Faculdade de Engenharia da Universidade do Porto

FEUP

Application of Digital Partial Discharge and Dissipation Factor Measurements for the Diagnosis of High Voltage Generator Insulation

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VERSÃO FINAL

Dissertação realizada no âmbito do
Mestrado Integrado em Engenharia Electrotécnica e de Computadores
Major Energia

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Julho de 2008

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Resumo

Este trabalho baseia-se no estudo de dois procedimentos experimentais usados no diagnóstico do estado do isolamento dos geradores de alta tensão. As medições de Descargas Parciais e do Factor de Perdas são efectuadas, não só em geradores completos, mas também em barras do estator, ambos novos ou usados.

Várias medições foram efectuadas em barras do estator novas, com o propósito de controlo de qualidade, bem como para investigação de mudanças levadas a cabo no processo de fabrico. Para além disso, a interpretação feita aos resultados obtidos é de grande interesse em termos tecnológicos e no desenvolvimento de novos metodos de produção.

A análise dos resultados foi baseada na teoria existente e, também, fazendo a comparação com outros casos apresentados. Sempre que possível, foi, também, mencionada a localização de falhas existentes nos isolamentos.

Finalmente, depois de reunidos os resultados de mais de mil barras, foi tentado encontrar uma correlação, até agora pouco explorada nesta área científica, entre o Factor de Perdas e as Descargas Parciais. Este procedimento será uma ajuda e, também, um ponto de partida para futuros desenvolvimentos neste tema.

Abstract

This work is based on the study of two different measurements procedures for the diagnosis of insulation systems of high voltage generators. The Partial Discharge and the Dissipation Factor Measurements are carried out on complete generators and stator bars either they are new or already used.

Several measurements were done in newly produced stator bars not only for the purpose of quality check but also for the investigation of changes in manufacturing processes. Thus, the interpretation of the results is of great interest in the technology and development of new methods.

The analysis of the results was done based in the theory existent and also comparing with other presented cases. Whenever it was possible it was also mentioned the location of existing failures in the insulation system.

Finally, after gathering more than a thousand tested bar results it was attempted to find a correlation, that was not yet achieved in this scientific area, between the Dissipation Factor and Partial Discharges. This will be a help and starting point for further developments in this theme.

Acknowledgements

Firstly, the writing of this dissertation was only possible with the help of my supervisor Prof. Doutor Artur Costa and I want to thank him for his guidance, expertise, belief and good humour, always needed while doing a work like this.

A special thanks goes to the members of ALSTOM Power in Wroclaw, Poland, that kindly received me in such a different atmosphere making me feel like if I was in my home country. I must also express my gratitude for the help and time offered by the Managers of Bars Production Department during my internship, essential for the development of this work.

Another person that I cannot forget, who was of great help in this dissertation, is Professor Krystian L. Chrzan, from Wroclaw University of Technology, always giving me his advices when I needed.

I want to thanks all my friends, family and to Sara for the trust and support. I was absent for many months in Poland and many hours were spent while writing this dissertation and they were the ones who missed me the most. I could not have keep moving forward without them in my mind.

Finally, I want to thank to Faculdade de Engenharia da Universidade do Porto (FEUP) for the opportunity given to write the dissertation.

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Abbreviations List

DF	Dissipation Factor
e.g.	exempli gratia
HV	High Voltage
PD	Partial Discharge
PDIV	Partial Discharge Inception Voltage
PF	Power Factor
RIV	Radio Interference Voltage Meter

Chapter 1
Introduction

1.1 Initial Considerations

The development of the theme “Application of Digital Partial Discharge and Dissipation Factor Measurements for the Diagnosis of High Voltage Stator Bar Insulation” was a decision that could not be refused in the scientific environment present in Poland, which is a very well developed country in High Voltage Engineering. The existence of a factory – ALSTOM Power – which main target is the manufacturing of stators for turbogenerators, made the choice easy to make.

On one hand, this is not a well known subject and it is developed by a restrict group of investigators and related personnel.

On the other hand, this is an actual matter of great interest not only in the electrical machines area but also in power plants production and maintenance, as well as influencing energy production.

There is a lack of studies about this topic and the development of this work came in the line to provide more information about it. During the initial research to get to know the theme, it was understandable that there was almost anything written by Portuguese researchers about it. This fact just made this subject even more appealing.

1.2 General Context

As it is known, generators are the main basis of the energy chain production. It is an apparatus used to convert mechanical or chemical energy or any other form of energy into electrical energy.

The reliable manufacture and production of generators for power plants are well anchored in the quality control and maintenance. Nevertheless, in order to find the best maintenance plan for a specific machine it is essential to be aware of its weak points.

The causes for a generator breakdown can be divided in three big groups – Fig.1.1: the bearing related problems, the rotor related problems and, finally, the stator related problems.

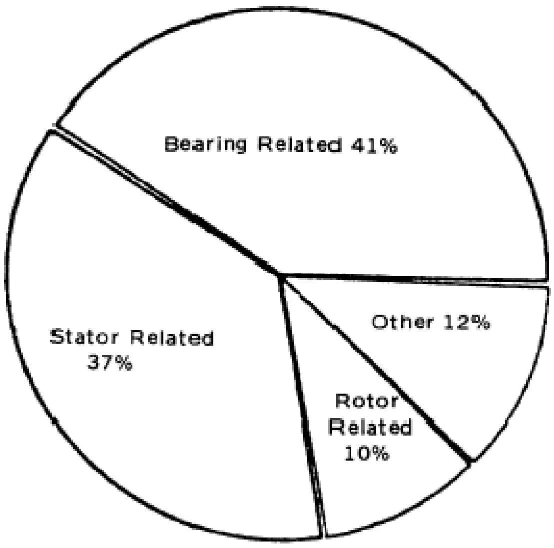


Fig.1.1 – percentage of failure of the generator by component [1]

PERCENTAGE FAILURE BY COMPONENT

Bearing related	
Sleeve bearings	16
Antifriction bearings	8
Seals	6
Thrust bearing	5
Oil leakage	3
Other	3
Total	41
Stator related	
Ground insulation	23
Turn insulation	4
Bracing	3
Wedges	1
Frame	1
Core	1
Other	4
Total	37
Rotor related	
Cage	5
Shaft	2
Core	1
Other	2
Total	10

Fig.1.2 – percentage of failure of generators by component [1]

Studies accomplished by IEEE [1] show that 37% of the collapses in generators are caused by stator related problems. Among this group, the ground insulation failure reaches 23% of the possible occurrences while the turn insulation can reach 4%, in a total of 27% of failure mechanisms due to insulation problems – Fig.1.2.

This value is still considerably high and it shows that manufacturers and customers of generators must give special attention to it.

When a generator collapses there are three primary costs associated [2]. First there is the *repair cost* which frequently involves a complete rewind. The *in-and-out cost* is related with the electrical disconnection of the generator, the removal of the damaged parts and the transportation to the repair facility. Finally, there is the *loss of production cost* which can easily be the highest of the three. It represents the outage time the generator must be disconnected from the network. In this case, it will not be possible to produce electrical energy as well as to supply it to the consumers and the effective cost of this operation can be also calculated and is considered a loss.

Processes to produce the insulation systems are, in this case, of great relevance so as to minimize defects and, eventually, preventing cost expenditure associated to generator's failure.

For these reasons, tests to prove insulation quality cannot be neglected. In order to describe the state of any insulation there are key parameters such as the *dissipation factor (DF)* together with *insulation resistance*, *dielectric strength and partial discharge (PD) levels*.

Since high dielectric losses can result in thermal breakdown of the material at relatively low voltage, DF measurements performed during production process are indispensable for quality control.

However, not only during production are these tests essential. DF associated with PD measurements can be a powerful tool to detect failures on reasonable time, their locations and to predict the effect of ageing phenomena. This gives the chance to the owners of the generators to control and forecast an acting plan when they consider more appropriate.

1.3 Objectives

This work was developed with the following objectives insight:

- Identifying testing procedures for the diagnosis of HV stator bar insulation.
- Defining distinctive quality parameters and requirements for such diagnosis.
- Identifying typical patterns of insulation failures in stator bars.
- Interpretation of patterns and presenting possible location and cause of such defect.

- Development of a possible relationship between Partial Discharge Measurements and Dissipation Factor Measurements for future advance in the state-of-the-art.

1.4 Dissertation structure

Initially, in chapter 2, it will be presented the actual state-of-the-art related with the subject in study. In order to understand the results and conclusions achieved, in chapter 3, it will be shortly introduced the theoretical part concerning the definition and interpretation of PD and DF measurements, types and sources of defects in insulation and possible measuring methods. Chapter 4 describes the procedures carried out to proper develop the measurements in terms of setup configuration and data collecting. In chapter 5, it is exposed the accomplished results as well as their possible interpretation. Finally, in chapter 6 it is presented the conclusions retained from the elaboration of the proposed work.

Chapter 2
State of the art

2.1 Partial Discharge Measurements

Partial Discharge measurements and location increasing interest gained relevance in the decade of 1940 and, for over than forty years, the phenomena were studied with little changes in the work achieved [3].

The basic techniques and apparatus used then did not allow the recording of results and the research was mainly conducted by organizations directly interested in the subject, such as universities and laboratories mostly owned by electrical product manufacturers.

In the early years of PD studies, the simple techniques used were basically the visual observation of “corona glow” in a dark room, complemented by the shooting of photos for further analysis and the use of altered portable radios with antennae for detection of external generated PD and corona.

Some years later, some studies of PD in various materials, such as gas-filled cavities in oil-impregnated paper insulation, were also carried out [4], followed by others in HV apparatus [5], dielectric materials [6] and turbine generator insulation systems [7].

With the rising interest of this subject within electric components manufacturers, among others, more researches were made in different sorts of situations. However, the measure and record of results in large scale was given more importance than to the interpretation of the results achieved.

The earliest interpretations with the objective of locating PDs dated 1949 and were carried out using ultrasonic detectors, X-rays to induce PDs and ultrasonic vector PD location.

Moreover, the first investigations regarding the interpretation of results stated that PDs were affected by cavity size and shape, temperature, pressure and electrical stresses. Later, other methods of analyzing PDs were studied, among them the analysis of PD amplitude, in 1968, by Kanoun [8].

One of the big advances in the PDs measuring system was presented by Austin and James, in 1976, with the online digital computer system [9].

Before that, the test equipments were basic and limited to oscilloscopes with restricted bandwidth, while all the other complementary apparatus had to be specifically designed to meet the testing requirements.

With the advance of the tests and apparatus, standards had to be implemented by manufacturers for routine measurements and test procedures.

Afterwards, new instruments were developed, such as the Radio Interference Voltage Meter (RIV), which, connected with an antenna available with an analog meter scaled in dB and μV, could give the possibility of listening to the sound pattern of radio interferences. The radio noise voltage, which appeared on conductors of electric equipment, was measured using this equipment as a two-terminal voltmeter in accordance with specified methods [10].

Although this instrument is still used, it has limitations due to high frequency interferences, and that led to the development of another low frequency detector. This had limited bandwidth and was independent to the high frequency attenuation of the tested apparatus and high frequency of the resonance of the test circuit configuration. As a result, this equipment was widely commercialized with the inclusion of an oscilloscope display.

For the expansion of this subject, the contribution of committees and seminars gathering specialists and researchers on this area was essential. Relationships between factors were found, for instance, the relation between RIV in μV and PD in pC [11] and the response of PD phenomena to impulses [12].

Recently, partial discharge analyzers were developed capable of reading and recording all sorts of data, from PD magnitude to the Normalized Quantity Number. As an example, one of the most commonly used detectors is the Haefely TE-571 [13] , released in 1994, and not only was considered one the most successful instruments in research and development applications but also proved to be universal, forcing the PD community to embrace digital instrumentation.

The above mentioned equipment's main goal is to detect and record the quantities, leaving the interpretation matter to human discretion. However, means of automatic analysis after measurement are already being developed [14]. In this area it is worth to mention the commercialized fingerprint technique TEAS diagnosis [15] [16].

Simultaneously to all the improvement made in terms of standards and equipments, the growth of tests within generators was developed based on on-site measurements [17]. Most of these tests were performed off-line with the machine forced to an outage time.

Nowadays, the most recent advances in technology allow the on-line and continuous monitoring of the various parameters related with the state of the machine insulation system with the benefit of not having to disconnect it from the network. These on-line methods [18] [19] are spreading and, along with the automatic pattern evaluation, are considered to be the future of the Partial Discharges Measurements.

2.2 Dissipation Factor Measurements

The first effort to acquire data in a non-destructive way from HV dissipation factor tests is dated 1920. Harald Schering, at that time working in the Physikalische Technische Reichsanstalt in Berlin, published his idea of a bridge for measuring capacitance and dissipation factor [20] [21]. Furthermore, European developments in this subject were able to provide the earliest published results in this area.

In the subsequent years, Schering bridges were built for DF measurements but also modified to obtain accurate ratio and phase angle measurements on instrument transformers.

At the same time, ten year old windings subjected to different operating voltage levels were tested by Siemer in an unsuccessful attempt to perform a non-destructive test to verify the state of the winding insulation - [22] referred by [21].

Relationship between volume of internal air-filled voids and the shape of the curve dissipation factor versus the increasing of electric field strength was developed by Meyer, but one of the most extensive investigations was performed by Edwin – [23] [24] referred by [21]. He tried to find, without practical success, a correlation between air volume, determined from dissipation factor, and the machine experience.

Edwin and Zwicknagl [25] found out that dissipation factor tip-up of insulation do not predict insulation performance in machines.

In 1941, the Edison Electric Institute reported a study which conclusions stated that dissipation factor data were of little value for locating faults in insulation systems, but might be useful to indicate a trend.

Studies were made on insulations with several years of service and examined in terms of dissipation factor test. Nevertheless, the acceptance of a good correlation between dissipation factor tip-up and visual examination only came with Findlay - [26] referred by [21].

In 1978, Johnston and Gjaja [21] concluded that the absolute level of dissipation factor tip-up depends on the kind of insulation system tested, and it does not correlate with service performance of insulation systems.

In spite of the theoretical advances described previously, the technology of the testing equipments was also developed. Some years later, after the Schering bridge presentation, Blumlein patented his own bridge design, which incorporated two coils and was considered the forerunner of the ratio arm bridge concept [20].

Over the next two decades, work focused on improvements of the circuits using solid state components and operational amplifiers were carried on. However, only in the early 1980 decade the fully automatic bridges became commercially available and economically attractive, with the incorporation of the microprocessors.

Finally, the relationship between Dissipation Factor and Partial Discharges Measurement can be one of the relevant advances in this area. Despite of the fact that these two measurements are independent of each other, they are coupled by their relationship between partial discharge and stator bar dielectric loss [26]. There was never established a consensual relation based on research and the theme is not well developed. Still, a rough relationship between PD and DF tip-up is established in papers written by F. T. Emery [26] with some possible interpretations of those results but further work must be developed to accomplish visible results.

Chapter 3
Theoretical Part

3.1 Generic Description of Partial Discharges

Partial discharge and his background have been studied for the last 120 years and, over the last 50 years, the effect of localized gas breakdown on the performance of solid insulating gained even more relevance. The general definition commonly used is given by the International Standard of the IEC (International Electrotechnical Commission) referred by [27]:

"Partial discharge is a localized electrical discharge that only partially bridges the insulation between conductors and which may or may not occur adjacent to a conductor".

Moreover, it is said: "Partial discharges are in general a consequence of local electrical stress concentrations in the insulation or on the surface of the insulation. Usually, such discharges appear as pulses of duration of much less than 1 µs".

Thus, PDs are often found in failure of the insulation of electrical materials and bridging electrodes in which the voltage is applied. This phenomenon can consist in different types of discharges:

- Internal discharges – in voids or cavities inside of dielectrics (liquids or solids)
- Surface discharges – on the borders of different insulation materials
- Corona discharges – on gaseous dielectrics when submitted to non-homogeneous fields
- Discharge channels – due to continuous discharges in solid dielectrics

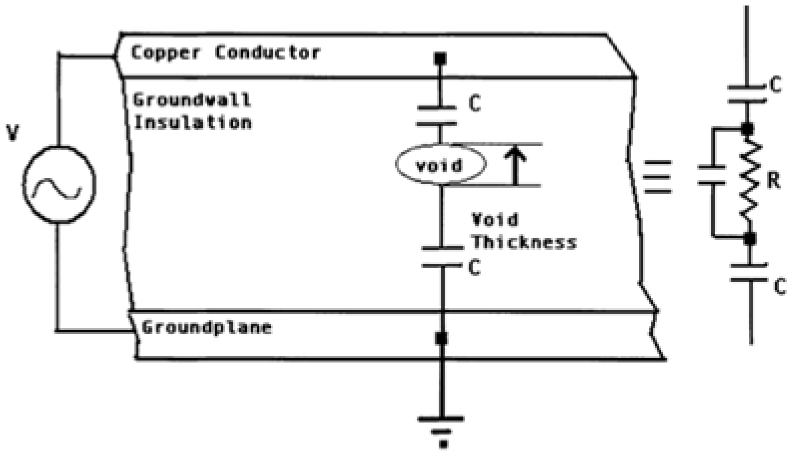


Fig.3.1 – stator bar void and its equivalent electrical circuit [27]

Fig.3.1 represents a void that is one of the possible situations for the occurrence of internal discharges. For this, the gap must exist with a certain minimum size and a voltage stress passing the void must be present. The void can be modulated as a resistance in parallel with a capacitance, as represented in the circuit on the right. These values of resistance and capacitance vary due to the size and the shape of the void changing the total capacitance of the insulation and also the losses.

Partial discharges cause deterioration of the material as a result of the impact of high energy electrons or accelerated ions leading to different chemical changes.

3.2 Dissipation Factor and Power Factor

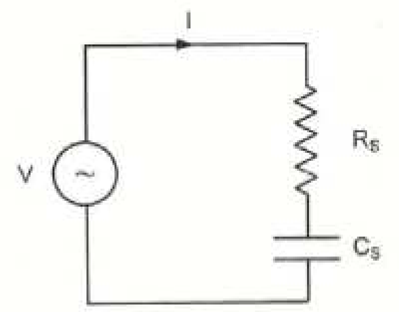
By definition, the Dissipation Factor is [29] the tangent of the loss angle δ or the cotangent of the phase angle θ between the vectors of the total circuit impedance with the cell capacitive reactance. For values less than 0.1, power factor and dissipation factor are essentially equal. It is also known as *dissipation angle* and more commonly named *tan delta*.

The physical phenomenon behind the expression happens when electrical insulation materials convert energy, even in small amount, into heat, causing dissipation of electrical energy while stressed by an electrical AC field [20].

The DF is an important data for the characterization of an insulation system. It provides information about the quality of insulation, his original dielectric losses and his general condition. When measured at low voltage, can be a valuable contribution for the knowledge of the insulation curing state and its degree of cleanliness.

The ideal insulation is a high voltage capacitance, and one with high quality should present a very low value for this factor. The best case would be a lossless capacitance and, in this case, the value of the factor would be zero. Obviously, this cannot be achieved, though seeking for the lowest dielectric loss stator bar is the aim of the manufacturers.

Furthermore, in association with the measurement of PD, this can be a powerful tool to acknowledge the status of an insulation system either if it is a new or an old one. The importance of this relationship, if it can be found, is known, although there is still lack of information and research which can give a precise and scientific conclusion. For the understanding of the Dissipation Factor, the equivalent series circuit of the stator bar insulation system must be kept in mind – Fig.3.2.1.



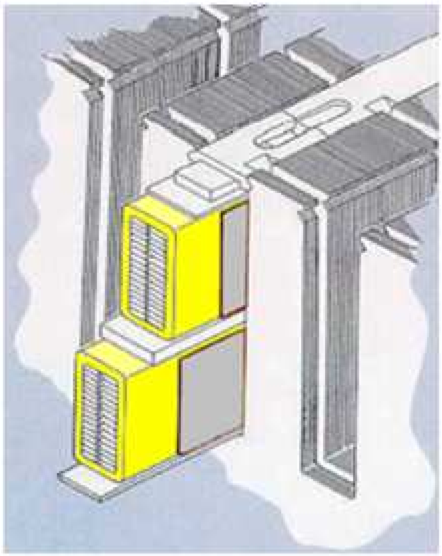


Fig.3.2 – series equivalent electric circuit of the stator bar insulation system and longitudinal view of bottom and top layer stator bars [30]

The capacitor consists of the HV stator bar with the copper and the outer ground electrode, forming the two plates of the capacitor, separated by the groundwall insulation, which constitutes the dielectric [27].

In Fig.3.2 there are the circuit components and R_s represents the dielectric loss in the stator bar groundwall insulation as a series resistor while C_s represents the stator bar cell insulation as a series lossless capacitor.

The phase angle δ is the one made between the vectors of the total circuit impedance with the cell capacitive reactance.

The dissipation factor is the tan δ and, for small angles, this factor is equal to the angle δ – Fig.3.3.

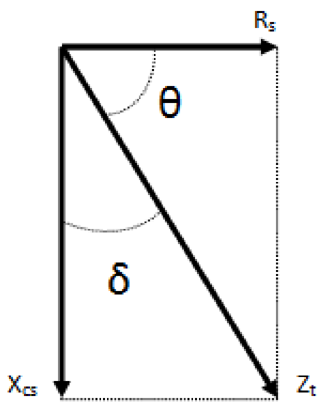


Fig.3.3 – series circuit impedance vector diagram for equivalent electrical circuit

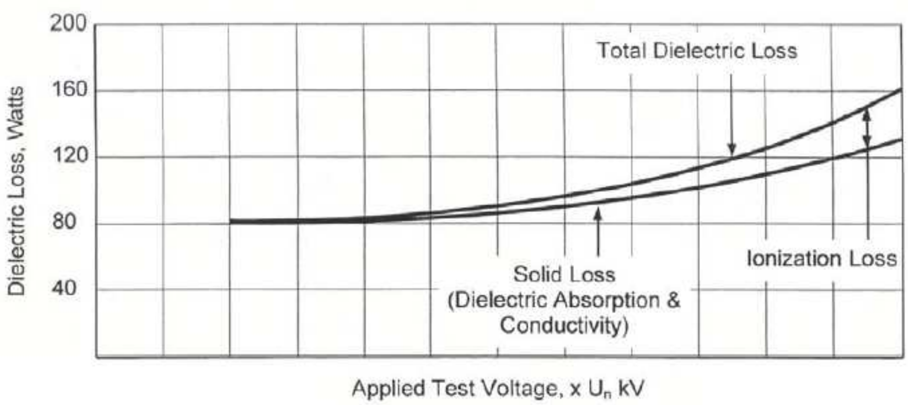


Fig.3.4 – dielectric loss [29]

The total dielectric loss is [29] a sum of two components which are the *dielectric absorption and conductivity* and the *ionization loss* – Fig.3.4.

The angle will be smaller with the diminution of the total dielectric loss represented by R_s. For the optimal case with no dielectric losses, R_s would be equal to zero and the angle δ would be also zero.

From the diagram in Fig.3.3, the relation between X_{cs} and R_s gives *tan δ* as shown below:

$$DF = \tan\delta = \frac{R_s}{X_{cs}} \tag{3.1}$$

with
$$X_{cs} = \frac{1}{\omega.C_s} \tag{3.2}$$

comes
$$\tan\delta = \frac{R_s}{\frac{1}{\omega.C_s}} = 2\pi f.C_s.R_s \tag{3.3}$$

with ω as the angular frequency and f as the frequency.

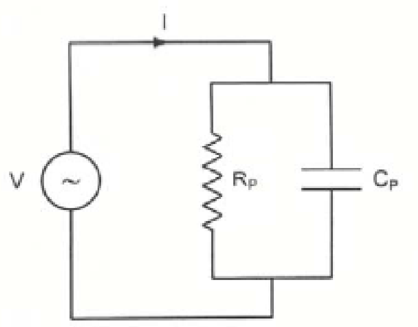


Fig.3.5 - parallel equivalent electric circuit of the stator bar insulation system

The same results could be found using the equivalent parallel circuit – Fig.3.5 – and the dissipation factor would have the following equation:

$$\tan\delta = \frac{1}{\omega.C_p.R_p} \tag{3.4}$$

with R_p representing the dielectric loss in the stator bar groundwall insulation as a parallel resistor and C_p representing the stator bar cell insulation as a parallel lossless capacitor.

Like the DF there is another term almost with the same value, used as measure of dielectric loss, which is the power factor, PF. The proper relationship between both is the following [21]:

$$PF = \cos\theta = \frac{DF}{\sqrt{1+(DF)^2}} \tag{3.5}$$

Although most of the measurements give directly the DF, the PF is more appropriated to describe losses when concerning to circuits in general.

3.1 Dissipation Factor Tip-Up and Power Factor Tip-Up

The definition of DF Tip-Up is the [29] “increment in the dielectric dissipation factor, tan delta, of the insulation measured at two designated voltages” or in a simpler way “it is used to describe the increase of dissipation factor with an increase of applied voltage” [21].

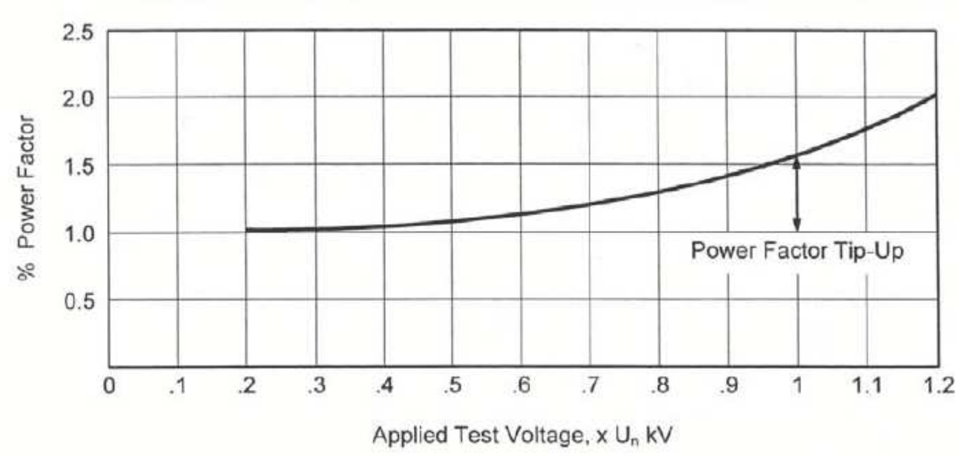


Fig.3.6 – Power Factor and Power Factor Tip-Up [29]

Both of these related factors are values which are sensitive to the amount of voids present within the insulation system [31]. In that matter, the quality of the processes leading to his manufacture and also the impregnation process are reflected on them.

Whenever a PD happens in the insulation, it absorbs energy that must be supplied by a power source - Fig.3.6. This dissipated energy [10] can be measured making possible to acknowledge the total discharge activity in the stator bars or winding and it is considered a dielectric loss.

Additionally, the dissipation factor is measured at low voltage, not allowing the manifestation of PD, and again at a higher voltage above the inception value already in the presence of PD. That increase on the dissipation factor with the increase of voltage is named DF tip-up.

3.3 Failure Mechanisms in Stator Windings

Although they are built and designed economically and to experience the longest life possible, the insulation systems are not expected to last forever. This is due to several failure mechanisms in stator windings which can be a combination of stresses such as thermal, mechanical, environmental and electrical.

During operation, the insulation breaks down or even crack under normal voltage caused by ageing, which reduces in a great way its electrical and mechanical strength. It can be also caused by an electrical transient such as lightning or switching voltage or even by a mechanical situation (e.g., faults in the power system network).

If the worst case happens, the insulation breakdown in the stator groundwall will lead to fault currents and consequently to circuit-breaker operation.

Fractures leading to mechanical failure can appear when windings are operating for long periods of time at high temperatures, making the insulation delaminate and oxide. Moreover, insulation abrasion can happen because of magnetically induced forces, which cause the winding to pressure and friction the stator core until the perforation of the insulation.

The surface of the endwinding can also become conductive because of pollution particles, and consequently small currents flow causing electrical tracking.

While operating, the machine is subjected to different values of load and these changes make the temperature vary. Such alterations in the temperature do not rise in the same way in all the different winding components. For that reason, forces and pressure are developed with greater value on one side then in the other of the components. After enough load cycles the groundwall insulation may separate from the conductors and an air gap turns out, ending in an insulation failure due to PD.

There can be several failures processes in stator windings caused by different stresses acting alone or together, but to know how long the process will take to cause a failure depends on some factors [31] as the following:

- design stress level and how much can the materials stand (e.g., operating temperatures or mechanical stresses);
- the way windings are produced and the techniques used (e.g., compression and impregnation);
- operating status of the machine (e.g., constant load value or overloading);
- external pollutants (e.g., dust, moistures, oils or other conductive particles);
- maintenance (e.g., cleaning level and tightening for vibration prevention).

Some of the most typical cases of deterioration mechanisms and their description can be shown in the following table [31].

Table 3.1 - winding deterioration mechanisms

Mechanisms	Description	Cause	Relative Speed of Deterioration
Thermal	Long-term operation at high temperatures, leading to transformation and insulation delamination	Overloading, ineffective cooling, unbalanced voltage, online-offline cycle	Slow
Load cycling	Rapid and frequent online-offline cycle leading to delamination	0% to 100% load changes in less than 15 minutes	Moderate
Poor impregnation	Voids in insulation leading to PD	Lack of penetration of mica tapes, by epoxy or polyester	Moderate
Internal water leaks	Saturation of insulation by water from cracks in hollow copper conductors	Water fittings in direct water cooled windings	Slow
Coil movement	Abrasion of insulation due to movement of coils/bars in slot	Insulation shrinkage over years, oil contamination, poor installation	Fast
Electrical slot	Partial discharge attack where semi-	Poorly made semi-conductive coating or	Slow

Mechanisms	Description	Cause	Relative Speed of Deterioration
discharge	conductive coating is missing or damaged from prolonged movement	deterioration due to abrasion of insulation	
Contamination	Surface discharges or sparking in end windings due to partly conductive pollution	Poor maintenance	Slow
Endwinding vibration	100/120 Hz vibration of coils leading to insulation abrasion, cracking	Poor design, oil contamination	Moderate
Electrical surges	Fractures of turn insulation by high voltage pulses	Voltages developed by motor switch-on or inverter-fed drives combined with poor or aged turn insulation	Slow
Inadequate spacing	Partial discharge attack of groundwall insulation	Insufficient spacing is provided between high voltage components of different phases	Slow

3.4 Sources of PD in Rotating Machines

In the generators there are several potential sources of PDs – Fig.3.7 and Fig.3.8.

The location, characteristics, behaviour and importance of PDs are firstly influenced by the generator design, materials used and the methods employed in the production chosen by the manufacturer itself. Secondly, by the owner of the machine, who determines the operating conditions and defines the maintenance given to that specific apparatus.

For instance, if voids, cavities and groundwall delamination are found in newly manufactured insulators they can present slightly different characteristics from those others found in insulators exposed to ageing phenomena and all sort stresses during operation [32].

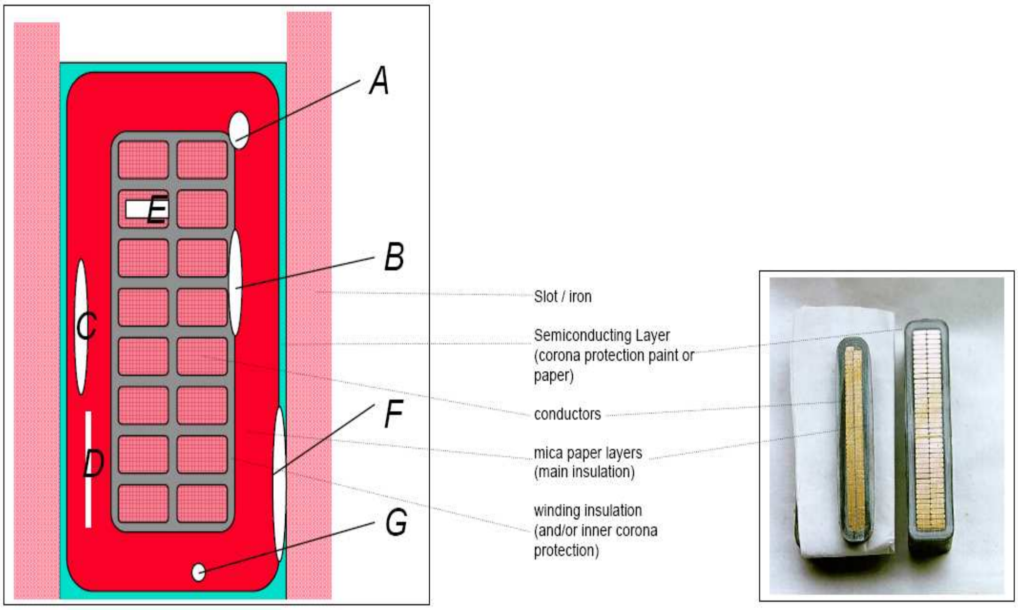


Fig.3.7 – location of internal discharges in stator bars [33]

Fig.3.7 is a transversal view of a stator bar and the letters flag the locations of internal discharges, with:

A – site of highest electric field and PD;

B – delamination in the main insulation;

C – delamination of tape layers;

D – treeing in layers;

E - broken strands;

F - semi-conductive paint abrasion.

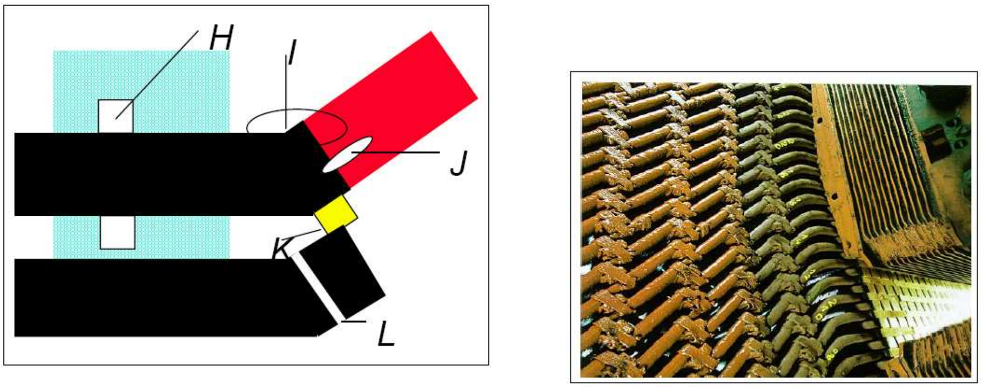


Fig.3.8 – external discharges and discharge sources in the endwinding [33]

Fig.3.8 shows a longitudinal view of a generator stator and the location of external discharges, with:

H – discharges in cooling duct;

I – delamination of insulation in the “elbow”;

J – endwinding surface discharge;

K – insufficient spacing;

L - connection area between slot corona protection and endwinding corona protection.

Until a certain amount, PD in rotating machines can be easily tolerated because it will not affect substantially the properties of the insulation. Its mica based constitution, which is intrinsically resistant to partial discharges, avoids until maximum as possible the development of discharges.

However, PD in several locations - Fig.3.7 and Fig.3.8 - can still occur and appear due to numerous factors and attack the insulation, provoking, in the worst case, its failure. By measuring it, the detection of ageing mechanisms which deteriorate insulation is possible. The sites of PD and the eventual reasons leading to them are described as follows [31]:

- ***Voids*** - A quality impregnation process is important to assure the minimum void content and size in the insulation. These voids are commonly found in resin impregnated mica tape insulation system and a certain amount of PD activity is tolerable.
- ***Delamination*** - Initially resultant from thermal overstressing these are more dangerous than voids and are found at the interface between the copper conductor and the main insulation. These not only reduce thermal conductivity, accelerating the ageing mechanism or even thermal runaway, but also can be a symptom that the strand insulation of the conductor may be seriously damaged.
- ***Slot*** - Discharges may occur as result of semi-conductive coating conditions, which can appear only when the machine starts operating or are already present since manufacture. Conditions such as discontinuities or high resistivity values in the coating can be caused also by chemical contamination. In many rotation machines, this semi-conductive surface coating is only located in the straight part of the bars. Between the stator core and the main insulation there is electric field which is minimized by the slot corona protection. The semi-conductive coating is extended over the slot exit in order to connect the electric stress grading tape in the enwinding area. Although this suppression of harmful surface discharges that can appear, if this coat is damaged due to some movements, erosion or abrasion, high energy discharges will occur, damaging even more the main insulator until insulation fault - Fig.3.4.1.

Fig.3.9 – damaged strand part of stator bar insulation due to high energy discharges

- ***Slot Exit*** - Discharges can appear due to similar cases as the previous one but also at the stress control coating as result of electric stress concentration at the interface between the semi-conducting slot coating and the stress control coating. Besides, it can also occur in mechanical damaged places or shortened stress control coating.
- ***Endwinding*** - At the interfaces between stator winding overhang part components subjected to high local electric fields PDs can occur. The erosion caused by surface discharges happen when the end corona protection is no longer effective in consequence of causes such as thermal stresses, contamination or even unsatisfactory designed interfaces. In addition, in the area of the phase separations, PD may also occur due to chemical contamination, floating metal particles or ineffective clearance – Fig.3.4.2.

Fig.3.10 – contamination of the stator bar ending

- ***External*** - Due to mechanical damage or near improperly installed RTD cables. On connection straps, within surge capacitors, bus bars or phase leads.

Although everything that was mentioned previously about potential sources of PD, it is still difficult to identify the exact one and its location. Even if some PD patterns can be easily identified others are not unique and can be a combination between problems.

3.5 General Characterization of On-line versus Off-line Measurements

There are two ways to acknowledge the condition of the stator winding insulation. One is while the machine is standstill by performing an off-line diagnosis, and the other is during its operation, using suitable methods for on-line measurement and diagnosis.

The constant increase of the competitive pressure related to the electricity market had, as consequence, the sharp decline of sale proceeds for electrical energy. As result, there was a strict cut in investments and in maintenance not losing the aim of reliability. Main companies had to manage their resources in such a way that not only the technical priorities but also the optimal economical benefits were accomplished.

In the past, tests made concerning PDs were carried off-line, meaning that the electrical machine was at that present moment not connected to the network system [34]. For this method an additional external power source was needed in order to provide AC current for the test.

These off-line tests have their importance and relevance. However, they tend to “forget” some variables and situations that only occur during a real operation status. This test is very similar to the ones performed when the equipment is still new in the quality control tests made by manufacturers and rewinders.

As it can be easily foreseen, the biggest disadvantage is the outage time of the machine. However, it is always good to remember that off-line tests carry with them the visual inspection itself, only possible in this situation, which still is the most important and reliable source of inspection for winding insulation.

The alternative for the off-line test was the on-line method, which obviously does not require the external power source since this one is performed with the machine operating without any restrictions and connected to the network.

For the last 15 years, on-line monitoring has become the one of the most widely applied methods for determining the condition of high voltage apparatus insulation. One of the greatest interests of the on-line method relates to the economic view of the situation. The necessity of disconnecting the machine on the off-line method brings us to the consequent lack of energy supplyment given by that specific tested machine. In the case of generators, the outage time can be extended for several hours or even days. Thus, depending on the power range of the machine the monetary losses can be easily calculated and it can be seen the relevance of keeping it on-line.

Moreover, this type of measurement was able to identify the reason electrical insulation is deteriorating. These causes are, among others, loose coils in the slots resulting in insulation abrasion, thermal deterioration or load cycling leading to insulation delimitation and electrical tracking caused by partly conductive contamination of the endwinding. Manufacturing problems such as poor impregnation with epoxy or coils being too close each other can be also detected, and conclusions can be taken about the severity they bring to the winding's long term life [35].

Concerning the stability point of view, the advantages of keeping the machine in the working state are also well known. The disconnection of the apparatus can sometimes provide serious stability problems and reduces the reliability of the transmission and distribution system.

However, and after what was previously written, one of the biggest questions one can have is why is the off-line method still used?

And for this, the disadvantages of the on-line method have to come to mind.

On one hand, there are security issues related with his implementation in high voltage equipments.

On the other hand, there is the reliability of the results obtained. This method is performed under serious adverse conditions that affect the tests, such as winding temperature, load and voltage, and also environmental humidity. The ambience that surrounds the working generator causes noise, which is found in the results affecting them with errors that cannot be ignored and that make difficult trending the PDs over time.

The off-line test can be a complement to the on-line test and it is quite often recommended by the manufacturers in case of non-reliability of some results given by the on-line tests.

There are some examples that can be given showing the relevance of the on-line tests. For example, in some hydrogenerator stator windings, the majority of these PD measurements are performed two times per year with the duration of 30 minutes. There are already several owners of these machines who take as advantage the continuous on-line measurement.

3.6 Dissipation Factor Interpretation

The measurements of DF are frequently quality tests in newly single bars or in complete winding. The voltage range used on the tests is already specified for that kind of bar or chosen by the testing responsible. However, there are many points that should be taken into consideration [29]:

- When dealing with a proper and quality insulation, the initial value obtained should be consistent with the "established value" for that kind of insulation system. As it is shown in Fig.3.11, PF increases with the increase of voltage. Since $\mathrm{PF} = \cos\theta$, when $\cos\theta$ rises there is also the rise of $\tan\delta$ and, consequently, that increase is valid for both parameters. The increase of the DF with the increase of the voltage is normal and it is due to the manifestation of the PD within voids.
- There can be slightly different results for the same type of bar. This can be considered normal and it happens because the initial voids are not equally distributed in every newly made bar – Fig.3.11.

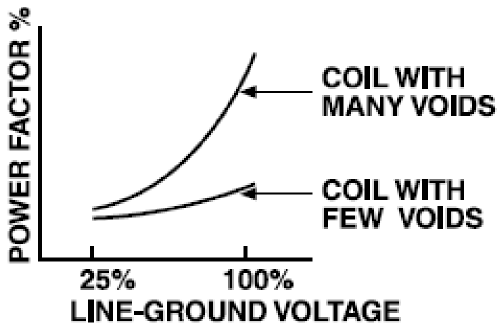


Fig.3.11 – Power Factor for coils with different void amounts [31]

- In the test there are significant points DF(Un) which can be measured depending on the specifications and on the objectives determined:
  - The first step in voltage (for instance 0.2 Un) is used to measure the initial DF value;
  - The DF tip-up value is calculated between two different values of voltage (for instance 0.2 Un and 0.8 Un);
  - A plot with different DF points can be made using values of different step voltage.

- The DF tip-up change during lifetime can happen due to deterioration processes previously described.
- There is not the possibility of comparing individual bar results with those obtained with complete winding, and the results of the measurements may not be used as absolute indicator of the condition of the insulation.

3.7 Partial Discharge Interpretation

The interpretation of PD measurements is one of the most complex and subjective parts of the whole testing processes. As it has been said, it is not an exact science, even though there are some lines of procedure that can be followed.

3.8.1 q-U curve

The q-U curve is a tool which helps to [36] analyze the effect of different levels of testing voltage on the discharge magnitude – Fig. 3.12.

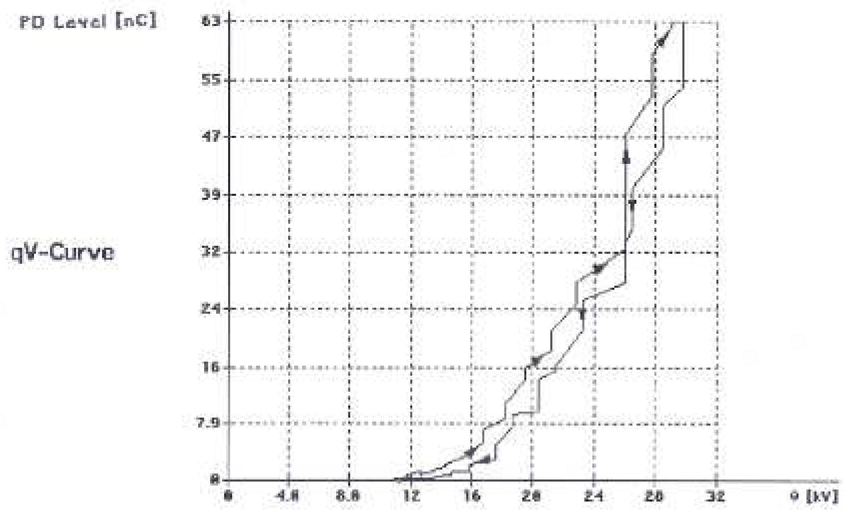


Fig. 3.12 – q-U curve for an individual stator bar of a hydro-generator

It is obvious that the manufacture of new bars with the application of the tape layers and impregnation process is not perfect and even with the best technologies, voids of different sizes and shapes eventually happen to exist.

The manifestation of these voids depend on the applied voltage in the insulation since small voids need less voltage to get active while bigger voids need an upper level of voltage.

The plot of the q-U curve represents the test voltage in the x-axis and the magnitude of discharges in the y-axis. There are two important values that must be analyzed in the first place:

- *Inception voltage (PDIV):* the first concern while analyzing this plot is to acknowledge the value of the inception voltage. This is the first voltage point at which the manifestations of PD appear. PD inception in insulation is associated with the presence of free electrons inside the cavity. Such electrons may be either generated by background radiation or extracted at the material-cavity interface. The voltage level at which the first-electron disengage the discharge is named partial discharge inception voltage (PDIV). Depending on the kind of bar tested this value must be higher than the requirements. For instance, if the requirement for the inception voltage is 6 kV and the value measured is 5 kV the bar must be rejected.

- *Highest PD magnitude:* other important measurement is the highest PD magnitude occurred during the test. The logic test of this parameter is similar to the previous one and works in a true or false analysis. If the value is lower than the required one, this parameter for the bar can be approved. High values of PD can reveal bad quality of the impregnation process.

However, this is not the only important element given by this measurement. The behaviour of the curve must also be kept in mind.

On one hand, for new bars, if the discharge magnitude continuously rises until certain point with the rise of voltage it means that there are voids of different types and shapes included in the insulation.

On the other hand, if the discharges reach certain point and keep almost the same value with the rise of voltage, it means that voids present in the insulation are in some kind of way similar to each other.

For used bars it is known by experience that if the q-U curve reaches high values of magnitude and has little variation when the voltage is raised above the inception level it is symptom of internal discharges in the dielectric bounded cavity [36].

If the discharges magnitude is high and steadily increases during the raise of voltage above the inception voltage it can characterize internal discharges between conductor and dielectric in a number of cavities of various sizes.

3.8.2 $H_n(\varphi,q)$ Distribution

The $H_n(\varphi,q)$ distribution is used to display a 3-dimensional relationship between *discharge magnitude, discharge intensity and voltage phase angle* [37] – Fig.3.13.

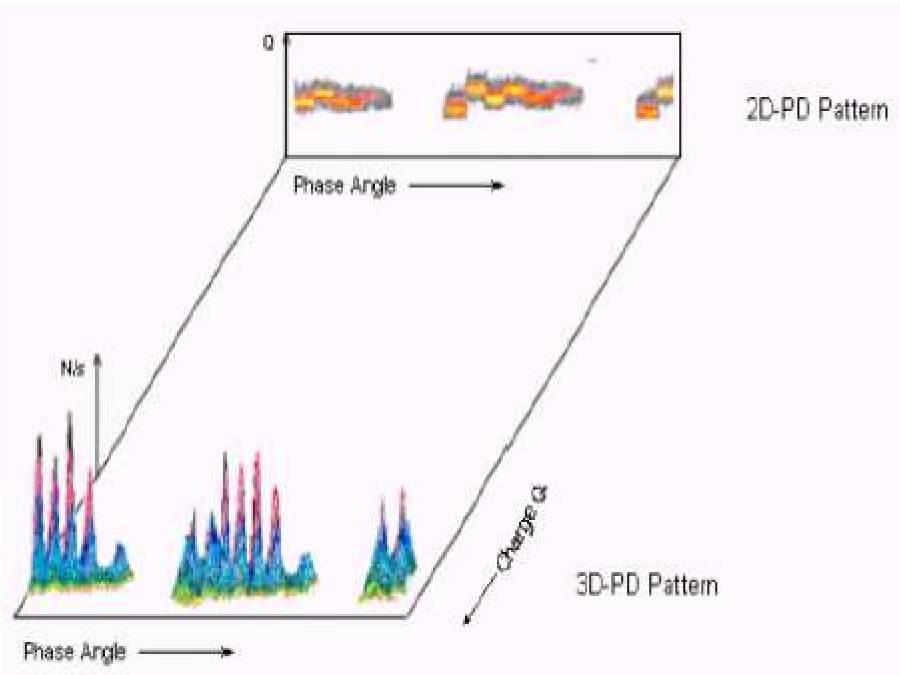


Fig.3.13 – generic 3-dimensional and 2-dimensional representation of PD [38]

Different insulation defects are characterized by typical differences in the landscape of the 3-dimensional plots. This distribution can be very useful to analyze the discharge processes on insulations [39].

The difference to the 2-dimensional pattern is the *discharge intensity* represented with the variable brightness and contrast of the colour used – Fig.3.13.

The popularity of this new method shows his importance in the PD interpretation area. Patterns contain sufficient information for discharge discrimination and recognition [40]. Many studies are being developed in order to provide an automatic recognition to this analysis [14][15].

Meanwhile, the interpretation is done by expert engineers who throughout the years, in contact with different situations and defects, established empiric rules to locate the source of those PDs.

Generally, in order to do the interpretation of PD patterns, four characteristics must be taken into consideration [31]:

- **PD magnitude** which is related with the size or volume of the voids;
- **PD pulse count rate** which is related with the quantity of voids;
- **PD polarity** which is related with the location of voids in insulation;
- **PD position relative to the phase-to-ground voltage** which is related with the location of defects whether in the endwinding or in the slot.

Each characteristic may vary and that variation can ultimately give information about positions, types of problems/defects and indication about ageing phenomena.

There are some typical features on discharge patterns that should not remain ignored whether PD is measured in complete windings, single stator bars or only in experimental configurations [40]:

- Patterns with approximately equal discharge magnitude in both half cycles of the test voltage mean PD occurs **between dielectric surfaces** – Fig.3.14 and Fig.3.15.

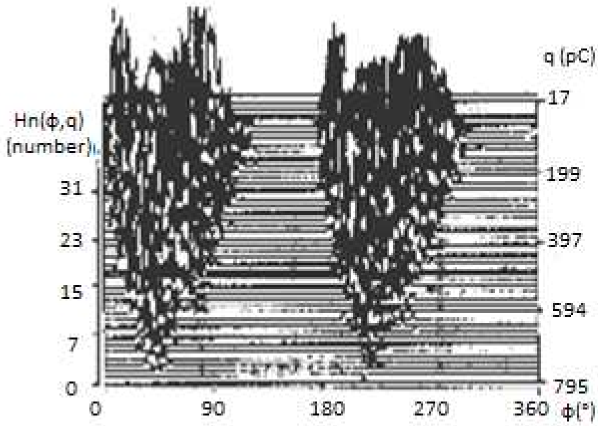


Fig.3.14 – PD between dielectric surfaces [40]

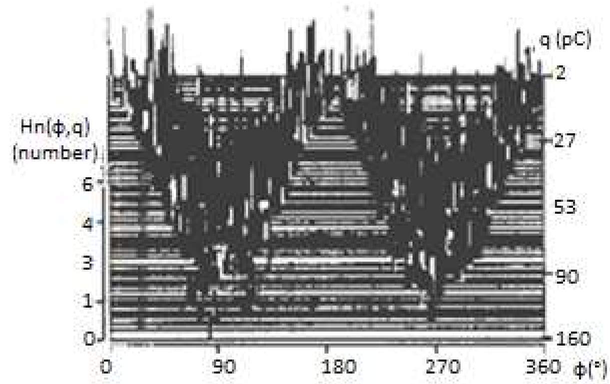


Fig.3.15 – PD between dielectric surfaces [40]

- Discharges with unequal magnitude in the positive and in the negative half cycle of the test voltage mean that a **metal electrode is involved in the discharge process** – Fig.3.16. For instance, when the main insulation is separated from the conductors.

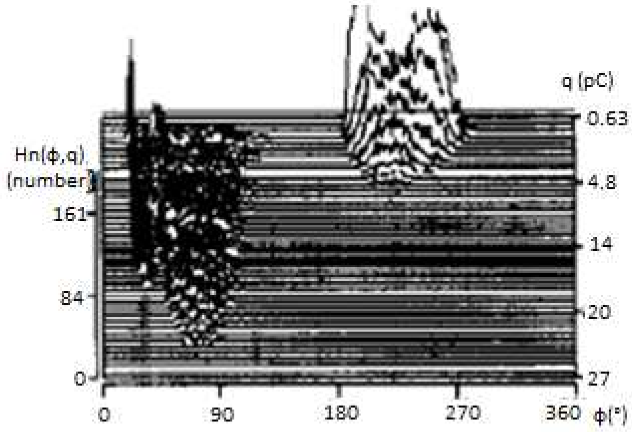


Fig.3.16 – PD when a metal electrode is involved in the discharge process [40]

- When discharges occur only in one half cycle of the test voltage **single-point corona** may be the cause of the phenomenon - Fig.3.17.

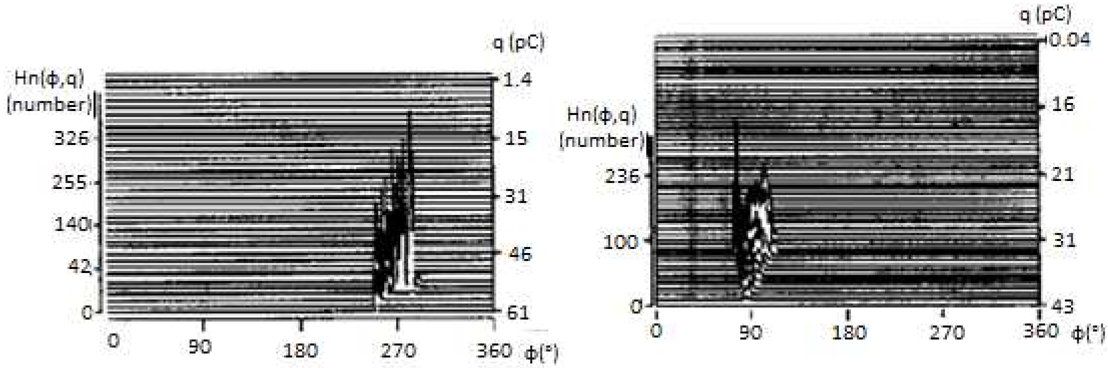


Fig.3.17 – different patterns for single-point corona [40]

- For **background noise** the disturbance pulses occur at constant phase angles – Fig.3.18.

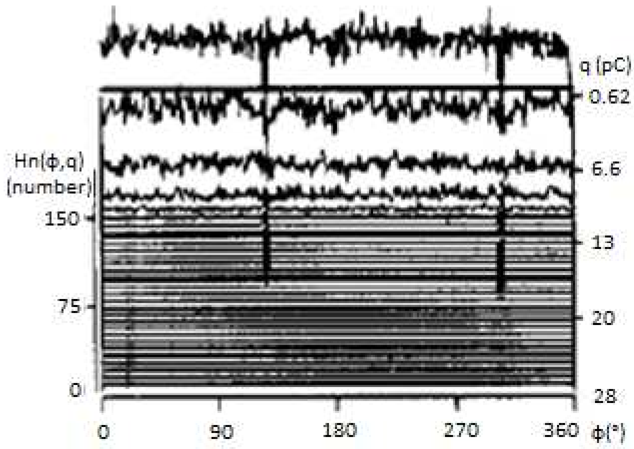


Fig.3.18 – pattern for background noise [40]

When tests are performed in complete windings or only in single stator bars patterns can present distinguish characteristics [33].

The types of *External Discharges* existent are:

- Slot discharges – it can be the most harmful defect in insulation as it was previously mentioned. Typical **asymmetric** pattern with **higher negative halfcycle magnitude** than positive. In the negative halfcycle it is noticed a **distinct triangular shape** with a sharp rise around the negative voltage zero.
- Endwinding discha*rges* – the causes of endwinding discharges were already mentioned before. However the pattern can change depending on the type of

discharge that happens. The typical pattern shows also **asymmetry** and comparing with slot discharges there is a different shape of the **triangle** which is more **oriented to the voltage maximum**.

Internal Discharges have, also, characteristics that make them different from those just described.

The typical pattern for a *Internal Discharge*, for instance, delamination of the tape layers, presents **symmetry in both positive and negative half cycles** (its centre of gravity lies around 30 degrees).

Other internal discharges can present different patterns like **slight asymmetry with the positive half cycle having higher discharges**. This may be symptom of delamination in the main insulator.

Bad contacts between layers or corona shield can be a cause of PDs and the patterns usually show **high magnitudes**.

Finally, there is one important defect that happens when the main insulation separates from the conductors when the machines are submitted to different load and temperature cycles. The pattern is quite similar to the one given by the slot discharge however in this case the asymmetry shows **higher discharges on the positive half cycle instead of the negative**.

Several examples of *Internal Discharges* will be given in Chapter 5, where results will be presented and discussed.

Chapter 4
Experimental Procedures

4.1 Introduction

The theoretical presentation shown in the previous chapter describes not only two different types of measurements – PD and DF – but also a global view of the consequence of the results achieved in electrical apparatus insulation (turbo-generators, transformers, electrical cables, etc.).

This subject we are studying is not so commonly known and has a wide range of possible studies, from off-line tests in complete generators (including 3-phase winding tests) to the on-line measurements given by sensors coupled to the machines.

In the second part of this dissertation it will be shortly presented the environment in which the tests were performed, the main products and the factory's manufacture processes.

Moreover, following it will be shown some measurements done during the internship. The main objective of the testing department of stator bar manufacturing is to assure the quality of bars used in the windings. The tests are performed to 100% of the bars produced and the results are compared with the requirements for each type of generator bar.

The main tests are the Dissipation Factor (DF) measurement and Partial Discharge (PD) measurement but this last is only performed when it is specifically required.

On one hand, it will be presented separately some DF and PD measurements and the conclusions resulting of each test.

On the other hand, it will be presented a complete study of more than one hundred bar set, which were tested with both DF and PD measurements regarding the objective of finding a relation between both factors.

The factory does not have any research department and all the information gathered is sent to the headquarters in Switzerland where it is handled and studied in the main investigation department. For that reason this last research was a special proposition that could not be refused due to the innovating experience it would carry.

4.1.1 Introduction to the Workplace

This work had, as background, a practise done in one of ALSTOM's workshops located in Wroclaw (Poland).

ALSTOM is a global specialist in energy and transport infrastructures, which employs over 70000 people in 70 countries worldwide, making this company one of the biggest in the world, in his sector. In the past, ALSTOM Power has supplied about 650 gigawatts of installed capacity of power equipment, which is about 20% of the total worldwide [41].

The ALSTOM Power in Wroclaw's branch has three units: the Generator Factory, the New Generator Unit and the Power Service Unit.

The work was performed in the Generator Factory which produces turbo-generator's stators for utility in power plants and industrial power sector. This factory was only renamed ALSTOM after 1999, since previously it belonged to DOLMEL, from 1947 to 1990, and ABB, from 1990 to 1999.

As it can be easily seen, due to more than half a century of experience, the activities related with the production of electrical machines are greatly improved and it provided an excellent basis for developing the designated work.

4.1.2 Characterization of the Workplace

The factory has a 16964 m^2 area and the layout has five main areas: the Stator Winding Manufacturing, the Stator Manufacturing and Generator Assembly, the Testing Station, the Casing Manufacturing and the Main Store.

From several different bars manufacturing till the assembly of all stator, a large range of activities are performed there.

In order to understand the environment in which this work was performed there is a brief description of the three manufacturing areas above mentioned.

The Stator Winding Manufacturing activities are:

- Green bar manufacturing;
- Bars manufacturing in Micadur;
- Insulation applying;
- Insulating systems;
- VPI process.

The Stator Manufacturing and Generator Assembly concerns with:

- Segments cutting and varnishing;
- Stacking of the generators;
- Stator winding;
- Assembly of Stators and Generator;
- Planning, preparing and execution of running tests;
- Electrical tests in the production processes;
- Diagnostics in power plants.

Finally, the *Casing Manufacturing* main activities are:

- Welding of casings and components;
- Machining;
- Annealing;
- Pressure tests.

4.1.3 Main Products

The production of stators for different types of generators is the main activity of the factory. Each generator has individual requirements and stator bars are not the same depending on it. The complexity of the bars changes if it is an air-cooled, water-cooled or hydrogen-cooled generator – Table 4.1.

Table 4.1 – type of turbogenerators

Type of generator	Power Supplied
Air cooled	Up to 480 MVA
Hydrogen cooled	Up to 500 MVA
Hydrogen-Water cooled	Up to 1333 MVA

4.1.4 Stator Production Processes

The stator and its components is one of the objects of study in this work and in order to perform the insulation tests, the understanding of its production must be kept in mind. There are some processes worth to be mentioned in this area and shown in the diagram below - Fig.4.1.

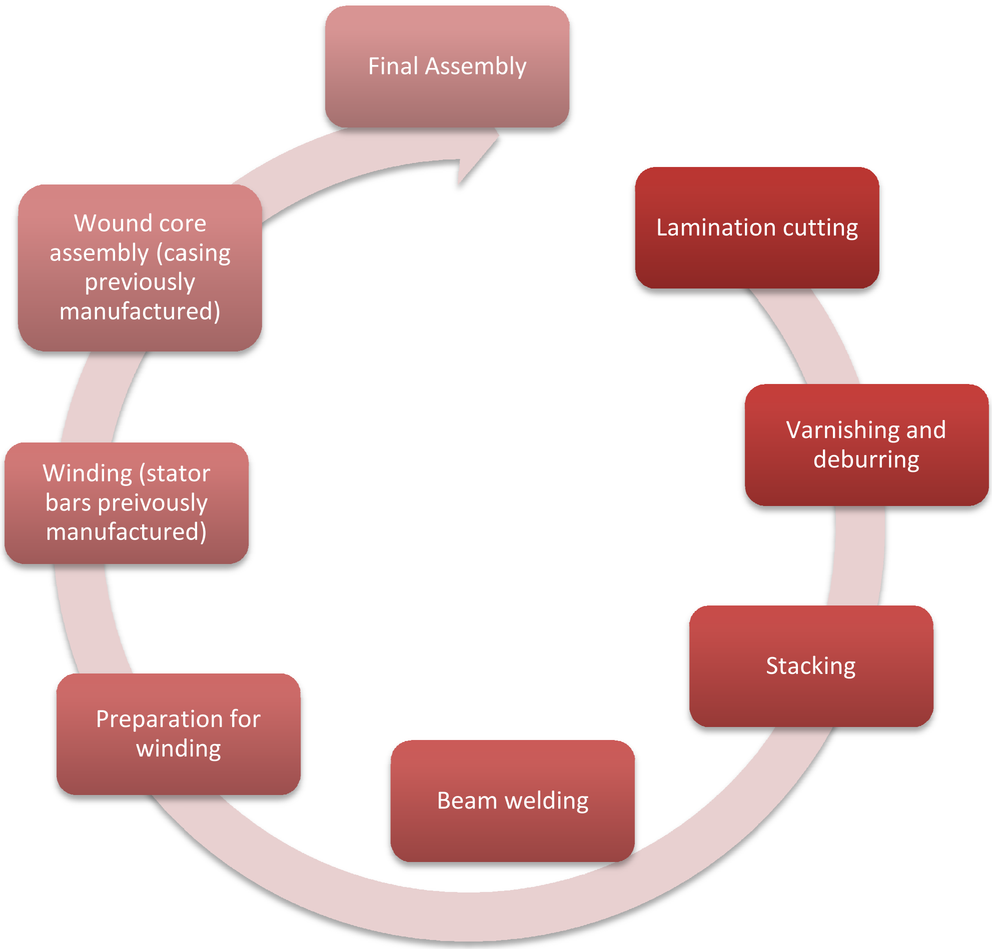


Fig.4.2 - diagram of processes for complete stator production

The tests which will be described next were performed in the 3 different kinds of winding bars produced in the factory. Each one has a different production method and each one has to meet different requirements for different types of generators. In the same way, it can also be seen that not all have the same cost of production, since some will be used in bigger power plant generators then others - Table 4.2.

Table 4.2 – stator bar production processes

name of process	type of generator in which is used	short description
PROC.1	Hydrogen and Water cooled	Dedicated to water-cooled generators; Water flows through stainless steel hollow conductors; Accurate bar dimensions with narrow tolerances by process of pressing impregnated bar before hardening; Expensive and time-consuming.
PROC.2	Air-cooled and Hydrogen-cooled	Cost effective way for keeping bar geometry; Reduced cost by process of closing of green bar in steel plates (envolute and straight part).
PROC.3	Air cooled	Dedicated for small bars; Lower stator winding voltage; Bar geometry deviations compensated by bar flexibility; Low cost process due to the closing of green bar in steel plates for straight part only.

4.2 Stator Insulation Systems

A very complex and sophisticated process starts when dealing with the production of high voltage stator bars – Fig.4.2. The steps until the final product require a huge optimization in order not only to guarantee a reliable product but also at the lowest cost possible. The expectations are higher every day and the goal is to achieve better performances and longer life term stability of the windings.

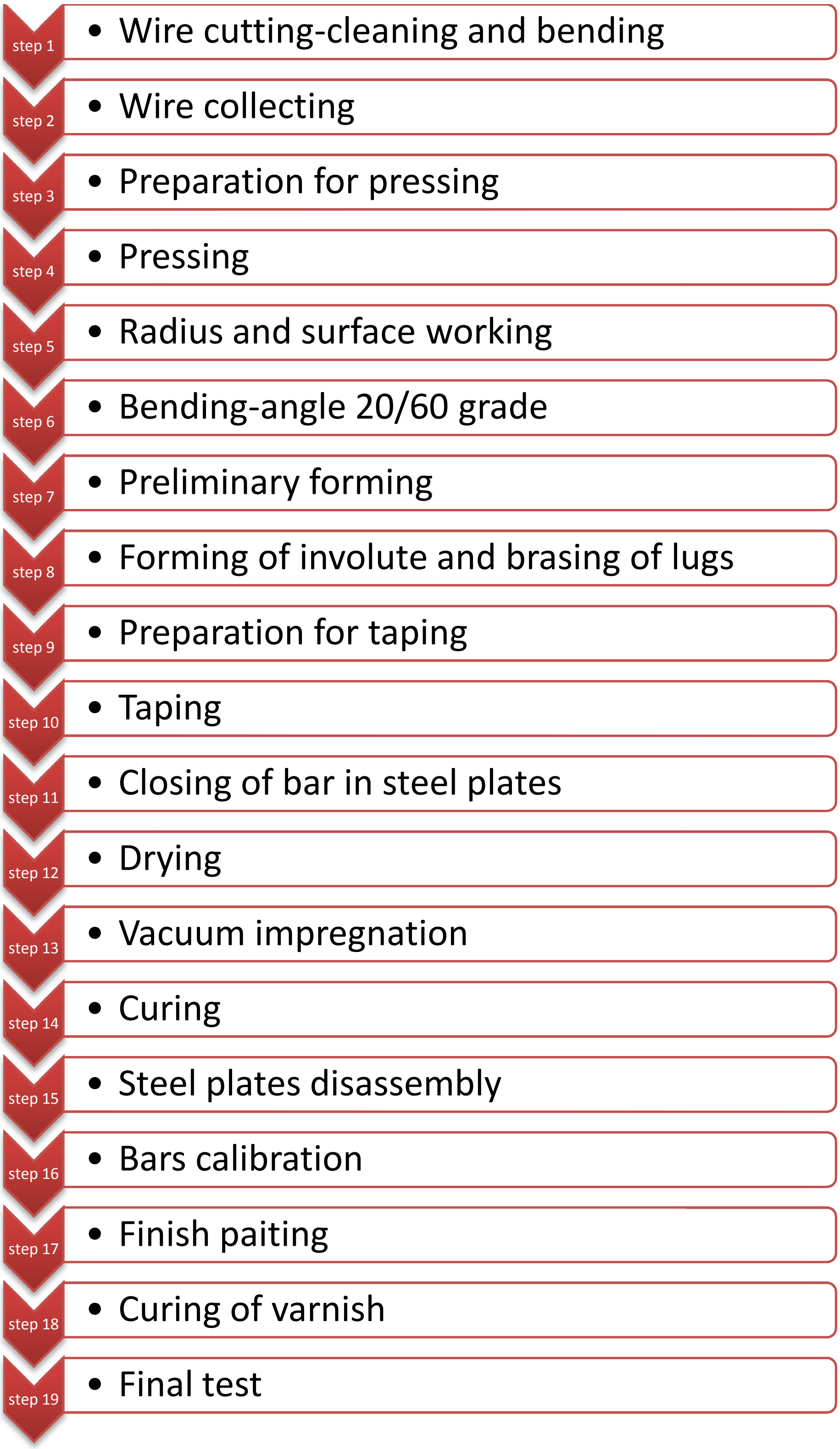


Fig.4.2 - diagram of processes for stator bar manufacturing

The PD tests conducted are also a very influent data concerning the improvement of the insulation systems and processes. They are able to detect mistakes or lack of effectiveness on the production in a way those can be prevented in future. A small change in any of those previously mentioned steps can affect the results achieved in the quality testing.

The main objective when projecting the processes for a high quality insulation system is trying to guarantee minimum voids possible and the maximal reduction of the internal stresses. Moreover, the bars are planned to have [42] "uniform density, cured at the desire degree, have the mica and reinforcements fully wetted and have perfect bonding between layers"

There are two fundamental processes while the manufacturing of the insulation system. One is the "taping" and the other is the "curing".

The "taping" is described as the [42] "paramount for a high quality product: lap registration and precision, tension, taping angle and weaving selection are only a few of the key requirements to provide the basic structure of the ground wall. The way a tape is applied has a major impact also on the proper flow of the resin and impregnation of the laminated structure"

The "curing" has as base process the VPI which consists of [42] "vacuum treating in a pressure vessel, coils taped with dry tapes and encased in appropriate shaping tools and impregnating the with a low viscosity resin. While still immersed, pressure is applied with an inert gas over the mass of resin and after removal the coils are cured in ovens under isothermal conditions".

4.3 Single Stator Bar Dissipation Factor Measurement

4.3.1 Introduction

To certify the quality of all stator bars used in the windings of all generators a complete scan is performed and all bars produced are tested in terms of Dissipation Factor. If any anomaly is detected during the tests, it is rejected and goes back again to the manufacturing area where the defect is corrected.

4.3.2 Setup Configuration

The configuration used to test each bar is presented in Fig.4.3 with all the necessary material properly described. Moreover, there are photos of the laboratory while the tests were being performed illustrating the configuration used – Fig.4.4 - and some of the components - Fig.4.5, Fig.4.6, Fig.4.7, Fig.4.8 and Fig.4.9. In the photos there are several bars but each bar is tested separately.

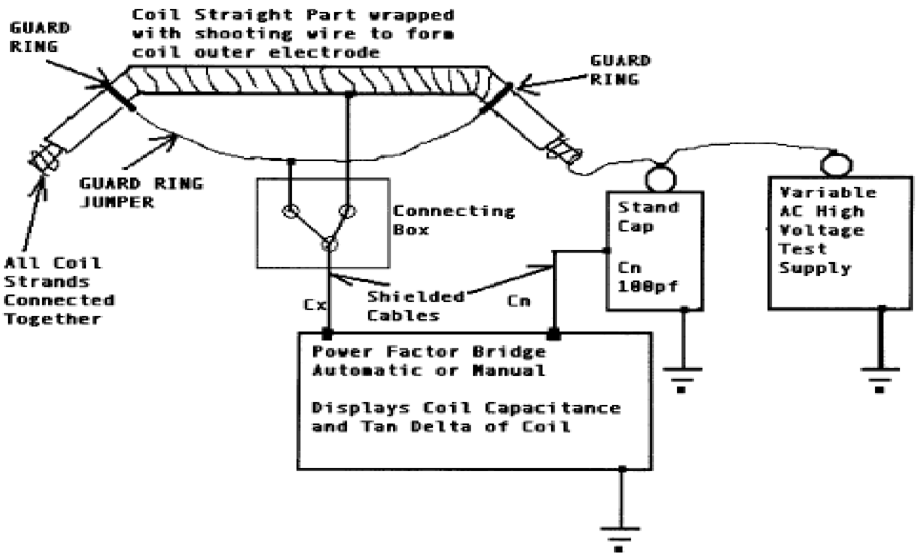


Fig.4.3 – factory setup of single bar testing for dissipation factor measurement [27]

The equipments used to measure DF in stator bars use a bridge-balancing technique based on the Schering Bridge method to measure the coil capacitance and internal coil resistance, which makes the dielectric loss component [42] – Fig. 4.3.

The measurements are done when the bridge is automatically balanced and that happens when $Z_{CX}/Z_3 = Z_{CN}/Z_4$ - Fig.4.4.

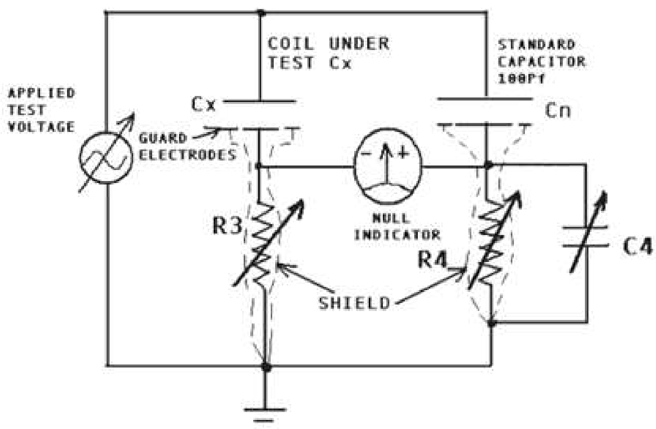


Fig.4.4 – basic Schering bridge circuit designed to measure coil capacitance and DF [42]

The Fig. 4.4 represents the Basic Schering bridge circuit and helps to explain what happens in Fig. 4.3. The variables in the circuit represent:

C_x – capacitance of the tested stator bar;

C_n - standard capacitor (typically 100PF);

R_3 and R_4 – Schering Bridge resistance component;

C_4 – Schering Bridge automatic variable capacitor component;

The testing circuit is composed by the AC voltage source with both kVA and kV rating and an automatic capacitance bridge. It also has a high voltage capacitor – C_n – and a connection box to correctly connect the stator bar electrodes into the bridge circuit. Finally, guard rings are used to confine the area of the stator bar which will be tested and prevent external discharges in the end turn corona suppression to affect the measurements.

The expression for DF is $\tan\delta = \mathrm{K.R_3.C_4}$ where K depends on the brand and type of automatic bridge used for the measurements. In this case the bridge used was an *automatic bridge TETTEX AG Instruments – type 2871.*

The cell capacitance is also measured at each voltage step and is used to check that correct impregnation of the stator bar was done during manufacturing. The expression which allows the bridge to measure the capacitance is $C_x = (C_n.R_4)/R_3$. The measured cell capacitance should agree with the calculated value that outcomes from the stator bar geometry [26]. For a parallel plate capacitor the capacitance (C) is given by [28]

$$C = \epsilon A/d, \tag{4.1}$$

where ϵ is the permittivity, *A* is the area of the plate, *d* the separation distance and the dimensions of the electrode must be larger than *d*.

Fig.4.5 – laboratory configuration for DF measurement

Fig.4.6 – other view of laboratory arrangement for DF measurement

Fig.4.7 – stator bar with the connecting box

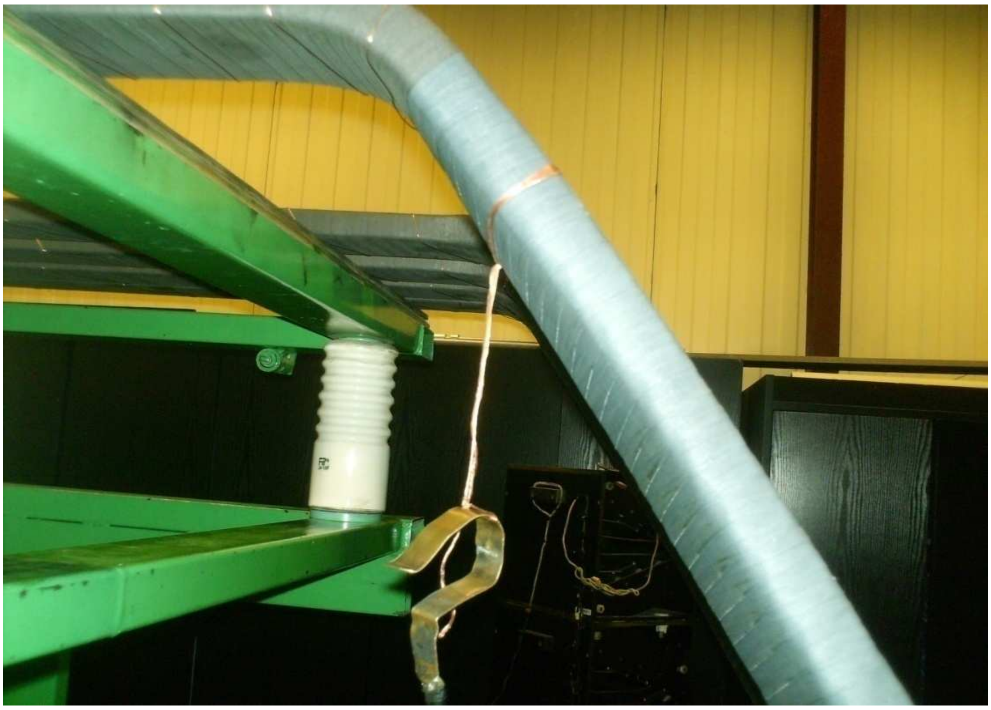


Fig.4.8 – stator bar with the guard ring connected to the guard ring jumper

Fig.4.9 – stator bar with shooting wire to form coil outer electrode

4.4 Partial Discharge Measurement

4.4.1 Introduction

PD measurement is currently one of the tests used for quality control in high voltage apparatus using solid insulation. Since PDs are not only the symptom of ageing but are also the cause of that deterioration, they have been used as a tool for the detection and diagnosis, in convenient time if possible, of a wide range of problems, some already born in the production.

And it is on this point where the measuring and analysis of the partial discharges gain relevance to prevent total failure of the equipment. This application has widespread over the past 15 years and has contributed for a database collection of over 30000 test results. By analysing statistically those results it is shown that many factors influence and are critical to the interpretation, such as the cooling method used in the machine, voltage class or even the type of partial discharge detector used.

4.4.1 Setup Configuration

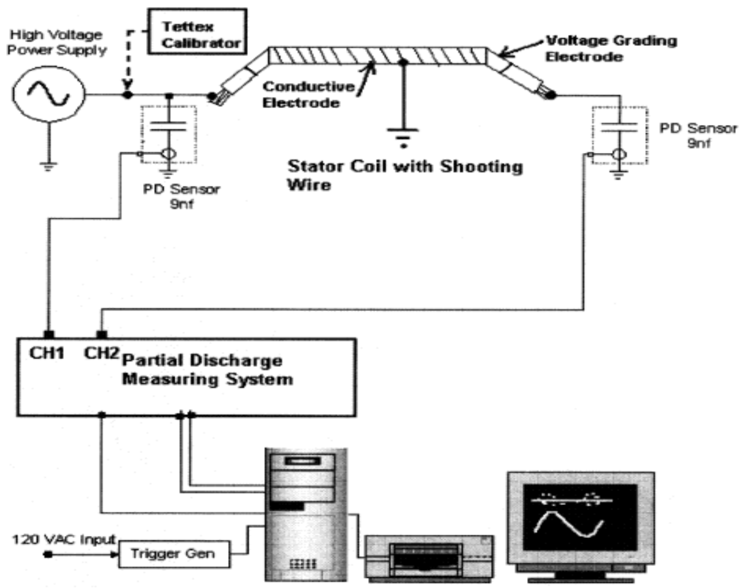


Fig.4.10 – setup of PD measurement test [27]

The PD measurements have the test setup circuit as shown in Fig.4.10.

A copper shooting wire is wrapped around the outer ground plane of the stator bar along the full length of the ground electrode, up to the start of the stress control electrodes. The two nF coupling capacitors are the PD sensors connected to each end of the stator bar's copper strands, which enter on each of the two channels of the PD system [27] – CH1 and CH2.

An adjustable AC power supply source is connected between the stator bar copper and the ground. PDs are then recorded for both ends of the stator bar and that consists, basically, on the record of the energy supplied by the source for each partial discharge.

The partial discharge measuring system used for the tests is the *Tettex Instruments - TE 571 Partial Discharge Analyzer* [10].

This equipment is a complete partial discharge detection system designed to measure, record and display PD.

This digital PD detector provides continuous transfer of PD to the computer during a measurement as well as real-time processing, storage and displaying of PD measuring data.

While performing the tests there are two possible measurements:

- *Routine Measurement* (variable test time from 15 seconds to 10000 seconds) done when a commissioning test is required. During several minutes the continuous recording of the time or voltage behaviour of the maximum discharge magnitude is the most important.
- *Analyze Measurement* (variable test time from 2 minutes to 100 hours) is characterized as a long term test, where not only is measure the basic information, but also are recorder as much as possible of the PD quantities for diagnostics aims.

Chapter 5

Results and Interpretation

The first group of results which will follow were measurements performed in stator bars for water-cooled generators. The first presentation of this chapter is the comparison between two bars of the same type which will be used in the same generator in order to explain differences present in the results.

5.1 DF measurement results

For each bar, the Dissipation Factor was performed at a determined voltage depending on the nominal voltage at which the bar would be used when integrated in the whole generator. The measuring started at a voltage of 0.1Un, finished at 2.0Un and having a step voltage of $0.1U_n$.

The examples given below are quality test measurements of two completely new stator bars manufactured with the same production method. For this matter, the most significant values are the first value of DF – $tg\delta_{0.2Un}$ – and the maximum tip-up value - $\Delta tg\delta/\Delta U_{max}$.

The measurements consist in a table with the values of capacitance (in pF), dissipation factor (tg δ in ‰) and the dissipation factor tip-up (Δtg δ/dU in ‰/kV) following by a plot of those values.

Table 5.1 – DF measurement results for stator bar 1

	Cx [pF]	dCx [pF]	tgδ [‰]	Δtgδ [‰]	U [kV]	dU [kV]	Δtgδ/dU [‰/kV]
1	13116,131	0,000	7,703	0,000	3,157	0,000	0,000
2	13118,890	2,759	7,884	0,181	6,042	2,885	0,063
3	13121,510	2,620	8,045	0,161	8,765	2,723	0,059
4	13123,870	2,360	8,181	0,136	11,536	2,771	0,049
5	13126,729	2,859	8,332	0,151	14,367	2,831	0,053
6	13130,170	3,440	8,504	0,171	17,259	2,892	0,059
7	13134,250	4,080	8,690	0,187	20,120	2,861	0,065
8	13138,681	4,431	8,882	0,192	22,891	2,771	0,069
9	13143,480	4,800	9,073	0,191	25,783	2,892	0,066
10	13148,681	5,200	9,269	0,196	28,674	2,892	0,068
11	13153,900	5,220	9,464	0,195	31,566	2,892	0,067
12	13159,160	5,260	9,635	0,171	34,427	2,861	0,060
13	13164,900	5,740	9,841	0,206	37,252	2,825	0,073
14	13170,830	5,930	10,024	0,184	40,120	2,867	0,064
15	13176,400	5,570	10,183	0,159	42,891	2,771	0,057
16	13192,351	5,950	10,338	0,155	45,782	2,892	0,054
17	13188,460	6,109	10,474	0,136	48,674	2,891	0,047
18	13194,240	5,780	10,579	0,105	51,505	2,831	0,037
19	13200,380	6,140	10,691	0,112	54,600	3,095	0,036
20	13205,880	5,500	10,795	0,103	57,202	2,602	0,040

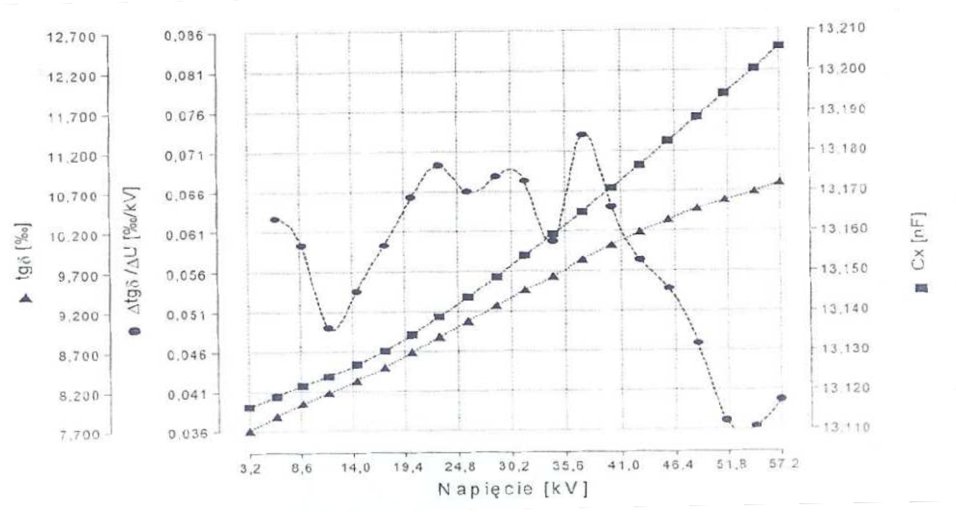


Fig.5.1 – plot of DF measurement results for stator bar 1

Table 5.2 – DF measurement results for stator bar 2

	Cx [pF]	dCx [PF]	tgδ [‰]	Δtgδ [‰]	U [kV]	dU [kV]	Δtgδ/dU [‰/kV]
1	13648,990	0,000	9,497	0,000	3,190	0,000	0,000
2	13665,530	16,540	10,397	0,899	6,060	2,870	0,313
3	13680,650	15,120	11,179	0,782	8,954	2,894	0,270
4	13629,729	12,079	11,814	0,635	11,517	2,563	0,246
5	13706,670	13,940	12,529	0,716	14,351	2,834	0,258
6	13721,380	14,710	13,283	0,754	17,306	2,955	0,286
7	13736,300	14,920	14,014	0,730	20,109	2,804	0,260
8	13751,780	15,480	14,719	0,705	22,913	2,804	0,251
9	13768,370	16,590	15,412	0,693	25,747	2,834	0,245
10	13785,051	16,681	16,051	0,639	28,611	2,864	0,223
11	13802,040	16,989	16,608	0,557	31,415	2,804	0,199
12	13819,370	17,330	17,115	0,507	34,370	2,955	0,172
13	13834,030	14,660	17,537	0,422	36,902	2,533	0,167
14	13851,050	17,020	17,914	0,377	40,008	3,105	0,121
15	13866,390	15,340	18,279	0,365	42,812	2,804	0,130
16	13880,921	14,531	18,541	0,262	45,736	2,924	0,090
17	13896,120	15,199	18,827	0,287	48,751	3,015	0,095
18	13907,960	11,840	19,040	0,213	51,083	2,332	0,091
19	13921,460	13,500	19,191	0,151	54,329	3,245	0,047
20	13933,990	12,530	19,366	0,175	57,253	2,924	0,060

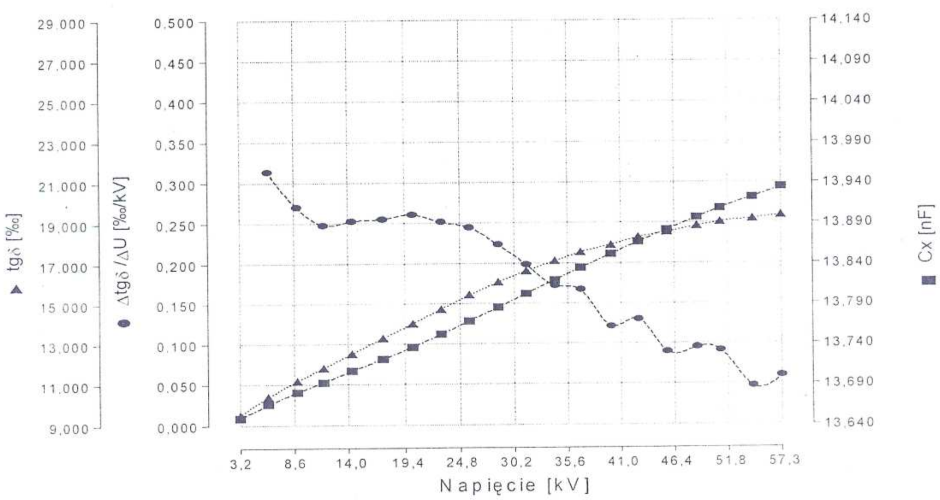


Fig.5.2 – plot of DF measurement results for stator bar 2

Both are newly bars which are part of a water-cooled generator and were tested at a nominal voltage of 27 kV.

The $\Delta tg\delta/\Delta U_{max}$ is the biggest value chosen from the right column of the table while the $tg\delta_{0.2Un}$ is a required quality control value.

For the stator bar 1 – Table 5.1 and Fig.5.1 - the relevant values were $tg\delta_{0.2Un}$ = 7,884 ‰ and $\Delta tg\delta/\Delta U_{max}$ = 0,073 ‰/kV.

For the stator bar 2 - Table 5.1 and Fig.5.2 - the values achieved were $tg\delta_{0.2Un}$ = 10,397 ‰ and $\Delta tg\delta/\Delta U_{max}$ = 0,313 ‰/kV.

All the values measured for both bars were considered acceptable for the factory requirements. The DF value was consistent with the “established value” for this kind of bar.

Although they belonged to bars of the same type, those results were not completely equal.

This was predictable and was already mentioned in the theory – Chapter 3. It happens due to different states of impregnation and manufacturing. The number of initial voids in each newly bar is not the same.

Even though results were both acceptable the one of the first bar is better than the second. Both DF and DF tip-up were lower in the first case. This means that the insulation of the first bar was better consolidated than the insulation of the second one.

Besides, it can be also observed that the value of DF increases with the increase of voltage and this happens because of the PD manifestation within voids.

Finally, the capacitance value is similar to both bars and around 13 nF and 13,5 nF. This value is not supposed to vary much with the change of voltage because it is an intrinsic value of the insulation system – Chapter 4.

5.2 PD measurement results

The same two stator bars tested with DF measurements were also tested for PD measurements. The results will be presented individually for each bar with the possible interpretation of each case.

5.2.1 Stator bar 1

The *routine measurement* was performed with a testing time of 1 minute and 30 seconds – Fig. 5.3.

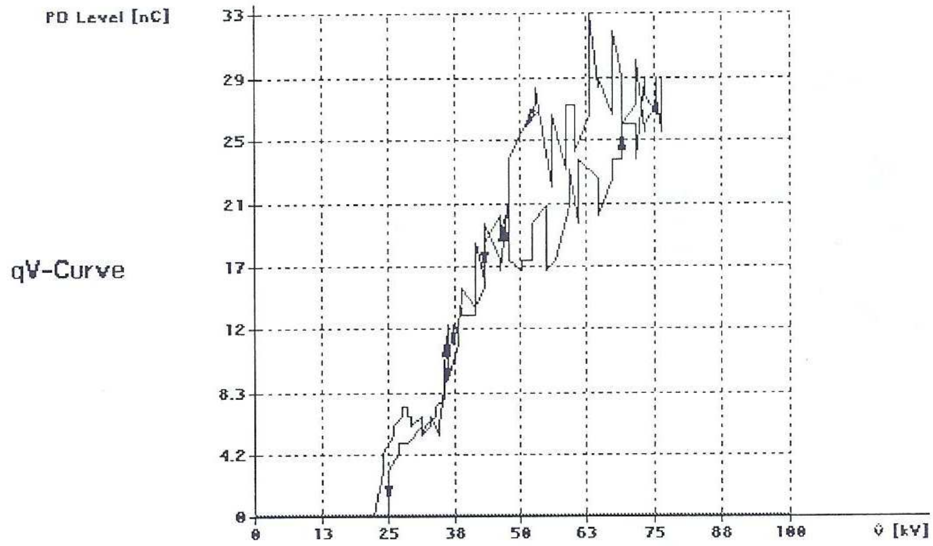


Fig.5.3 – q-U Curve for stator bar 1

In the qU-curve for bar 1 – Fig.5.3 – the inception level is above 20 kV which is a good value for a new stator bar. The discharge magnitude rises with the rise of the voltage above the PDIV and the highest PD result for this measurement was **33,317 nC**.

After the *routine measurement* it was performed the *analyze measurement* and the $H_n(\varphi,q)$ distribution is shown in Fig.5.4 and Fig.5.5.

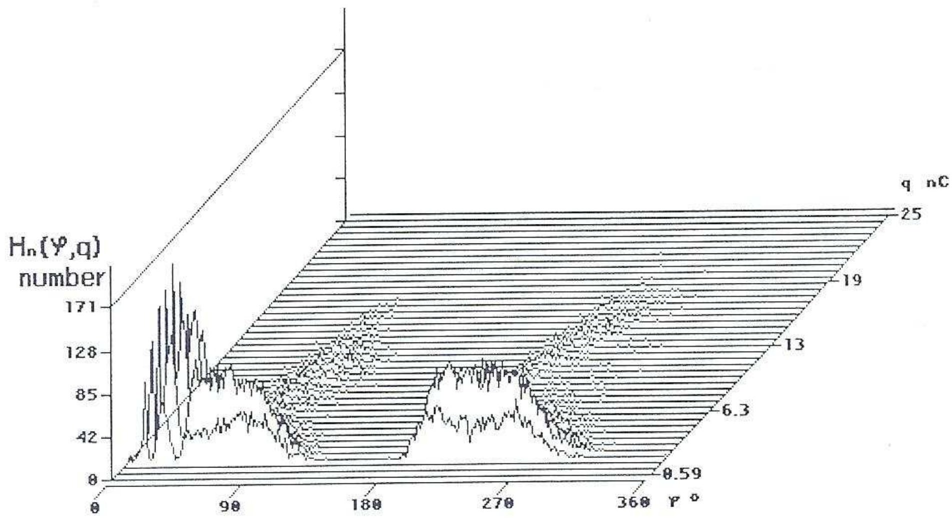


Fig.5.4 – 3D-display of Partial Discharges for bar 1 at 27kV, 50Hz

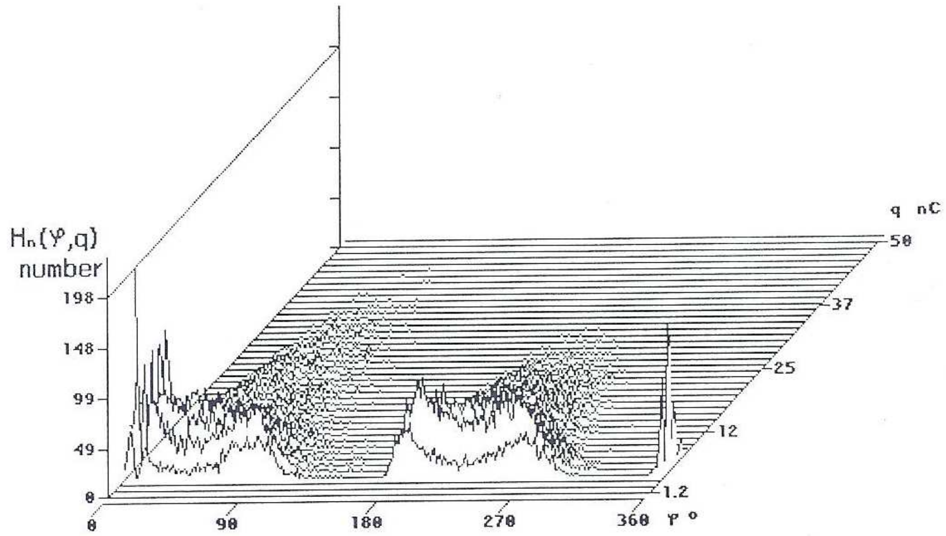


Fig.5.5 – 3D-display of Partial Discharges for stator bar 1 at 41kV, 50Hz

The testing parameters in *analyze measurement* mode for bar 1 were:

- Test measuring time: 2 minutes
- Bandwidth: 40-400 kHz
- Voltage: 27 kV and 41 kV at 50Hz

The 3-dimensional relationships of bar 1 show abnormal magnitudes of PD for a newly manufactured bar. At the voltage of 27 kV the highest PD reaches **25 nC** while at 41 kV the highest value is **50 nC**.

The plot is however not elucidative about the future location of possible issues. It only reveals that future problems are probable to happen as it can be easily foreseen due to the high values of PD measured and the landscape of the 3-dimensional display obtained.

The distinct pattern for any defect that can happen in the future will only appear after the generator is exposed to several hours of usage.

5.2.2 Stator bar 2

The *routine measurement* was performed with a testing time of 1 minute and 30 seconds – Fig.5.6.

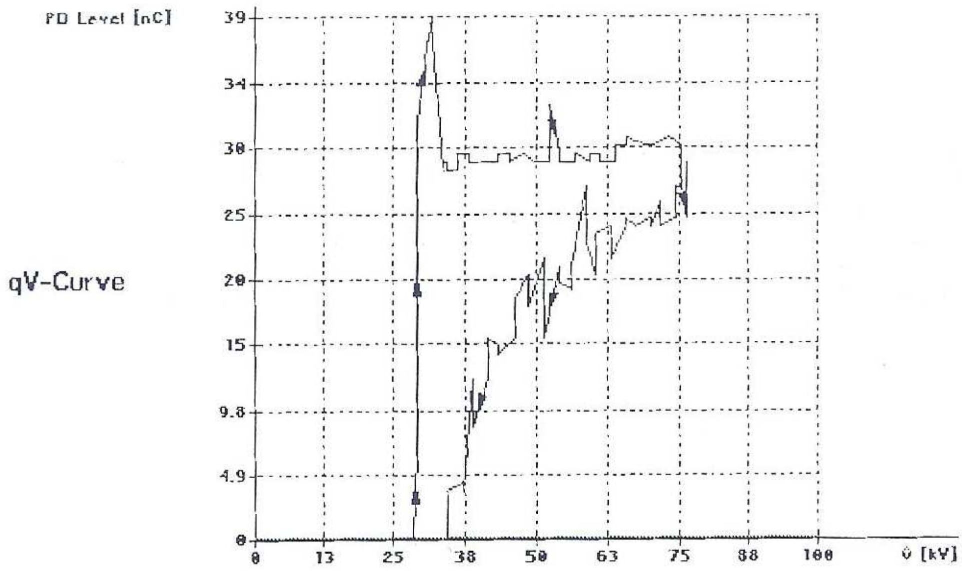


Fig.5.6 – q-U Curve for stator bar 2

In the qU-curve for stator bar 2 – Fig.5.6 – the inception level is above 26 kV which is a better value than the one for stator bar 1. The discharges magnitude rises to a maximum value of **39,375 nC** and then drops, stabilizing and having little variation with the rise of voltage. This kind of curve shows that internal discharges are present in the insulation and the voids within are very similar to each other – Chapter 3.

After the routine measurement it was performed the analyze measurement and the $H_n(\varphi,q)$ distribution is shown in Fig.5.7 and Fig.5.8.

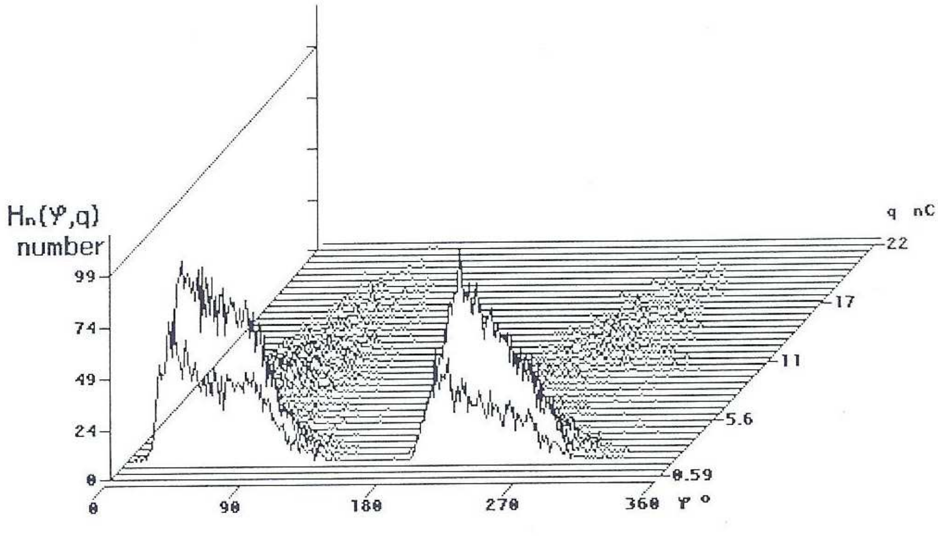


Fig.5.7 – 3D-display of Partial Discharges for stator bar 2 at 27kV, 50Hz

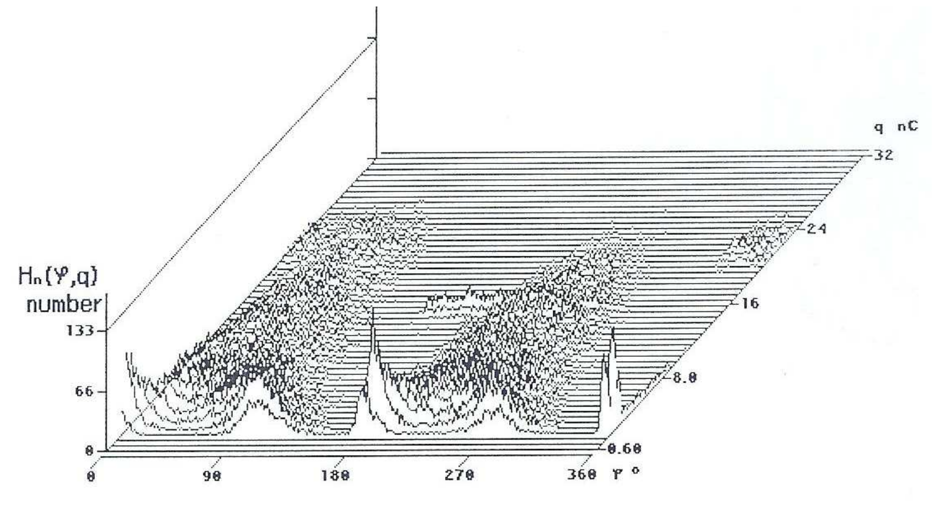


Fig.5.8 - 3D-display of Partial Discharges for stator bar 2 at 41kV, 50Hz

The testing parameters for bar 2 were:

- Test measuring time: 2 minutes
- Bandwidth: 40-400 kHz
- Voltage: 27 kV and 41 kV at 50Hz

The 3-dimensional relationships of bar 2 show a *near symmetry in both positive and negative half-cycles* with medium discharges with values above the desirable for a good quality bar. At 27 kV - with the highest value of PD of **22 nC** - this is not so perceptible but when the voltage is raised at the level of 41 kV, the magnitude of the discharges is too high - highest PD of **32 nC** - and this can be a symptom of *future issues within tape layers* – Chapter 3.

5.2.3 Quality control of new technologic processes used in stator bar 3

Although it may suffer future changes inherent to deep analysis of results, the technologic process, used in the production of the previously mention bars, is consolidated.

However, quality test for this kind of situation is not the only experiment performed with PD measurements. When new types of stator bars are developed based in different technologic processes, modifications in materials used, dimensions, among others, new tests must be done in order to check the reliability and the efficiency of those changes.

The results that will follow were one of such examples of the attempt on changing a particular detail in the production. For privacy reasons those details could not mentioned to the author neither described in this dissertation.

The stator bars tested were developed to be used in a *air-cooled* generator – Chapter 4.

5.2.4 Stator bar 3

For stator bar 3, the measurements described were specifically performed in terms of PD. The *routine* procedures were made two different times with two results.

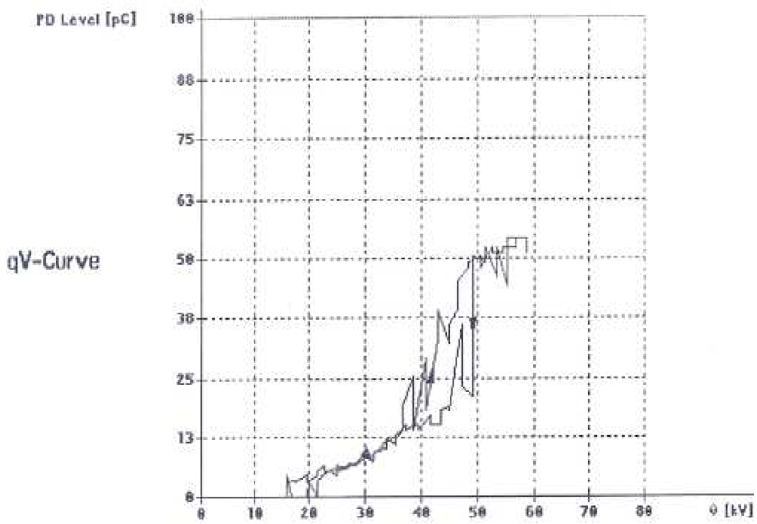


Fig.5.9 – q-U Curve for stator bar 3

For the measurement of Fig.5.9 the test measuring time was 1 minute and 15 seconds, the highest PD magnitude was **54 pC** and the inception voltage was above 15 kV.

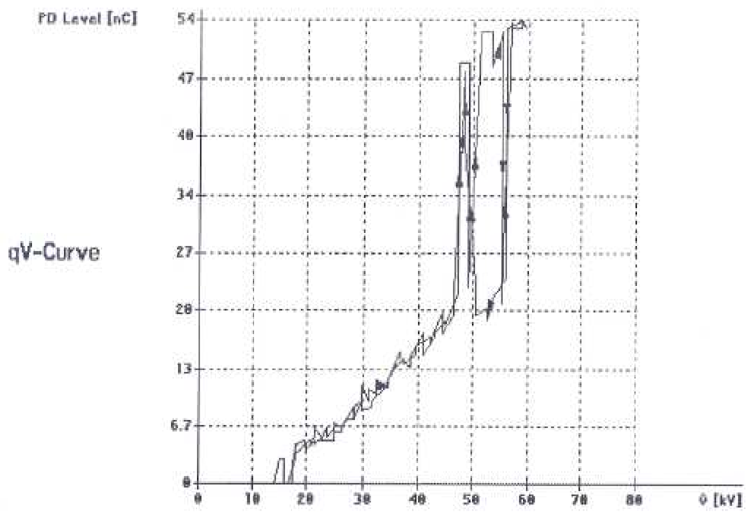


Fig.5.10 – q-U Curve for stator bar 3

For the measurement of Fig.5.10 the test measuring time was 1 minute and 15 seconds having as highest PD magnitude the value of **53,97 nC**. The inception voltage was about 14 kV.

Although the q-U curves are not so similar (Fig.5.9 and Fig.5.10), both highest values are the same – **54 nC** – and it can be seen that something is not quite correct when the voltage reaches values between 40 kV and 60 kV. This is exactly the purpose of a *routine measurement*, identifying the behaviour of the discharges to the rise of voltage level. The technologic process must be reviewed in order to achieve a better shape of this curve.

The *analyze measurements* were performed during 2 minutes and the highest PD magnitude for the first plot – Fig.5.11 – was **23 nC** for the voltage of 22 kV. As for the next one – Fig.5.12 and Fig.5.13 – the highest magnitude was **52 nC** for a voltage of 31 kV.

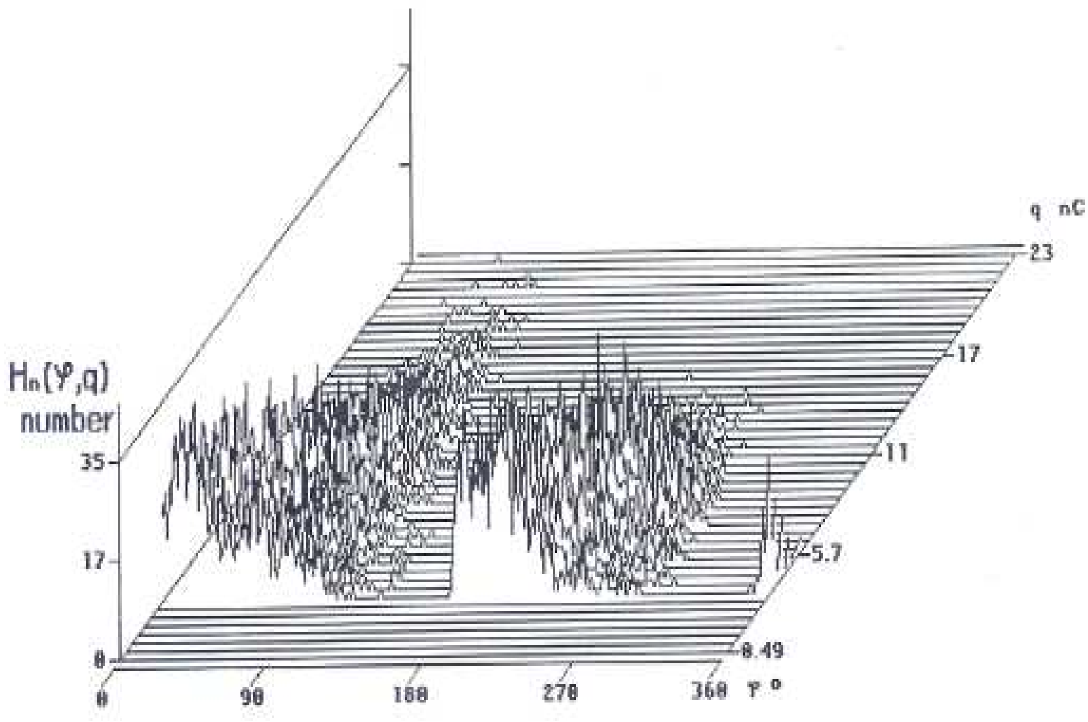


Fig.5.11 – 3-dimensional display of PD for stator bar 3 at voltage of 22 kV, 50 Hz

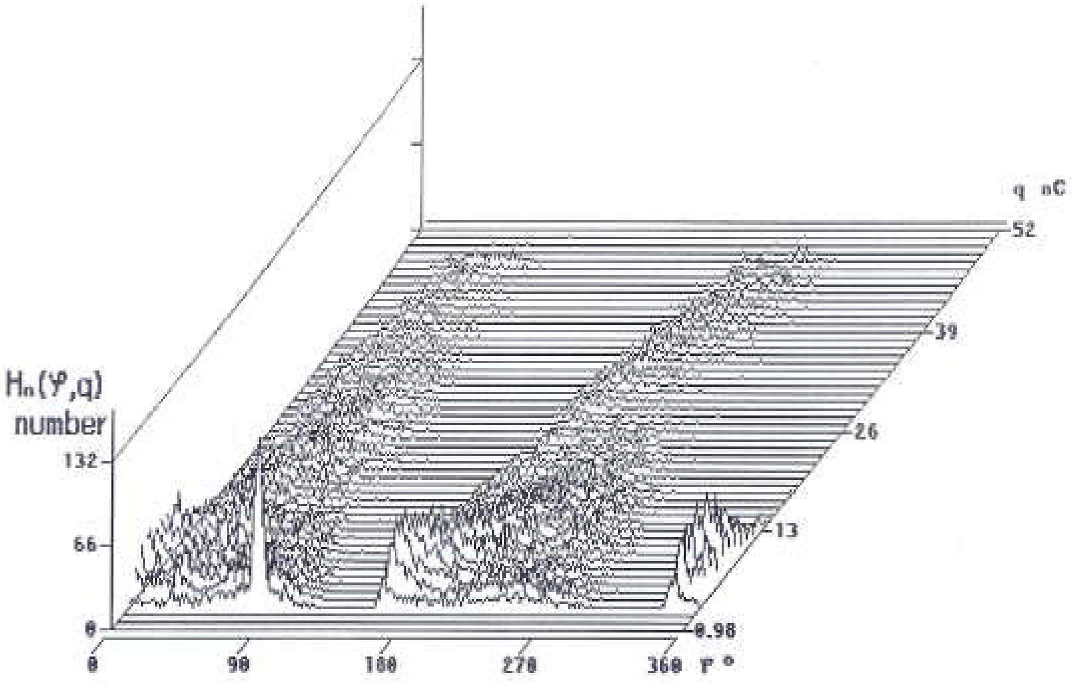


Fig.5.12 – 3-dimensional display of PD for stator bar 3 at voltage of 31 kV, 50 Hz

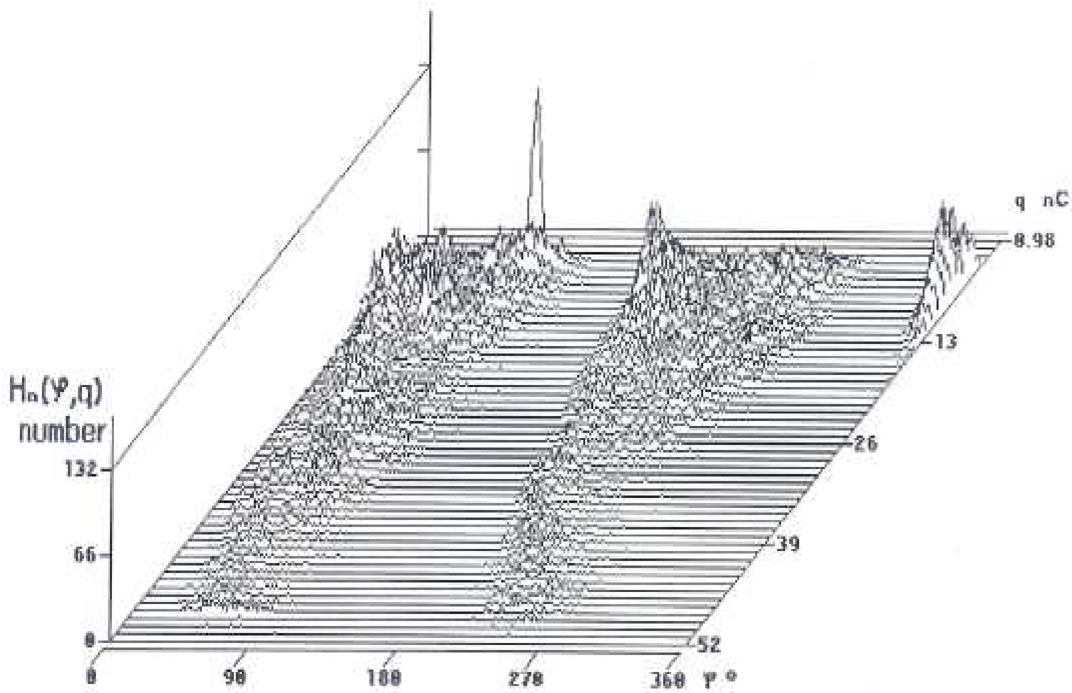


Fig.5.13 – 3-dimensional display of PD for stator bar 3 at voltage of 31 kV, 50 Hz (scale of magnitude *q* decreasing)

The Fig.5.11 shows a slight asymmetry with highest PDs in the positive half cycle. In the second plot – Fig.5.12 and Fig.5.13 – the asymmetry is less accentuated and there is the existence of a big trail. Even though a trail (higher magnitudes) is predictable, with the rise of voltage the one evidenced in this figure is too extended.

When looking to Fig.5.11, the diagnosis for such pattern can be symptom of *future delamination in the main insulator*. However, with the rise of voltage – Fig.5.12 – the pattern modifies and there is another possibility of diagnosis such as the *delamination between tape layers*.

Since PD interpretation is rather subjective, the proposals for diagnosis cannot be completely accurate. In this case only with progress of the patterns due to ageing phenomena will be possible to understand with more exactness if both defects happen or which one will.

Nevertheless, the best way to know if the diagnosis turned out correct is to perform a visual inspection to the bars from time to time but that can only be done with an off-line test.

5.2.5 Introduction to Stator bar 4, 5 and 6

Another three measurements related with different bars and defects will be presented next. The PD patterns distinguish from each other and the bars belong to different types of generators.

5.2.6 Stator bar 4

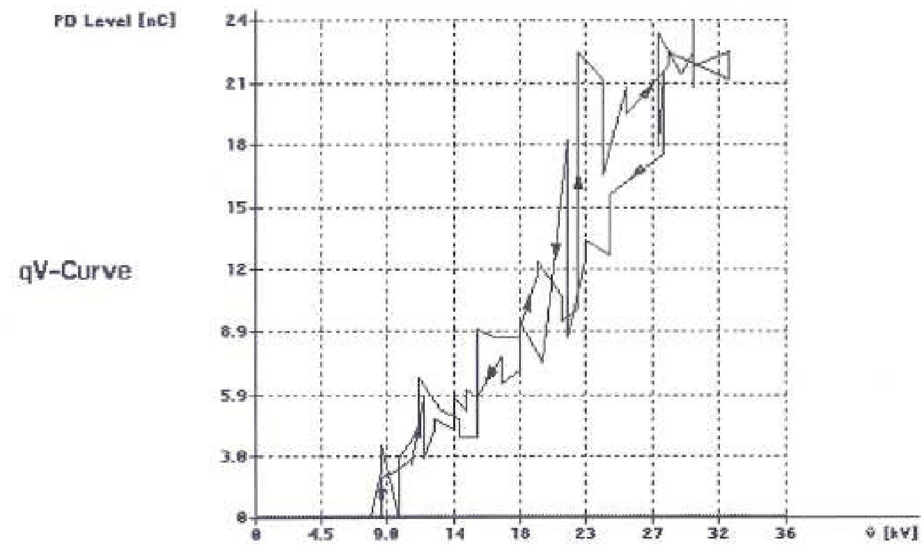


Fig.5.14 – q-U Curve for stator bar 4

The qU-curve in Fig.5.14 is not completely clear about the behaviour of the discharges in terms of variation of voltage. The PDIV is lower than 9 kV, a low value showing that the discharges do not need high voltage to start. In contrast, the peak magnitude value is not so high, with **24 nC**, foretelling that the voids present in the insulation system may not have such large size.

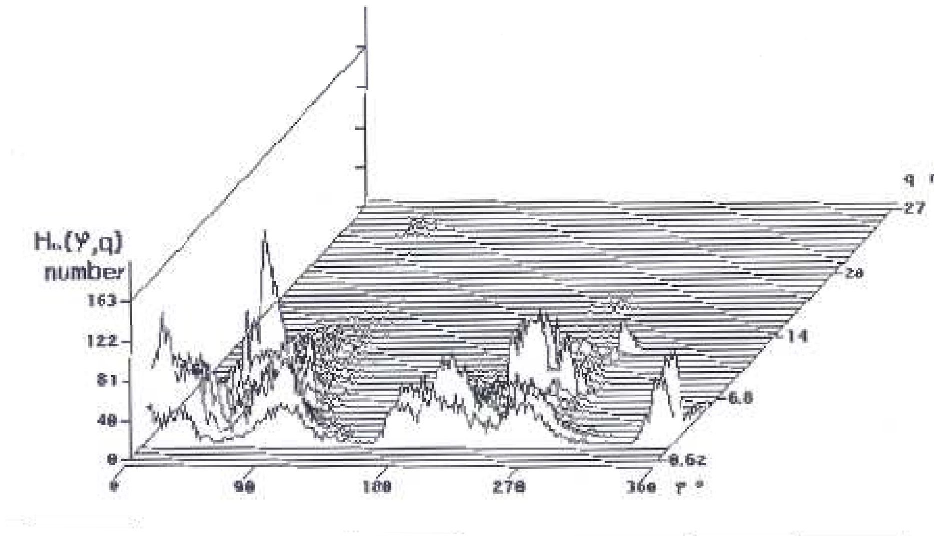


Fig.5.15 – original 3-dimensional display of PD for stator bar 4 at voltage of 22 kV, 50 Hz

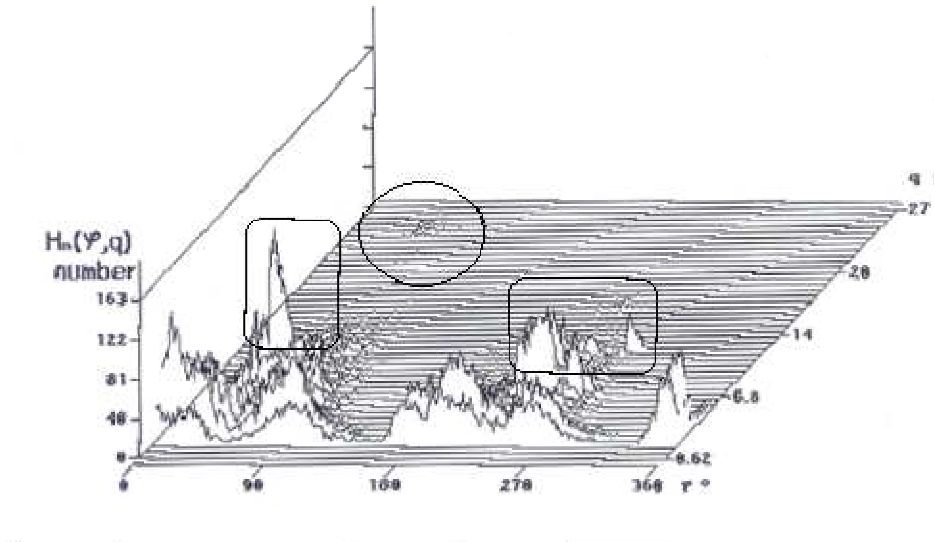


Fig.5.16- changed 3-dimensional display of PD for stator bar 4 at voltage of 22 kV, 50 Hz

Inside the geometric figures – Fig.5.16 - it is shown irregular discharges that were not supposed to exist in a normal pattern.

Though it is not easy to predict the cause of some of the irregular discharges, the Fig.5.17 shows a *quite accentuated asymmetric pattern and highest discharges on the positive half-cycle*. In the future this may lead to problems *between main insulator and the copper conductors*.

5.2.7 Stator bar 5

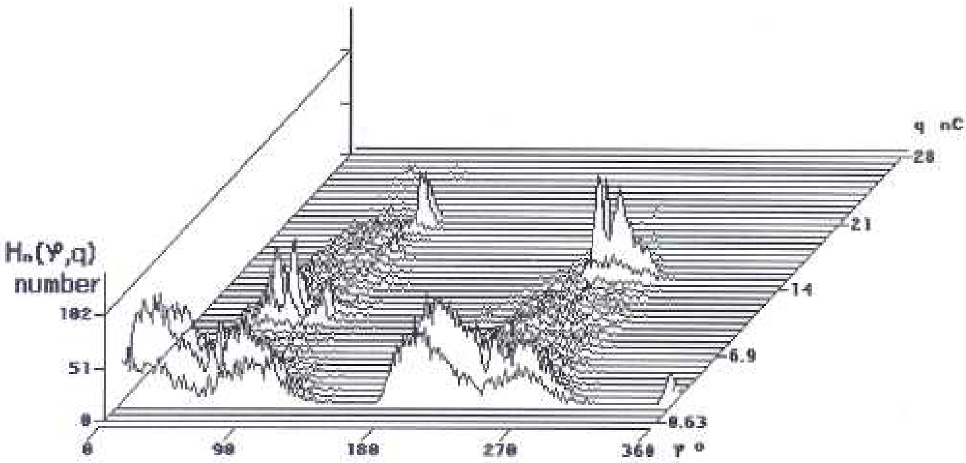


Fig.5.16 - original 3-dimensional display of PD for stator bar 5 at voltage of 22 kV, 50 Hz

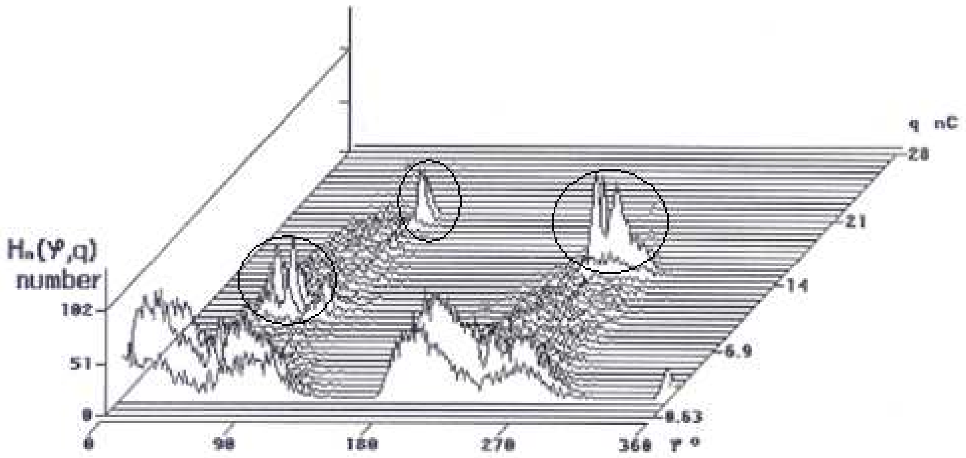


Fig.5.17 – changed 3-dimensional display of PD for stator bar 5 at voltage of 22 kV, 50 Hz

In the case of the stator bar 5 – Fig. 5.16 and Fig.5.17 – apart from disturbances marked with circles it can be seen a *slight asymmetric pattern in both half cycles with highest magnitudes in the positive half cycle*. In the future this can indicate *delamination in the main insulator*.

5.2.8 Stator bar 6

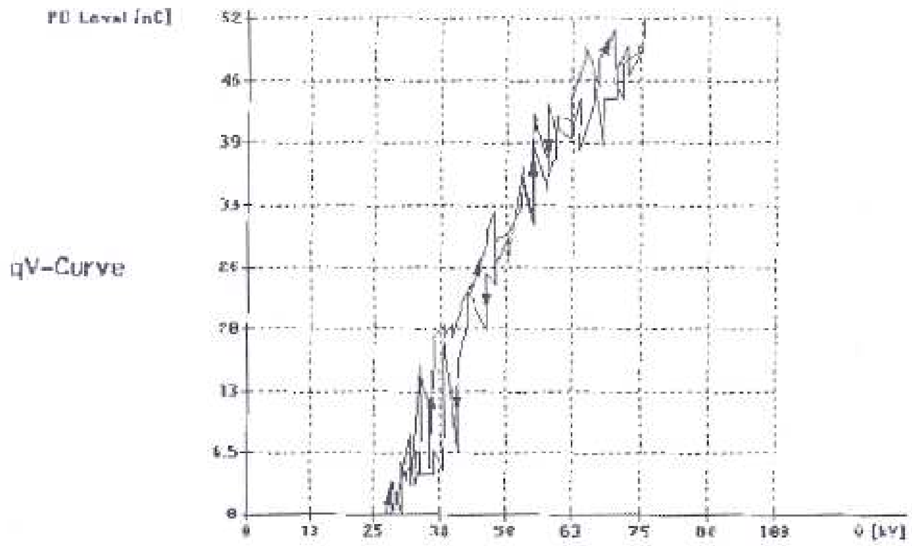


Fig.5.18 – q-U Curve for stator bar 6

In this case – Fig.5.18 -, the PDIV is higher than in stator bar 4, with the value above 25 kV. This value is quite good for this kind of insulation. However, the highest magnitude of the discharges is **52 nC** which can tell that the size of the biggest voids of this insulation is higher than the values of the biggest voids for stator bar 4. It is normal and it must be observed that the bars are not used with the same level of voltage. The stator bar 6 is used in bigger power generators than the stator bar 4.

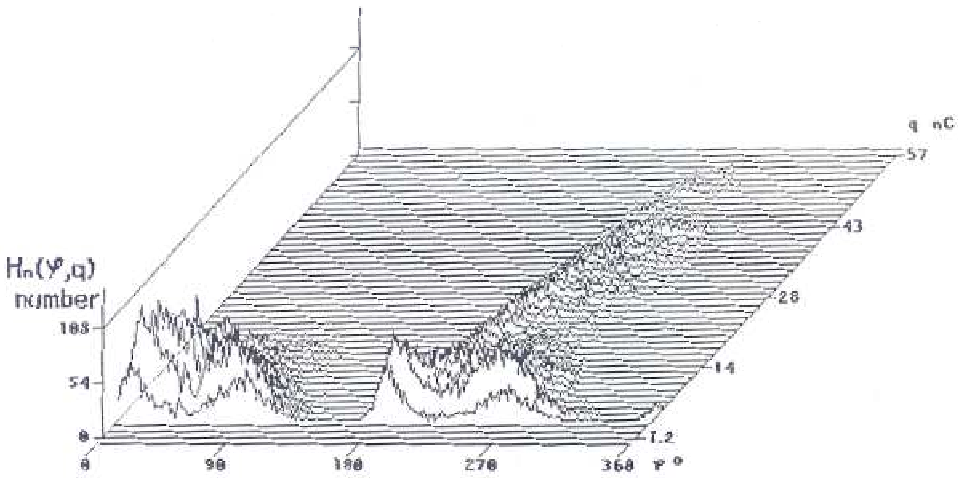


Fig.5.19 – 3-dimensional display of PD for stator bar 6 at voltage of 53 kV, 50 Hz

The last case – Fig.5.19 – is quite obvious the difference between half cycles. The high magnitudes present in the negative half cycle can stand for some kind of *bad contacts between layers of corona shield*.

5.3 Relationship between DF and PD measurements

5.3.1 Introduction

For the last decades many measuring tests have been performed not only for DF but also for PD. However a relation between those two measuring tests was never properly researched and never consensually accepted.

With the internship came the opportunity of developing this subject by performing a battery of tests in a set with more than one thousand bars produced for a hydro-generator used in a level of voltage lower than 10 kV.

The tests were performed for each bar exactly as it was described in the previous section. This was a long term project due to the fact of each bar had to be tested independently, for both types of measurements and only few bars could be at the same time in the testing station.

For the DF measurements the relevant values were the $tg\delta_{0.2Un}$ and the $\Delta tg\delta/\Delta U_{max}$. For the same stator bar but in PD test, the *maximum value of PD* was considered both for the routine measurement and for the analyze measurement – table 5.3.

These bars were all from the same type and composed with the same insulation system. The generator used more than one hundred bars and half of them belonged to the top layer while the others belonged to the bottom layer – Fig.5.20. This fact was responsible for the division of the bars in two different groups.

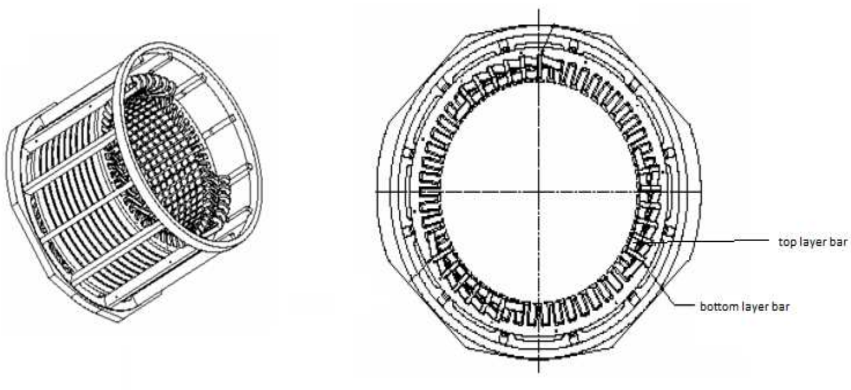


Fig.5.20 – generator's stator side view and generator's stator bar front view – top and bottom layers [43]

The only variation between top-layer bars and the bottom-layer bars exist in the endings due to interconnection aspects. The ending part of each bar changes because of welding differences.

5.3.2 Data presentation

The tests performed have the same layout of those shown previously for stator bar 1 and stator bar 2. The measurements of PD and DF are presented in small samples due to intellectual rights of manufacturer – Table 5.3, Table 5.4, Table 5.5 and Table 5.6.

Table 5.3 – PD and DF results for *routine measurements* – bottom-layer bars

Nr. set	Nr. bar	U_i (kV)	Qmax (nC)	tgδ at 0.2Un	Δtgδ/ΔU
1	397	10	4	8,20	0,67
5	522	15	4	9,02	0,79
1	24	8,5	5	9,53	0,57
1	149	10,5	5	6,31	0,60
1	165	7	5	9,76	0,88
1	400	6,1	5	7,56	0,60
1	53	6,1	6	6,41	0,73
...	...	...	...	...	...
...	...	...	...	...	...
...	...	...	...	...	...
3	463	13	22	9,84	0,90
3	476	12	22	8,82	0,49
5	497	14	22	8,68	0,59
5	507	10	22	7,98	0,56
5	510	11	22	7,75	0,61
5	495	11,5	23	7,73	0,53
5	502	11	23	10,37	1,72
7	526	10	26	8,77	0,68

Table 5.4 – PD and DF results for *routine measurements* – top layer bars

Nr. set	Nr. bar	U_i (kV)	Qmax (nC)	tgδ at 0.2Un	Δtgδ/ΔU
2	564	9,5	5	9,48	1,04
2	566	10,5	5	9,91	0,97
2	567	9,5	5	9,04	0,83
2	534	6,1	6	8,56	1,21
2	604	6,1	6	8,40	1,01
2	619	9	6	9,45	0,90
2	836	7,5	6	12,29	0,90
2	918	6,5	6	6,62	0,62
…	…	…	…	…	…
…	…	…	…	…	…
…	…	…	…	…	…
8	1056	14	22	9,00	0,73
6	1046	7,5	23	8,56	0,57
6	1048	10	23	9,40	0,68
6	1050	11	23	8,68	0,54
8	1055	11	23	8,35	0,64

Table 5.5 – PD and DF results for *analyze measurements* – bottom layer bars

Nr. set	Nr. bar	Qmax (nC)	tgδ at 0.2Un	Δtgδ/ΔU
1	397	3	8,20	0,67
1	24	4	9,53	0,57
1	149	5	6,31	0,60
1	165	5	9,76	0,88
1	96	5	7,17	0,50
1	173	5	6,94	0,56
1	225	5	5,80	0,64
5	522	5	9,02	0,79
…	…	…	…	…
…	…	…	…	…
…	…	…	…	…
5	489	22	8,80	0,73
5	491	22	8,92	0,69
5	497	22	8,68	0,59
5	502	23	10,37	1,72
7	526	23	8,77	0,68

Table 5.6 – PD and DF results for *analyze measurements* – top layer bars

Nr. set	Nr. bar	Qmax (nC)	tgδ at 0.2Un	Δtgδ/ΔU
2	566	4	9,91	0,97
2	567	4	9,04	0,83
2	564	5	9,48	1,04
2	709	5	7,32	0,66
2	836	6	12,29	0,90
2	933	6	8,37	0,63
...	...	...	...	...
...	...	...	...	...
...	...	...	...	...
6	1050	23	8,68	0,54
8	1056	23	9,00	0,73
8	1055	23	8,35	0,64
6	1028	28	9,30	0,50
6	1015	28	11,33	0,91

The PD *routine measurements* were performed during 1 minute and 30 seconds at a nominal voltage U_n, while the *analyze measurements* were performed during 2 minutes at a voltage of $1.5U_n$.

The first column has the number of the set from which the bar belongs. This number along with the number of the bar is just a control number. Bars with odd set number belong to the bottom layer while bars with even set number belong to top layer.

The U_i column presented on the routine measurement stands for inception voltage, which is the first value with manifestation of PD. The requirement for the value of this type of bar states that the value must be higher than 6,07 kV.

The requirements for the PD highest value in both measurements were a value less than 50 nC.

It is understandable by reading the tables that all the bars met the requirements.

5.3.3 Data analysis and comparison

In terms of analysis the main objective was trying to relate the PD levels with the levels of DF or DF tip-up.

In order to do so, bars were separated, as it was said before, in top layer and bottom layer groups. Then, all the values were ordered in increasing value of PD magnitude. From that point, it was calculated for each level of PD the mean of *tgδ at 0.2Un* and the mean of *Δtgδ/ΔU*.

Later, plots were given automatically by the *Excel* program along with a linear regression and consequent equation that describes the curve. It was given different weights for each value of PD depending on the number of measured results for each particular PD value.

For instance, in Table 5.3, there were two pairs of measures (Q_{max}, $tg\delta$) with Q_{max} = 4 nC and four pairs of measures with Q_{max} = 5 nC. The weight given to the value Q_{max} = 5 nC is twice the one given for the other value. This will influence the trend-line and the equation obtained.

The plot obtained for the bottom-layer bars with the relation between $tg\delta$ and Q_{max} is in Fig.5.21 and Fig.5.22.

The equation and the correlation square (R^2) are obtained automatically by the program. The symbol R stands for the correlation and it will always be a value between -1.0 and +1.0. If this value is negative there is a negative relationship; if it is positive, the relationship is also positive [44]. The generic formula for the correlation is:

$$R = \frac{N\sum xy - (\sum x)(\sum y)}{\sqrt{[N\sum x^2 - (\sum x)^2] - [N\sum y^2 - (\sum y)^2]}} \tag{5.1}$$

Where:

N – number of pairs of scores

Σxy – sum of the products of paired scores

Σx – sum of x scores

Σy – sum of y scores

Σx^2 – sum of squared x scores

Σy^2 – sum of squared y scores

5.3.4 Plots for the relation between Dissipation Factor (tgδ) at 0.2 U_n and Partial Discharges (Q_{max})

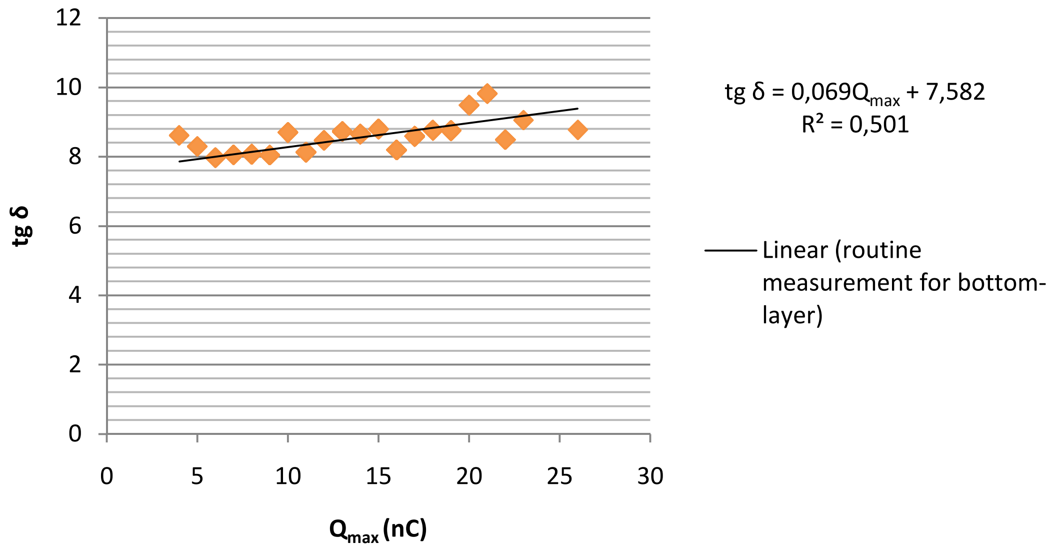


Fig.5.21 - plot of relation between tgδ and Q_{max} for bottom-layer stator bars in routine measurement

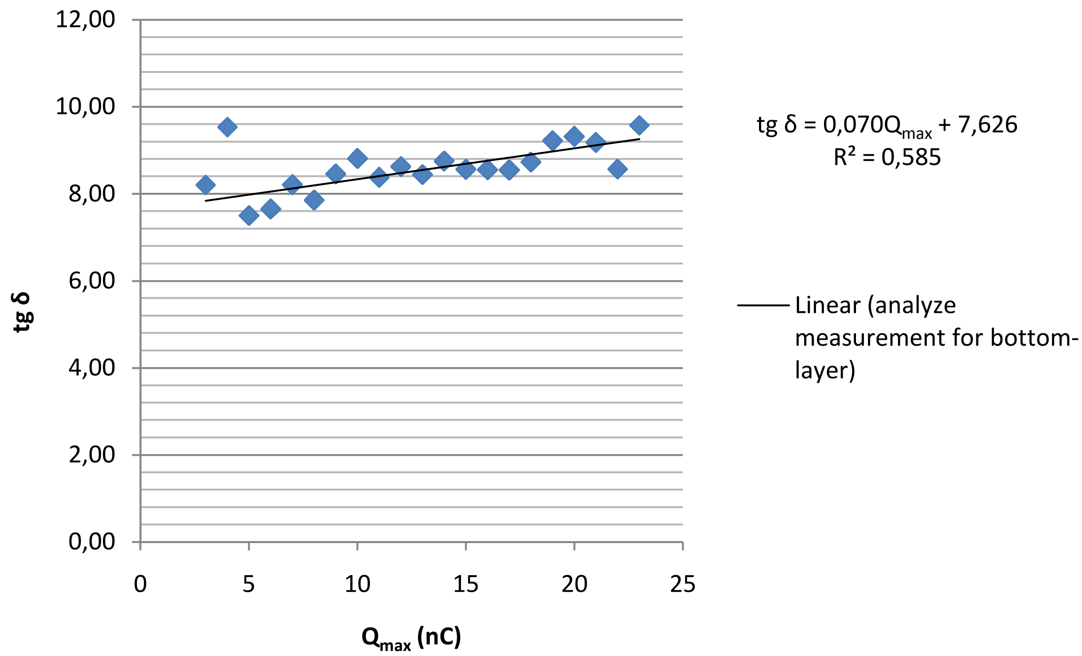


Fig.5.22 - plot of relation between tgδ and Q_{max} for bottom-layer stator bars in analyze measurement

The plots given for the bottom-layer in each different measurement have positive correlations - Fig.5.21 and Fig.5.22.

In a positive relationship, high values on one variable are associated with high values on the other and low values on one are associated with low values on the other [44].

The correlation, for the case in Fig.5.21, is R = 0,708 while for Fig.5.24 is R = 0,765 which are both **fairly strong positive relationships**.

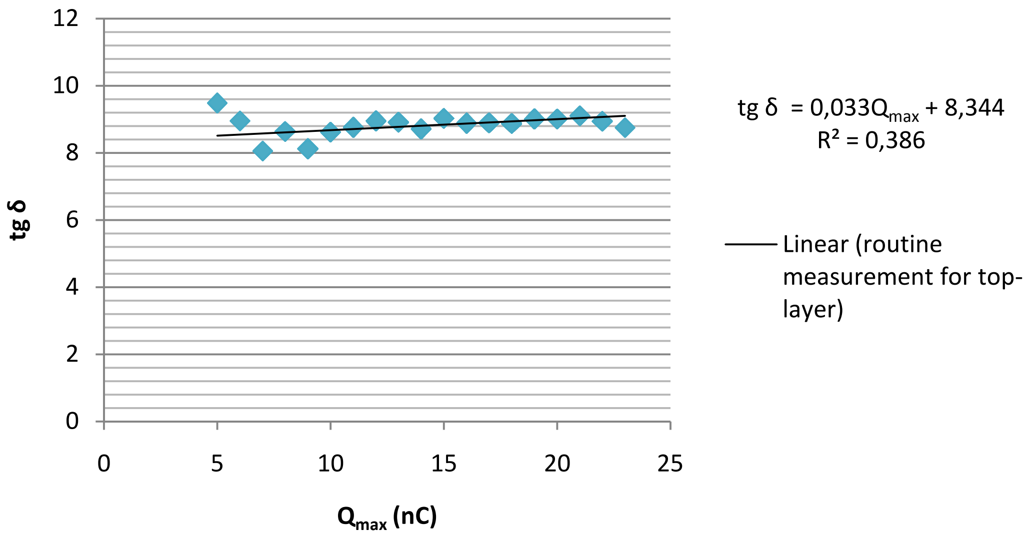


Fig.5.23 - plot of relation between tgδ and Q_{max} for top-layer stator bars in routine measurement

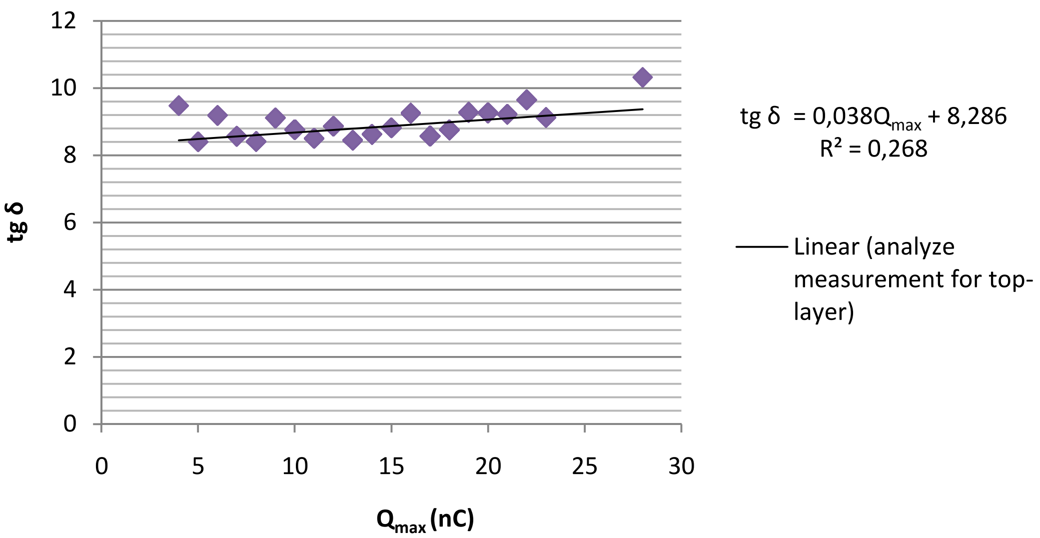


Fig.5.24 - plot of relation between tgδ and Q_{max} for top-layer stator bars in analyze measurement

In the case of top-layer bars, the **relationships are also positive** – Fig.5.23 and Fig.5.24. The correlation factors are R = 0,621 for Fig.5.23 and R = 0,518 for Fig.5.24.

These values are not as high as for the bottom-layer bars, and the reason is not directly connected with the kind of insulation system used. The insulation which composes the bars is the same either for bottom or for top layers. This discrepancy can only be explained due to differences of the bar endings, as it was said before, or with errors during the measurement process. However, the success of these measurements along with the attempt of finding a correlation was reasonably achieved.

5.3.5 Relation between Dissipation Factor tip-up (Δtgδ/ΔU) and Partial Discharges (Q_{max})

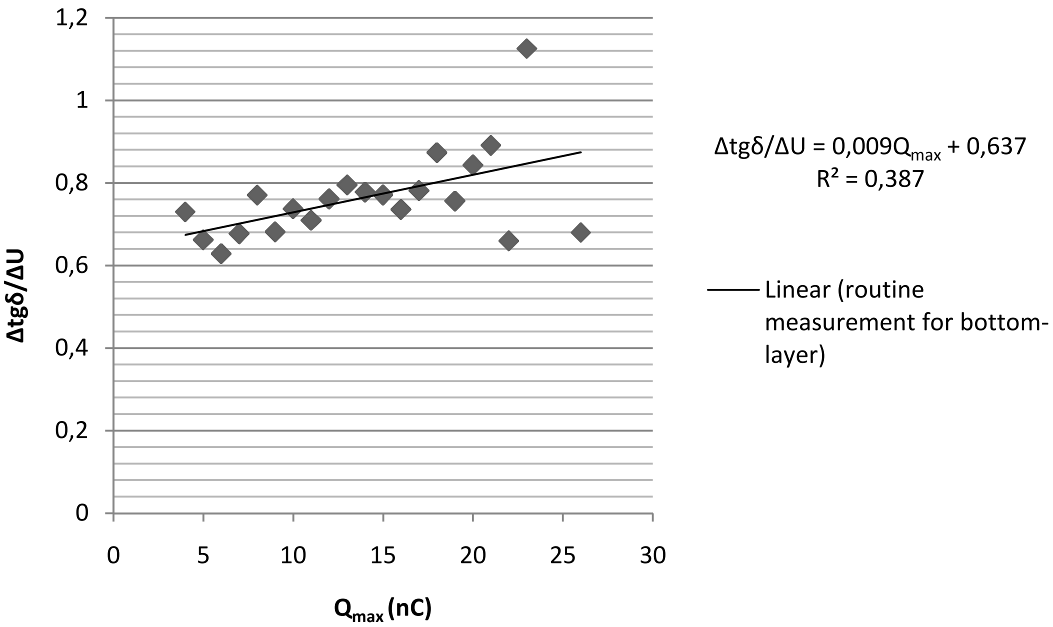


Fig.5.25 - plot of relation between Δtgδ/ΔU and Q_{max} for bottom-layer stator bars in routine measurement

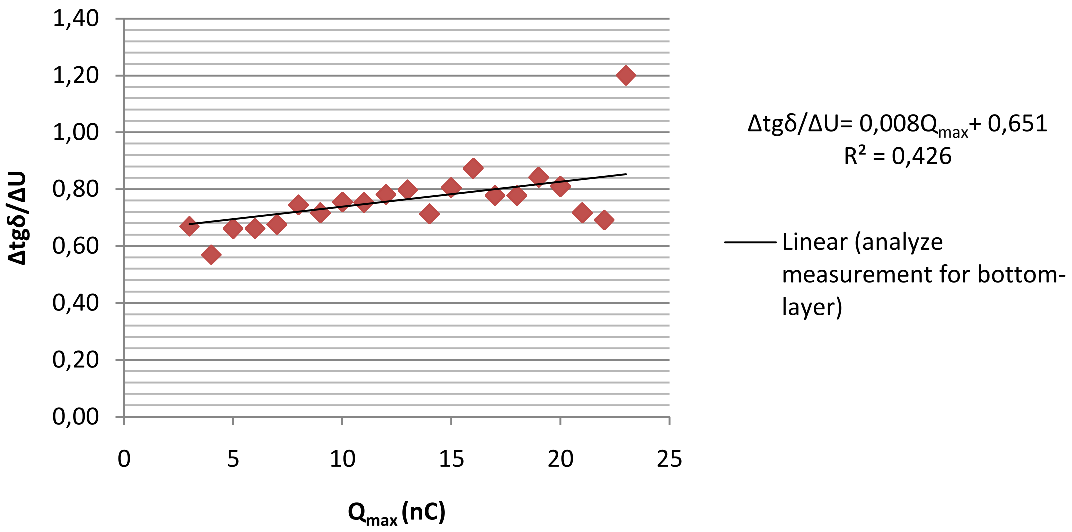


Fig.5.26 - plot of relation between Δtgδ/ΔU and Q_{max} for bottom-layer stator bars in analyze measurement

For the bottom-layer measurements the correlation factor is R = 0,622 for Fig.5.25 and R = 0,653 for Fig.5.26 and both are positive correlations.

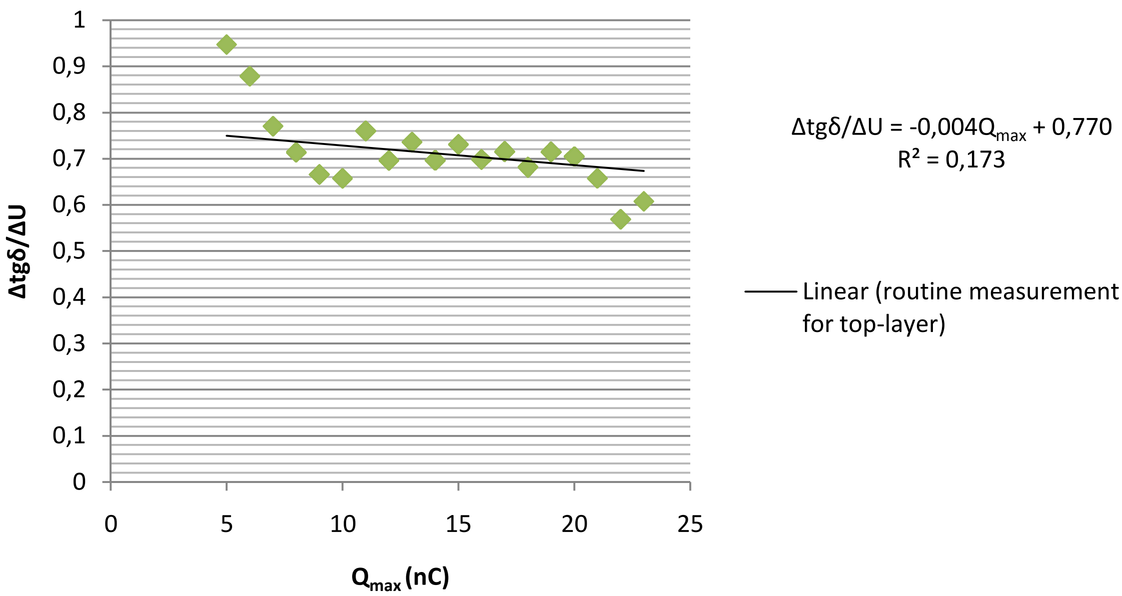


Fig. 5.27 - plot of relation between Δtgδ/ΔU and Q_{max} for top-layer stator bars in routine measurement

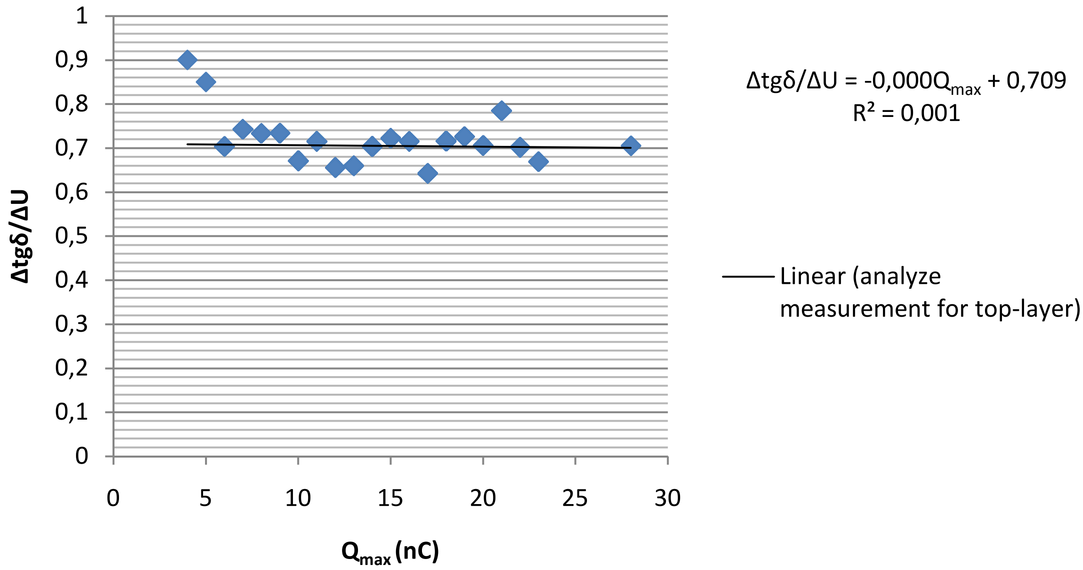


Fig.5.28 - plot of relation between Δtgδ/ΔU and Q_{max} for top-layer stator bars in analyze measurement

For the top-layer measurements the correlation factor is R = -0,416 for Fig.5.27 and R = -0,032 for Fig.5.28.

These are negative correlations and the values are not strong. Thus, comparing top-layer with bottom-layer measurements there is a big divergence of values. As result, the attempt to find a relation between these two factors (Δtgδ/ΔU and Q_{max}) was unsuccessful since the differences found between both layers are quite big.

CHAPTER 6
Conclusions

6.1 Accomplishment of the objectives

The knowledge of these two tests performed and described in this dissertation is not widespread. As a result of that, it was of great difficult to compile information about this theme and its scientific importance on the energy area. In Portugal, the group of expert people in this subject is a minority and there was the necessity of presenting a work that could contribute for the spread of this information.

In order to do so, the first action taken was the gathering and posterior reading of all the relevant data available. It was then chosen the parts that were considered more important to mention and written in chapters 1 and 2.

The first three objectives defined before the developing of the work were discussed in chapters 2 and 3. There was identified the testing procedures, quality parameters and typical patterns for insulation failures not only in stator bars but also in generators in general. During Partial Discharges Measurements, in the presence of a qU-curve, the essential features are the *highest PD magnitude*, the *PDIV* and the *behaviour of the curve* itself. While observing the 3D-display of PDs, for later pattern interpretation, attention should be given to the detection of similarities between patterns with possible analogous situations. There are some typical patterns and characteristics that can lead to the identification of prospect failures in insulation systems.

In PD tests there are *routine* and *analyze measurements* and their difference consists on the variation of the test measuring time. The *analyze measurement* is able to record several parameters and, for that reason, is the most complete. In the *routine measurement* the qU-curve is presented along with the *highest PD magnitude* and the *PDIV*. These are parameters that can clarify the quality of the insulation in terms of voids. Lowest PDIV means that the level of voltage needed to ignite the discharges is not so high.

In chapter 2 were presented the external and internal discharges possible in generators. External discharges can only happen when the generator is totally assembled and after some time in usage. On the other hand, internal discharges can also happen in newly manufactured bars.

Among all the failures, the most important defect that can be found is the separation between the main insulation and the conductors due to different load and temperature cycles. The pattern inherent to this failure is *asymmetric in both positive and negative half-cycles with the highest discharges on the positive half-cycle*.

Whenever possible, it was done the interpretation of the results which was also a defined objective. One of the conclusions it is worth mentioned is that it is not always possible to predict the causes and future failures on generator components. There are patterns that are very clear about the possible issues but there are others that are not so obvious. This uncertainly related with some patterns can happen due to combined problems in insulation systems and, sometimes, even noise connected with the testing surrounding ambience. Sources of PD can vary due to small changes in ambient or operating condition. Thus, caution must be taken so that successive and future tests are done under similar conditions. Finally, other patterns just become clear after some years of usage of the components, since voids become bigger and bigger with the ageing time. The best test that still exists now is the *visual inspection* and it is only possible when the machine is not working nor connected to the network.

The DF measurement is an important tool for the diagnosis of the HV insulation in generators in common and more specifically in stator bars. The measurements of DF and DF tip-up can automatically reveal if the curing and VPI processes were correctly carried out. In case of quality tests, the DF measurement works as a true or false indicator. The values are compared with the values given for such stator bar and if they are inside the range it passes as acceptable. Moreover, with the DF test another parameter is also measured – the capacitance. This value is intrinsic to the insulation and should not vary much with the rise of voltage. It can be calculated theoretically if the bar parameters are given.

It is also worth mention that one of the disadvantages of measuring DF remains from the fact it can only be applied in single stator bars or with the generator out of service.

During the development of this work there is a reference to the attempt of finding a correlation between PD and DF measurements. The results show that this correlation can be real. It was found a *strong positive correlation* between Dissipation Factor (tg δ) at $0{,}2U_n$ and PD magnitude at nominal voltage (U_n) and also at $1{,}5U_n$. The results for top and bottom layer bars show similarities and the correlation factors are strong.

Although, in general, all relationships tell about the correspondence between two variables, there is a particular type of relationship that states that the two variables are not only in correspondence, but that one *causes* the other. This is the key distinction between a simple *correlational relationship* and a *causal relationship*. A *correlational relationship* just says that two things perform in a synchronized way [44]. In this case, it is not clear if we are in the presence of a *causal relationship*. However, there is, at least, a simple *correlational relationship* and this can be useful in future measurements. As it was said previously, the PD measurements are only performed when specifically demanded. This study can provide a future advance in the prediction of the magnitude of PD only with the measured value of Dissipation Factor. Further studies are required in this area for the validation of this relationship.

The same cannot be confirmed about the relation between DF tip-up ($\Delta tg\delta/\Delta U$) and PD measurements. In this case, the results were ambiguous and lack reliability. The correlation factors were weak for several samples. More measurements should be done, futurely, to prove the absent of a relationship.

6.2 General Conclusions

The development of production and manufacturing processes is highly influenced by results achieved after testing or by causes and sources of discharges identified. After performing these actions, corrective actions can be executed to reduce or even eliminate internal and external stator bar discharges.

The implementation of onsite and continuous on-line measurements can be a great advantage for maintenance of power plants worldwide, since it gives real-time information on ageing processes and development of certain failures. More information about the development of these processes can be found in [45] and [46]. Therefore, the supervisor can trace an upcoming plan for future changes in the apparatus with enough time.

However, for this to happen, electrical companies responsible for these machines must understand the relevance of such monitoring. It not only can prevent total failure in the generator but it also can be economically very attractive. As it is understandable, this is the most relevant item of evaluation in every new technology. This process can be rentable if applied in newly machines and can prevent undesirable outage time, saving a considerable amount of money.

Finally, comparing this work with others in this area, for example [47] and [48], it is understandable that all of them are unanimous in relation to the advantages of PD and DF measurements for the diagnosis of insulation of HV apparatus. Although the identification of failures and sources of PD is the main goal in all the papers, not all follow the same paths to reach this objective. For instance, there are some that simultaneously to PD measurement also perform vibration measurement on the stator core. Others give relevance to the evaluation of Ozone concentration during the tests which is a symptom of the presence of corona effect.

This dissertation differs from the other studies due to the analysis done on new single stator bars and the attempt to find a real relationship between the PD and the DF measurement. It is once more worth mention that it was based in a large amount of samples which not always can be available for studying purposes as it happened during this work.

6.3 Further Work

The analysis presented on the second part of the dissertation was based on newly single stator bars tests. It can also be here suggested, for further work, tests on complete windings which can complement those previously here presented.

Although some cases of failures were described in the interpretation section, these were just a small part from a large amount of patterns that can be found in several defects. A continuous assembly of information is needed to compare between different situations that can happen.

Finally, the correlation found, between Dissipation Factor and Partial Discharge, needs a deep analysis and more test measurements to definitely consolidate these conclusions. However, it can only be done with the access to huge amount of samples only available in production factories.

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