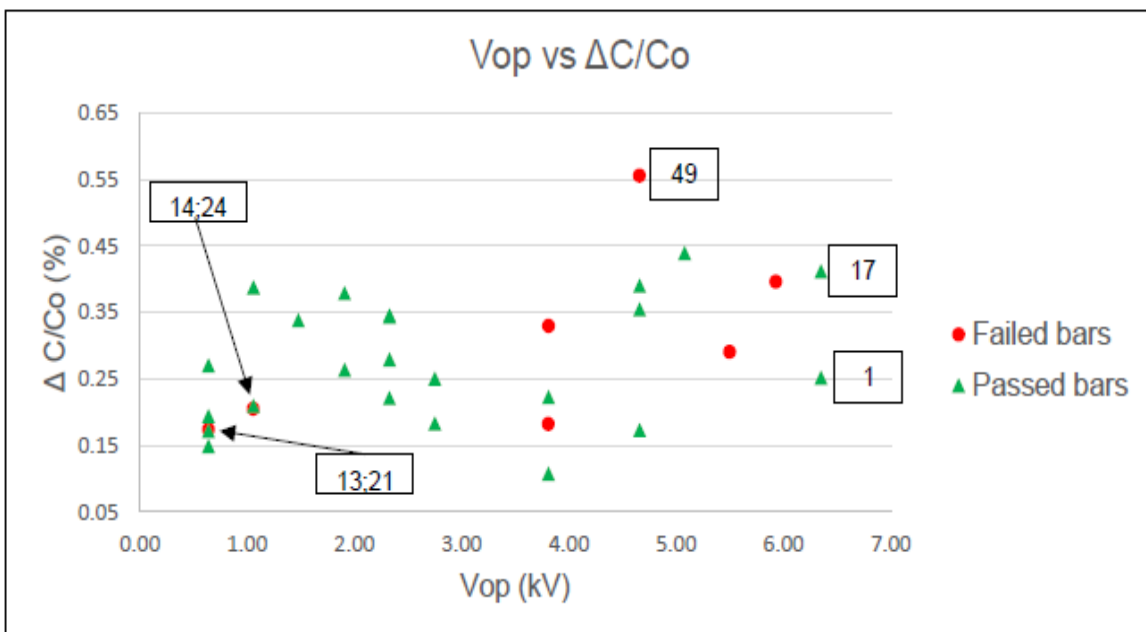


Figure 5-9: Vop vs $\Delta C/Co$

Further analysis of table 5-2 shows that other than the $\Delta C/Co$ and $\Delta \tan \delta$ strong correlation, the only other strong correlations are between Q_{Avg} and Q_{Peak} , as well as the capacitances C_H and C_L which are in essence very similar parameters. Hence, other than the mentioned strong correlations and to a degree between Q_{Peak} and TVA, there is very little correlation between the different diagnostic tests.

5.6. Other combinations of test parameters

As can be seen from section 5.5, once again, no obvious patterns emerge when analysing the various combinations of the test parameters.

The analysis displays no clear failing parameter(/s) or a combination thereof indicating imminent insulation failure. Instead, the analysis shows contrasts between passed and failed bars of some of the parameters analysed in figures 5-7 to 5-9. The analysis also shows unexpected contradictory results in that bars that were expected to pass the HV test failed and vice versa.

Subsequently, the analysis required investigation of even more complex relationships between the test parameters.

5.6.1. Vop vs $\Delta \text{Tan } \delta$ vs $\Delta \text{C/Co}$

Figure 5-10 is corresponding with the findings of figure 5-7 in that those bars with very similar diagnostic test values, and in this case an additional parameter of operating voltage, both passed and failed (bars with black border line) at very similar values: 13 and 52; 14 and 24; 6 and 25. It is also showing the contrast that bar 17 with a combination of high $\Delta \text{C/Co}$ and $\Delta \text{Tan } \delta$ does not mean failure at the higher operating voltage contrasting to bar 13 with a combination of almost the lowest test values and operating voltage. Therefor re-affirming that these parameters are not good indicators of imminent insulation failure.

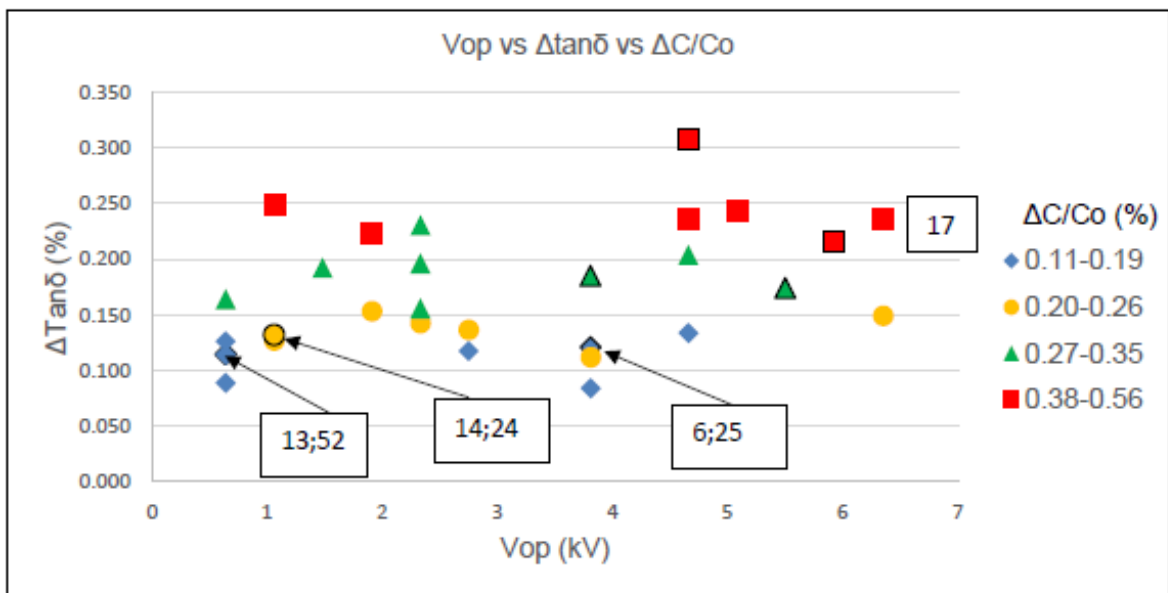


Figure 5-10: Vop vs $\Delta \text{Tan } \delta$ vs $\Delta \text{C/Co}$

5.6.2. DIV vs $\Delta C/Co$ vs Vop

Bar 49 is a failed bar with the highest $\Delta C/Co$ and it implies that the insulation condition of bar 49 is the worst compared to the other bars and an expectation that bar 49 will have a DIV in the lower range, if not the lowest. However, figure 5-11 shows this not to be the case with only bars 25 (3.6 kV) and 34 (3.8 kV) having higher DIV values than bar 49 (3.5 kV). By DIV definition the state of deterioration of insulation of the other bars should then be similar or worst given that they all have lower DIV values. Practically this seems not to be the case given that the DIV values of all the passed and failed bars, except bars 25 and 34, are either equal, bars 21, 22, and 28, or lower than 3.5 kV.

Again, some of the passed and failed bars display similar values for all three parameters: bars 3 and 17. Bars 15 and 43 have similar DIV and $\Delta C/Co$ values and operating voltages of 3.81 kV and 2.33 kV respectively. The same for bars 6 and 14 with operating voltages of 3.81 kV and 1.06 kV respectively. Clearly showing that operating voltage is not the failing mechanism.

Also, although bars 25 and 49 are failed bars with capacitance tip-ups of 0.18% and 0.56% respectively, 78% of the passed bars have tip-up values between these values thereby indicating that the combination of tip-up and DIV value is also not indicative of future insulation failure.

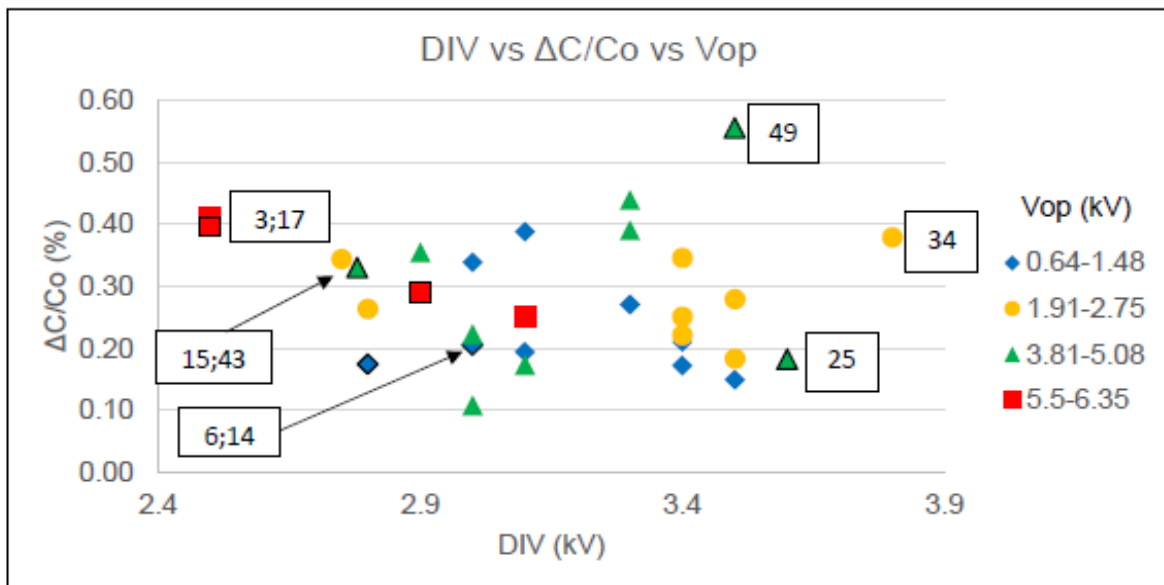


Figure 5-11: DIV vs $\Delta C/Co$ vs Vop

5.7. Conclusion of interpretation of the test results

It can be deduced from the analysis in the previous sections and given the low level of correlations as per table 5-2 that there is no parameter, or combination of parameters, to indicate imminent failure of the insulation material. Nor is there any correlation between any of the parameters and/or operating voltage of the bar. This once again implies that the ageing mechanism present is not electrical stress [101]

What is, however, significant about the test results is the fact that all the failures had occurred in the endwinding region.

All of the above results will be discussed further in the following chapter.

6. DISCUSSION

Chapter 5 provided an analysis of the test data and concluded that no particular parameter, or a combination of parameters, could indicate imminent failure of the insulation material and that all failures occurred in the endwinding region.

In this chapter a further discussion is performed to establish whether any correlation, in predicting insulation failure, exists between any of the parameters, as well as the endwinding failures. This chapter will also provide some insights into the validity of these results when analysed critically.

6.1. Insulation resistance (IR) profiles

Figure 5-2 showed that bars 30 and 53 have different profiles to the other bars. This was not immediately evident during testing as the test results were only analysed afterwards. Unfortunately, when this was discovered, it was not possible to return and retest these bars as a possible option would have been to retest with guarded electrodes. Figure 6-1 shows that bar 30 in figure 5-2 could possibly had inconsistent data being recorded as the “before” profile in figure 6-1 shows a normal profile. The “after” profile of bar 30 is however showing an inconsistent curve between minutes 4 and 8 which could again possibly point to inconsistent data being recorded as the HV test cannot have that much of an effect compared to the “before” profile.

On the other hand, the profiles of bar 53 show to be reproduceable to those in figure 5-2, albeit at lower IR and PI values of 38.2 GΩ and 1.61 respectively, compared to the average values of 93.92 GΩ and 4.32 of the other tested bars. However, the low IR value of bar 53 is still much higher than the defined acceptance value (100 MΩ) in [82] albeit for a complete winding.

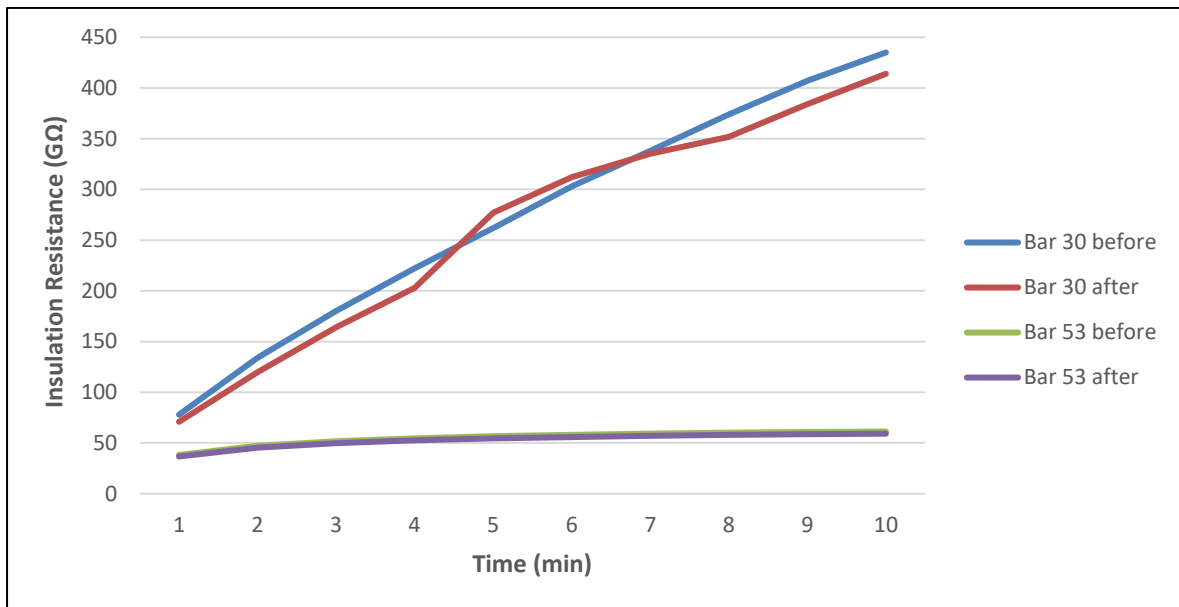


Figure 6-1: Bar 30 and 53 'before' and 'after' HV test profiles

Figure 5-2 clearly demonstrates that the IR value is not an indicator of impending insulation failure as there are bars of lower readings, that is, Bars 53 and 28, with values of 14.4 GΩ and 77.3 GΩ respectively, and bars of higher readings, Bars 41 and 2, with values of 741 GΩ and 764 GΩ respectively, all passing the HV tests.

This is further demonstrated when comparing the profiles of certain failed (red profiles) and passed bars to each other as per figure 5-3 with failed bars having values between the lower and upper readings. Also, some of the passed and failed bars bear strikingly similar profiles (figure 5-3):

- Bars 2 and 14 & 18
- Bars 24 and 3
- Bars 34 and 49
- Bars 1 and 15
- Bars 21 and 13
- Bars 20 and 25

This indicates that the IR value is not a parameter accurately describing insulation deterioration and/or failure mechanisms.

These test results concur with [32] as it is clearly demonstrated by the similar IR profiles of both passed and failed bars at high IR values, even at ($G\Omega$) range.

6.2. Tan delta (TD) profiles

Figure 5-5 shows the profiles of all the passed bars (23) and depending on the groupings, they all demonstrate similar profiles with slight differences in amplitude.

The TD (%), I and C parameters of the failed and passed bars, with similar profiles, are compared in figure 5-6:

Bars 3 and 5 show very similar TD and C profiles. The same can be observed for Bars 18, 25 and 40, with a 1% differential between the failed and passed bars capacitance.

Bars 41 and 49 (figure 5-6) begin with a very similar TD (%) profile until around the 0.6 X.Un mark and then diverge to a differential of 5 % as the bars are reaching the PD inception voltage, 3.1kV and 3.5 kV respectively, at this point (Farahani et al, [92]) and that Bar 49 exhibits higher PD activity. This is evident by Bar 49 having 57% higher PD activity than Bar 41, 103 nC to 65.58 nC, as measured by the PD test. However, this stands in contrast to the occurrence found in the similar profiles of Bars 3 and 5 even though Bar 3 (53.86 nC) measured 2.14 times more PD activity than Bar 5 (25.14 nC).

This contrast is further demonstrated by the similar profiles of Bars 13, 14 and 22 with PD values of 35.39 nC, 118.4 nC and 88.3 nC respectively, with Bar 22 constituting the passed bar.

Hence, the expected consistent relationship between TD and PD (Q_{Avg}) measurements does not exist in this case. This is confirmed by the low correlation factor of 0.03 in table 5-2.

However, both the TD and capacitance profiles are almost consistent as those found by Farahani et al [102] during accelerated thermo-electrical and thermo-mechanical ageing test results that they concluded cannot predict imminent insulation material failure conclusively.

6.3. $\Delta C/Co$ vs $\Delta \tan \delta$ and V_{op}

It was expected that the bars measuring a combination of the highest $\Delta C/Co$ and $\Delta \tan \delta$ and operating at the higher voltage would have the most deteriorated insulation and therefore fail the HV test. This seems to hold true only for bar 49 having the highest reading for both $\Delta C/Co$ and $\Delta \tan \delta$ and operating at 4.66 kV, but not the other failed bars. Comparing this bar to the others there are two contrasting scenarios. Firstly, bars 37 and 17 passed the HV test having the second and third highest $\Delta C/Co$ values as well as the third and fourth highest $\Delta \tan \delta$ respectively. Secondly that bars 13, 14 and 25 failed the HV test with $\Delta C/Co$ values within the bottom 20% of the test values, within the lower third of the $\Delta \tan \delta$ test values and operating at voltages of 0.64 kV, 1.06 kV and 3.81 respectively.

Also, bars 13, 14 and 25 had failed the HV while bars 21, 22, 24, 40 and 52 having very similar $\Delta C/Co$ and $\Delta \tan \delta$ values and operating at voltage of 0.64 kV, 2.75 kV, 1.06 kV, 0.64 kV and 0.64 kV respectively have passed the HV test. This clearly shows that insulation failure is not operating voltage dependant when monitoring these diagnostic parameters.

6.4. Endwinding failures

Industry is currently using both AC and DC hipot tests as proof of dielectric strength of insulation material [75]). However, continuous debate about the preferred test method persists although both methods have their own advantages and disadvantages.

The persistence of the debate can be ascribed to contention around the effectiveness of using the AC or DC test, as the respective tests subject the insulation material to different electrical stress distributions [72,75,76,50]. The electrical stress distribution across the insulation material during an AC hipot is similar to those experienced during service. The insulation materials are predominantly capacitive, and the stresses are controlled by their dielectric constants, whereas the DC stresses are resistive and controlled by the resistivities of the insulation materials [72,96,103].

During an AC test the endwinding surface potential is effectively the same as the copper, therefore the electrical stresses are minimal in this region. Contrary to this, during a DC test, a large part of the endwinding surface is grounded and hence stressed at a higher level [72, 77]. There is a possibility that the efficacy of the two tests lies within the fact that they detect different deficiencies in different parts of the winding of different types of insulation systems.

Hence, neither test can be considered superior to the other. The different stress relationships between AC and DC testing appear to be complicated and could be even further complicated when dealing with significantly degraded insulation material. This relationship lends itself to further research.

It must also be understood that although DC testing is an accepted method of testing these AC machines, no actual DC ageing is occurring in the stator bar insulation during operation.

The EPRI survey [75] concludes that contention around which of the two tests to conduct persists in industry. It appears that the AC and DC tests detect different deficiencies in different areas of windings and could possibly be validated by further experimental studies that detail the AC and DC BDV, location of breakdown, failure mechanism, and so on. Admittedly, collecting that sort of data for an array of generators would take years. The findings of this thesis would contribute significant statistical data to such a study.

6.5. Conclusion

The expectation was that the diagnostic test results would provide an indication of the level of deterioration of the insulation material, that is, the bars with the worst readings should be the most deteriorated and therefore would fail the HV tests.

However, the research concludes otherwise, in that there is no parameter, or combination of parameters that can predict imminent insulation failure. In fact, the analysis shows no clear failure parameter as in some cases both the parameter values and/or profiles are common for both passed and failed stator bars (figures 5-3; 5-6; 5-7; 5-8; 5-9 and 5-10).

It can therefore be expressed that in concurrence with [16] these particular diagnostic tests are unable to predict insulation failures.

However, what is significant is that all the seven bars failed in the endwinding section, giving validity to the argument that DC testing is possibly more sensitive for failure mechanisms in the endwinding region rather than in the slots as suggested by [50,72,74,77]. This is supported by [10] finding of a failure in one endwinding. This failure occurred when testing a bar with DC voltage after it passed an AC test. The test values were 26.5 kV and 20 kV respectively. The DC value equates to 76% of the AC test value. This led [10] to conclude that DC testing might constitute a more probing test for endwindings, but also that more data would be needed to confirm this.

The endwinding failures could possibly be attributed to the difference in stresses distribution compared to those of AC testing, as the surface potential is almost the same as the copper whereas the slot section is connected to the grounded core.

7. CONCLUSION

The thesis started off seeking answers for what could possibly have been perceived to be random stator bar failures. Some diagnostic tests were identified to provide more information regarding these failures. That is, determining the level of deterioration of the insulation and indicating possible failure mechanisms. It was anticipated that some parameter measurements would be correlated or supplemented by others in predicting impending insulation failure.

7.1. An assessment of the research

The research attempted to answer some key questions raised at the start of the research, as stated in chapter 1. A summary of the research findings is presented below:

To what extent can tests directly predict imminent insulation failure in a hydro generator stator

No single test or even combinations of diagnostic parameters can consistently offer a strong diagnostic evaluation of imminent insulation failure as these tests are not sensitive to all insulation failure mechanisms. The clearly defined accepted limits in [90] are challenged by [104] as they conclude that ageing tests indicated that the service performance of insulation systems cannot be guaranteed by stipulating specific values.

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 diagnostic parameters may produce valuable information when trending the parameters while also taking cognisance of past test data, incidents and operating history.

Are generator diagnostic tests results repeatable?

As many factors influence the diagnostic parameters, that is, temperature, humidity, machine loading, voltage level, machine cooling, vibration and so on, it is highly unlikely that the exact conditions can be replicated. Hence, it is unlikely that the exact test results could be repeated. Therefore some questions remain regarding the repeatability and reproducibility of diagnostic test results [8]. Moreover, because of the complexities of the operating conditions, different insulation systems, designs and manufacturing processes of insulation systems, it is unlikely

that the absolute condition can be assessed by one measurement only. Consequently, dissection becomes the only method to assess the actual condition of insulation objectively.

Is stator bar operating voltage in the generator significant with respect to ageing?

There appears to be contrasting views as shown by the findings of [13] and [16]. This research concurs with [16] in that it found no correlation between BDV and stator bar operating voltage. That is, the failure mechanism is not driven by voltage only, rather, other failure mechanisms are either contributing to the failure or are driving the actual failure mechanism in its entirety.

What relationships can be identified between generator non-destructive diagnostic tests, DC BDV and the location of any DC high voltage failure?

No direct correlation was found between the diagnostic tests and the failures of the insulation material during the DC voltage withstand tests. The research also produced some unexpected contradictory results in that bars that were expected to pass the HV test failed and vice versa. All failures occurred in the stator bar endwindings.

There is a strong suggestion that breakdown voltage is not a function of stator bar operating position (location) but could possibly be attributed to duty cycle (especially peaking stations) in combination with temperature rise and close to end-of life cycle due to overall deterioration of the insulation material.

7.2. Validity of Hypothesis

As a visual inspection does not provide all the needed data to evaluate a machine's condition, particularly from an insulation degradation perspective, it is accepted that diagnostic tests would provide more information. It is currently perceived that these tests would detect, confirm or identify areas of concern for which the corrective maintenance, if needed, would be determined.

However, from this research it can be concluded from these various tests that the expected results did not materialise. That is, no parameter or a combination of parameters, indicating imminent failure of the insulation material exists. There is also no obvious failure pattern such

as a direct correlation between one parameter and another. Similarly, no clear pattern of failure between various combinations, derived values of the tested parameters is present.

In fact, in some cases the analysis show similarities in both the parameter values and profiles for both passed and failed bars.

Given the above, it is concluded that the research did not provide significant evidence to support the hypothesis that traditional diagnostic tests of in-service aged stator bars can indicate incipient faults caused by ageing and can be verified by DC breakdown voltage a

7.2.1. Points of discussion

It is possible that BDV is not being determined in its entirety by the biggest measurable discharge pulses, meaning that the initial ionisation could start in a different area resulting in insulation failure in that particular area. Additionally, not all insulation failures are initiated by PD. There are possible separate cases of short term and long term (PD driven) failure.

In-service insulation ageing and failure are not linear events, owing to both the complex interactions of the different stresses and random transient events. Random transient events could puncture already-deteriorated insulation that would otherwise have been fit for service.

With only seven bars failing the 50 kV DC test, (after passing both the VLF and 30 kV DC tests), it is possible that the test specimens had not aged significantly. This is shown by the tan delta test values, shown in 5.3 and 5.4.3 to be below the defined acceptance limits of [90]. This could mean that the particular diagnostic parameters, in this case, appear not to be very sensitive to insulation material that has not deteriorated significantly. However, these parameters might provide better insight when measuring insulation material that is close to failure.

7.3. Conclusion

The results of the research exhibit similar results to some of Stone et al [16] findings that these diagnostic tests (PD, TD) do not effectively confirm the level of degradation of insulation material or the development of incipient faults. This is because some test values that were within accepted limits, as per the international standard, only Tan δ has an accepted standard [90], failed unexpectedly while expected failures did not occur. Hence, these are not reliable and consistent parameters to indicate the level of insulation degradation.

It could be that these particular test specimens did not age significantly, meaning that the failure mechanisms could be occurring at a slow rate suggesting slow degradation of the insulation. This would mean that testing engineers would need to reassess the analysing capabilities of these diagnostic tests when dealing with slow failure mechanisms.

Test engineers should also be objective when considering test values in context: that is, what the machine history, design and manufacturing deficiencies, operating regime (typical machine loading, winding temperature rise), transient events and past test data are, before deciding on continued operation or return to service of machines. This means that operational decisions should not be based on only one set of test data. Analysing trends, that is, any deviation, instead of absolute values, would provide more insight into the actual deterioration of insulation.

The exact degradation process of insulation material in rotating machines is a highly complex phenomenon and remains unresolved with our current knowledge. Although significant progress has been achieved, some topics still require to be researched [105]. The insulation material is subjected to simultaneous stresses continuously, meaning that various factors are affecting it simultaneously, albeit not all to the same extent. The combination of all the stresses has a different complex effect on the degradation of the insulation material. Even accelerated ageing tests performed under controlled conditions produced elementary results in terms of long-term performance capabilities [13]. Hence, the need for understanding the complex degradation process under in-service conditions needs to be further explored and developed.

Unfortunately, this research did not produce definite conclusions from these particular combined parameter analyses. There is no clear correlation between the diagnostic test parameters of this research and DC hipot testing. However, the failed location of all seven bars were in the endwinding region giving validity to the claim that DC testing is more sensitive to failure mechanisms in the endwinding region, as suggested by [72;74;77]. This lends credence to the claim that AC and DC testing could possibly detect different deficiencies in different types of insulation systems. Hence, more research is required to understand the differences of AC and DC testing in detecting insulation deficiencies.

The non-correlation of HV breakdown testing and CM parameters confirms the work of [16;76;106]. However, the location of their failures is documented as slot failures leading them and [73] to express that AC is a more probing test.

This research finds the statement to be too broad as the literature does reveal endwinding failures when subjected to HV DC testing (Gupta and Culbert, [10]. Further, this research subjected 30 stator bars to 23 kV VLF, 30 kV DC and 50 kV DC hipot testing and seven bars failed. The fact that the failed bars had previously passed both the VLF and 30 kV DC tests, indicates definite insulation failure at the higher stress level (50 kV).

The DC failures are consistent with the previous work of [72;74;77]. where they advocate that the DC test constitutes a more probing test for endwinding deficiencies and that the DC test also provides more diagnostic information.

This lends credence to the results of this research. Hence, the statement of AC constituting a more probing test should perhaps be limited to the slot section only. Further, in order to validate insulation integrity for continued operation or return to service of generators, it appears necessary to conduct both AC and DC testing, especially when suspecting endwinding deficiencies.

However, we should take cognisance of the fact that the test results were obtained from stator bars that were seemingly in good working condition, as the 50 kV test voltage was 25% higher than the pass voltage stipulated (39.8 kV) in [96] for new bars of this machine rating. Therefore, as stated earlier, more data is required to make more conclusive statements; for example, HV DC endwinding test should be conducted on stator bars with known severe degradation.

Furthermore, it seems that, currently the best value to be derived from these applied diagnostic tests (IR, PI, TVA, TD, PD) would be as trending tools and combined with newly developed monitors, could possibly be used to assess the level of degradation of insulation successfully. The collected data from this research could possibly be used as statistical data by future research seeking correlation between diagnostic tests and insulation breakdown.

The dissection and examination of test specimens would add valuable insights into the level of degradation and the failure mechanisms present, and, thereby, enhance the credibility and reliability of diagnostic tests when well-correlated with the findings, if proofed to be the case.

Diagnostic tests play a pivotal role in industry as asset management decisions as made based on these test results. Therefore, industry requires better clarity or consensus on how to use this important information. For example, more emphasis on trending the data rather than

relying solely on individual data points, could significantly enhance the level of confidence and applicability of diagnostic tests within industry.

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9. APPENDICES

Appendix A : Summary of test results

Table A-1 : Summary of test results

Bar no	Operating V	Machine TVA	(7-9/12/16) IR & PI Before PD,TVA, Tan δ Temp (25.2-27.0) °C; RH (43-51.9)%				PD (nC) @ 6.4 kV (7-9/12/16)	TVA (mA) @ 6.4 kV (7-9/12/16)	Tan δ x 10 ⁻³ @ 6.4 kV (7-9/12/16)	(3-7/02/17) IR & PI Before HV tests Temp (23.5-28.4) °C; RH (48.8- 67.0)%				HV tests (3-7/02/17)						(3-7/02/17) IR & PI After HV tests Temp (23.5-28.3) °C; RH (48.3- 67.0)%				
			IR(GΩ)	PI	I (nA)	DAR				PD Avg (nC)	TVA (mA)	Tan δ	IR(GΩ)	PI	I (nA)	DAR	23 kV (VLF)		30 kV (DC)		50 kV (DC)		IR(GΩ)	PI
	C (nF)	I leak (μA)					IR(GΩ)	C (nF)	I leak (μA)								IR(GΩ)	I leak (μA)						
1	6.35	15	127	5.77	41.5	1.57	35.1	15	11.24	149	6.06	35.2	1.55	10.5	151	1.4	7.7	28	1.1	90	129	4.05	40.6	1.54
2	1.91	26	137	6.03	41.7	1.54	108.6	90	8.65	95.9	6.18	54.2	1.68	9.2	134	1.6	7.6	26	1.1	16	68.0	4.61	77.3	1.43
3	5.93	16	111	6.44	43.2	1.69	53.86	85	8.65	86.7	2.55	60.7	1.35	10.8	155	2.1	80.0	30	0.988					
5	4.66	29	111	6.16	48.1	1.55	25.14	70	9.05	104	5.2	51.2	1.57	10.5	149	1.4	7.8	28	1.1	112	85.9	4.49	61.3	1.48
6	3.81	27	100	6.62	53.4	1.47	26.32	72	11.93	109	4.98	48.1	1.45	10.2	147	1.1	9.2	26	1.1	76	67.8	6.10	77.4	1.47
13	0.64	9	112	2.75	44.6	1.52	35.39	40	9.11	108	2.65	46.9	1.46	10.4	152	0.864	8.0	36	0.840					
14	1.06	6	120	6.73	42	1.52	118.4	52	8.69	118	5.17	44.7	1.56	10.2	147	1.5	9.4	27	1.1					
15	3.81	6	119	6.38	44.9	1.52	49.83	102	9.20	83.6	3.64	60.8	1.66	9.6	140	1.6	7.7	25	1.2					
17	6.35	8	93.4	4.26	56.3	1.45	62.33	110	9.82	120	4.47	43.8	1.44	10.4	150	1.5	7.7	26	1.2	78	101	3.40	52.1	1.40
18	5.50	60	91	8.99	56.9	1.57	23.58	70	8.89	107	4.15	49.1	1.47	9.9	141	1.5	9.8	29	1.0					
19	2.33	48	146	4.26	36.1	1.44	74.59	74	6.10	139	4.72	38.4	1.44	9.7	140	1.6	7.5	28	1.1	110	104	4.27	50.5	1.43
20	1.48	70	68.2	2.48	76.1	1.34	103.7	50	6.57	63.7	3.64	81.00	1.42	10.0	142	2.3	9.8	31	0.980	130	50.0	3.02	105	1.48
21	0.64	34	121	2.93	41.3	1.37	37.11	50	6.44	90.3	2.51	61.4	1.33	9.8	138	2.3	8.3	28	1.1	40	72.3	2.72	75.7	1.37
22	2.75	46	43.7	1.92	120	1.23	88.3	66	7.40	64.8	2.92	78.9	1.34	9.9	141	1.5	10.2	25	1.2	110	55.1	2.84	94.3	1.32
24	1.06	80	190	3.9	27.5	1.34	57.25	70	7.09	101	5.67	52.1	1.47	9.5	134	1.6	7.9	19	1.6	78	50.0	5.46	105	1.33
25	3.81	120	78.9	2.46	64.1	1.33	50.34	30	7.75	92	1.6	57.6	1.17	9.7	137	1.6	9.3	31	0.975					
28	2.33	60	46.8	1.68	113	1.27	106.4	90	8.54	74	2.28	71.2	1.36	9.8	136	1.2	8.0	20	1.5	110	53.9	2.01	97.7	1.23
30	0.64	42	51.2	9.99	103	1.23	144.4	150	7.46	77.9	5.67	65.3	1.44	9.6	139	0.937	9.3	32	0.935	75	70.9	5.92	74.2	1.42
33	2.75	46	43.3	1.88	103	1.25	137.5	84	7.71	71.5	3.2	73.6	1.37	9.9	141	1.5	9.4	31	0.976	40	41.4	2.10	127	1.31
34	1.91	36	78.4	6.07	67.2	1.46	97.47	28	10.34	97.5	4.43	54	1.52	10.3	149	1.1	7.4	28	1.0	110	86.5	4.84	60.8	1.51
37	5.08	34	120	4.95	42.7	1.47	24.97	95	6.31	84.9	5.20	62	1.58	9.7	140	1.6	7.5	30	0.990	70	67.0	3.31	78.5	1.45
39	4.66	10	117	5.09	45	1.55	251.9	240	8.63	107	4.65	48.1	1.51	9.4	133	1.6	7.0	29	1.0	58	97.7	4.36	53.9	1.49
40	0.64	32	116	5.11	45.6	1.47	74.11	60	7.51	105	5.46	50.2	1.52	9.9	140	1.5	7.8	27	1.2	110	69.2	4.95	76.0	1.47
41	1.06	9	92.9	8.09	56.6	1.48	65.58	58	7.47	89.2	5.65	58	1.54	9.4	138	1.2	7.3	25	1.2	110	45.1	5.63	116	1.40
42	3.81	20	82.4	8.76	62.3	1.53	26.63	46	6.33	91.4	6.44	57.6	1.53	10.5	150	1.4	8.8	26	1.2	38	19.2	2.91	271	1.39
43	2.33	10	87.3	7.35	60.3	1.49	115	60	7.72	85.6	6.31	60.5	1.52	10.3	148	1.5	8.9	29	1.0	56	78.0	6.05	64.5	1.54
49	4.66	25	97.4	4.96	1.4	52.30	103	80	7.18	102	4.57	51.6	1.46	9.9	143	0.910	6.5	36	0.843					
52	0.64	20	113	4.33	46.7	1.51	88.34	60	7.41	68.1	3.03	74.2	1.63	9.6	145	0.456	4.7	29	1.1	115	30.9	1.42	170	1.20
53	2.33	42	12.5	1.16	422	1.07	78.6	48	6.90	38.2	1.61	138	1.21	10.1	144	1.1	7.4	26	1.1	54	36.7	1.63	144	1.21
55	4.66	22	64.5	3.91	81.6	1.44	79.14	80	13.02	93.2	5.06	55.7	1.49	10.6	148	1.1	8.0	17	1.8	98	81.8	3.89	64.3	1.46

Appendix B: Test results

Table B-1: In-situ IR and PI tests

Time (Minutes)	Red phase (MΩ)	White phase (MΩ)	Blue phase (MΩ)
0.5	590	581	552
1	993	958	913
2	1595	1549	1482
3	2130	2030	1955
4	2510	2460	2410
5	2890	2860	2760
6	3220	3230	3150
7	3610	3560	3480
8	3870	3890	3780
9	4230	4180	4230
10	4490	4400	4440
PI	4.52	4.59	4.86

Appendix C: Test results of removed bars

Table C-1: IR and PI test results before PD, TVA and TD tests

1	Bar no	U1
Min	R (GΩ)	I (nA)
1	127	41.5
2	228	22.1
3	312	16.8
4	386	13.6
5	454	11.6
6	514	10.2
7	566	9.9
8	604	8.6
9	673	7.7
10	720	7.3
PI	5.67	
PI Meas	5.77	
C	0.01	μF
DAR	1.57	

2	Bar no	C314/3
Min	R (GΩ)	I (nA)
1	137	41.7
2	227	22.1
3	306	17.2
4	383	13.4
5	451	11.7
6	520	10.1
7	586	8.9
8	634	8.14
9	706	7.45
10	764	6.9
PI	5.58	
PI Meas	6.03	
C	0.01	μF
DAR	1.54	

3	Bar no	C359/3
Min	R (GΩ)	I (nA)
1	111	43.2
2	223	23.2
3	309	17.1
4	373	14.6
5	429	12.3
6	486	10.8
7	555	9.49
8	622	8.45
9	671	7.8
10	726	7.25
PI	6.54	
PI Meas	6.44	
C	0.01	μF
DAR	1.69	

5	Bar no	C236/3
Min	R (GΩ)	I (nA)
1	111	48.1
2	194	27.3
3	265	19.8
4	330	16
5	391	13.5
6	458	11.7
7	506	10.4
8	562	9.38
9	616	8.68
10	664	7.93
PI	5.98	
PI Meas	6.16	
C	0.01	μF
DAR	1.55	

6	Bar no	C308/3
Min	R (GΩ)	I (nA)
1	100	53.4
2	172	30.4
3	234	22.5
4	293	18.0
5	352	14.9
6	409	12.7
7	462	11.4
8	534	9.18
9	599	8.89
10	662	7.96
PI	6.62	
PI Meas	6.71	
C	0.01	μF
DAR	1.47	

13	Bar no	C349/3
Min	R (GΩ)	I (nA)
1	112	44.6
2	172	30.2
3	204	25.2
4	227	23.0
5	246	21.4
6	262	20.1
7	277	19.0
8	286	18.4
9	292	18.0
10	303	17.4
PI	2.71	
PI Meas	2.75	
C	0.01	μF
DAR	1.52	

14	Bar no	C258/3
Min	R (GΩ)	I (nA)
1	120	42.0
2	229	24.0
3	304	17.4
4	384	14.7
5	457	11.5
6	528	9.9
7	599	8.74
8	664	7.87
9	731	7.18
10	793	6.64
PI	6.61	
PI Meas	6.73	
C	0.01	μF
DAR	1.52	

15	Bar no	C289/3
Min	R (GΩ)	I (nA)
1	119	44.9
2	212	25.4
3	293	18.6
4	368	14.5
5	435	12.1
6	502	10.4
7	562	9.23
8	621	8.42
9	678	7.62
10	737	7.14
PI	6.19	
PI Meas	6.38	
C	0.01	μF
DAR	1.52	

17	Bar no	U3
Min	R (GΩ)	I (nA)
1	93.4	56.3
2	152	36.4
3	196	26.8
4	233	22.5
5	266	19.8
6	295	17.8
7	323	16.3
8	350	15
9	376	14
10	398	13.2
PI	4.26	
PI Meas	4.26	
C	0.01	μF
DAR	1.45	

18	Bar no	C265/3
Min	R (GΩ)	I (nA)
1	91	56.9
2	176	30.0
3	257	20.5
4	338	15.6
5	417	12.6
6	498	10.6
7	577	9.12
8	654	8.03
9	730	7.22
10	804	6.55
PI	8.84	
PI Meas	8.99	
C	0.01	μF
DAR	1.57	

19	Bar no	C290/3
Min	R (GΩ)	I (nA)
1	146	36.1
2	237	22.2
3	307	17.1
4	363	14.4
5	405	13.0
6	457	11.5
7	498	10.6
8	534	9.86
9	580	9.04
10	613	8.59
PI	4.20	
PI Meas	4.26	
C	0.01	μF
DAR	1.44	

20	Bar no	C319/3
Min	R (GΩ)	I (nA)
1	68.2	76.1
2	97.1	54.2
3	115	45.7
4	129	40.9
5	137	38.3
6	148	35.2
7	155	34.0
8	160	32.9
9	165	32.0
10	169	31.2
PI	2.48	
PI Meas	2.48	
C	0.01	μF
DAR	1.34	

21	Bar no	C326/3
Min	R (GΩ)	I (nA)
1	121	41.30
2	179	29.40
3	219	24.00
4	241	21.20
5	273	19.30
6	294	17.90
7	312	16.90
8	325	16.20
9	342	15.40
10	352	15.00
PI	2.91	
PI Meas	2.93	
C	0.01	μF
DAR	1.37	

22	Bar no	C267/3
Min	R (GΩ)	I (nA)
1	43.7	120
2	56.7	91.6
3	63.7	82.8
4	68.7	76.2
5	72.8	72.4
6	75.8	69.5
7	78.2	67.4
8	80.6	65.3
9	82.4	63.9
10	83.5	63.1
PI	1.91	
PI Meas	1.92	
C	0.01	μF
DAR	1.23	

24	Bar no	C311/3
Min	R (GΩ)	I (nA)
1	190	27.5
2	253	20.0
3	310	17.0
4	371	14.2
5	429	12.3
6	486	10.9
7	543	9.71
8	618	8.61
9	679	7.82
10	740	7.11
PI	3.89	
PI Meas	3.90	
C	0.01	μF
DAR	1.34	

25	Bar no	C334/3
Min	R (GΩ)	I (nA)
1	78.9	64.1
2	113	46.2
3	135	39.1
4	149	35.3
5	161	32.8
6	169	31.1
7	177	29.8
8	183	28.9
9	188	28.0
10	192	27.9
PI	2.43	
PI Meas	2.46	
C	0.01	μF
DAR	1.33	

28	Bar no	C274/3
Min	R (GΩ)	I (nA)
1	46.8	113
2	58.3	90.2
3	63.1	83.4
4	66.9	78.7
5	69.6	75.8
6	71.8	73.4
7	73.5	71.7
8	75.1	70.2
9	75.4	70.1
10	77.3	68.1
PI	1.65	
PI Meas	1.68	
C	0.01	μF
DAR	1.27	

30	Bar no	C285/3
Min	R (GΩ)	I (nA)
1	51.2	103
2	66.8	78.8
3	78.4	68.1
4	86.6	60.7
5	98.3	53.6
6	123	42.8
7	146	36.0
8	365	14.4
9	477	11.0
10	525	10.0
PI	10.25	
PI Meas	9.99	
C	0.01	μF
DAR	1.23	

33	Bar no	C305/3
Min	R (GΩ)	I (nA)
1	43.3	103
2	62.7	82.8
3	70.4	74.6
4	75.5	69.0
5	79.8	65.1
6	83.0	63.4
7	85.2	61.8
8	87.3	60.2
9	89.1	59.1
10	90.4	58.3
PI	2.09	
PI Meas	1.88	
C	0.01	μF
DAR	1.25	

34	Bar no	C316/3
Min	R (GΩ)	I (nA)
1	78.4	67.2
2	136	38.8
3	181	29.0
4	225	23.4
5	266	19.8
6	308	17.2
7	348	15.2
8	388	13.5
9	429	12.3
10	469	11.2
PI	5.98	
PI Meas	6.07	
C	0.017	μF
DAR	1.46	

37	Bar no	C263/3
Min	R (GΩ)	I (nA)
1	120	42.7
2	205	25.7
3	280	18.9
4	318	16.6
5	389	13.5
6	445	11.8
7	487	10.8
8	520	10.1
9	550	9.3
10	583	9.04
PI	4.86	
PI Meas	4.95	
C	0.01	μF
DAR	1.47	

39	Bar no	C266/3
Min	R (GΩ)	I (nA)
1	117	45.0
2	202	26.0
3	275	19.0
4	331	15.9
5	382	13.8
6	427	12.3
7	470	11.2
8	512	10.3
9	553	9.53
10	587	8.98
PI	5.02	
PI Meas	5.09	
C	0.01	μF
DAR	1.55	

40	Bar no	C230/3
Min	R (GΩ)	I (nA)
1	116	45.6
2	197	26.8
3	261	20.2
4	317	16.6
5	369	14.3
6	415	12.7
7	465	11.3
8	510	10.3
9	545	9.66
10	575	9.15
PI	4.96	
PI Meas	5.11	
C	0.01	μF
DAR	1.47	

41	Bar no	C353/3
Min	R (GΩ)	I (nA)
1	92.9	56.6
2	169	31.1
3	245	21.6
4	308	17.1
5	377	14.0
6	447	11.5
7	517	10.2
8	584	8.99
9	660	7.92
10	741	7.11
PI	7.98	
PI Meas	8.09	
C	0.01	μF
DAR	1.48	

42	Bar no	C354/3
Min	R (GΩ)	I (nA)
1	82.4	62.3
2	161	34.1
3	223	23.6
4	300	17.6
5	363	14.6
6	434	12.1
7	505	10.4
8	577	9.11
9	647	8.14
10	710	7.41
PI	8.62	
PI Meas	8.76	
C	0.01	μF
DAR	1.53	

43	Bar no	C356/3
Min	R (GΩ)	I (nA)
1	87.3	60.3
2	154	33.9
3	214	24.6
4	273	19.3
5	334	15.8
6	398	13.2
7	457	11.5
8	519	10.6
9	577	9.1
10	642	8.2
PI	7.35	
PI Meas	7.46	
C	0.01	μF
DAR	1.49	

49	Bar no	C335/3
Min	R (GΩ)	I (nA)
1	97.4	52.3
2	161	32.6
3	210	25.0
4	254	20.0
5	294	17.9
6	334	15.7
7	372	14.2
8	408	12.9
9	442	11.9
10	477	11.0
PI	4.90	
PI Meas	4.96	
C	0.01	μF
DAR	1.4	

52	Bar no	C264/3
Min	R (GΩ)	I (nA)
1	113	46.7
2	193	27.6
3	248	21.2
4	299	17.6
5	340	15.5
6	375	14.1
7	405	13.0
8	435	12.1
9	462	11.4
10	482	10.9
PI	4.27	
PI Meas	4.33	
C	0.01	μF
DAR	1.51	

53	Bar no	C261/3
Min	R (GΩ)	I (nA)
1	12.5	422
2	13.4	393
3	13.6	388
4	13.8	381
5	14.0	377
6	14.1	373
7	14.2	370
8	14.3	367
9	14.5	363
10	14.6	362
PI	1.2	
PI Meas	1.16	
C	0.01	μF
DAR	1.07	

55	Bar no	C215/3
Min	R (GΩ)	I (nA)
1	64.5	81.6
2	108	48.4
3	144	34.1
4	165	31.8
5	186	28.3
6	203	26.0
7	217	24.2
8	231	22.9
9	241	21.3
10	252	20.9
PI	3.91	
PI Meas	3.95	
C	0.01	μF
DAR	1.44	

Table C-2: PDA_{Avg}, TVA, Δ Tan δ and DIV test results

BAR NO	TVA READING (mA)	PD READING (nC)	ΔTanδ (%)	DIV (kV)
1	15	35.10	0.149	3.1
2	90	108.60	0.153	2.8
3	85	53.86	0.216	2.5
5	70	25.14	0.204	2.9
6	72	26.32	0.112	3.0
13	40	35.39	0.115	2.8
14	52	118.40	0.132	3.0
15	102	49.83	0.185	2.8
17	110	62.33	0.237	2.5
18	70	23.58	0.174	2.9
19	74	74.59	0.196	3.4
20	50	103.7	0.192	3.0
21	50	37.11	0.089	3.5
22	66	88.30	0.117	3.5
24	70	57.25	0.127	3.4
25	30	50.34	0.121	3.6
28	90	106.40	0.156	3.5
30	150	144.40	0.164	3.3
33	84	137.50	0.137	3.4
34	28	97.47	0.223	3.8
37	95	24.97	0.244	3.3
39	240	251.9	0.134	3.1
40	60	74.11	0.126	3.1
41	58	65.58	0.249	3.1
42	46	26.63	0.084	3.0
43	60	115.00	0.231	2.8
49	80	103.00	0.308	3.5
52	60	88.34	0.114	3.4
53	48	78.60	0.143	3.4
55	80	79.14	0.236	3.3

Table C-3: TD test results

1	Bar no	200	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)
1.28	11.244	2.612	7.54
2.56	13.819	5.882	7.58
3.84	16.532	9.074	7.61
5.12	22.506	12.342	7.68
6.40	26.182	15.090	7.73
5.12	22.895	12.340	7.68
3.84	18.112	9.291	7.62
2.56	14.131	6.212	7.58
1.28	11.391	2.781	7.54

2	Bar no	314	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)
1.28	8.651	2.745	7.20
2.56	10.522	5.760	7.22
3.84	13.755	8.788	7.25
5.12	19.600	11.407	7.32
6.40	23.995	14.715	7.39
5.12	21.050	11.977	7.34
3.84	14.888	8.738	7.26
2.56	10.855	5.875	7.22
1.28	8.637	2.656	7.20

3	Bar no	359	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)
1.28	8.651	2.848	7.57
2.56	10.052	5.837	7.59
3.84	14.758	9.858	7.64
5.12	25.972	13.200	7.78
6.40	30.211	15.757	7.87
5.12	26.210	13.016	7.78
3.84	15.783	9.336	7.64
2.56	10.257	6.148	7.59
1.28	8.788	2.839	7.57

5	Bar no	263	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)
1.28	9.052	3.038	7.61
2.56	10.536	6.109	7.63
3.84	14.022	9.232	7.66
5.12	24.864	12.709	7.79
6.40	29.466	15.536	7.88
5.12	25.475	12.674	7.79
3.84	15.291	9.081	7.67
2.56	10.782	6.182	7.63
1.28	9.160	3.083	7.61

6	Bar no	308	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)
1.28	11.933	2.849	7.18
2.56	12.935	5.785	7.20
3.84	14.001	8.606	7.22
5.12	19.553	11.787	7.29
6.40	23.140	14.635	7.34
5.12	20.831	11.819	7.29
3.84	14.815	7.907	7.22
2.56	13.234	5.871	7.20
1.28	12.243	2.940	7.18

13	Bar no	349	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)
1.28	9.114	2.939	7.45
2.56	10.721	5.906	7.46
3.84	12.825	8.959	7.49
5.12	16.727	12.043	7.53
6.40	20.601	15.143	7.58
5.12	18.603	12.133	7.53
3.84	14.691	9.092	7.49
2.56	11.527	6.052	7.47
1.28	9.315	3.064	7.45

14		Bar no	258	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)	
1.28	8.693	2.903	7.32	
2.56	10.309	5.849	7.33	
3.84	11.795	8.831	7.35	
5.12	17.428	11.905	7.41	
6.40	21.921	14.349	7.47	
5.12	19.378	11.956	7.42	
3.84	14.237	8.883	7.36	
2.56	10.830	5.958	7.33	
1.28	9.238	2.969	7.32	

15		Bar no	289	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)	
1.28	9.204	2.810	7.27	
2.56	10.793	5.738	7.29	
3.84	12.344	8.748	7.31	
5.12	21.456	11.907	7.41	
6.40	27.740	14.997	7.51	
5.12	25.028	12.089	7.42	
3.84	17.013	8.948	7.33	
2.56	11.113	5.974	7.29	
1.28	9.265	2.926	7.27	

17		Bar no	197	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)	
1.28	9.821	2.833	7.28	
2.56	11.380	5.631	7.30	
3.84	14.400	8.641	7.33	
5.12	27.338	11.916	7.47	
6.40	33.554	14.916	7.58	
5.12	28.412	12.260	7.48	
3.84	17.274	8.888	7.34	
2.56	11.800	5.895	7.30	
1.28	10.049	2.992	7.28	

18		Bar no	265	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)	
1.28	8.893	2.823	7.21	
2.56	10.895	5.775	7.23	
3.84	14.103	8.677	7.26	
5.12	22.164	11.773	7.35	
6.40	26.321	14.929	7.42	
5.12	22.623	11.887	7.35	
3.84	17.104	8.802	7.28	
2.56	11.650	5.904	7.23	
1.28	9.071	2.957	7.22	

19		Bar no	290	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)	
1.28	6.098	2.700	6.94	
2.56	6.941	5.546	6.95	
3.84	10.683	8.426	6.98	
5.12	20.589	11.326	7.10	
6.40	25.722	14.274	7.18	
5.12	22.284	11.504	7.10	
3.84	13.359	8.504	7.00	
2.56	7.053	5.635	6.95	
1.28	6.163	2.750	6.94	

20		Bar no	334	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)	
1.28	6.578	2.846	7.09	
2.56	7.543	5.734	7.10	
3.84	11.143	8.643	7.12	
5.12	21.224	11.613	7.23	
6.40	25.817	14.715	7.33	
5.12	24.605	11.979	7.26	
3.84	18.799	8.835	7.15	
2.56	10.855	5.794	7.10	
1.28	6.779	3.003	7.09	

21		Bar no	326	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)	
1.28	6.438	2.774	7.36	
2.56	7.270	5.937	7.37	
3.84	8.887	8.900	7.40	
5.12	12.636	11.959	7.43	
6.40	15.340	14.868	7.47	
5.12	14.747	12.171	7.43	
3.84	12.526	9.314	7.40	
2.56	9.132	6.048	7.37	
1.28	7.670	3.975	7.37	

22		Bar no	267	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)	
1.28	7.398	2.804	7.09	
2.56	8.673	5.642	7.10	
3.84	10.288	8.512	7.12	
5.12	15.153	11.496	7.17	
6.40	19.147	14.384	7.22	
5.12	16.876	11.544	7.18	
3.84	12.691	8.665	7.13	
2.56	9.258	5.771	7.10	
1.28	7.863	2.930	7.09	

24		Bar no	311	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)	
1.28	7.087	2.837	7.14	
2.56	8.215	5.743	7.16	
3.84	9.586	8.642	7.17	
5.12	16.093	11.572	7.22	
6.40	19.803	14.661	7.29	
5.12	18.725	11.857	7.24	
3.84	15.179	8.936	7.19	
2.56	10.709	6.068	7.16	
1.28	7.277	2.770	7.14	

25		Bar no	334	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)	
1.28	7.754	2.859	7.14	
2.56	8.651	5.663	7.15	
3.84	10.048	8.637	7.16	
5.12	16.859	11.746	7.23	
6.40	19.849	14.145	7.27	
5.12	17.500	11.954	7.24	
3.84	11.298	8.353	7.17	
2.56	8.823	6.106	7.15	
1.28	8.520	4.734	7.15	

28		Bar no	274	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)	
1.28	8.539	2.795	7.16	
2.56	9.756	5.731	7.17	
3.84	13.625	8.681	7.21	
5.12	19.954	11.707	7.30	
6.40	24.152	14.770	7.36	
5.12	21.905	11.768	7.30	
3.84	16.174	8.709	7.22	
2.56	10.452	5.852	7.18	
1.28	8.865	2.881	7.16	

30		Bar no	285	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)	
1.28	7.457	2.708	7.02	
2.56	8.519	5.594	7.03	
3.84	9.771	8.432	7.04	
5.12	18.729	11.390	7.13	
6.40	23.877	14.407	7.21	
5.12	20.508	11.497	7.13	
3.84	13.389	8.579	7.06	
2.56	8.931	5.623	7.03	
1.28	7.701	2.889	7.02	

42		Bar no	354	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)	
1.28	6.329	2.884	7.41	
2.56	7.241	5.847	7.42	
3.84	8.038	8.858	7.43	
5.12	11.149	11.889	7.46	
6.40	14.738	15.063	7.49	
5.12	12.508	12.082	7.46	
3.84	9.229	9.051	7.43	
2.56	7.471	6.010	7.42	
1.28	6.574	3.020	7.41	

43		Bar no	356	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)	
1.28	7.722	2.689	6.98	
2.56	9.963	5.583	7.00	
3.84	12.113	8.433	7.02	
5.12	22.918	11.447	7.13	
6.40	30.784	14.497	7.22	
5.12	26.644	11.572	7.14	
3.84	13.970	7.828	7.02	
2.56	10.203	5.723	7.00	
1.28	7.960	2.921	6.98	

49		Bar no	335	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)	
1.28	7.181	2.598	6.66	
2.56	8.268	5.353	6.67	
3.84	10.443	8.060	6.69	
5.12	28.783	11.026	6.88	
6.40	37.961	14.035	7.03	
5.12	31.311	11.258	6.89	
3.84	15.395	8.154	6.72	
2.56	8.645	5.392	6.67	
1.28	7.528	2.664	6.66	

52		Bar no	264	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)	
1.28	7.414	2.826	6.97	
2.56	8.207	5.292	6.98	
3.84	9.837	8.382	6.99	
5.12	14.987	11.256	7.04	
6.40	18.841	14.200	7.09	
5.12	16.169	11.495	7.05	
3.84	11.351	8.559	7.00	
2.56	8.689	5.666	6.98	
1.28	7.445	2.830	6.97	

53		Bar no	261	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)	
1.28	6.904	2.884	7.23	
2.56	7.874	5.863	7.24	
3.84	8.954	8.637	7.25	
5.12	17.240	11.980	7.33	
6.40	21.192	14.575	7.39	
5.12	17.535	11.853	7.33	
3.84	11.440	8.873	7.26	
2.56	8.028	5.830	7.24	
1.28	6.970	2.985	7.23	

55		Bar no	215	
RMS V (kV)	Tan delta $\%.(10^{-3})$	I (mA)	C (nF)	
1.28	13.022	2.775	7.43	
2.56	16.866	5.938	7.47	
3.84	19.907	8.761	7.50	
5.12	29.353	12.250	7.62	
6.40	36.589	15.300	7.72	
5.12	31.826	12.342	7.63	
3.84	23.780	9.163	7.53	
2.56	17.587	6.046	7.47	
1.28	14.173	2.988	7.44	

Table C-4: IR and PI test values before HV tests

1 Bar no 200		
Date	2017/02/04	
Temp	26.1 °C	
Hum	51.90%	
Min	R (GΩ)	I (nA)
1	149	35.2
2	277	19
3	382	13.8
4	478	11
5	554	9.49
6	632	8.36
7	696	7.56
8	768	6.84
9	834	6.3
10	891	5.9
PI	5.98	
PI meas	6.06	
C	0.01	μF
DAR	1.55	

2 Bar no 314		
Date	2017/02/07	
Temp	23.5°C	
Hum	67.00%	
Min	R (GΩ)	I (nA)
1	95.9	54.2
2	183	29.4
3	253	21.1
4	314	17.4
5	376	13.9
6	429	12.2
7	472	11.1
8	517	10.7
9	545	9.59
10	583	9.03
PI	6.08	
PI meas	6.18	
C	0	μF
DAR	1.68	

3 Bar no 359		
Date	2017/02/03	
Temp	26.1 °C	
Hum	51.10%	
Min	R (GΩ)	I (nA)
1	86.7	60.7
2	124	42.4
3	136	36
4	162	32.5
5	175	30.1
6	185	28.4
7	194	27
8	204	25.8
9	211	24.9
10	218	
PI	2.51	
PI meas	2.55	
C	0.01	μF
DAR	1.35	

5 Bar no 236		
Date	2017/02/03	
Temp	26.1°C	
Hum	51.10%	
Min	R (GΩ)	I (nA)
1	104	51.2
2	184	28.5
3	250	21.1
4	305	17.3
5	354	14.9
6	392	13.4
7	437	12
8	475	11.1
9	496	10.6
10	531	
PI	5.11	
PI meas	5.2	
C	0.01	μF
DAR	1.57	

6 Bar no 308		
Date	2017/02/06	
Temp	25.4 °C	
Hum	59.30%	
Min	R (GΩ)	I (nA)
1	109	48.1
2	178	29.4
3	235	22.4
4	287	18.7
5	337	15.6
6	380	13.8
7	427	12.3
8	472	11.1
9	572	10.4
10	543	9.69
PI	4.98	
PI meas	5.02	
C	0.01	μF
DAR	1.45	

13 Bar no 349		
Date	2017/02/04	
Temp	28.4 °C	
Hum	48.80%	
Min	R (GΩ)	I (nA)
1	108	46.9
2	163	32.4
3	196	27.1
4	218	24.1
5	235	22.4
6	248	21.2
7	260	20.2
8	267	19.6
9	276	19.1
10	282	18.7
PI	2.61	
PI meas	2.65	
C	0.01	μF
DAR	1.46	

14 Bar no 258		
Date	2017/02/06	
Temp	25.3 °C	
Hum	60.00%	
Min	R (GΩ)	I (nA)
1	118	44.7
2	211	24.9
3	286	18.4
4	349	15.9
5	402	13.1
6	450	11.7
7	494	10.6
8	532	9.89
9	567	9.28
10	599	8.79
PI	5.08	
PI meas	5.17	
C		μF
DAR	1.56	

15 Bar no 289		
Date	2017/02/07	Failed 50 kV
Temp	23.5 °C	
Hum	67.00%	
Min	R (GΩ)	I (nA)
1	83.6	60.8
2	168	30.9
3	215	24.4
4	255	20.9
5	275	19.1
6	295	17.9
7	297	17.7
8	300	17.5
9	299	17.5
10	298	17.6
PI	3.56	
PI meas	3.64	
C	0.01	μF
DAR	1.66	

17 Bar no 197		
Date	2017/02/04	
Temp	26.1°C	
Hum	51.90%	
Min	R (GΩ)	I (nA)
1	120	43.8
2	198	26.4
3	258	20.4
4	309	17
5	352	14.9
6	390	13.5
7	429	12.3
8	462	11.4
9	496	10.6
10	529	9.95
PI	4.41	
PI meas	4.47	
C	0.01	μF
DAR	1.44	

18 Bar no 265		
Date	2017/02/06	
Temp	25.2 °C	
Hum	59.10%	
Min	R (GΩ)	I (nA)
1	107	49.1
2	173	30.4
3	224	23.5
4	266	19.8
5	304	17.3
6	338	15.6
7	368	14.3
8	391	13.4
9	420	13
10	439	12
PI	4.1	
PI meas	4.15	
C	0.01	μF
DAR	1.47	

19 Bar no 290		
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20 Bar no 319		
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21 Bar no 326		
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22 Bar no 267		
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24 Bar no 311		
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Date	2017/02/04	
Temp	26.1°C	
Hum	51.90%	
Min	R (GΩ)	I (nA)
1	139	38.4
2	237	22.1
3	301	17.5
4	360	14.6
5	411	12.8
6	460	11.4
7	519	10.9
8	542	9.98
9	604	8.64
10	656	8.02
PI	4.72	
PI meas	4.85	
C	0.01	μF
DAR	1.44	

Date	2017/02/07	
Temp	25.6 °C	
Hum	63.70%	
Min	R (GΩ)	I (nA)
1	63.7	81
2	105	50
3	137	38.1
4	166	31.8
5	184	28.5
6	199	26.4
7	208	25.2
8	217	24.3
9	221	23.6
10	229	23
PI	3.59	
PI meas	3.64	
C	0.01	μF
DAR	1.42	

Date	2017/02/06	
Temp	24.7°C	
Hum	58.10%	
Min	R (GΩ)	I (nA)
1	90.3	61.4
2	129	41.2
3	162	32.3
4	179	29.7
5	190	27.6
6	201	26.4
7	208	25.3
8	214	24.6
9	220	23.9
10	224	23.5
PI	2.48	
PI meas	2.51	
C	0.01	μF
DAR	1.33	

Date	2017/02/06	
Temp	24.7 °C	
Hum	58.10%	
Min	R (GΩ)	I (nA)
1	64.8	78.9
2	94.8	56.5
3	114	46.7
4	130	40.8
5	144	37.5
6	155	34.2
7	164	32.1
8	173	30.7
9	180	29.3
10	187	28.1
PI	2.89	
PI meas	2.92	
C	0.01	μF
DAR	1.34	

Date	2017/02/04	
Temp	26.1 °C	
Hum	51.90%	
Min	R (GΩ)	I (nA)
1	101	52.1
2	168	31.4
3	220	23.9
4	273	19.2
5	324	16.2
6	373	14.1
7	423	12.4
8	472	11.1
9	521	10.1
10	566	9.3
PI	5.6	
PI meas	5.67	
C	0.01	μF
DAR	1.47	

25	Bar no	334
Date	2017/02/06	
Temp	24.7°C	
Hum	58.10%	
Min	R (GΩ)	I (nA)
1	92	57.6
2	110	46.9
3	121	43.4
4	129	40.8
5	132	39.6
6	136	38.5
7	140	37.5
8	143	36.7
9	145	36.2
10	146	36
PI	1.59	
PI meas	1.6	
C	0.01	μF
DAR	1.17	

28	Bar no	274
Date	2017/02/04	
Temp	28.4 °C	
Hum	48.80%	
Min	R (GΩ)	I (nA)
1	74	71.2
2	105	50.9
3	122	43.8
4	134	39.2
5	141	37.1
6	148	35.7
7	154	34.1
8	158	33.2
9	163	32.2
10	167	31.2
PI	2.26	
PI meas	2.28	
C	0.01	μF
DAR	1.36	

30	Bar no	285
Date	2017/02/07	
Temp	23.5 °C	
Hum	67.00%	
Min	R (GΩ)	I (nA)
1	77.9	65.3
2	134	39.2
3	180	29.1
4	222	23.5
5	262	20.5
6	303	17.4
7	338	15.7
8	374	13.9
9	407	12.8
10	435	12.1
PI	5.58	
PI meas	5.67	
C	0.01	μF
DAR	1.44	

33	Bar no	305
Date	2017/02/06	
Temp	25.2°C	
Hum	59.10%	
Min	R (GΩ)	I (nA)
1	71.5	73.6
2	109	48.5
3	135	38.9
4	157	33.5
5	174	30.3
6	188	28.1
7	200	26.3
8	210	25.1
9	220	23.9
10	227	23.1
PI	3.17	
PI meas	3.2	
C	0.01	μF
DAR	1.37	

34	Bar no	316
Date	2017/02/03	
Temp	26.1 °C	
Hum	51.10%	
Min	R (GΩ)	I (nA)
1	97.5	54
2	165	31.8
3	212	24.8
4	255	20.7
5	289	18.2
6	321	16.4
7	349	15.1
8	375	14
9	400	13.1
10	425	
PI	4.36	
PI meas	4.43	
C	0.01	μF
DAR	1.52	

37	Bar no	263
Date	2017/02/07	

39	Bar no	266
Date	2017/02/06	

40	Bar no	230
Date	2017/02/06	

41	Bar no	353
Date	2017/02/06	

42	Bar no	354
Date	2017/02/06	

Temp	23.5 °C	
Hum	67.00%	
Min	R (GΩ)	I (nA)
1	84.9	62
2	166	31.4
3	238	22.1
4	294	17.9
5	338	15.8
6	368	14.3
7	400	13.1
8	411	12.8
9	429	12.3
10	434	12.1
PI	5.11	
PI meas	5.2	
C	0.01	μF
DAR	1.58	

Temp	23.9 °C	
Hum	61.50%	
Min	R (GΩ)	I (nA)
1	107	48.1
2	180	28.5
3	230	22.4
4	271	19.8
5	303	18.1
6	334	15.5
7	363	14.6
8	386	13.7
9	409	12.7
10	486	10.8
PI	4.54	
PI meas	4.65	
C	0.01	μF
DAR	1.51	

Temp	23.9°C	
Hum	61.50%	
Min	R (GΩ)	I (nA)
1	105	50.2
2	184	28.6
3	247	21.3
4	302	17.4
5	352	14.9
6	403	13
7	449	11.8
8	488	10.8
9	528	9.96
10	564	9.32
PI	5.37	
PI meas	5.46	
C	0.01	μF
DAR	1.52	

Temp	25.4 °C	
Hum	59.30%	
Min	R (GΩ)	I (nA)
1	89.2	58
2	161	32.2
3	219	24
4	275	19.1
5	321	16.4
6	363	14.5
7	401	13.1
8	436	12.1
9	477	11.3
10	496	10.6
PI	5.56	
PI meas	5.65	
C	0.01	μF
DAR	1.54	

Temp	25.4°C	
Hum	59.30%	
Min	R (GΩ)	I (nA)
1	91.4	57.6
2	169	31.1
3	235	22.4
4	296	17.7
5	354	14.9
6	405	13
7	456	11.6
8	502	10.5
9	545	9.67
10	580	9.07
PI	6.35	
PI meas	6.44	
C	0.01	μF
DAR	1.53	

43	Bar no	356
Date	2017/02/06	
Temp	25.4 °C	
Hum	59.30%	
Min	R (GΩ)	I (nA)
1	85.6	60.5
2	159	33.1
3	222	23.8
4	274	19.2
5	322	16.4
6	368	14.3
7	416	12.6
8	461	11.4
9	497	10.6
10	532	9.89
PI	6.21	
PI meas	6.31	
C	0.01	μF
DAR	1.52	

49	Bar no	335
Date	2017/02/06	
Temp	25.4 °C	
Hum	59.30%	
Min	R (GΩ)	I (nA)
1	102	51.6
2	169	31.1
3	222	23.7
4	268	19.7
5	306	17.2
6	337	15.6
7	368	14.3
8	405	13
9	434	12.1
10	460	11.4
PI	4.51	
PI meas	4.57	
C	0.01	μF
DAR	1.46	

52	Bar no	264
Date	2017/02/07	
Temp	25.6 °C	
Hum	63.70%	
Min	R (GΩ)	I (nA)
1	68.1	74.2
2	116	44.7
3	148	35.6
4	164	32.1
5	174	30.1
6	183	28.5
7	190	27.6
8	196	26.2
9	197	26
10	203	25.9
PI	2.98	
PI meas	3.03	
C	0.01	μF
DAR	1.63	

53	Bar no	261
Date	2017/02/06	
Temp	25.3 °C	
Hum	60.00%	
Min	R (GΩ)	I (nA)
1	38.2	138
2	47.2	112
3	51.8	102
4	54.6	96.1
5	56.6	92.1
6	58	90.6
7	59.2	88.7
8	60.2	87.4
9	60.7	86.6
10	61.3	85.8
PI	1.6	
PI meas	1.61	
C	0.01	μF
DAR	1.21	

55	Bar no	215
Date	2017/02/04	
Temp	26.1°C	
Hum	51.90%	
Min	R (GΩ)	I (nA)
1	93.2	55.7
2	160	32.8
3	216	24.6
4	263	20
5	306	17.2
6	344	15.3
7	380	13.8
8	411	12.8
9	439	12
10	465	11.3
PI	4.99	
PI meas	5.06	
C	0.01	μF
DAR	1.49	

Table C-5: Test results of HV tests

Bar no	HV tests						
	23			30			50
	C (nF)	I leak (μ A)	R(G Ω)	C (nF)	I leak (μ A)	R(G Ω)	I leak (μ A)
1	10.5	151	1.4	7.7	28	1.1	90
2	9.2	134	1.6	7.6	26	1.1	16
3	10.8	155	2.1	80	30	0.988	
5	10.5	149	1.4	7.8	28	1.1	112
6	10.2	147	1.1	9.2	26	1.1	76
13	10.4	152	0.864	8	36	0.84	
14	10.2	147	1.5	9.4	27	1.1	
15	9.6	140	1.6	7.7	25	1.2	
17	10.4	150	1.5	7.7	26	1.2	78
18	9.9	141	1.5	9.8	29	1	
19	9.7	140	1.6	7.5	28	1.1	110
20	10	142	2.3	9.8	31	0.98	130
21	9.8	138	2.3	8.3	28	1.1	40
22	9.9	141	1.5	10.2	25	1.2	110
24	9.5	134	1.6	7.9	19	1.6	78
25	9.7	137	1.6	9.3	31	0.975	
28	9.8	136	1.2	8	20	1.5	110
30	9.6	139	0.937	9.3	32	0.935	75
33	9.9	141	1.5	9.4	31	0.976	40
34	10.3	149	1.1	7.4	28	1	110
37	9.7	140	1.6	7.5	30	0.99	70
39	9.4	133	1.6	7	29	1	58
40	9.9	140	1.5	7.8	27	1.2	110
41	9.4	138	1.2	7.3	25	1.2	110
42	10.5	150	1.4	8.8	26	1.2	38
43	10.3	148	1.5	8.9	29	1	56
49	9.9	143	0.91	6.5	36	0.843	
52	9.6	145	0.456	4.7	29	1.1	115
53	10.1	144	1.1	7.4	26	1.1	54
55	10.6	148	1.1	8	17	1.8	98

Table C-6: IR and PI test values after HV tests

1 Bar no 200		
Date	2017/02/04	
Temp	26.4 °C	
Hum	51.70%	
Min	R (GΩ)	I (nA)
1	129	40.6
2	224	23.4
3	294	17.9
4	347	15.2
5	392	13.4
6	432	12.2
7	460	11.4
8	480	11
9	503	10.4
10	521	10.1
PI	4.04	
PI meas	4.05	
C	0.01	μF
DAR	1.54	

2 Bar no 314		
Date	2017/02/07	
Temp	25.3 °C	
Hum	64.60%	
Min	R (GΩ)	I (nA)
1	68	77.3
2	112	47.1
3	148	35.7
4	178	29.6
5	204	25.7
6	229	23
7	251	20.9
8	272	19.3
9	291	18.1
10	310	17
PI	4.56	
PI meas	4.61	
C	0.01	μF
DAR	1.43	

3 Bar no 359		
Date	2017/02/03	Failed 50 kV
Temp	26.1°C	
Hum	51.10%	
Min	R (GΩ)	I (nA)
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
PI		
PI meas		
C		μF
DAR		

5 Bar no 236		
Date	2017/02/03	
Temp	26.1°C	
Hum	51.10%	
Min	R (GΩ)	I (nA)
1	85.9	61.3
2	149	35.3
3	188	27.9
4	223	23.6
5	259	20.3
6	285	18.4
7	310	17
8	331	15.9
9	349	15.1
10	380	13.8
PI	4.42	
PI meas	4.49	
C	0.01	μF
DAR	1.48	

6 Bar no 308		
Date	2017/02/06	
Temp	24.9 °C	
Hum	60.50%	
Min	R (GΩ)	I (nA)
1	67.8	77.4
2	117	44.7
3	164	32.1
4	206	25.5
5	242	21.8
6	287	18.3
7	312	16.9
8	347	15.2
9	380	13.8
10	408	12.9
PI	6.02	
PI meas	6.1	
C	0.01	μF
DAR	1.47	

13 Bar no 349		
Date	2017/02/04	Failed 50 kV
Temp	28.4 °C	
Hum	48.80%	
Min	R (GΩ)	I (nA)
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
PI		
PI meas		
C		μF
DAR		

14 Bar no 258		
Date	2017/02/06	Failed 50 kV
Temp	25.1°C	
Hum	60.50%	
Min	R (GΩ)	I (nA)
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
PI		
PI meas		
C		μF
DAR		

15 Bar no 289		
Date	2017/02/07	Failed 50 kV
Temp	23.5 °C	
Hum	67.00%	
Min	R (GΩ)	I (nA)
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
PI		
PI meas		
C		μF
DAR		

17 Bar no 197		
Date	2017/02/04	
Temp	26.4 °C	
Hum	51.70%	
Min	R (GΩ)	I (nA)
1	101	52.1
2	157	33.4
3	196	26.6
4	229	22.9
5	255	20.7
6	281	18.7
7	290	18.2
8	306	17.2
9	323	16.3
10	334	15.7
PI	3.31	
PI meas	3.4	
C	0.01	μF
DAR	1.4	

18 Bar no 265		
Date	2017/02/06	Failed 50 kV
Temp	25.2 °C	
Hum	59.10%	
Min	R (GΩ)	I (nA)
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
PI		
PI meas		
C		μF
DAR		

19	Bar no	290
Date	2017/02/04	
Temp	26.4 °C	
Hum	51.70%	
Min	R (GΩ)	I (nA)
1	104	50.5
2	166	31.7
3	227	23.2
4	270	19.4
5	307	17.1
6	341	15.4
7	373	14.1
8	401	13.1
9	424	12.4
10	440	11.8
PI	4.23	
PI meas	4.27	
C	0.01	μF
DAR	1.43	

20	Bar no	319
Date	2017/02/07	
Temp	25.3 °C	
Hum	64.60%	
Min	R (GΩ)	I (nA)
1	50	105
2	84.8	61.4
3	106	49.7
4	119	44.4
5	124	41.3
6	132	39.9
7	135	39.1
8	138	38.2
9	142	37.1
10	149	35.3
PI	2.98	
PI meas	3.02	
C	0.01	μF
DAR	1.48	

21	Bar no	326
Date	2017/02/06	
Temp	24.0 °C	
Hum	60.50%	
Min	R (GΩ)	I (nA)
1	72.3	75.7
2	108	51.3
3	131	42.8
4	146	35.8
5	159	33.1
6	169	32.4
7	177	29.7
8	183	28.6
9	189	27.9
10	194	27
PI	2.68	
PI meas	2.72	
C	0.01	μF
DAR	1.37	

22	Bar no	267
Date	2017/02/06	
Temp	24.0 °C	
Hum	60.50%	
Min	R (GΩ)	I (nA)
1	55.1	94.3
2	78.9	66.7
3	95.1	55.4
4	108	48.7
5	118	44.4
6	128	41.9
7	136	38.9
8	143	36.4
9	150	35.1
10	155	33.5
PI	2.81	
PI meas	2.84	
C	0.01	μF
DAR	1.32	

24	Bar no	311
Date	2017/02/04	
Temp	26.4 °C	
Hum	51.70%	
Min	R (GΩ)	I (nA)
1	50	105
2	78	67.4
3	103	51.1
4	129	40.8
5	152	34.5
6	176	29.9
7	201	26.2
8	225	23.4
9	248	21.2
10	270	19.5
PI	5.4	
PI meas	5.46	
C	0.01	μF
DAR	1.33	

25	Bar no	334
Date	2017/02/06	Failed 50 kV
Temp	24.7°C	
Hum	58.10%	
Min	R (GΩ)	I (nA)
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
PI		
PI meas		
C		μF
DAR		

28	Bar no	274
Date	2017/02/04	
Temp	28.3 °C	
Hum	48.30%	
Min	R (GΩ)	I (nA)
1	53.9	97.7
2	69	76
3	77.2	68.1
4	83.7	62.9
5	88.9	59.3
6	92.7	57
7	96.7	54.4
8	101	52.1
9	105	50.1
10	107	49
PI	1.99	
PI meas	2.01	
C	0.01	μF
DAR	1.23	

30	Bar no	285
Date	2017/02/07	
Temp	25.3 °C	
Hum	64.60%	
Min	R (GΩ)	I (nA)
1	70.9	74.2
2	120	43.7
3	164	32.2
4	203	26
5	277	19
6	312	16.9
7	335	15.8
8	352	14.9
9	384	13.7
10	414	12.7
PI	5.84	
PI meas	5.92	
C	0.01	μF
DAR	1.42	

33	Bar no	305
Date	2017/02/06	
Temp	24 °C	
Hum	60.50%	
Min	R (GΩ)	I (nA)
1	41.4	127
2	60.3	87.4
3	74.9	76.1
4	70.5	74.1
5	72.7	72.4
6	75.9	69
7	79.2	66.4
8	81.5	64.9
9	84.4	62.6
10	86.3	60.9
PI	2.08	
PI meas	2.1	
C	0.01	μF
DAR	1.31	

34	Bar no	316
Date	2017/02/03	
Temp	26.1 °C	
Hum	51.10%	
Min	R (GΩ)	I (nA)
1	86.5	60.8
2	149	35.3
3	197	26.7
4	233	22.5
5	267	19.7
6	304	17.3
7	329	16
8	331	15.9
9	391	13.5
10	413	12.7
PI	4.77	
PI meas	4.84	
C	0.01	μF
DAR	1.51	

37	Bar no	263
Date	2017/02/07	
Temp	25.3 °C	
Hum	64.60%	
Min	R (GΩ)	I (nA)
1	67	78.5
2	111	47.5
3	139	37.8
4	167	31.6
5	181	29
6	191	27.8
7	196	27.5
8	200	26.3
9	214	24.5
10	219	24
PI	3.27	
PI meas	3.31	
C	0.01	μF
DAR	1.45	

39	Bar no	266
Date	2017/02/06	
Temp	24 °C	
Hum	60.50%	
Min	R (GΩ)	I (nA)
1	97.7	53.9
2	164	32.1
3	214	24.6
4	255	20.6
5	290	18.1
6	324	16.6
7	344	15.3
8	362	14.5
9	389	13.5
10	419	12.5
PI	4.29	
PI meas	4.36	
C	0.01	μF
DAR	1.49	

40	Bar no	230
Date	2017/02/06	
Temp	24 °C	
Hum	60.50%	
Min	R (GΩ)	I (nA)
1	69.2	76
2	114	46
3	150	35
4	181	29
5	210	25
6	239	22
7	261	19.9
8	291	18.1
9	313	16.8
10	338	15.6
PI	4.88	
PI meas	4.95	
C	0.01	μF
DAR	1.47	

41	Bar no	353
Date	2017/02/06	
Temp	24.9 °C	
Hum	60.50%	
Min	R (GΩ)	I (nA)
1	45.1	116
2	76	69.2
3	105	50
4	132	39.7
5	158	33.2
6	181	29.1
7	203	25.9
8	219	24
9	237	22.2
10	251	21
PI	5.57	
PI meas	5.63	
C	0.01	μF
DAR	1.4	

42	Bar no	354
Date	2017/02/06	
Temp	24.9 °C	
Hum	60.50%	
Min	R (GΩ)	I (nA)
1	19.2	271
2	29.9	176
3	36.5	144
4	41.2	128
5	45.1	116
6	47.9	110
7	50.8	104
8	52.7	99.5
9	53.8	95.8
10	55.8	94.3
PI	2.91	
PI meas	2.91	
C	0.03	μF
DAR	1.39	

43	Bar no	356
Date	2017/02/06	
Temp	24.9 °C	
Hum	60.50%	
Min	R (GΩ)	I (nA)
1	78	64.5
2	143	36.7
3	196	26.8
4	244	21.8
5	286	18.4
6	325	17.1
7	364	14.3
8	400	13
9	429	12.2
10	465	11.3
PI	5.96	
PI meas	6.05	
C	0.01	μF
DAR	1.54	

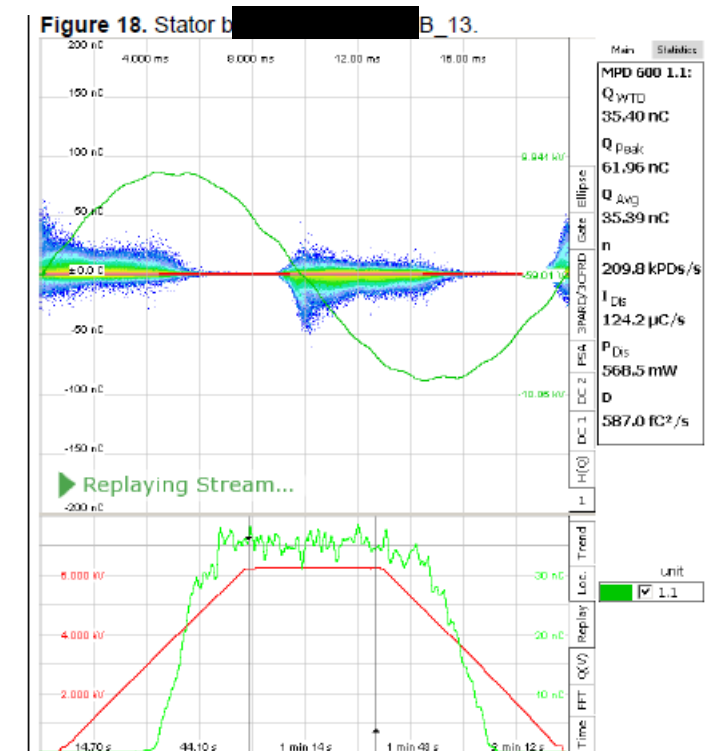
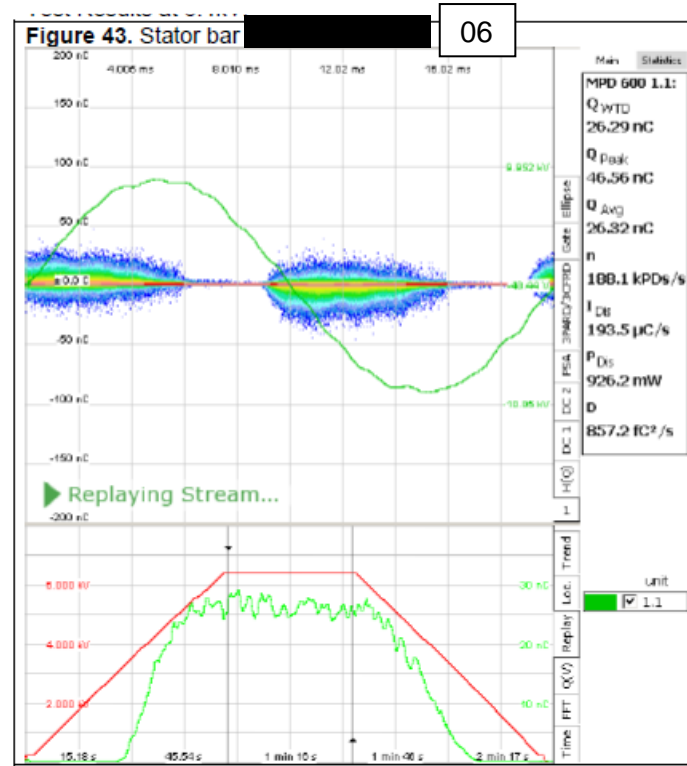
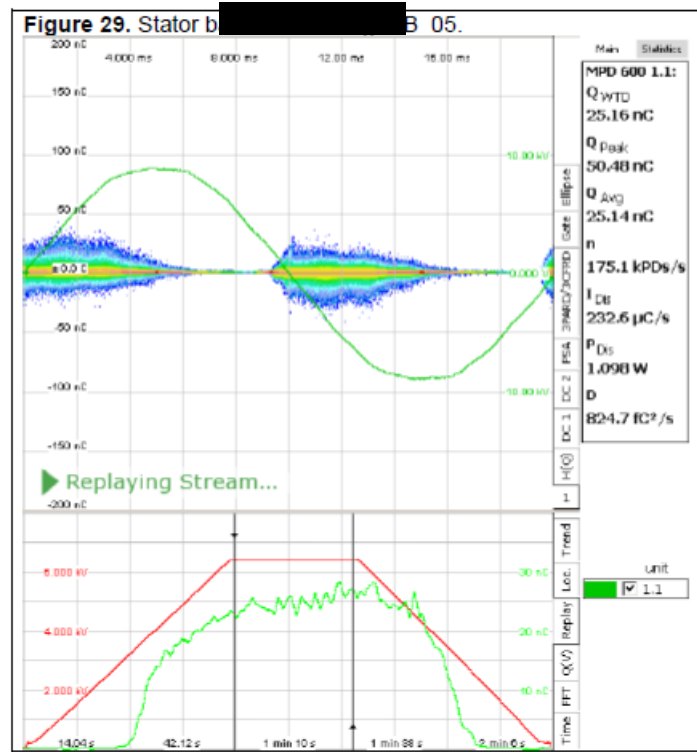
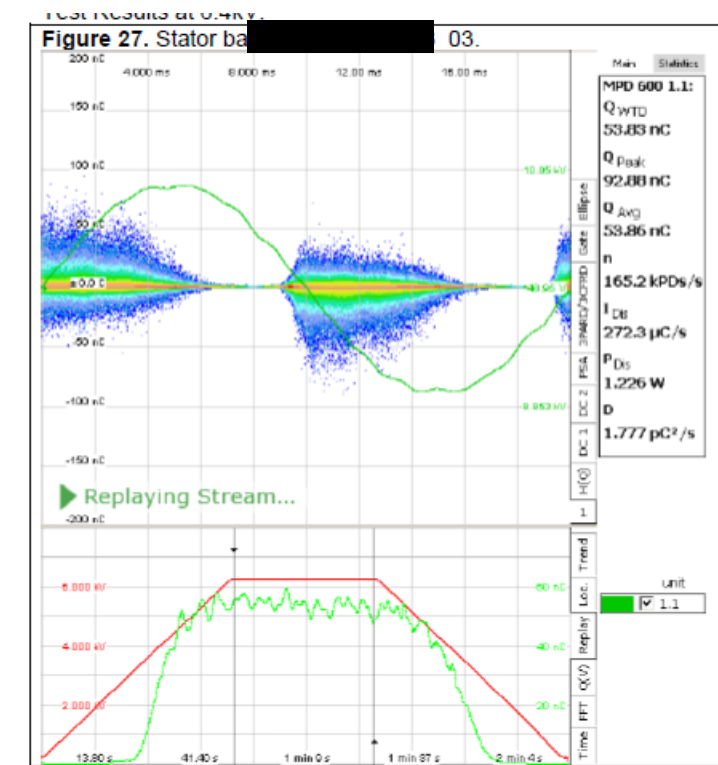
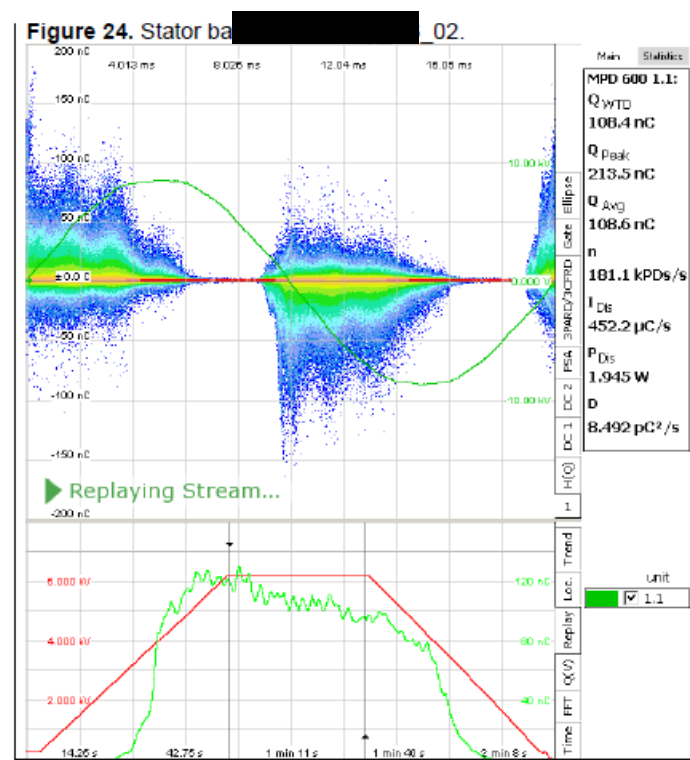
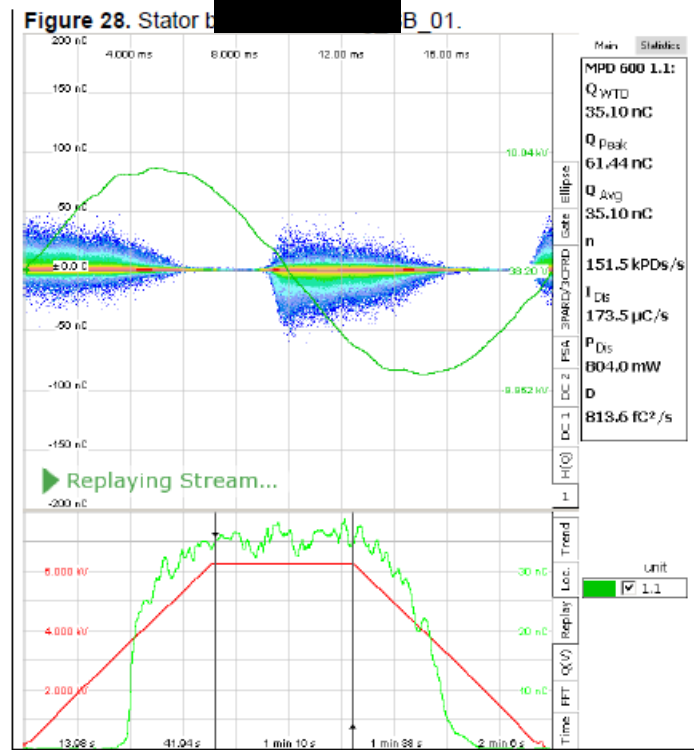
49	Bar no	335
Date	2017/02/06	
Temp	25.4 °C	
Hum	59.30%	
Min	R (GΩ)	I (nA)
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
PI		
PI meas		
C		μF
DAR		

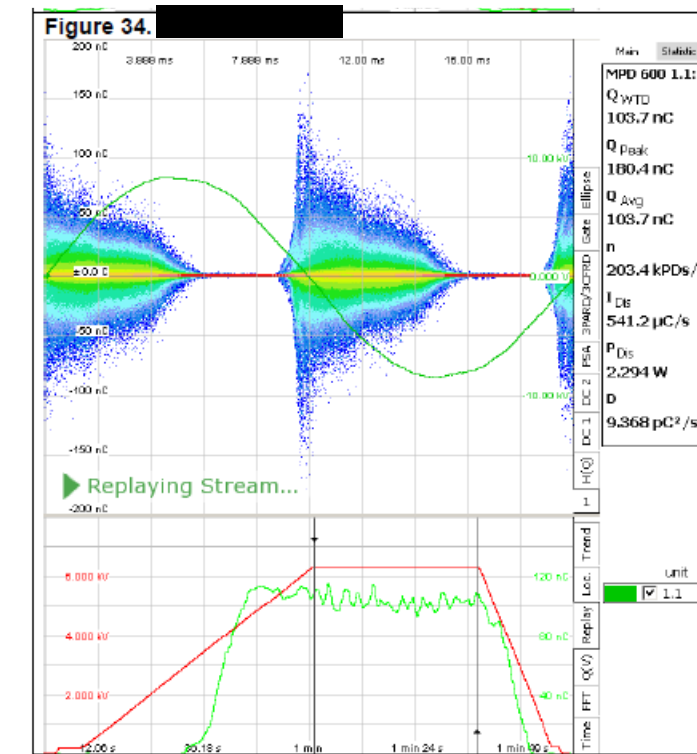
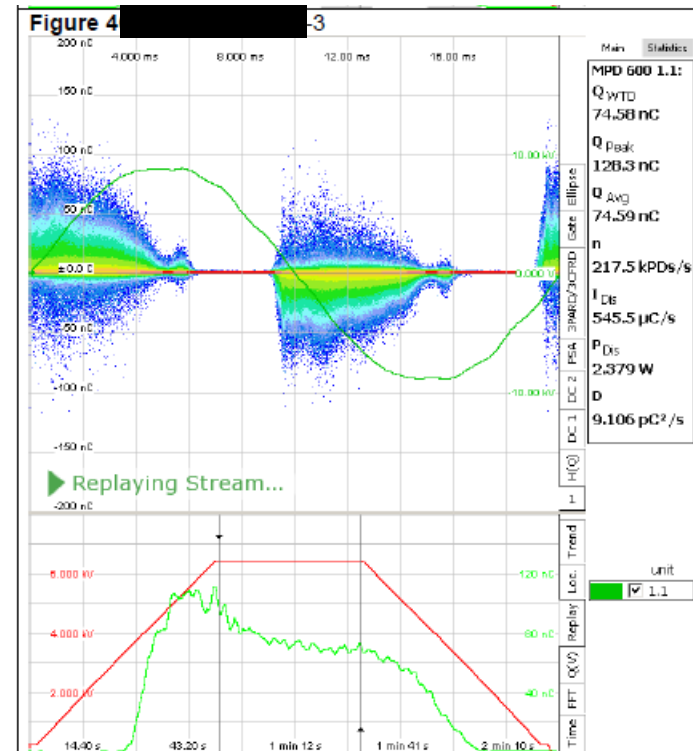
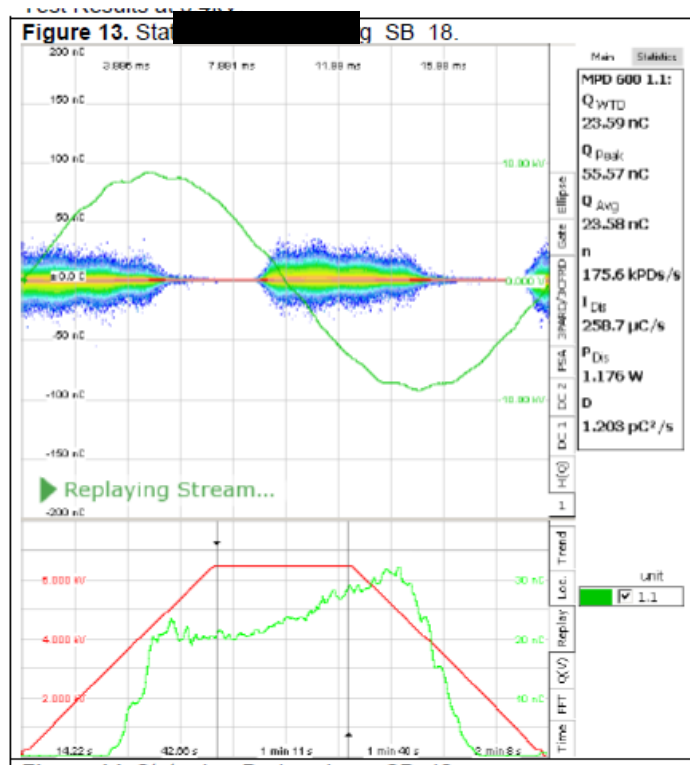
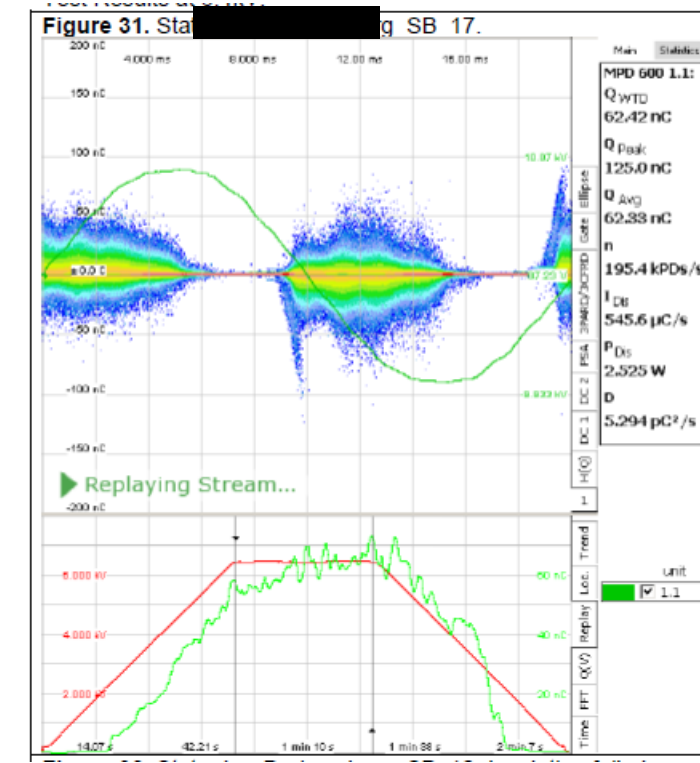
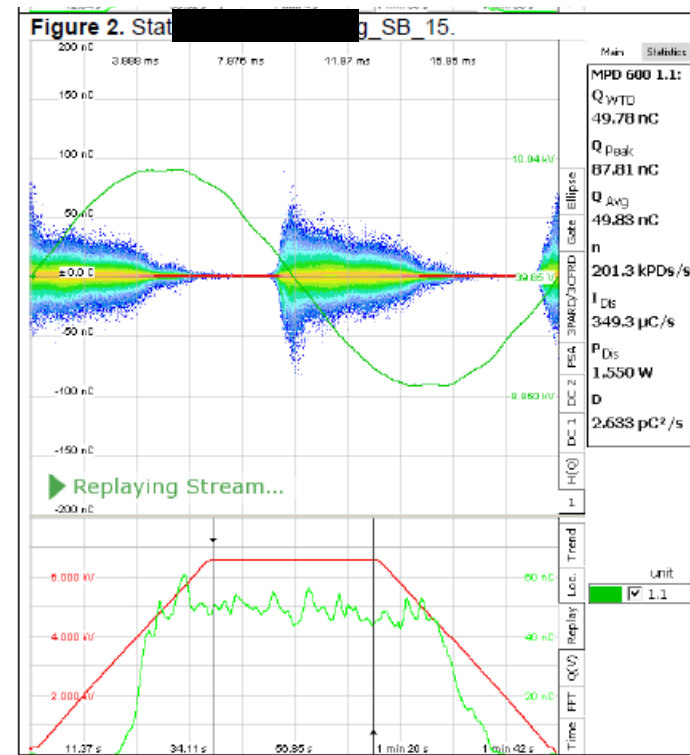
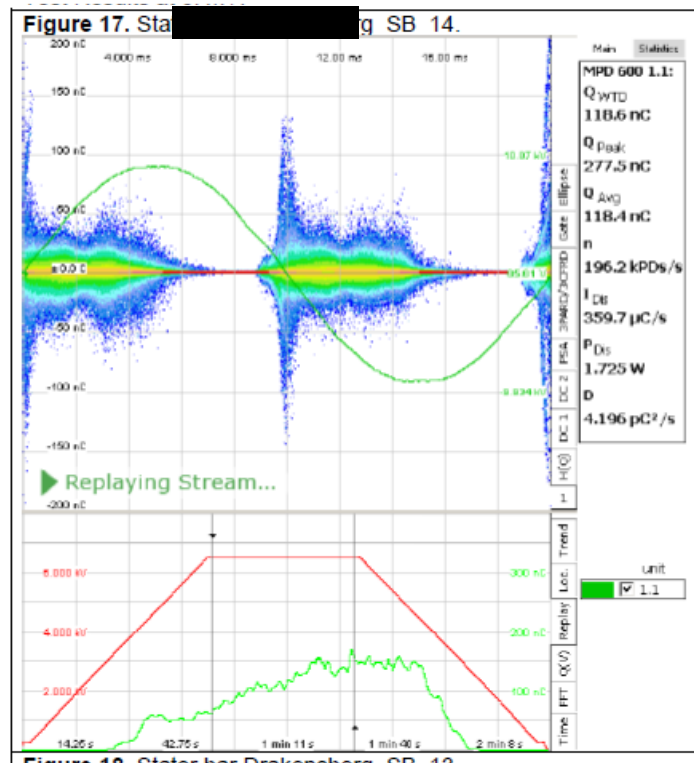
52	Bar no	264
Date	2017/02/07	
Temp	25.3°C	
Hum	64.60%	
Min	R (GΩ)	I (nA)
1	30.9	170
2	33.2	158
3	39.5	138
4	30.9	170
5	28.8	182
6	37.3	141
7	39.5	134
8	42.6	124
9	41.3	127
10	43.4	121
PI	1.4	
PI meas	1.42	
C	0.01	μF
DAR	1.2	

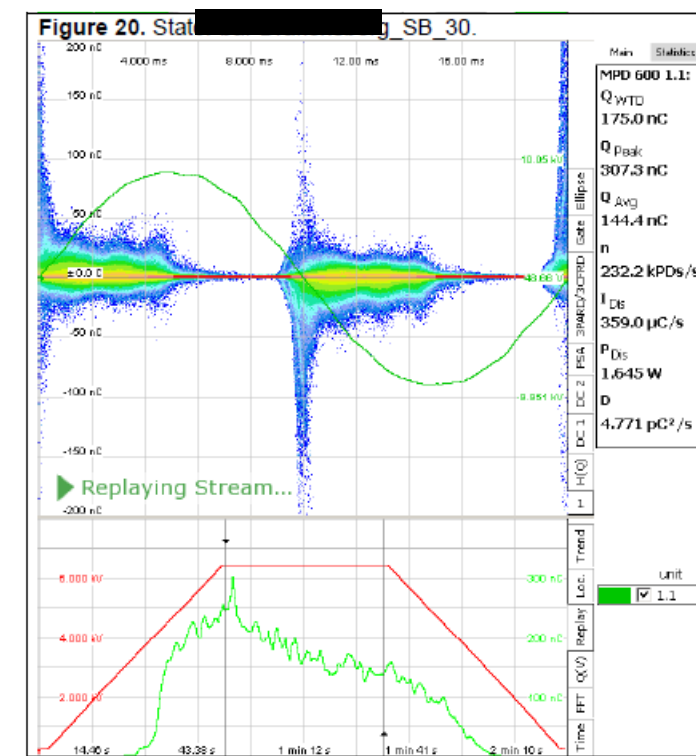
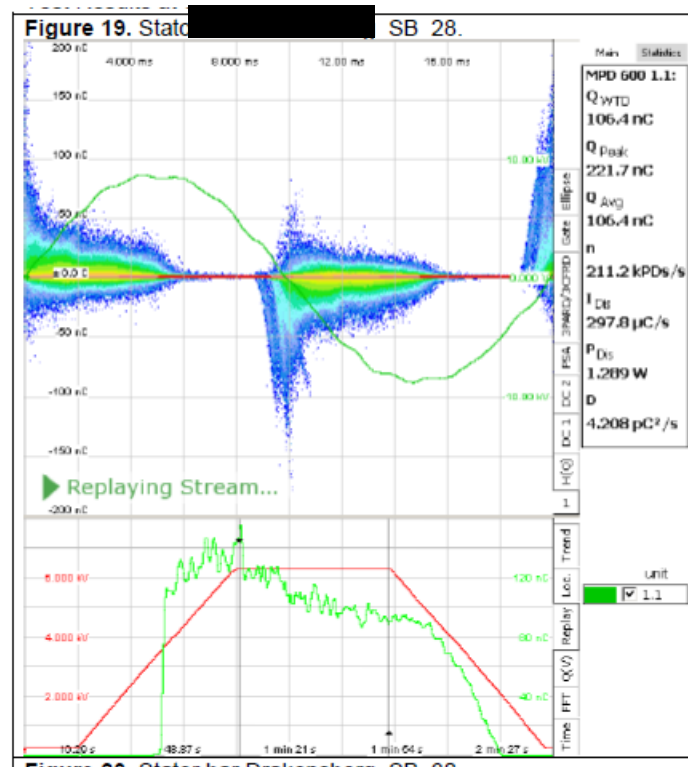
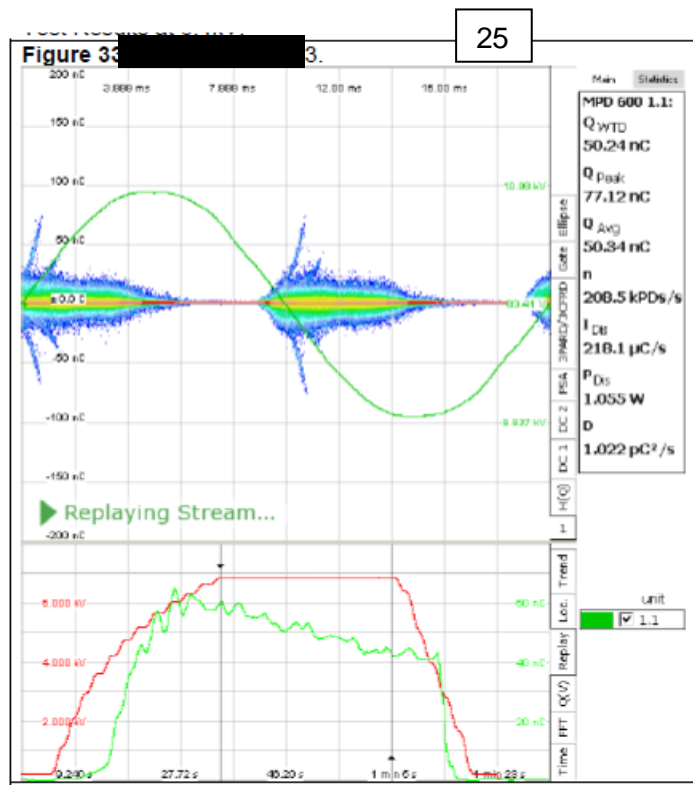
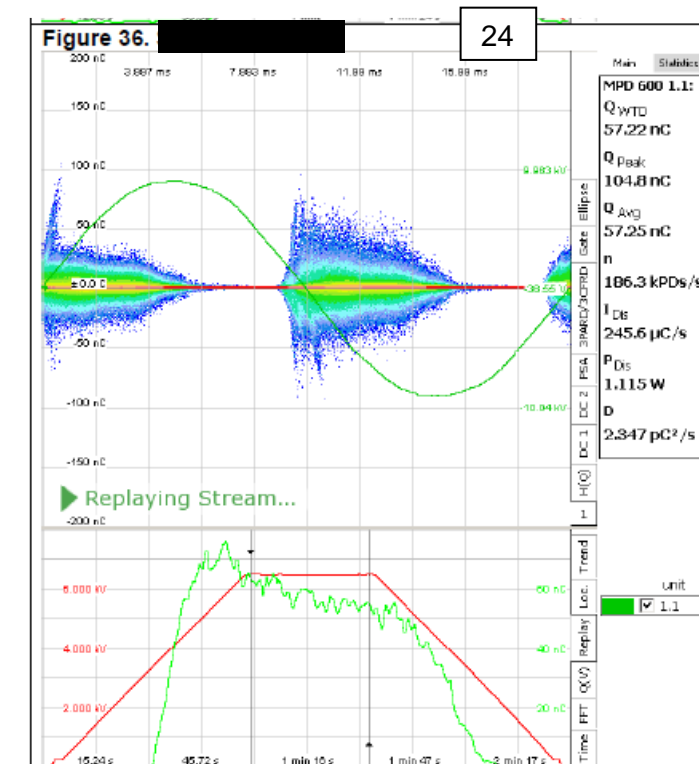
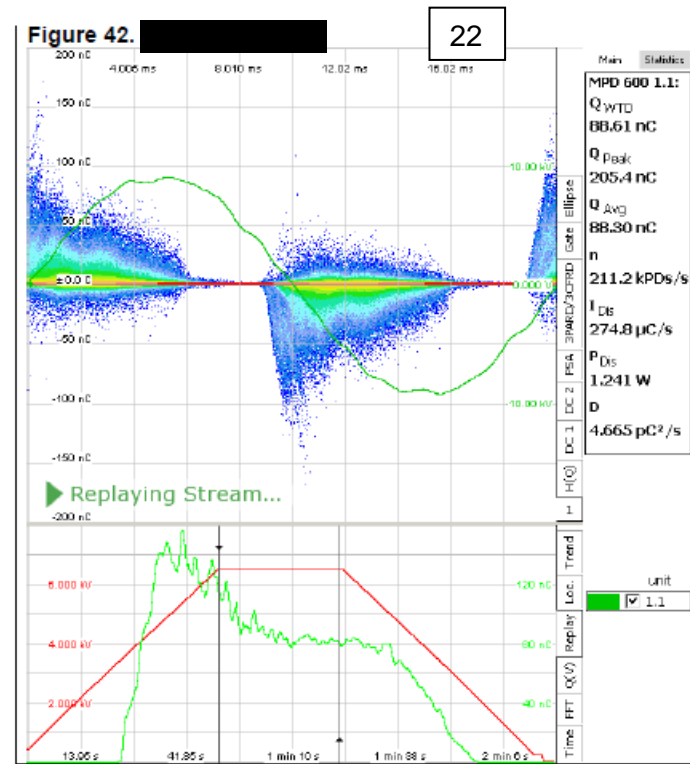
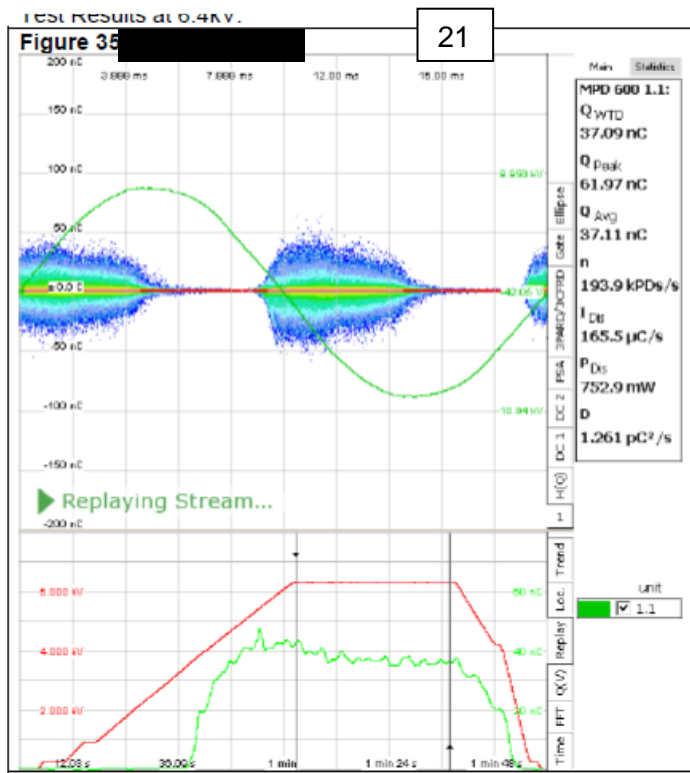
53	Bar no	261
Date	2017/02/06	
Temp	24.9°C	
Hum	60.50%	
Min	R (GΩ)	I (nA)
1	36.7	144
2	45.3	116
3	49.7	105
4	52.5	100
5	54.5	96.4
6	55.9	94
7	57	92.7
8	58.1	90.3
9	58.7	89.2
10	59.2	88.8
PI	1.61	
PI meas	1.63	
C	0.01	μF
DAR	1.21	

55	Bar no	215
Date	2017/02/04	
Temp	26.4°C	
Hum	51.70%	
Min	R (GΩ)	I (nA)
1	81.8	64.3
2	134	39.1
3	172	30.5
4	205	26.6
5	235	22.4
6	256	20.5
7	274	19.2
8	290	18.2
9	302	17.4
10	314	16.7
PI	3.84	
PI meas	3.89	
C	0.01	μF
DAR	1.46	

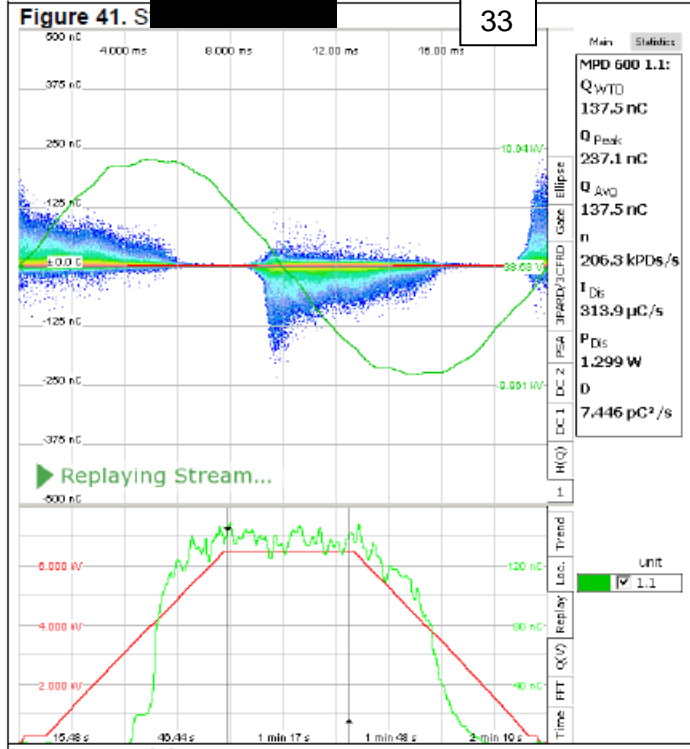
Appendix D: Phase Resolved Partial Discharge (PRPD) plots



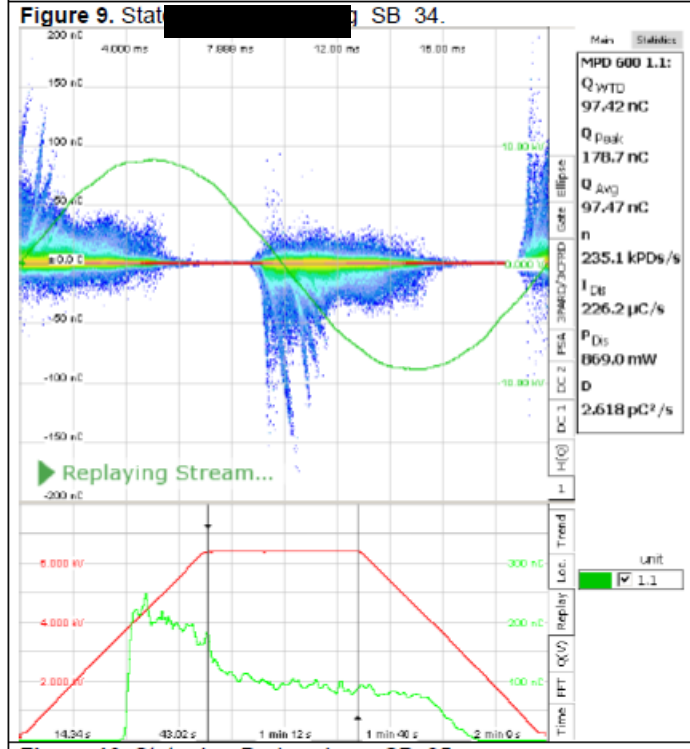




Test Results at 6.4kV



Test Results at 6.4kV



Test Results at 6.4kV

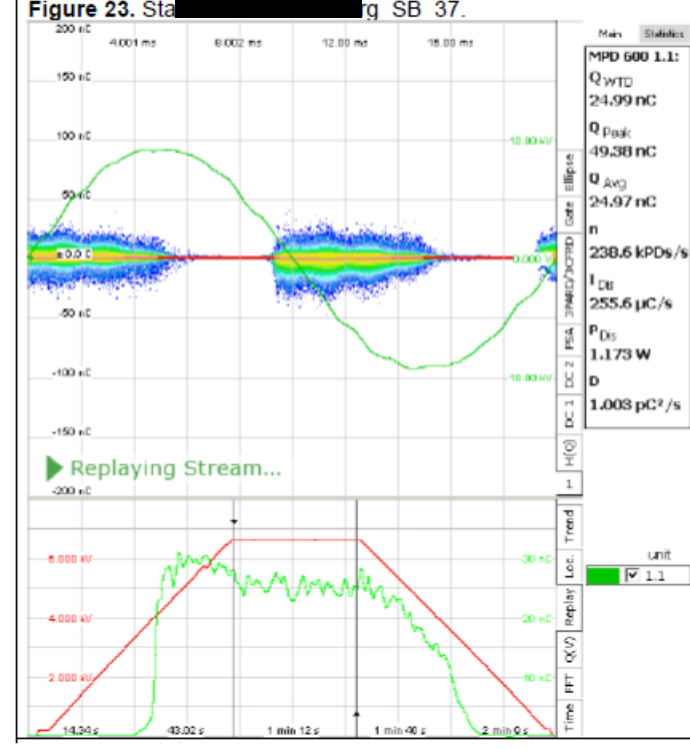


Figure 22. Stat [redacted] SB 39

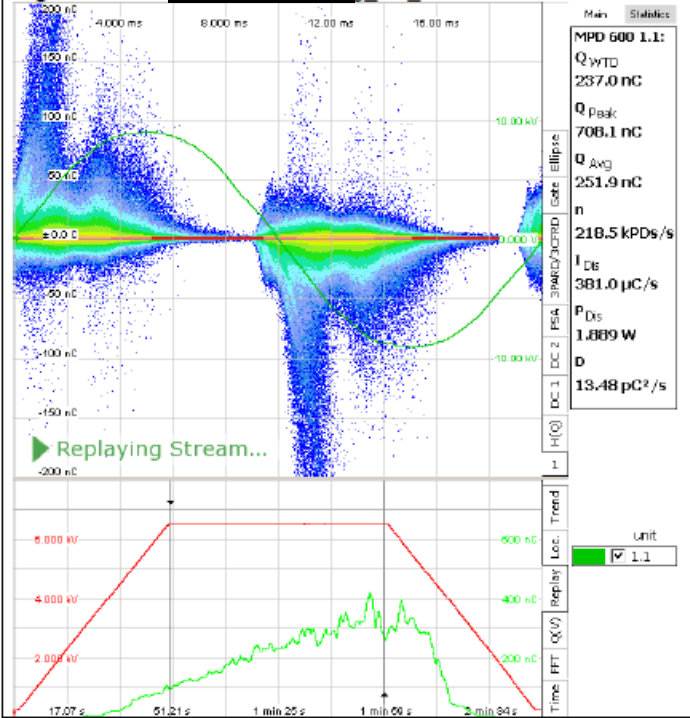


Figure 14. Stat [redacted] SB 40

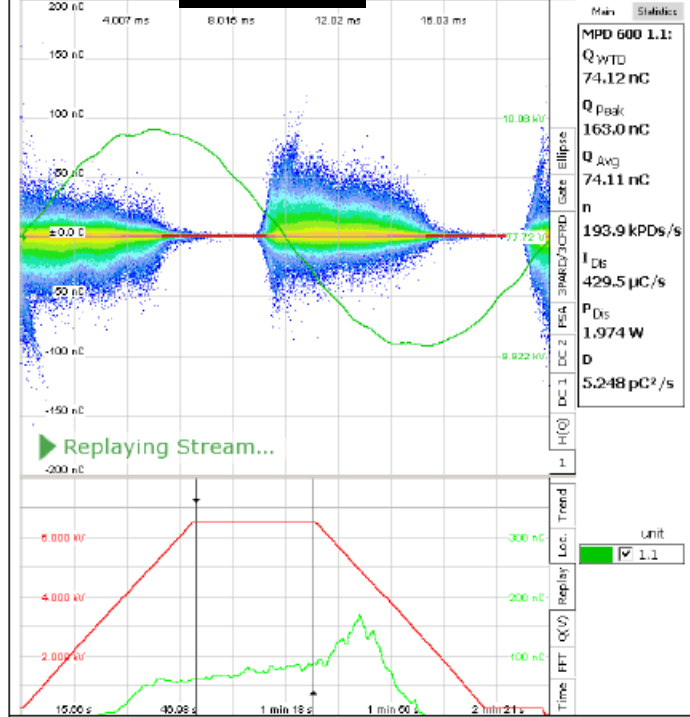


Figure 5. Stat [redacted] SB 41

