Review of Partial Discharge and Dielectric Loss Tests for Hydropower Generator Bars

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Abstract

Condition assessment of hydropower generators is important to ensure high serviceability of power stations. Many of the in-service generators are old and current load operation schemes demands more than the design load, which makes the remaining lifetime of the generators uncertain. The reviewed literature shows many works regarding identifying signature PRPDA patterns for different relevant defects in the generator. Calibration is however impossible, due to variable signal propagation in the generator from the partial discharge source. The results regarding complex permittivity as function of frequency as a measure on water ingress are promising. However, the field grading paint at the ends of the bars are affected by the low frequency and gives a variable capacitance. The literature is still focused on qualitative measurements without giving quantitative answers.

1. Introduction

The majority of the Norwegian hydropower generators was installed between 1960 and 1990, and many of these will soon reach their expected lifetime and therefore refurbishment is needed [1]. In addition to age, new operation loading schemes demands more than the design load, with frequent starts and stops that reduces the lifetime with an unknown quantity. To plan any replacement, it is important to know whether the bars are in a good shape, should be considered replaced or if refurbishment should be performed.

The main purpose of this review is to describe important methodologies to investigate insulation deterioration electrically. First, a description of the failure mechanisms is presented before an evaluation of the most important off-line electrical detection methods are given.

2. Electric design

Previously, until the 1970s, engineers designed generators based on experimentally based handbooks and analytical calculations. The quality of the material used were uneven and the design was therefore often over dimensioned. This can be illustrated by the fact that some generators that were installed as early as in 1920s are still in service [2]. Since then, the material quality and design tools have developed and the ratings are more accurate related to the specified operation conditions.

A detailed historical overview can be found in the review of Boulter and Stone [2]. The most important aspects are summarized in the following paragraph. The first available insulation was based on natural deposits of fibers of cellulose, silk, flax, cotton, wool and natural resins derived from trees, plants and insects and from petroleum. Mica in different shapes become popular due to its excellent withstand strength to partial discharge activity, which is inherit present in stator insulation. It was combined with different kinds of resins, in the beginning asphalt was used, and today refined and synthetic materials, such as epoxy or polyester resins are used. The mica has developed from simple mica splittings to mica paper, a product where the mica is refined and has even better properties. This development has led to thinner insulation, operating at higher electric stress with smaller safety margins.

The modern groundwall insulation in hydropower stators consists of three major parts; a barrier, a support and a filler. It is constructed as a thin tape, wrapped around the conductor in many layers, see Figure 1. The barrier material is usually mica flakes or mica paper, which has a strong resistance to partial discharges, but need mechanical support, usually provided by glass fiber, PETP film or polyester fleece. To avoid air bubbles in the tape and between the tape layers, a binder material of polyester or epoxy resin is used. The resin is usually impregnated to the rest of the insulation under vacuum and pressure, or just heated and pressurized. Additionally, the insulation system consists of outer and inner corona protection, as well as filler between the copper strands and inner corona protection layer, to reduce corona activity and preserve the shape.

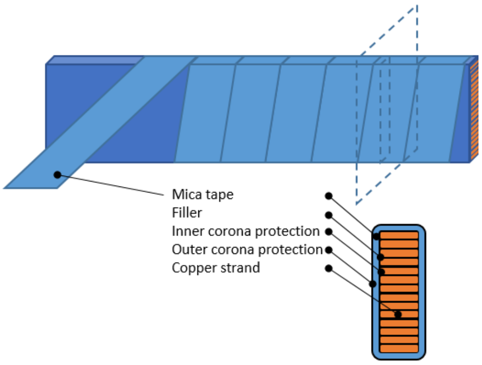


Figure 1: Physical structure of the main part of a generator bar.

3. Failure mechanisms in stator insulation

It is important to distinguish between fast and slow deterioration mechanisms to take correct action to prevent breakdown. Defects might originate during production or during service. Several different external stresses facilitate deterioration that could cause breakdown. They can be categorized in four; thermal, electric, ambient and mechanical – TEAM. These stresses, which could initiate ageing, happen often in combination, which enhances the deterioration process. The ageing process introduces localized defects and also weaken the whole material in general. It is common that stresses in combination with electric stress results in detectable partial discharges (PDs). Internal voids are impossible to avoid during the impregnation process, in which voids can cause internal discharges during voltage application. The PD from internal voids could become harmful over time. An overview of the breakdown steps caused by external stresses is given in Figure 2.

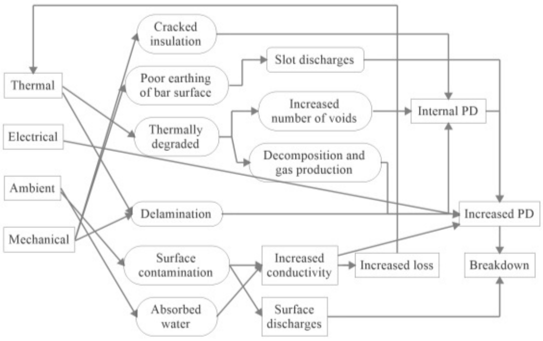


Figure 2: Different kinds of external stresses can lead to electrical breakdown via different processes.

One attempt to reveal the most frequent failure mechanisms was done by Cigré working group A1.10, who conducted a worldwide survey [3] in 2009. Sixteen utilities and one manufacturer in total of five countries replied to the questionnaire. Insulation damage, which mainly include the groundwall insulation of the winding, was reported as the largest cause of failure. The damages were mainly correlated to stator fault, 45 %, followed by insulation burning, 13 %, surface erosion, 12 %, and rotor fault, 12 %. The root cause of the insulation failure was reported as follows; 30 % suffered from ageing, 25 % had contaminations, 22 % suffered from internal partial discharge, 10 % had loosening of bars and 7 % had reported thermal cycling or overload. Fatigue of materials was reported in 16 % of the failures and loosening of rotor parts was reported in 13 %.

The most relevant standard for condition assessment of the stator insulation. is IEEE std 1434, IEEE Guide for the Measurement of Partial Discharges in AC Electric Machinery [4]. It defines three types of PD activity that are considered the most severe:

a. Discharges in voids or delaminations within the insulation
b. Discharges occurring between the surface of the coil/bar and the stator core, commonly known as slot discharge
c. Discharges in the end-winding area and circuit ring bus bar

Partial discharges are inherently present in stator insulation due to voids from the impregnation process. The most important diagnostic goal is therefore to distinguish these three harmful PD activities from the less harmfully present PDs, as the voids in aged insulation may have different behavior than voids in new insulation. Hudon et al. [5] found that no voids were observed inside the lateral side of the groundwall. All voids were at or close to the corner of the bars. This coincides with where the field enhancement occurs.

4. Diagnostic techniques used today

There exist several common methods online or offline of detecting deteriorations in insulation. Online techniques can monitor and discover trends in temperature, PD, ozone production, end winding vibration and leakage current, see e.g. the review in [6]. These monitoring techniques identifies changes in the measurements and by that indicate if the insulation deteriorations are beyond the preset safety limits. Online tests are limited by the operating voltage and measurements on a complete generator. Offline measurements with significant dismantling allows other electrical stresses to be applied, and isolating different parts of the generator from each other. Research on different mechanisms is mainly done on single bars or simple insulation systems to control the parameters. Strong offline tests include visual inspection, surface DC resistance test, PD test, tanδ at $0.2U_N$, $0.6U_N$, $0.8U_N$ and U_N, polarization/depolarization measurements and dielectric spectroscopy. These methods have the possibility to distinguish between different failure mechanisms and indicate the severity level.

Most of the electric tests are made to describe operation at 50 Hz. A few tests consider lower frequencies, and one standard exists for this measurement [7]. However, the comparison factor between 50 Hz and 0.1 Hz are based on empirical numbers from asphalt systems and are not necessarily useful on other insulation systems.

There exist many relevant test standards, some of the most relevant are mentioned in this paper. Relevant PD tests for stator are briefly described and discussed by Stone et al. [8] in a format of a simple FAQ for a broad audience. Standardized test methods can be found in IEEE std 1434-2014 [4] and IEC 60034-18-34 [9].

The electrical tests will be empathized here. The dielectric dissipation factor and complex permittivity as function of frequency provides no indication of the distribution of the loss within the bar, whereas PD tests can give indications to which defects that are present due to their partial discharge phase resolved pattern signature (PRPDA).

5. Experience with partial discharge tests

Each defect has its own unique phase resolved partial discharge amplitude pattern (PRPDA) [10]. This and the magnitude of the PD help to identify the PD source and decide if it is necessary to take action, and it is not surprising that detection of PDs is a popular diagnostic method. Hudon et al. [10] have performed several studies regarding correlation between PRPDA and the specific defects and created a large database in Hydro Quebec as a reference for new PD measurements. A summary of the findings are compiled in Figure 3. However, the PRPDA from different sources might overlap each other when measuring on a bar or generator. This makes it difficult to uniquely determine the main PD source. IEEE std 1434 states that the user should be cautioned that no technology exists today that can uniquely identify the exact source of the defect causing PD, based on the PRPDA.

In order to get comparable results, calibration is important in all test methods. However, calibration in hydropower windings is difficult. IEC 60034-27 [11] states that it is not possible to calibrate the PD signal from the windings in machines due to pulse propagation, resonance and mutual cross coupling. This is why rotating machines are one of the few items of high-voltage equipment that do not have PD specifications [4]. Calibration procedures are then changed to normalization procedures that gives a normalized signal referred to a signal originating at the measurement spot. Absolute numbers are therefore difficult to compare between different machines due to many different designs and signal modification during signal propagation. Pattern recognition and trending are therefore preferable for diagnosis of hydropower windings.

Bélec et al. demonstrated how PD monitoring can be used to plan re-winding of a 202 MVA hydro generator [12]. The PD rate and maximum PD amplitude were stable until 2004 when it rapidly started to increase. They read this as a pre-warning and three years later, the generator was re-winded. As a comparison, the same group described another case in [13], a 184 MVA generator that suffered from slot PD. The PD monitoring showed, however, stable and high PD numbers until failure. The PD rate and magnitude fell after re-winding, but slowly increased for 6 years until the article was published. This illustrates that PD monitoring is not always informative if the PD rate and magnitude changes slowly and are interpreted as constant. Despite this, continuously monitoring is beneficial, especially on large generators in remote areas where it is very costly to transport personnel for routine tests [14] and there is a high cost of repair.

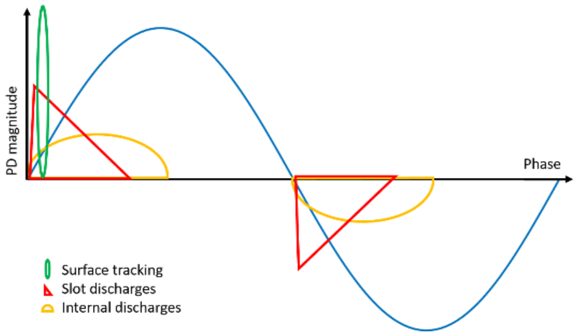


Figure 3: Typical shapes of PRPDA patterns for different defects. The PDs are mainly happening on rising edge.

To understand the PD mechanisms, it is necessary to investigate single bars to reduce the number of unknown variables as much as possible. Therefore, many researchers focus on varying a few parameters on single bars or model insulation systems. The variations try to mimic realistic stress that the bars might encounter during service. Hopefully, these artificial defects can give recognizable PD patterns that can give a relevant reference for later measurements with unknown source.

Generator windings are exposed to a high service voltage. An accelerated electric test could be a voltage endurance test at a higher voltage than the rating. An example of that was a test performed at 59.5 kV, both AC and DC, for up to 2200 hours until breakdown at a constant temperature of 110 °C, on six Roebel bars rated 13.8 kV [15]. PRPDA tests were performed at 8 kV AC. For AC voltage endurance, the PD count as function of time increased between 7 % and 180 % for the different bars, whereas for DC voltage endurance tests, the PD count decreased between 35 % and 60 % on the different tested bars. This indicates that AC overvoltage is more dangerous than DC overvoltage.

Voltage endurance tests at 8.3 kV/mm [16] (15 kV, 50 Hz, 2.5 times service stress) with PD monitoring show a rapid increase before a slowly decrease over a longer time. Measurements 25 h before breakdown (short relative time) show no indications of an electrical breakdown in development. This was explained by the possibility of transition from streamer to Townsend mechanism or that acids can be formed inside the gas void, that suppresses the PD activity.

PD as function of temperature was found in [16], and there was a slight increase in the PD pulse count up to the design temperature at 155 °C, where temperatures above resulted in much higher PD pulse rate. The PRPDA pattern changed slightly, but was comparable to the start. The same study used thermal cycling to mimic rapid start and stops and a temperature gradient in the insulation. The temperature of the copper conductor increases rapidly, while the temperature in the insulation increases more slowly, as it is cooled by the surrounding material. In this experiment, the bar was heated for 30 min by a current to 155 °C, and then cooled by a fan for 30 min. 155 °C was chosen because it was the design limit. The PD rate increased much until about 2000 cycles, where the increase was slower. This can indicate that the number of internal voids increased rapid until a certain saturation level.

Slot discharges are harmful and also one of the most frequently occurring failure modes and was therefore studied by Hudon et al. [17]. The bars were placed in slots with 0, 0.25, 0.5 and 1 mm gap. The PD magnitude and activity increased significantly for both gap size and temperature, especially above the glass transition. However, increasing the temperature, the insulation was expanded and hence the slot gap decreased. The PRPDA patterns were documented and described, but the background physics were not explained.

PDs can also be detected by high frequency (HF) methods. HF sensors can be embedded in the machine and provide non-galvanic-contact with the machine [18].

6. Experience with dielectric loss tests

The dielectric losses, or leakage currents, can be described by several quantities. The dissipation factor, tan(δ) is the most common, especially at 50 Hz, whereas the complex permittivity or capacitance can be found in either frequency (dielectric spectroscopy) or time domain (polarization/depolarization test). In principle, it is possible to perform a Fourier transform to get to the other [19]. The focus in the following will be in the frequency domain. It could be mentioned that dielectric spectroscopy is mainly performed on single bars or coils, rather than on complete windings [6].

Farahani et al. [19] performed dielectric spectroscopy on single bars at different temperatures and during thermoelectrically ageing. The tan(δ) curve as function of frequency changed for all frequencies. During ageing, it decreased during an initial period, before it increased. The loss increased for increased temperature, but the loss-frequency shape was preserved with just another amplitude factor. After ageing, the insulation was considered brittle and general thermal degraded.

Dielectric spectroscopy can be used to detect changes in the loss, such as a loss increase due to water ingress [20]. Water has a higher conductivity, ion dissociation and permittivity than the mica-epoxy insulation and therefore the leakage currents increase significantly. Even small quantities of water can be detected if measurements are compared with results from the sample in dry condition recorded earlier.

The generator bars have end-corona protection that acts as field grading at some parts outside the stator core. This field grading material affects the measured capacitance at low frequency and should be considered if non-guarded measurements are performed. Taylor [21] described the end-winding contribution to dielectric spectroscopy, from 0.1 mHz to 100 Hz, and the importance of guarding when measuring the main insulation. The total capacitance could increase as much as 13 % for the lowest frequencies. At power frequency, this capacitance increase was only 0.05 % at 300 V and 1.5 % at 14.4 kV. The lower frequencies let the high voltage potential to be over a larger area than at higher frequencies.

PDs increase the losses in the insulation. These losses are more significant at a high voltage than at lower. The tip-up method is to compare the 50 Hz tan(δ) value at 0.2 U_N and 0.6 U_N. IEC 60034-27-3 [22] describes dielectric dissipation factor measurement on stator winding insulation of rotating electrical machines. By comparing the machine to itself, the variance between different units are eliminated. The main goal is to reveal voids that create PDs or other mechanisms that increase the loss. When the PD rate is too high, the conventional PD measurement systems do not count all. The dissipation factor is a measure on the average and can be suitable to indicate the total number of voids present in the insulation [16]. A too high PD rate could also result in a constant PD current, which is not possible to trig and give individual PDs.

Cimino et al. [23] used tip-up test to verify decreased strength at bending points of a bar. They vibrated a bar, while fixing one side. The contact point where the bending angle were largest suffered from the highest loss increase. The tip-up test revealed that voids, delamination or cracks were created due to the vibration.

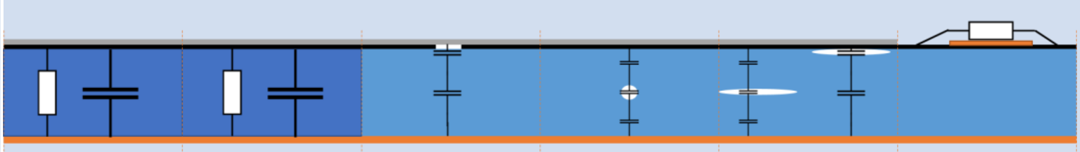
The standard, IEC 60034-27-3 describes a limit for allowed tip-up value. Sedding et al. [24] discussed this standard and questioned the limit. They think that more work is needed to verify or disprove the values. 210 stator coils and bars were tested and all met the 2 % requirement, but a significant number did not meet the 0.5 % tip-up requirement. This made them question if the limits were set too conservative.

7. Interpretation of the measured results

When online measurements of PD, ozone generation or temperature have detected significant changes in trending, offline measurements need to be performed to further investigate the generator and identify the root cause of the measurement. Offline tests can be performed with variable degree of dismantling. The more dismantling, the more certain about the defect location. However, this is a costly process and is only performed if necessary. It is then necessary to have accurate correlations between defect and measured result to identify possible root causes of the measurement.

Different defects produce different PRPDA that acts as signatures for the specific defect. This helps in condition assessment to identify the defect. The comprehensive study by Hudon et al. [10] provides a useful background for comparing different PRPDA patterns. However, different defects have overlapping PRPDA and it could be difficult to distinguish between the different defects. Research is therefore performed on single bars to control the variables and from that know the relation between failure and measurement. Slot gap distances are varied,

Table 1: Summary of the different deterioration mechanisms.

	Thermal	**H2O**	**Slot**	**Void**	**Delamination**	**Surface**
Electrical equivalent circuit						
Model	Resistance in parallel with a capacitance	Resistance in parallel with a capacitance	Two capacitors in series	Three capacitors in series	Two/three capacitors in series	Variable surface resistor
Ageing	Number of voids increases, overall condition is weakened	% of water increases, overall condition is weakened	The slot gap expands	The void expands or more arise	The delamination expands	More contaminations
Characteristic	The effective resistance is lowered	The effective resistance is lowered	Relative C in slot decreases, PD occurs	Relative C in void decreases, PD occurs	Relative C in void decreases, PD occurs	Conductivity and E increases, PD occurs
Preferred diagnostic method	Permittivity, tan(δ), PD	Permittivity, tan(δ)	PD, PRPDA, rate and magnitude	PD, PRPDA, rate and magnitude	PD, PRPDA, rate and magnitude	PD, PRPDA, rate and magnitude

temperature increased and lowered, deterioration by bar vibration, artificial voids inserted to the insulation and voltage endurance tests to describe how the defects can be measured. However, no detailed physical explanation of the measured signals has been presented.

The measurement of dielectric losses by dissipation factor or complex permittivity/capacitance is a useful tool to measure the overall condition of the generator bar. It is a good measure on leakage currents that might arise. These currents might originate from water ingress, overall more PD activity or just a general deterioration of the insulation strength. The loss-frequency curve might be compared to known loss sources and from that identify the source and perform the correct action.

There exists no complete physical explanation of the breakdown and pre-breakdown process and signal propagation within the bar. Therefore, absolute numbers for acceptance criteria are not proposed in the reviewed literature. This results in the limited test evaluation that trend changing of the variables for the same unit are more informative than comparing the absolute numbers with other generators. A summary of the described mechanisms and preferred detection methods is given in Table 1.

A condition assessment should reveal insulation defects before they cause breakdown. To do so, it is important to know which measured physical state that characterizes ageing, contaminations and internal partial discharges. When the physical state of these defects is known, it is possible to correlate the measured signal and the root cause of the signal. This leads to increased reliability of condition assessment and reduces the risk of unexpected breakdown.

8. Conclusion

Electrical condition assessment is currently performed on hydropower stator bars by mainly partial discharge, insulation resistance, dissipation factor and complex permittivity measurements. Partial discharges can give indications of the maximum void size or most severe defect and also the location. The phase resolved amplitude plot is a strong characteristic of which defect that causes the PD. Each source has each own signature and analyses can substantiate which faults that are present based on a PRPDA plot. The resistance measurement, dissipation factor and complex permittivity are measuring leakage currents. Whereas the resistance measurement is based on DC, the dissipation factor and complex permittivity can be found for a variety of frequencies. The frequency variation gives more information about the defect source and it is possible to identify the source. Water ingress and enlarged PD activity can be detected by frequency varied measurements. The physical explanation of deteriorations and how to make measurement are mainly qualitative in the literature. More research is needed to explain the quantitative relations and give a complete physical explanation.

9. Acknowledgement

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