PARTIAL DISCHARGES IN ELEVATOR MACHINERY

Lappeenranta–Lahti University of Technology LUT

Master's Thesis in Electrical Engineering

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Examiners: Professor Juha Pyrhönen

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ABSTRACT

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Partial discharges in elevator machinery

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Keywords: Partial discharge, elevator machinery, PDIV, PDEV, AFPMSM, low voltage, electrical machine, PRPD, complete stator winding, fractional slot winding

Partial discharges are usually less of a concern in low-voltage machines (below 1 kV). However, they can also occur in these machines, even if the rated voltage is below 1000 V. Cable reflections can double the supply voltage on machine terminals, resulting in higher than the designed voltage. Due to this overvoltage, partial discharges can occur even though they would not occur with nominal voltages. Low voltage machines are usually designed so that no partial discharges should occur. The organic insulating materials used in them are generally not resistant to partial discharges. Over time, partial discharge can cause faster deterioration than normal ageing processes, and therefore shorten the service life.

In this thesis, partial discharge measurements are carried out on a stator of an axial flux permanent magnet machine, which represents the technology and materials currently in use. The objective is to find out the inception and extinction voltages of the test stator, and how they relate to the operating voltages. Partial discharge measurements can be used to determine the condition of the insulation system by taking several measurements at intervals. From these measurements, a trend can be seen in the rate of change in the voltages with time and operation, which can give an indication of the condition of the insulation system.

The measurements are performed first on a new, unused stator, after which the stator is stressed in a tester for about three weeks. The measurements are then carried out again. The measurements show that the inception and extinction voltages are close to the voltage level that may occur during normal operation. Although the stator was stressed for only a short period of time, the results show a slight decreasing trend on the inception and extinction voltages of partial discharges. However, the uncertainty is quite large, and more measurements are required to see the trend with certainty.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT
LUTin energiajärjestelmien tiedekunta
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Teemu Pasanen

Osittaispurkaukset hissikoneistossa

Sähkötekniikan diplomityö
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Osittaispurkaukset jäävät yleensä pienemmälle huomiolle pienjännitekoneissa (alle 1 kV). Niitä voi kuitenkin esiintyä myös näissä koneissa, vaikka nimellisjännite on alle 1000 V. Kaapeliheijastukset voivat jopa kaksinkertaistaa sähkökoneen kokeman syöttöjännitteen, jolloin voidaan saavuttaa myös suunniteltuja suurempia jännitetasoja. Näiden jännitteiden seurauksena voi tapahtua osittaispurkauksia, joita ei nimellisjännitteellä tapahtuisi. Pienjännitekoneet on yleensä suunniteltu niin, että niissä ei tapahdu osittaispurkauksia. Niissä käytetyt orgaaniset eristemateriaalit ovat myös yleensä sellaisia, jotka eivät kestä osittaispurkauksia. Ajan myötä osittaispurkaukset voivat heikentää eristysmateriaalia tavallista ikääntymistä nopeammin, ja tämän vuoksi johtaa lyhyempään käyttöikään.

Tässä diplomityössä suoritetaan osittaispurkausmittauksia eräälle aksiaalivuokestomagneettitahtikoneen staattorille, joka edustaa nykyisin käytössä olevia materiaaleja ja tekniikkaa. Tavoitteena on selvittää mikä on testistaattorin osittaispurkausten syttymis- ja sammumisjännite, ja kuinka ne suhteutuvat käyttöjännitteisiin. Osittaispurkausmittauksia voidaan käyttää eristyksen kunnon selvittämiseksi suorittamalla useita mittauksia tietyn ajan välein. Näiden mittausten perusteella voidaan nähdä trendi edellä mainittujen jännitteiden muutoksessa ajan ja käytön myötä, joka voi antaa viitteitä eristyksen kunnosta.

Mittaukset suoritetaan ensin uudelle staattorille, jonka jälkeen staattoria rasitetaan testerissä noin kolmen viikon ajan, ja mittaukset suoritetaan uudelleen. Mittausten perusteella osittaispurkausten syttymisjännite on lähellä sellaista jännitetasoa, joka voi esiintyä normaalissa käytössä. Vaikka staattoria rasitettiin vain lyhyen aikaa, tulokset näyttävät hienoisen laskevan trendin syttymis- ja sammumisjännitteissä. Epävarmuus on kuitenkin suurta, ja mittauksia vaaditaan lisää, jotta trendi voidaan nähdä varmuudella.

SYMBOLS AND ABBREVIATIONS

Roman characters

A	Constant for saturation ionization
B	Constant related to ionization and excitation energies
d	Distance
E	Electric field strength
k	Scale factor
p	Pressure
Q	Charge
Q_m	Largest repeatedly occurring PD magnitude
q	Number of slots per pole and phase
t	Time
u	Voltage
U_b	Breakdown voltage
U_DC	DC-link voltage
U_pk	Peak voltage

Greek characters

γ	2nd Townsend coefficient
Γ	Overshoot factor

Abbreviations

AC	Alternating Current
AFPMSM	Axial Flux Permanent Magnet Synchronous Machine

DC	Direct Current
FSCW	Fractional Slot Concentrated Winding
HV	High Voltage (> 1000 V AC)
IEC	International Electrotechnical Commission
LV	Low Voltage (< 1000 V AC)
PD	Partial Discharge
PDEV	Partial-Discharge Extinction Voltage
PDIV	Partial-Discharge Inception Voltage
PMSM	Permanent Magnet Synchronous Machine
PWM	Pulse Width Modulation
PRPD	Phase Resolved Partial Discharge
RMS	Root Mean Square
RPDEV	Repetitive Partial Discharges Extinction Voltage
RPDIV	Repetitive Partial Discharges Inception Voltage
VPI	Vacuum Pressure Impregnation

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Symbols and abbreviations

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Appendix 1. Analysis results from the official test stator and from an unofficial stator.

1 Introduction

Partial discharge activity can be an indicator regarding the condition of insulation system in electrical rotating machines and in other electrical equipment. The measurements can be used to follow the trend of insulation condition and to detect some possible defects from manufacturing or those caused by external factors. Generally high-voltage devices are more prone to partial discharges, however that does not close out the possibility of that in low-voltage equipment.

This thesis deals with partial discharges (PDs) in low-voltage electric machines, especially the ones applied in the industry. PDs are created in the insulation system of an electrical machine under high enough electric field strength E in non-homogenous insulation material. Especially voids containing gas having a lower dielectric strength than the neighbouring insulation material are prone to partial discharges. Traditionally only high-voltage (HV) machines have suffered from partial discharges. There the solution is to use a PD tolerating insulation material. Typically, the solution in HV machines is based on using mica flakes in the insulating materials. In addition, careful vacuum pressure impregnation (VPI) removes most of the voids from the insulation. Mica tolerates PD without disintegrating. In low-voltage (LV) machines PD phenomenon has earlier been inherently avoided but the high $\mathrm{d}u/\mathrm{d}t$ values produced by modern power-electronic switches may result in high enough E-field values that trigger PDs. As LV machines typically do not contain PD tolerating materials in the insulation system, it is important to know if PDs occur in such machines, as they will accelerate the ageing of the insulation.

The objective of this thesis is to study partial discharge phenomenon in the elevator drive motors. Windings and materials that are in use now are tested and measured to find out if there is a need for improvement, if the insulation can be optimized in some sense or if voltage levels could be increased. This thesis and the measurements aim to create a wider understanding about the situation in terms of partial discharges. Partial discharges can be detected by many different methods, for example electrical, visual and acoustic methods. PD measurements can also be conducted as on-line or off-line. This thesis focuses only on the off-line electrical detection and measuring methods of PDs in electric machines.

Electric machines considered in this thesis are random wound axial flux permanent magnet synchronous machines (AFPMSMs). Partial discharges can affect the ageing and the lifetime of insulation system in electric machines and PD activity can be an indicator about the status of the electric machine insulation. Due to these factors, it is useful to observe and measure the PD activity to detect possible defects in the insulation, and to use multiple PD measurements taken with a certain time interval to follow the insulation ageing trend. This can provide benefits from a maintenance point of view, as the state of the insulation can be monitored, and maintenance can be performed before the machine fails and thus reducing the downtime. PD measurements can also be used as quality control method to check new machines in case of manufacturing defects.

The main objective of this thesis is to find out whether there are partial discharges in these machine windings. The results can be used to optimise either the construction or the materials of the machine windings, or the operation of the machinery. Increasing the switching frequency and especially increased $\mathrm{d}u/\mathrm{d}t$ values with future wide bandgap semiconductor devices can be seen as a potential threat to motor winding insulation system. Some research questions relating to this objective are:

- If there are partial discharges, are they how significant with the voltage levels used in the converter-supplied operation of these machines?
- If the PD activity is very low, how much can the voltage levels be increased?
- What is the voltage level above which the PD activity is increased significantly?
- How much and how fast does the PD activity increase when machine is in operation?
- What different factors affect the PD measurement results?

First, a literature review is conducted of the background of electric machines, partial discharges and on other research and standards related to PDs in electric machines. In the third chapter, measuring principles of PDs are described. After that, a measurement plan is constructed to answer the research questions. In the fifth section the measurement results are presented and analysed, and the implications of these are depicted. Finally, the thesis is concluded with assessing the results and their impact and possible actions that could be taken based on them. Ideas for future research and actions are presented.

2 Literature review

In this literature review section, partial discharges and low voltage winding insulation systems are in the focus. Different standards and research papers about partial discharges, as well as different measurement devices, technologies and analysation methods are studied. Other tests used to assess the condition of insulation system are briefly examined. Based on these, measurement plans are made and different factors affecting the measurements and partial discharges are considered.

2.1 Low voltage stator windings

Generally, low-voltage machines, according to the EU's low-voltage directive – are considered to have a rated voltage below 1000 V AC RMS (Root Mean Square). However, IEC standards 60034-18-41 and 60034-18-42 define two types for rotating electrical machines and their insulation system with a different voltage threshold. In these standards, machines are classified into two categories relating to their insulation system, Type I and Type II. Type I insulation system is dealt with in IEC 60034-18-41 and Type II in IEC 60034-18-42.

Type I systems are generally used in rotating electrical machines with random-wound windings and with a voltage rating of 700 V RMS or less, and Type II systems in machines typically with form-wound windings and rated voltage of above 700 V RMS. Type I insulation systems are not expected to experience any PD activity during their service time. Type II system is expected to withstand any PD activity it might experience during its service life. These Type II insulation systems generally contain PD resistant materials, such as mica-based materials. With random-wound windings round wires are used, and flat wires are used with form-wound windings (Petri et al., 2022).

The machines tested in this thesis are not specified to belong to either of these types, but they have random-wound windings and rated voltage below 700 V. There have not been any PD related issues detected with these machines, which represent the technology in use nowadays. These measurements are to find out the limits, which ensure that no PD related issues will arise. In the future, possible changes in operation parameters, such as increased voltage levels or faster d*u*/d*t* rates with new switching technology, might introduce a need for taking actions, if these cause the limits for safe operation to be exceeded. Figure 1 below shows a schematic example of random-wound winding in a stator slot, and the different insulation components.

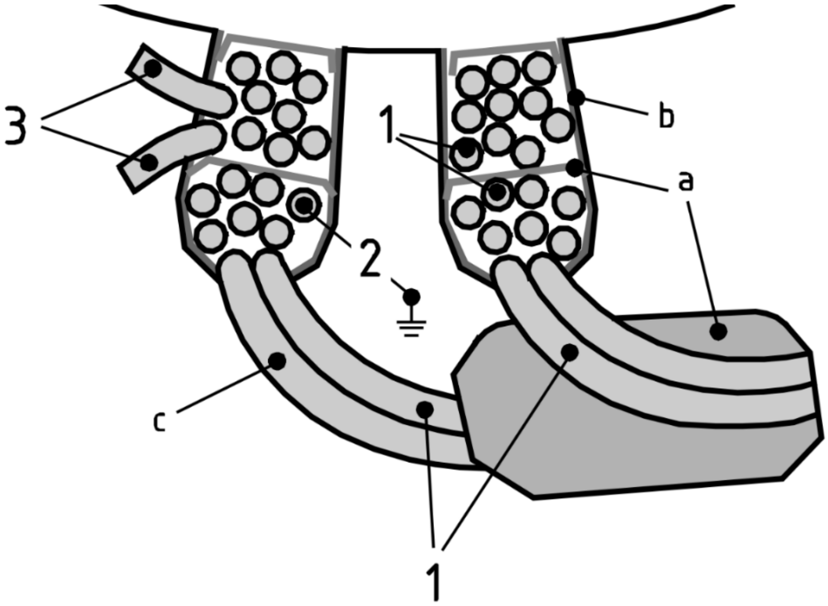


Figure 1. Example of a random-wound winding design. 1 depicts phase-to-phase voltage, 2 depicts phase-to-ground voltage and 3 depicts turn-to-turn voltage. Phase insulation is shown by a, mainwall insulation with b and turn insulation by c. Figure adapted from IEC 60034-18-41.

As shown in Figure 1, the stator slot can contain coil sides of two different phases, and so a phase-to-phase insulation is needed between those, and also at the end winding between two phases, as shown by a. Mainwall insulation or slot insulation insulates the windings from the stator core. Turn insulation provides insulation between the different turns of the winding. In addition to these, also connection leads at the end windings have to be insulated, which is done with insulation sleeves (Pyrhönen et al., 2008). Insulating sleeves also provide mechanical protection for example against sharp edges.

The slots can also be filled with impregnation liquid, which once it cures, provides additional insulation, better heat transfer capabilities and prevents the coils from vibrating and thus wearing out mechanically (Chapman et al., 2008). Vibration and movement of coils could lead to wearing out the insulation layer and furthermore in a breakdown of the insulation system.

The insulation system is divided into primary and secondary insulation. Primary insulation consists of phase insulation, mainwall insulation and turn insulation, and the secondary insulation is the impregnation. For insulation systems defined as Type I, the materials used are nowadays organic temperature resistant polymers, for example polyimides or polyamide-imides as wire enamels. For Type II systems, inorganic materials are used, such as porcelain and beforementioned mica, which provide high resistance for PDs. (Petri et al., 2022.) Porcelain and mica are non-flexible materials and therefore have to be immersed in a supporting flexible matrix, typically as flakes.

2.1.1 Winding topologies

Stator windings can be of integral slot winding type or fractional slot winding type. In integral slot winding, the number of stator slots per phase and pole q is an integer, while in fractional slot winding q is a fraction. Stator windings can be also divided into concentrated and distributed windings. Usually, distributed windings are used as stator windings in AC machines. Concentrated non-overlapping windings (i.e. tooth-coil windings) can also be used in fractional slot permanent magnet synchronous machines (PMSMs) as stator winding. (Pyrhönen et al., 2008.)

Distributed fractional slot windings are either diamond or concentric windings, and they can include one or two layers (Pyrhönen et al., 2008). Difference between concentric and diamond winding is demonstrated in Figure 2 below.

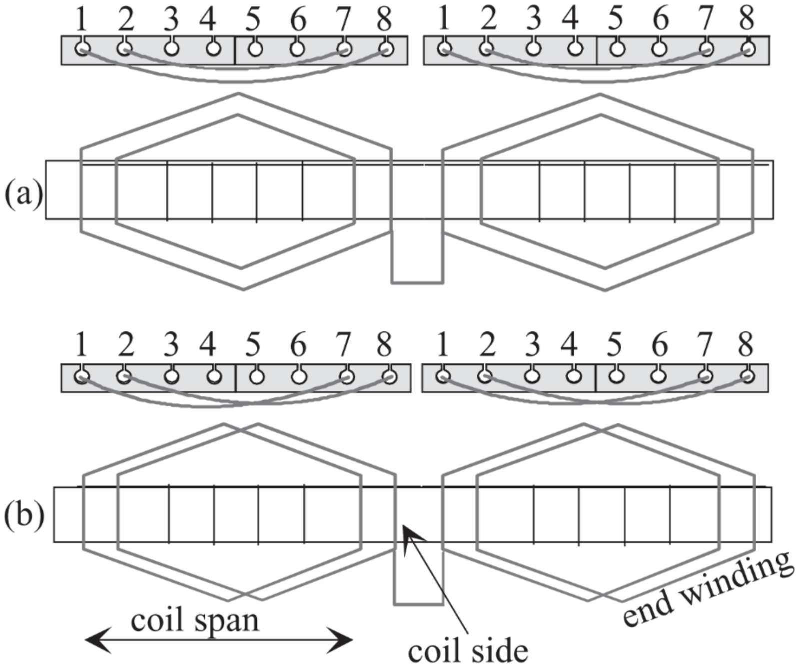


Figure 2. Example of concentric winding (a), and a diamond winding (b). Figure adapted from (Pyrhönen et al., 2008).

As Figure 2(a) shows, in a concentric winding the coils are inside of each other and thus the coils are of different width. With diamond winding, shown in Figure 2(b), the coils are of same width, so they are overlapping each other.

Fractional slot concentrated non-overlapping winding (FSCW) refers to a winding with $q < 1$ (in practice $q \leq 0.5$), and thus also q being fractional. This leads to the end windings to not overlap with other phases. This type of winding is also referred to as tooth-coil winding. (Prieto, 2015.) According to Pyrhönen et al. (2008) with PMSMs, when $q > 0.5$, the stator winding is generally a distributed rotating-field slot winding.

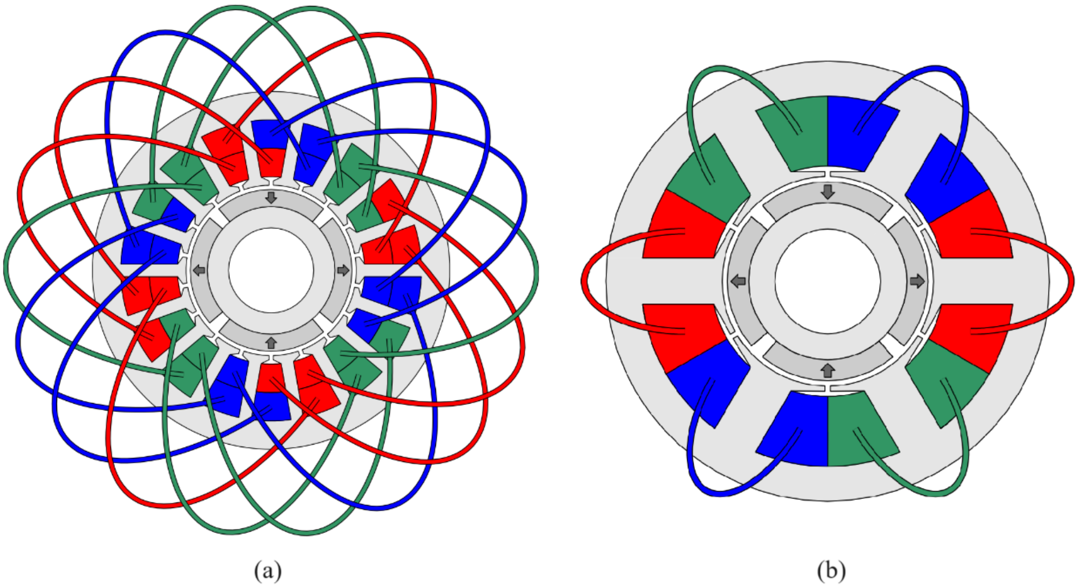


Figure 3. Schematic examples of two stator windings of three-phase four-pole double-layer radial flux PMSMs. (a) shows a fractional-slot distributed winding with $q = 3/2$. (b) shows an FSCW with $q = 1/2$. Figure adapted from (Prieto, 2008).

As Figure 3(a) shows, with distributed winding the phases overlap with each other in the end windings. In Figure 3(b) it can be noticed that with the FSCW the phases do not overlap. These figures do not show the completed end windings, as the coils of the same phase on the opposite sides of the stator would be connected to each other. However, this reduces the overlapping of different phases at the end winding. Although with distributed winding the phases are insulated from each other at the end windings with a separate insulator, this could decrease the chance of PDs between the phases in the end winding as there are less overlaps between phases. Machines tested in this thesis are with non-overlapping fractional slot stator winding, as depicted in Figure 3(b).

2.2 Effect of increased slew rate

According to the nature of random-wound windings, the turns are located randomly in the slot so, that the first and last turn can be adjacent to each other. In this case, almost the whole voltage of the coil can be present over the turn-to-turn insulation. Also, higher slew rates for voltage applied by the inverter can cause issues for the winding, due to not uniform voltage distribution in the windings.

Advances in semiconductor technology has led to higher and higher voltage slew rates in semiconductor switches. Thus, the windings of converter fed electric machines will be exposed to higher d*u*/d*t* values. In addition to traditional silicon (Si) switches, new wide bandgap silicon carbide (SiC) and gallium nitride (GaN) switch technologies have arisen. These provide higher switching frequencies, shorter voltage rise times and lower switching losses (Kikuchi et al., 2023). The rise times of traditional Si switches are in the range of 100…500 ns, while with SiC switches rise times are generally less than 50 ns (Ju et al., 2021). Regarding slew rates, state-of-the-art Si switches can achieve a d*u*/d*t* of 5 kV/µs, and with SiC switches slew rates of over 100 kV/µs can be achieved (Petri et al., 2022).

In the standard IEC 60034-18-41 there is a figure which shows the worst case for voltage stressing the turn-to-turn insulation as a function of voltage rise time, as shown in Figure 4. This figure is based on data gathered from a variety of different random wound stators.

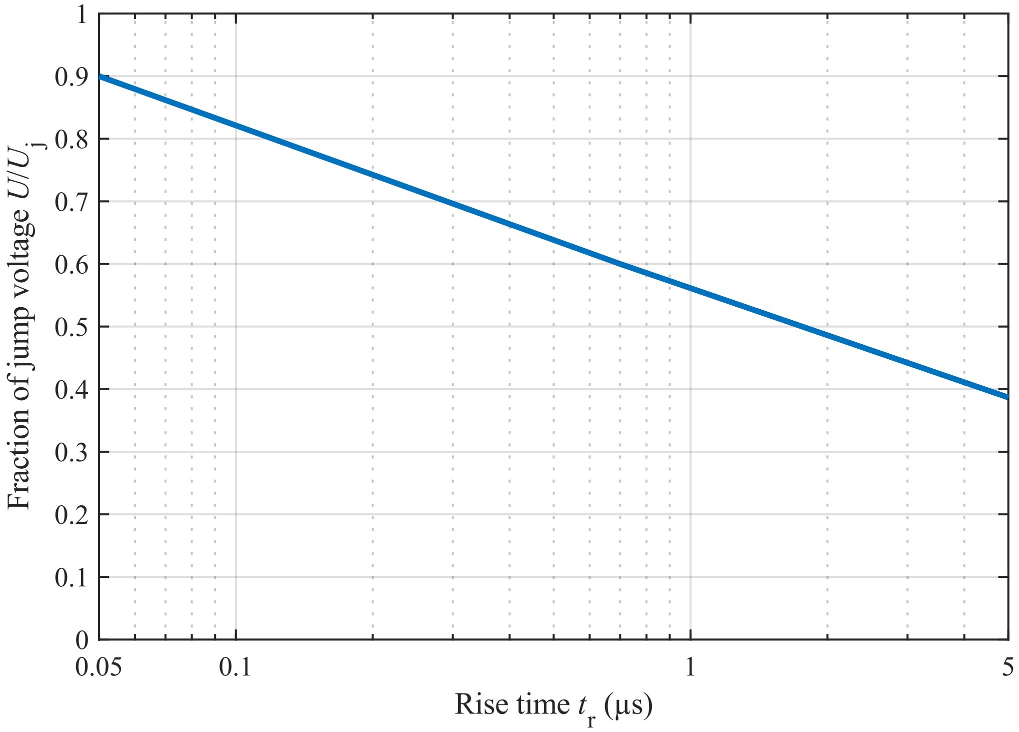


Figure 4. Worst case of impulse voltage stressing the turn-to-turn insulation as a function of the voltage rise time. Figure adapted from IEC 60034-18-41.

The vertical axis shows the fraction of the jump voltage that is stressing the turn-to-turn insulation. On the horizontal axis is the rise of the voltage impulse in microseconds presented on a logarithmic scale. Jump voltage is the peak phase-to-ground voltage at the machine terminals when applying a voltage impulse, by a converter for example. Fraction of 1 in Figure 4 means that this total peak voltage would be stressing the turn-to-turn insulation.

Experiment conducted by Oyegoke (2000) in his dissertation shows similar results regarding the voltage distribution. With two random-wound induction machines, the measured voltage drop across the first coil is around 60% of applied voltage with both machines. If the first and last turn of the coil happen to be adjacent, this voltage is stressing the turn-to-turn insulation in the coil. The rise time of the voltage applied is undeclared, however the figures (54, 55) presented show the peak voltage is reached at around t = 0.2 microseconds. Depending on the accuracy of the starting point in the figure, the rise time could be assumed to be 0.2 microseconds. When compared to Figure 4, this was not the worst-case situation.

Another machine tested by Oyegoke (2000) shows a peak voltage drop across the first coil as 433 V (Fig 48), when the peak of the motor terminal voltage at that time instant was 670 V (Fig 45). This equals to about 65% of the applied voltage to be over the first coil. The voltage over the first coil rapidly decreases, as when t = 2 microseconds, the voltage is decreased to below 50 V.

2.2.1 Impedance mismatch

In addition to fast slew rates causing issues with uneven voltage distribution in the winding coils, also impedance mismatch with the motor and the supply cable can cause issues as generating voltage overshoot at the motor terminals.

When the motor is supplied by PWM pulses with short rise times, impedance discontinuities in the transmission medium will cause the voltage pulses to reflect partially. As the characteristic impedance of a motor is generally much higher than the characteristic impedance of the supply cable, it will cause voltage reflections at the motor terminals (Ju et al., 2021).

Voltage overshoot is increased as the length of cable is increased, and the voltage pulse rise time is decreased. The voltage overshoot factor Γ is defined as

$$\Gamma = \frac{U_{\mathrm{pk}}}{U_{\mathrm{DC}}} \tag{1}$$

where U_{pk} is the peak voltage (V) and U_{DC} is the DC-link voltage (V). (Driendl et al., 2023.)

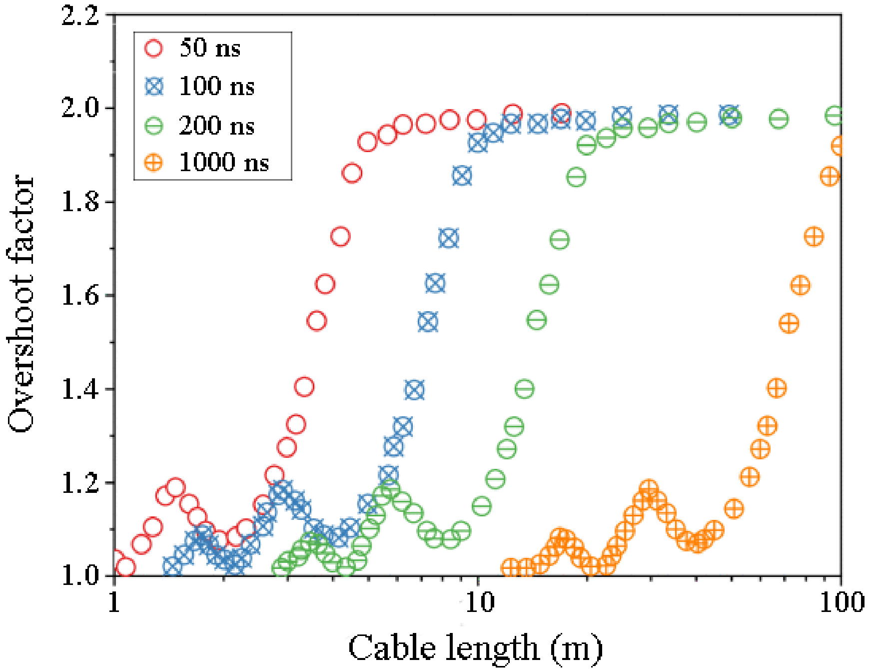


Figure 5. Overshoot factor Γ for voltage experienced by the motor as a function of cable length, with four different voltage pulse rise times of 50 ns, 100 ns, 200 ns and 1000 ns. Figure adapted from (Ju et al., 2021).

As the data points in Figure 5 show, as the cable length increases, also Γ increases. Shorter rise times also introduce higher overshoots. As can be also seen in Figure 5, the overshoot factor reaches a maximum value of around 2, so the voltage pulse motor is experiencing can be twice the DC-link voltage.

As the SiC and GaN switches bring shorter and shorter rise times, it is becoming more and more difficult to avoid this overshoot caused by the voltage reflection. These have to be taken into account when considering the insulation systems, as they are almost unavoidable in practice, as the cable lengths would have to be so short.

The motor supply cables used with elevator machinery have usually a length of four to six meters. Longest cable options are even up to 35 meters. Considering the rise times of the latest power switches such cable lengths can be considered “long”.

2.3 Other electrical insulation tests

In addition to partial discharge tests, other electrical tests to assess the condition of insulation system of an electrical machine exist. These include insulation resistance (IR), polarization index (PI), dielectric absorption ratio (DAR) and surge test. These are so called off-line test procedures, because they require the machine to be taken out of operation and unenergized while these tests are conducted. These tests are relatively easy to carry out and interpret the results when compared to PD testing, although they do not provide the same information.

2.3.1 Insulation resistance

Measurement of IR and PI is described in standard IEC 60034-27-4, and according to the standard, insulation resistance describes the capability of the insulation of an electrical machine to resist direct current. According to Stone et al. (2004), IR and PI tests only find contamination, such as moisture, and serious defects of the winding.

Insulation resistance measurement is conducted with direct voltage. IR is the applied direct voltage divided by the current flowing through the machine insulation. Generally, the IR measurement result is recorded at one minute or 10 minutes after applying the test voltage. Temperature of the winding affects these measurements, so results should be corrected to a base temperature of 40 °C. (IEC 60034-27-4.)

The total current comprises of several current components, those being polarization, conduction, surface leakage, capacitive, and stress control coating currents. Conduction, surface leakage, and stress control coating currents are constant over time, while polarization and capacitive currents being currents that decay over time. (IEC 60034-27-4.)

Ideally this resistance would be infinite as the purpose of electrical insulation is to prevent current from flowing. Generally, the lower the IR of a machine is, the more likely it is to have issues with the insulation system (Stone et al., 2004). If the IR has a decreasing trend, without the moisture increasing, then probably also partial discharges can increase, but there is no correlation between these presented in the literature.

According to IEC 60034-27-4, the recommended minimum values for IR at one minute are 5 MΩ for LV windings and 100 MΩ for HV synthetic resin form-wound windings. For shellac- and asphalt-based insulation systems, the recommended minimum value of IR in MΩ is the rated voltage (in kV) + 1.

2.3.2 Polarization index and dielectric absorption ratio

Polarization index is the ratio of IR measured at 10 minutes to the IR measured at one minute after voltage application. As the name suggests, the difference between resistances at 10 minute and one minute mark is due to the slowly decaying nature of the polarization current. (IEC 60034-27-4.)

As the IR measurement, also PI indicates mainly contamination or moisture of the winding or some serious defects, but not large voids in the impregnation, for example, as PD test would reveal. According to IEC 60034-27-4, PI test can also find if shellac- and asphalt-based insulation systems have been thermally aged.

According to IEC 60034-27-4, recommended minimum values for PI are 1.5 for shellac- and asphalt-based insulation, and 2.0 for synthetic resin-based insulation systems. These minimum values are not applicable for “small machines with random-wound windings…”. Such machines are defined in the scope of the standard to be machines with rated power below 750 W, so these are applicable for the machines dealt with in this thesis.

Dielectric absorption ratio is basically the same measurement as PI, but the measurements are taken at different times. In LV random-wound machines the polarization current may decay to close to zero faster, even in less than a minute. Generally, the corresponding times for DAR are 60 seconds and 30 seconds, that is DAR being the ratio of IR at 60 seconds divided by IR at 30 seconds. This can be used to detect the same problems from the insulation system as with PI test. (IEC 60034-27-4.)

Standard IEC 60034-27-4 does not provide any pass/fail criterion for assessing the results of DAR test. According to Megger (2017), a DAR above 1.4 is considered being “good”, and above 1.6 is considered being “excellent”, however these values are said to be tentative and relative.

2.3.3 Surge test

Surge test means applying a short rise time voltage impulse to the winding. This test can be conducted on both form-wound and random-wound windings. Surge test is effective for finding problems in the turn-to-turn insulation. If the turn-to-turn insulation fails during the test, two turns will be shorted out. This affects the inductance of the coil. Change of inductance is detected by a change in the resonance frequency of the coil. (Stone et al., 2004.)

According to Electrom (2024), this measurement is not destructive, if it is carried out properly. Test voltage should be achieved quickly, and the test should not be extended for a too long period of time. If there is a weakness in the turn-to-turn insulation, there will be a discharge from turn to turn. If the surges are applied after this, it may lead to carbon tracking and a discharge might occur at lower voltages, too.

The result of a surge test is either a pass or a failure. No additional information of the winding condition is really obtained with just a surge test. If combined with a PD test, the PD activity could provide insight on the insulation condition, even if the surge test is passed with no full discharges between the turns. If the machine fails the test, i.e. a failure of turn-to-turn insulation is detected, the machine should be serviced. (Stone et al., 2004.)

2.4 Partial discharges

According to International Electrotechnical Commission (IEC) (2010), partial discharge is an “electric discharge that only partially bridges the insulation between conductors” and it can happen “inside the insulation or adjacent to a conductor”. Partial discharges can be caused by defects during manufacturing, physical damage while installing or in service, or excessive electrical or thermal stress while in service, and also due to natural insulation ageing (IPEC, 2024). It should be noted that PDs may also occur in the cable, whether it being the supply cable for a machine or for testing the machine.

Partial discharges generally occur at locations where the insulation is inhomogeneous. This usually happens when there is a gas void in the insulation material, such as in the wire insulation or in the impregnation. In that void, electric field strength exceeds the breakdown strength of the gas, and thus a partial discharge occurs inside that void. Partial discharge does not lead to immediate complete breakdown of the insulation. However, partial discharges will deteriorate organic insulation materials, thus eventually leading to breakdown of the insulation (IEC 60034-27-1.)

The energy released in a PD is generally very low, as the energy or charge is usually measured in picocoulombs. PD magnitude can be measured also in millivolts, depending on the measurement method and device. The duration of a PD is very low, usually lasting for a few microseconds. (Dmitriev et al., 2024.) According to IEC 60270, the duration of PD is much shorter than a microsecond. The magnitude, quantity, frequency, location and significance of PDs depend on a large number of different factors, such as design, materials, manufacturing, operating conditions and ageing (IEC 60034-27-1).

Partial discharges create acoustic, electric, electromagnetic and chemical emissions. Electromagnetic emissions can be in both visible light range and higher frequencies. Electrical methods are generally the most used methods to detect and measure PDs, but other emissions can also be used to detect the presence of PD activity, but not necessarily to measure the magnitudes or other characteristics. (IEC 60270.)

2.4.1 Mechanisms of partial discharge

Partial discharges and discharges in general take place when the dielectric strength of insulating material is exceeded. As PDs usually take place in a gas, Paschen’s law can be considered. Paschen’s law defines the breakdown voltage U_b of a gas as a function of the product of pressure and distance between the electrodes. Paschen’s law is expressed as follows

$$U_\mathrm{b} = \frac{B \cdot p \cdot d}{\ln(A \cdot p \cdot d) - \ln(\ln(1 + \gamma^{-1}))} \tag{2}$$

where B is a constant related to ionization and excitation energies (V/kPa·cm), A is a constant for saturation ionization (kPa·cm), p is the pressure (kPa), d is the distance between electrodes (cm) and γ is the 2nd Townsend coefficient (Husain & Nema, 1982).

The values of the parameters A and B depend mainly on the intermediate gas. The value of γ depends also on the material of the electrodes and the temperature (Kemari et al., 2022). According to Husain & Nema (1982), the values for A and B for air are A = 112.50 kPa·cm and for B = 2737.50 V/kPa·cm. The values of A and B depend also on the temperature, but in the paper by Husain & Nema (1982) the temperature is undefined. Thus, it is assumed to apply for the normal temperature of 20 °C. According to Kemari et al. (2022), the value commonly used for γ is 0.01, however their research showed that with a polyimide insulation between the electrodes in temperature of 20 °C, the value is $\gamma = 6.5 \cdot 10^{-4}$. This value of γ provided by Kemari et al. (2022), and the values of A and B provided by Husain & Nema (1982), are used to draw the Paschen curve for air at 20 °C in Figure 6.

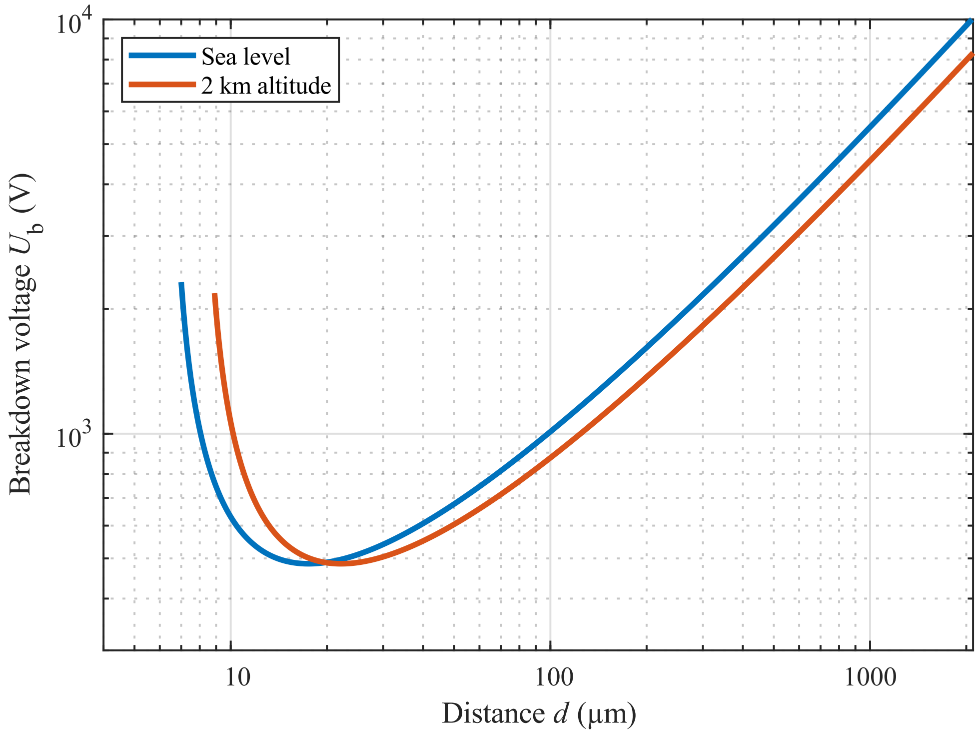


Figure 6. The Paschen curve which shows the breakdown voltage of air as a function of air gap length in standard pressure of 101.325 kPa at sea level and with a pressure of 80.156 kPa corresponding to an altitude of 2 km.

Figure 6 shows that the lowest breakdown voltage of 485 V is reached at a distance of around 17 µm at sea level atmospheric pressure. With an atmospheric pressure corresponding to altitude of 2 km, the lowest breakdown voltage is the same, but it is achieved with an air gap length of about 22 µm. Breakdown will happen where the voltage stress is above the Paschen curve, and as can be seen in Equation (2), it is dependent on the pressure and the air gap. If the electric stress for example in an air bubble in between the insulation exceeds this U_b shown in the figure, PDs are very likely to happen.

The curves in Figure 6 show a special case with the pressure being constant. The shape of the curve stays the same, and the product of p and d define the position along the horizontal axis. As can be seen from the figure, when the ambient pressure decreases, the curve moves to the right meaning that with longer distances the breakdown voltage decreases. Elevator machines are rated to be used in altitudes up to 1 km, and above that the performance of the machine must be derated.

As polyimide is used commonly in LV machines as turn-to-turn insulation on enamelled wires in the winding, this Paschen curve in Figure 6 depicts more accurately the situation where turn-to-turn insulation is being stressed by electric field as the coefficient γ is better suited for this insulation material being present.

Partial discharges in a gas can be described by Townsend criterion for gas discharge processes. In a gas discharge process, the gas molecules are ionized and split into positively and negatively charged particles. For a PD to occur, in addition to breakdown electric field strength being present, also a starting electron has to be available. The starting electron is accelerated by the electric field. If the electron has enough energy to ionize a gas molecule, the separated electron will also accelerate in the electric field and possibly ionize then more gas molecules. Positively charged gas ions will then travel to opposite direction and hit the cathode material where they can release more starting electrons. This phenomenon is called electron avalanche. (Driendl et al., 2023.)

2.4.2 Types of PD in rotating electrical machines

Internal discharges take place in the internal voids in insulating materials. Voids are caused in the insulation by defects during manufacturing. Especially in the case of HV machines with mica tape insulation, voids are in practice unavoidable. These voids cause a reduction in the dielectric strength of the insulation, and thus the electric field strength will exceed the dielectric strength of the material. (IEC 60034-27-1.) In a HV machine, partial discharges are present during the whole operating life of the machine.

Internal delamination can occur when the layers of the insulating material separate. Internal delamination can be caused by mechanical or thermal stress, and also due to insulation ageing. Internal delamination can also be caused by impregnation resin not impregnating or curing properly (IEC 60034-27-1). Mechanical stress by tension and compression, or high temperatures can lead to delamination of the insulation, which can lead to large voids inside the insulating material. These large voids result then in high-energy partial discharges, which will deteriorate the insulation even further. (Dmitriev et al., 2024.)

Partial discharges may take place in different locations also at the end windings. These discharges can take place for example between the winding and stator core and also between the windings of different phases. Partial discharges in the end winding can be caused by slow ageing of the end winding insulation by contamination or thermal effects for example. (IEC 60034-27-1.) The area between the conductor and the stator stack end is the most difficult place from the electric field stress point of view. The sharp corner creates a strong *E*-field concentration. To avoid too high stresses there, stress-grading insulation material is used on the winding to gradually let the winding insulation surface reach the conductor potential at the end winding.

2.4.3 Consequence of PD

In HV electrical machines with Type II insulation system, for example mica-based insulation, partial discharges will happen. These do not necessarily cause or indicate any problems, as the insulation materials are PD resistant, and some PD activity is unavoidable. However, if the PD magnitudes are substantially large, there might be issues with the insulation system. As PD measurements are relative, no threshold values can be given. This is where several measurements carried out with longer time intervals come in handy, as those can be used to follow the trends of different PD characteristics.

Generally partial discharges themselves do not pose great threats for PD resistant insulation systems, and PDs are merely an indicator of insulation condition. Depending on the conditions, in some cases PDs can also affect the ageing of insulation. PD activity can indicate for example the types of insulation problems described in section 2.4.2. In addition to these, in HV machines which have conductive slot coating, slot discharges can happen when the coating is compromised (IEC 60034-27-1).

In LV machines, or machines with Type I insulations systems, the insulating materials are usually organic polymers. These do not tolerate partial discharges for longer periods, so these machines are generally designed to be PD free. PDs are also an indication of the insulation condition, but in addition to that, PDs will degrade the organic insulating materials. When PD occurs, the energy of electrons accelerated is enough to break chemical bonds in the material and create an erosion, which grows until full breakdown of the insulation (Hermansyah et al., 2018). According to study by Hermansyah et al. (2018), organic insulating materials containing inorganic fillers, can significantly increase the life of insulation in presence of PDs.

2.5 Related standards

Standards describe the requirements for the measuring devices and how measurements should be conducted, and what environmental and other factors should be considered. These standards also define the used terms in partial discharge measurement and evaluation.

As mentioned before, standards IEC 60034-18-41 and 60034-18-42 focus on the Type I and Type II insulation systems. IEC 60034-27-1 provides guidance for off-line PD measurements, IEC TS 60034-27-5 provides an off-line measurement method of PD inception voltage under repetitive impulse voltage, with IEC TS 61934 providing more information on PD measurements under repetitive voltage impulses. IEC 60270 provides definitions and general guidance on test circuits and procedures.

IEC 60034-27-2 discusses about on-line PD measurements for machines with rated voltage above 3 kV, thus not relevant for this thesis. Not directly related to PDs, IEC 60034-27-4 recommends test procedures for IR and PI measurements.

2.5.1 Definitions

Partial discharge inception voltage (PDIV) is the lowest voltage where PDs are detected, or their magnitude is higher than specified limit, when the applied test voltage is gradually increased from a lower value where no PDs are detected. Partial discharge extinction voltage (PDEV) is the voltage when PDs are no longer detected, or their magnitude is below the specified limit, when the test voltage is gradually decreased. With sinusoidal applied voltage the PDIV or PDEV is the RMS value of the voltage, and with impulse voltages, PDIV and PDEV is the applied peak-to-peak voltage. (IEC 60034-27-1, IEC 60034-18-41.)

Repetitive partial discharge inception voltage (RPDIV) is the lowest peak-to-peak impulse voltage at which PD pulses occur with a probability of 50 % or higher, against the repetitive test voltage impulses. Repetitive partial discharge extinction voltage (RPDEV) is the highest peak-to-peak voltage at which PD pulses occur with less than 50 % probability. (IEC TS 60034-27-5.)

Figure 7 illustrates the definition of PDIV, PDEV, RPDIV and RPDEV, according to the standards. Step-by-step method refers to a testing method where the impulse voltage level rises in steps, with for example ten pulses on each voltage level, and then decreases. The figure illustrates PD testing with impulse voltage. Testing can also be done with sinusoidal voltage, however in that case the repetitive inception and extinction voltages cannot be measured. The definition of PDIV and PDEV follow the same principle with sinusoidal test voltage. Whenever the first PD pulse above set threshold is detected while increasing the voltage, that is the partial discharge inception voltage.

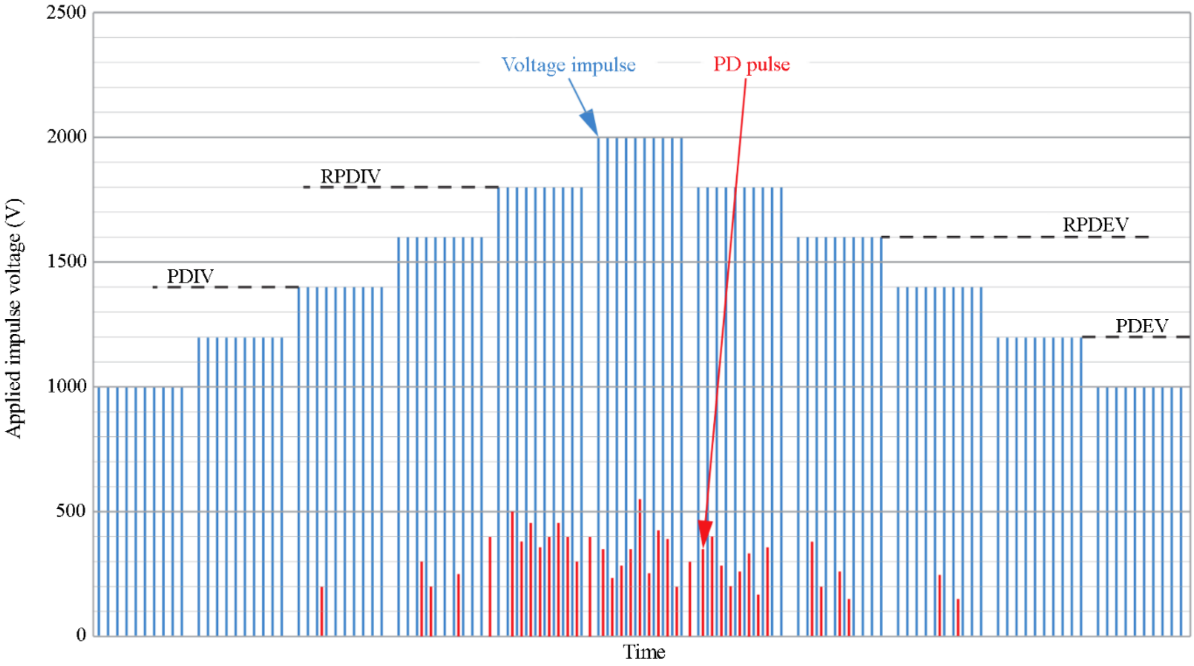


Figure 7. Example of impulse voltage PD testing with step-by-step method, and recognition of PDIV, PDEV, RPDIV and RPDEV. Figure adapted from IEC TS 61934.

Phase resolved partial discharge (PRPD) pattern is a common way to visualize PD test results. It shows the PD magnitude on vertical axis, and the phase of occurrence of the PD in relation to applied AC test voltage on the horizontal axis. The repetition rate for each PD of certain magnitude and phase is shown with a color scale. (IEC 60034-27-1.)

On-line measurement refers to a PD measurement while the rotating electrical machine is in normal operation. Off-line measurement is a measurement taken when the electrical machine is at standstill and disconnected from the power system supplying the machine under normal operation. With off-line measurement, the test voltage is provided from a separate voltage source. (IEC 60034-27-2.)

According to IEC 60034-27-1 and IEC 60034-27-2, noise is defined to be not pulse-like signals which originate outside of the winding in test, for example thermal noise from the detection circuit or device or from external sources like radio transmitters. Disturbances are defined to be electrical or electromagnetic pulses of short duration, which may have characteristics similar to PDs, but they are not originating from PDs. These could be originating from the pulse generator itself, or from adjacent electrical devices.

PD magnitude can be measured either in picocoulombs (pC) or in millivolts (mV). In accordance with IEC TS 61934 and IEC TS 60034-27-5, picocoulombs are used with sinusoidal test voltages, and millivolts with impulse test voltages.

2.5.2 Important notes from standards

IEC 60270 defines that the specified PD magnitude is the largest PD magnitude permitted in the test object at a specified voltage. According to IEC 60270 noise or disturbance cannot exceed 50 % of this magnitude, if it does, then measures should be taken to reduce the disturbances. According to IEC 60034-27-1 with complete windings, the noise level produced by the test circuit should not exceed 50 % of maximum PD magnitude measured in pC. Noise and disturbance levels should also be reported with the test report.

To ensure that the test arrangement has sufficiently low noise and disturbance, the test object can be replaced with an appropriate PD-free capacitor, or with the test object disconnected from the circuit. Then the test voltage is increased to the maximum, and noise is observed. Means for decreasing the disturbances are described in IEC 60270 Annex G and in IEC 60034-27-1 Annex E.

The interpretation guidelines for PD test results provided in IEC 60034-27-1 do not apply if measurements were taken using sinusoidal test voltage with frequency out of the range of 45 Hz to 65 Hz, if the windings are not form-wound or if the machine does not have conductive slot coating. Machines tested in this thesis do not conform to these requirements, so the interpretation guidelines are not valid for these. However, some indications could probably be taken out of them. IEC 60034-27-1- also states that the testing procedures can be used for assessing the quality and the trending of other types of windings, too, which do not conform to the requirements mentioned.

According to IEC 60034-27-1, the PD coupling unit, for example the coupling capacitor, should be installed as close to the winding terminals as possible. Also, all the connecting cables should generally be as short as possible.

According to IEC 60034-27-1, in all tests used for example following the trending, the entire test circuit should be arranged in the same way, including all the components, measuring system, and the normalization procedure. In this way, comparable results can be obtained. Also, the test conditions should be well documented.

Performing an IR test is recommended by IEC 60034-27-1 before PD tests. Insulation resistance should be above the limits, which are presented in section 2.3.1. This test will reveal any serious defects or contamination of the winding.

According to IEC 60034-27-1, PD activity will typically decrease during the first minutes after applying voltage, so conditioning of the test object is recommended to achieve more stable PD behaviour. Conditioning of complete windings is recommended by applying the maximum test voltage for 5 minutes immediately before the PD test itself.

According to IEC TS 60034-27-5, PDIV and PDEV measurements with repetitive impulse voltage produces usually different results than with sinusoidal voltage. This is caused by the uneven voltage distribution phenomenon in the windings, which can be seen for example in Figure 4. Some parts might be stressed more than other parts with different supply voltage waveform, which can provide different test results.

According to IEC TS 61934, when testing the turn-to-turn insulation of a PWM converter driven machine with impulse voltage, a bipolar repetitive voltage impulse should be used. Polarity of successive voltage impulses affects the PD activity.

When measuring the RPDIV and RPDEV, IEC TS 61934 recommends at least five repeated measurements, as the PD activity is unstable around the inception and extinction voltages. Also, larger number of impulses and low increments in the test voltage can provide more stable measurement results. Repeating measurements is also beneficial when using sinusoidal voltage waveform.

3 Principles of PD measurements

Partial discharges create transient pulses with a very fast rise time, only a few nanoseconds. As a result, these PD pulses have high frequency characteristics, which need to be able to be detected with the measuring device. When PD occurs in a winding insulation, the fast pulse will attenuate while travelling through the winding to the terminals and to the measuring device. The shape and magnitude of the detected PD pulse can be largely different than at its origin. Therefore, also comparing pulse magnitudes and other characteristics between different machines do not usually produce meaningful results. PD test results should be mainly used to compare same machines or stators which each other, or to follow the trend in the results for the same individual machine. (IEC 60034-27-1.)

In addition to PD testing the elevator machine, supply cables could also be tested to make sure that they do not suffer from partial discharges. If the machines are fine even with higher voltage level, the cable might not be. It is important to consider the entire system that no weak links are present. However, this thesis focuses on the machines and their PD measurements.

3.1 Measuring techniques

Basically, there are two types of PD measurement, either with sinusoidal voltage at power frequency around 50 Hz, or with voltage impulses with short rise times. Instructions for PD testing of winding insulation with sinusoidal voltage are given in standard IEC 60034-27-1. The methods described in the standard are applicable with frequency of sinusoidal test voltage from 0.1 Hz to 400 Hz. Instructions for testing with voltage impulses are given in the standard IEC TS 61934.

For machines with Type I insulation systems, in IEC 60034-18-41 is defined that type tests for complete winding can be done using either sine wave voltage or impulse voltage. According to the standard, with sinusoidal voltage, phase-to-phase insulation and phase-to-ground insulation can be tested. Turn-to-turn insulation can be tested with only impulse voltage. Also, PD measurement can be conducted as on-line or off-line measurement.

There are a few electrical PD measuring methods presented in the standards. In standard IEC 60034-18-41 for PD measurements at power frequency, options are a HV coupling capacitor or a high frequency current transformer. In the standard IEC TS 60034-27-5 for testing with impulse voltages, in addition to the beforementioned options, also an antenna-type coupler to detect the electromagnetic signals can be used.

In the standard IEC 60034-27-1, basically the only presented measuring method is with a coupling capacitor. The standard also states that to be able to detect PDs from the whole winding, a wide band measuring system should be used. Lower frequency range provides good sensitivity for PDs close to the terminals where the PD measuring unit is connected, and also for PDs further away in the winding. However, the lower frequency is more prone to disturbances and noise. Very high frequency range is less subjected to noise and disturbances, but the sensitivity to PDs away from the terminals is drastically reduced. In accordance with IEC 60270, the lower cutoff frequency should be around some tens of kilohertz.

These beforementioned standards and measuring techniques apply for off-line PD measurements. According to standard 60034-27-2, a coupling capacitor and antenna-type sensors can be used for on-line PD measurements. So, for both off-line and on-line measurements, both galvanic and electromagnetic measuring techniques can be used.

3.2 Analysation methods

The PD magnitude is often defined as the largest repeatedly occurring magnitude Q_m. According to IEC 60034-27-1, Q_m is defined as the largest magnitude associated with a PD pulse repetition rate of 10 pulses per second.

As mentioned earlier, interpretation of PD test results is always comparative, and an acceptable limit for PD magnitude cannot be specified. The PD magnitude can be compared with measurements on the same machine over time, (i.e. trending), or with different machines with the same exact design or between different phases of one machine. For these results to be comparable, the same method, equipment, test circuit and conditions should be used (IEC 60034-27-1).

According to IEC 60034-27-2, judgement based solely on the PDIV and PDEV should not be done in the case of HV machines. In contrast, with PD-free (Type I) LV machine windings the PDIV and PDEV are proven to be suitable for assessing the suitability.

Following the trending of PD activity is a very effective way for detecting deterioration in the insulation. It is advisable to obtain an "initial fingerprint" from a new winding. The measurements should be conducted with the same voltage, temperature, humidity and with the same measurement device. Test voltage should be within ±2.5 %, and the temperature of the test object within ±10 °C. Variations of PD magnitude of for example ±25 % are normal, due to behaviour of PD processes and unavoidable changes in the test conditions. (IEC 60034-27-1.)

Phase resolved partial discharge pattern can be used to differentiate types of PDs and locations of PDs, and hence the severity of these PDs (IEC 60034-27-1). As stated earlier, the interpretation guidelines in IEC 60034-27-1 do not apply to machines tested in this thesis, so it is unclear in what degree the guidelines provided could be useful when interpreting PRPD patterns of these machines. However, trending amongst these PRPD patterns can be used to assess the ageing and deterioration, and comparing them between tests made on different phases of the same machine or with different machines with the same design can provide meaningful results.

The measurements should be conducted in an environment, where there is as little as possible external disturbance and noise from other electrical equipment. Also, when considering measurements taken at different times, for example to follow the trending of the results, the environmental factors should stay the same. This minimises the error in the measurement results caused by external factors, and thus they provide more accurate results. The differences in the measurements can then be more easily recognized to originate from changes in the test object itself, for example due to aging.

According to IEC TS 60034-27-5, temperature, humidity, and air pressure affect PD activity and correspondingly also PDIV and PDEV values. Room temperature and dry conditions are recommended for testing. The effect of humidity on PDIV and PDEV is complex, while lower air pressure increases PD activity as can be interpreted from Figure 6. According to IEC TS 60034-25, a temperature rise from 25 °C to 155 °C decreases the PDIV typically by 30 %.

According to a study by Driendl et al. (2021), an increase of temperature from 20 °C to 200 °C decreased the PDIV by 15 %. Measurements by Driendl et al. (2021) were done with ten twisted pair specimens representing the turn-to-turn insulation. Generally, as temperature increases, the PDIV and PDEV decrease. The median of measured PDIV between temperatures of 20 °C and 100 °C did not have a significant difference, although there was more variability with the higher temperature. PDIV value showed a noticeable decrease between temperatures of 0 °C and 20 °C, and between 100 °C and 150 °C, with a more significant decrease from 150 °C to 200 °C. However, PDEV experienced the biggest decrease between temperatures of 20 °C and 100 °C.

In the same study by Driendl et al. (2021), also effect of pressure and humidity was investigated. As expected, as pressure decreases, also PDIV and PDEV decreases quite steadily. Also, increased humidity decreases the PDIV and PDEV values. However, according to a study by Ji et al. (2022), increasing humidity in most cases increases the PDIV. In this study, too, the test specimens are twisted pairs. This study does show similar results regarding the temperature, that PDIV decreases with increasing temperature.

3.3 Normalization

IEC 60270 provides a calibration procedure, however according to IEC 60034-27-1, calibration with machine windings cannot be conducted, and thus a normalization procedure is needed. Normalization is performed with the same calibrator, or a reference pulse generator, as is used for calibration in IEC 60270. When performing normalization, the circuit is the same as is the test circuit for the partial discharge tests. All cables shall be as short as possible, and it is very important to have the HV voltage supply not energized, as generally calibrators do not tolerate high voltages.

A short duration current reference pulse of a certain value of charge is then injected, and that is measured by the PD measurement device. According to these results, a scale factor *k* is determined. According to IEC 60270, scale factor *k* is the factor by which the reading of PD measurement device is multiplied to achieve the value of the input quantity, input quantity being now the charge of injected reference pulse. The completed test circuit is used with normalization, with all the components and connections that are needed for the PD measurements, the test object included. The calibrator is then connected in parallel with the test object. The charge injected by the calibrator is then detected by the PD tester. The correction factor is then adjusted so, that the reading on the PD tester is the same as is injected by the calibrator into the test circuit. As the PD pulses attenuate when travelling along the winding, the pulses produced by the calibrator are also attenuated, and with adjusting the correction factor, the attenuation can be compensated for.

3.4 Safety

Regarding the safety of the potentially high voltage PD tests, IEC 60034-27-1 provides some safety requirements. The circuit shall include an over-current protection device, in the case of failure or flashover. HV connections should be made as short as possible and have secure connections to prevent disconnection during the tests. A grounding stick should be available. The test circuit and equipment should be clearly marked to notify people about possible high voltage. Two persons should be present while making the connections and applying the test voltage.

After tests, the phases shall be grounded, and before touching any parts that may have a voltage present after the tests, they should be confirmed to have no voltage. If the tests require floating potential for the frame for example, it shall be grounded too, as also recommended by IEC TS 60034-27-5.

4 Measurements

The aim of these measurements is to provide answers for the research questions mentioned in the Introduction, such as:

- Is there PD activity with voltage levels occurring normally in regular operation of the elevator electric drive system?
- How high can the voltage be increased before a significant increase in PD activity?
- Does operation increase the PD activity?

The answers for these are provided by the PD measurements. Measurements are conducted with sinusoidal test voltage. PDEV and PDIV measurement results provide the most valuable information. To follow the trending of the results, the measurements should be conducted in a similar way in the future too. The most important aspects to record considering the repeatability and reliability of future measurements for trending are the test circuit, measuring equipment and its settings and environmental conditions, along with the test results themselves. Environmental conditions, such as temperature and humidity, should be kept consistent, and the same settings for measuring shall be used. The test circuit and the arrangement of it could be recorded also in the form a photograph so it can be rearranged as similarly as possible in the future. Operational data from the time between the measurements together with the results can provide some insight on the factors affecting the ageing of the insulation.

4.1 Measurement plan

The measurements with sinusoidal voltage are conducted mainly by following the instructions given in the standard IEC 60034-27-1. In the standard, test circuit diagrams and connections are given for testing of complete windings. All the given configurations are based on Y-connected machines. The tested machine is also Y-connected, with inaccessible star point.

Different standards provide different recommendations for the values of test voltages. These measurements conducted in this thesis are not for any qualification tests or type tests, but to find out the different PD characteristics of the machines. Thus, the test voltage is increased, until the PDIV is achieved. Measurements are done with a continuously increasing and decreasing voltage ramp.

Before PD tests, basic motor tests are done, including measuring IR and DAR, as IEC 60034-27-1 also recommends the IR test before PD tests. If these produce nominal results, the PD test can be conducted. If not, there is an issue with the insulation that should be investigated. With the PD tests, PD activity at different voltage levels is recorded to find out values for PDIV and PDEV. Also, a PRPD pattern is recorded.

Before carrying out the PD tests, test samples should be conditioned, as recommended by IEC 60034-27-1. This provides more stable test results. A minimum recommended conditioning period is 5 minutes with the maximum test voltage. As with the tests in this thesis, the maximum test voltage is not defined beforehand, so a test voltage defined by IEC 60034-27-1 shall be used, that being the line-to-ground voltage. Also, before doing the actual PD test, noise level should be recorded, and the PD magnitude threshold should be set accordingly.

4.1.1 Effect of operation

With this test, a new, unused stator is tested, and after initial tests, the stator is joined with a rotor and the machine is then put into a machine tester. The machine is operated with a thermal cycling profile, which provides accelerated ageing, for about three weeks. After that, the stator is separated, and the same measurements are conducted to see if there are any notable effects caused by this period of operation. The PD tests are conducted with sinusoidal voltage, as no impulse voltage PD tester was able to be acquired in time for the initial testing. The values of inception and extinction voltages and differences between the PRPD patterns can be then compared with results from unused and used stator.

While conducting the PD tests, the stator core is grounded. Schematic diagrams of the connections are shown in Figures 8 and 9. U1, V1 and W1 refer to the phase terminals for the motor supply. Connections U2, V2 and W2 denote the end windings, and they are connected to create the star point of the stator winding, however the star point is inaccessible.

The standard IEC 60034-27-1 also includes connections for accessible star point, which could provide more information, but such a stator was not available in time for initial tests.

The connections for PD measurements from IEC 60034-27-1 for integrated test equipment for a closed star point are presented in Table 1. No phases are connected to ground with these measurements, just the stator core is grounded.

Table 1. Connections for the PD tests as defined in IEC 60034-27-1

Connection ID	**Voltage supply**	**Coupling capacitor**	**Ground**	**IEC number**
1	U1	U1	Core	I3.1
2	V1	V1	Core	I3.2
3	W1	W1	Core	I3.3
4	U1V1W1	U1V1W1	Core	I3.4

The connections from 1 to 3 in Table 1 connect one phase at a time to the PD tester. Connection number 4 connects all the phases directly to the test voltage supply. The standard IEC 60034-27-1 recommends measurements to be carried out with test equipment where the HV supply and coupling capacitor can be connected to different ends of the winding. Measurements using integrated equipment, that is where the HV transformer and coupling capacitor are internally connected in parallel, are also possible. However, according to this standard, this type of connection can introduce more noise from the HV supply to the measurements.

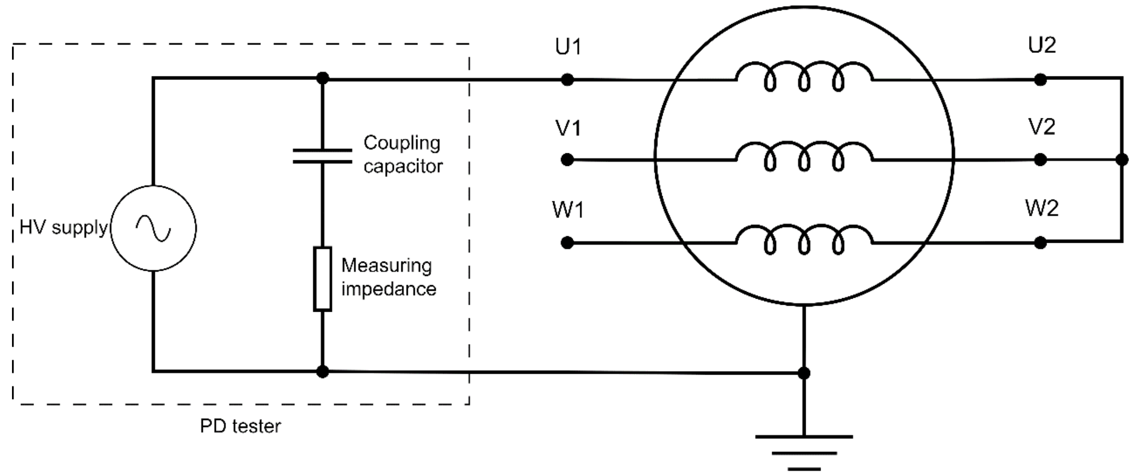


Figure 8. Connection schematic for connection 1. One phase is connected to the PD tester, while other phases are not directly connected.

In Figure 8 is a schematical connection diagram for the PD test with connection 1. The PD tester block represents the PD measuring system, and shows the most important components, HV supply to provide the test voltage, HV coupling capacitor and a measuring impedance to measure the PDs and output the signal to the measurement unit. The circle around the windings illustrates the machine frame and stator core, which are grounded in all test circuits. Connections 2 and 3 follow the same diagram, with a different phase connected to HV supply.

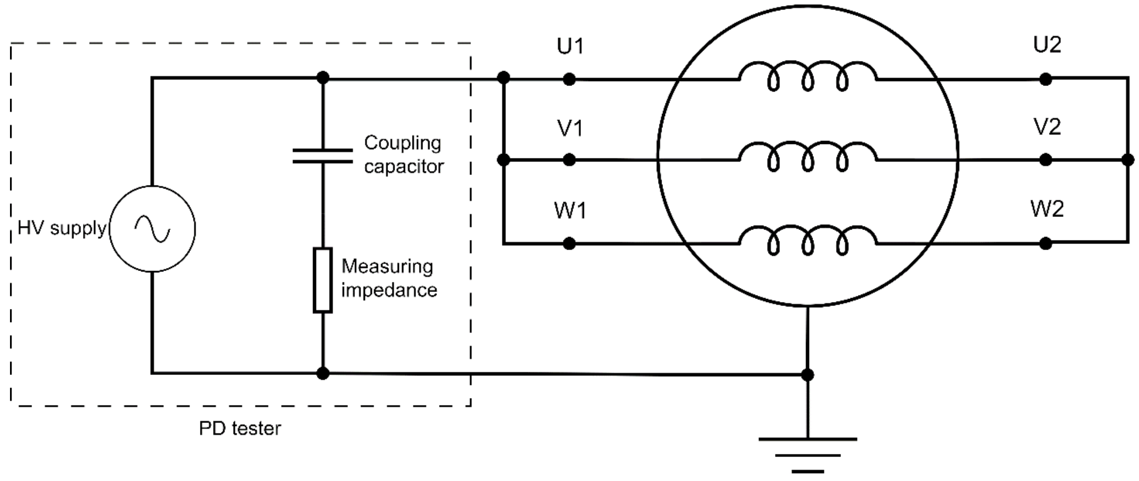


Figure 9. Connection schematic for connection 4. All the phases are connected to the PD tester.

Figure 9 shows the connection diagram for connection 4, where the PD tester is connected to all three phases simultaneously. These two figures present the connections for the PD tests carried out with the sinusoidal testing voltage.

Tested stator is from an AFPMSM, with a fractional slot concentrated non-overlapping winding. The rated line-to-line voltage of the stator is 440 V AC RMS. For this machine, the rated rotational speed is 159 rpm, with a ranging torque according to the use case and other parameters of the elevator and the electrical drive. The nominal power for the machine ranges from 8.2 kW up to 12.1 kW.

The test environment is an industrial laboratory building, with many possible sources for external electromagnetic disturbance. All of the environmental conditions are not totally constant. Temperature is around room temperature and should stay quite constant. Humidity might have some variation, but still stays around normal indoor humidity range. The measurements have been conducted during autumn, which means the relative humidity indoors has likely stayed between 40 % and 60 %. The amount of background electromagnetic disturbances varies day to day, depending on what devices are used inside the premises. To minimize the effect of external electromagnetic disturbances, the test object was placed inside a Faraday cage like chamber, as shown in Figure 10.

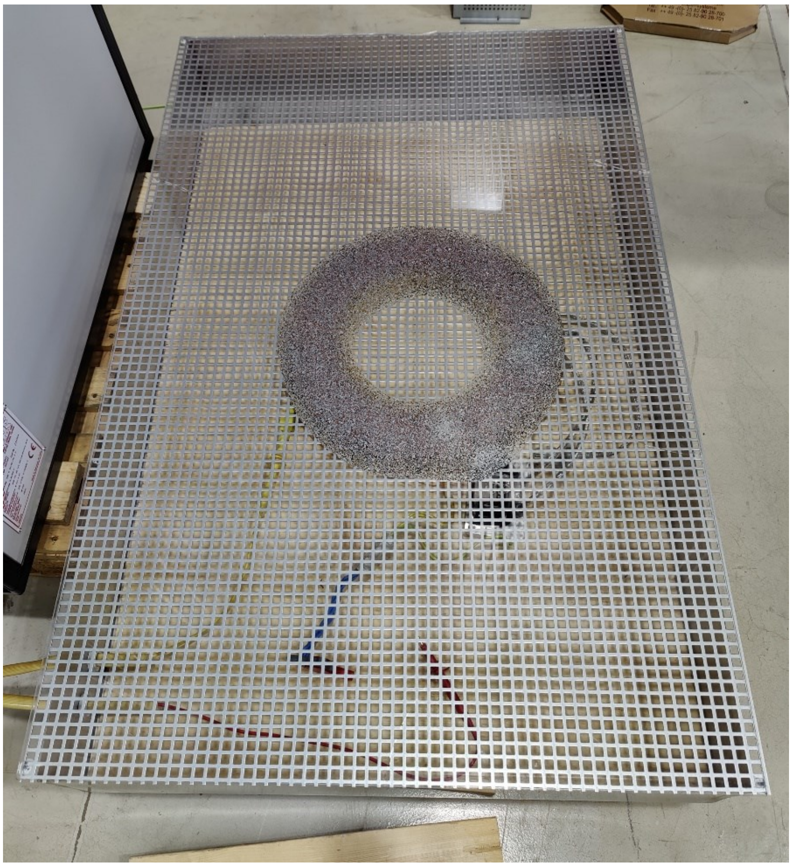


Figure 10. The test chamber used to decrease the effect of electromagnetic disturbance on the test object. The test object in this picture is not the one used in this thesis. The figure was edited to obscure the details of said object.

The test chamber has a sheet metal body and a metal mesh on top which have a galvanic connection. Test chamber is grounded, and a plywood sheet is used inside to galvanically isolate the test object from the chamber. Insulating sleeves were used on the ends of unconnected phase wires, to insulate them from the frame of the machine and stator core. Measuring cables are brought in through a bushing on the side of the chamber and connected to the phase(s) and the machine frame with clamps. The measuring cables are kept at a distance from each other inside the chamber, and outside they have an insulation sleeve which also extends inside the bushings. The measuring circuit including the test cables was tested to be PD free up to at least 1.5 kV RMS AC.

4.1.2 Test procedure

The basic motor tests were carried out with a MotorAnalyzer 2 motor tester by Schleich. PD measurements with sinusoidal voltage were conducted with a partial discharge test system TPP 10 by MPS Mess- & Prüfsysteme GmbH. The system is able to provide a sinusoidal test voltage of 10 kV RMS maximum. PD level at maximum 10 kV is claimed to be less than 1 pC, and a basic noise level to be generally from 0.1 pC to 0.3 pC, but below 0.7 pC. The PD measurement unit has different narrow-band and wide-band filters for PD measurement. The bandwidth of the narrow-band filter is 15 kHz, and the center frequency can be adjusted between 0.1 MHz…2.5 MHz. For the wide-band filters, there are four options with different bandwidths and cut-off frequencies.

The testing of the stator was done following the test procedure described next. Partial discharge measurements were conducted using the four connections provided in Table 1, according to the connection diagrams in Figures 8 and 9.

1. Basic motor tests

   Insulation resistance and dielectric absorption ratio were measured first. These are used to initially check the condition of the insulation system of the electric machine. If the value of IR is high enough, according to the standards as described in section 2.3.1, the PD tests can be conducted as no serious defects are present. Also, the winding resistance and inductance were measured to ensure the symmetricity of the phases. Also, the capacitance between the stator winding phases and the frame was measured.

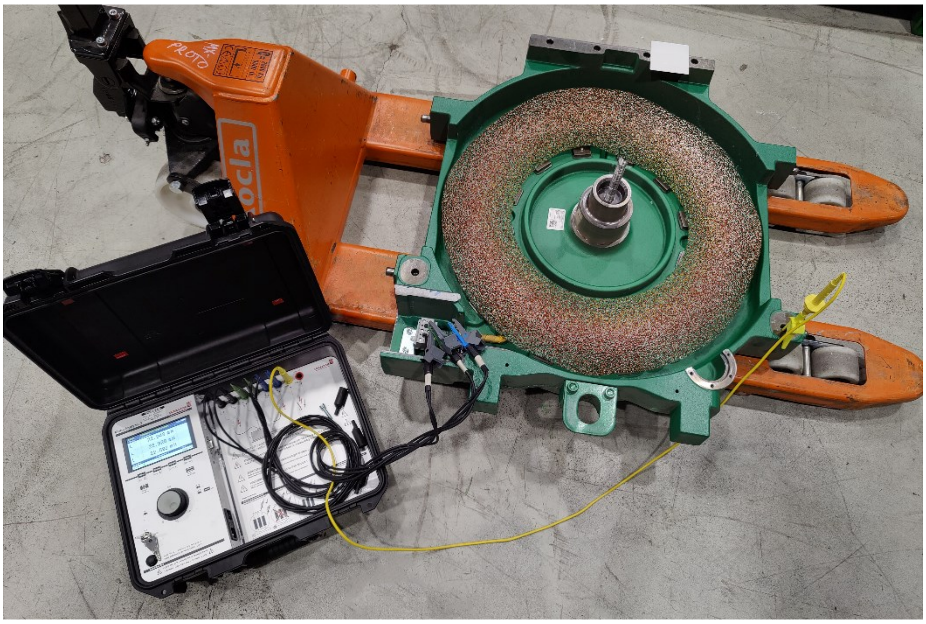


Figure 11. Measuring setup for basic motor tests with the MotorAnalyzer 2, and the test object used in this thesis. The figure has been edited to obscure details of the test object.

The setup for conducting the basic motor tests on the test object stator being tested in this thesis is shown in Figure 11. The stator is mounted onto the frame of the machine, with the rotor removed. Black measuring cables are connected to the phase terminals of the machine with clamps. Yellow measuring cable is for the ground, and it is connected to the frame which also has a galvanic connection to the stator core.

2. Noise and measuring frequency

The measurements were conducted in an environment where the suppression of external causes of disturbance and noise is difficult, and they might also vary over time. Thus, the noise level was recorded for all measurement connections. Measuring frequency also affects the noise being picked up by the measuring unit.

As stated in IEC 60034-27-1, wide-band filters are more commonly used for PD testing of rotating electric machines, and for off-line testing that provides good sensitivity to detect PDs from the whole winding. Lower limit frequency should be several tens of kilohertz, as recommended in IEC 60270, to limit the disturbance from power frequency harmonics and switching power supplies. Thus, a wide-band filter was used, with a frequency range of 80 kHz to 400 kHz. It is very important to note, that the same frequency should be used for the measurements following up, too. This enables more accurate comparisons of the results and trending.

3. Normalization

   Normalization was then conducted to find out the correction factor for PD measurement, as discussed in section 3.3. It indicates how much the pulses attenuate in the measurement circuit and the test object. Correction factor should generally not be more than two or three, depending on the test object and environment. Normalization was done for all four test connections separately. The normalization was done using calibration pulses of 25 pC.

4. Conditioning

   Conditioning of windings and winding components is strongly advisable before the PD tests. Conditioning of the stator was done for all four test connections separately, whenever the connection was changed, as the PD tests should be carried out immediately after conditioning. In normal operation, the machine can be supplied by a frequency converter with a DC link voltage of 620 V. This is the maximum voltage stressing the insulation in the machine, with no overvoltage taken into account. Conditioning was done by applying an AC voltage of 440 V RMS, thus peak voltage being 620 V, for 5 minutes. Conditioning was done for every connection, after normalization and right before PD tests.

5. PD tests

   For determining the PDIV and PDEV values, a threshold should be specified for PD magnitude. When the PD pulse magnitude is above this threshold, the test object is considered to have partial discharges and thus PDIV is reached. The used threshold was the charge used for normalization, 25 pC, to have accurate measurements of the PDIV. PDIV and PDEV were measured with this threshold, and the measurements were repeated 6 times. In addition, a PRPD pattern was recorded at a voltage level above the PDIV. PD test procedure included a voltage ramp where voltage was constantly increased at a steady speed until PDIV value was achieved. Then the voltage was raised to 10 % higher than the PDIV and kept there for 10 seconds. After

10 seconds the voltage was decreased with a steady voltage ramp until PDEV, and then set to zero. During that 10 second period, the PD magnitude was also measured. First five seconds were waiting time, where no values were recorded. The next five seconds were when the PD magnitude was measured and recorded. The PD magnitude measured and presented in Tables 3 and 5 is an average over that five second measuring time period.

Figure 12. The test setup for measuring the partial discharges.

The complete PD test setup is shown in Figure 12. It consists of a laptop computer, the TPP 10 test set, and a test chamber with the test object inside. The laptop is running a control software, which is used to control the test set and to record the measuring results. The TPP 10 test set consists of the control and measuring unit underneath the laptop, and the bigger HV unit. The HV unit includes the HV transformer with the coupling capacitor and other components of the measuring circuit, and a small test chamber. The voltage regulation of the HV transformer has 255 steps, so as the maximum voltage is 10 kV, the voltage can be controlled with a resolution of about 40 V. The test object for this thesis is too large to fit inside the test chamber of the test set itself, so it is placed next to it in a separate test chamber. Measuring cables are led out through the open door, as the connectors are inside the HV unit test chamber.

IEC 60034-27-1 recommends a maximum slew rate of 1000 V/s for 50 Hz sinusoidal test voltage. The test voltage slew rate was set to 200 V/s, both when increasing and decreasing the voltage. The tests were conducted with a wide-band band pass filter with lower cutoff frequency of 80 kHz, and higher cutoff frequency of 400 kHz. Correction factor was set for each connection separately according to the normalization. Threshold for defining the PDIV and PDEV was set to 25 pC, for which point the normalization was also done. The threshold was selected based on the noise and disturbance level when the test object was connected and based on earlier tests on a similar test object. The earlier tests were done to find out the best practises for carrying out the measurements on the official test object.

The stator was run in a tester for about three weeks. The test cycle comprised of loading the machine until the winding temperature reached 100 °C. After that, the machine was let to cool down until the winding temperature reached 50 °C. This cycle of warming up and cooling down took about 1 hour and 20 minutes. The test cycle was run in total for about 15 days during the period of three weeks. This corresponds to about 270 cycles, where the stator temperature increased and decreased. This provides some accelerated aging, as in normal operation in a residential building, the temperatures would rarely rise that high.

The second measurements, after the stressing period in a machine tester, were conducted in the same way as the initial measurements. Basic motor tests were done before doing the PD tests. Wideband filter with the same limit frequencies of 80 kHz and 400 kHz was used for measuring PD. Normalization and conditioning was done with the same procedure, and with the same values for all the test connections.

The test set was located in the same location, so environmental conditions are as close to the original measurements as possible. Electromagnetic disturbances in the environment might be different, as some equipment which produce these disturbances, might be used intermittently inside the premises.

5 Results

In this chapter, the results of the conducted basic motor tests and the PD tests are presented and analysed. PDIV is measured to find out when PDs start to occur and is it below or above the voltages that occur during nominal operation. PDEV affects the PD activity in the stator, too, and the level of that defines if the PDs will get extinguished during operation or not. The results of PD tests and basic motor tests are compared to provide some trend, however, with just two measurements, it is not possible to draw reliable conclusions.

In the IEC 60034-27-1 and IEC 60034-27-2, some guidelines for interpreting PRPD patterns are given, however, they do not apply for machines tested in this thesis for beforementioned reasons. They are used to provide some insight on the interpretation of the acquired PRPD patterns.

5.1 Effect of operation

The PDIV and PDEV measurements were conducted six times. Time between each consecutive measurement with the same connection was around 30 seconds or less. Time between measurements with different connections was longer, including the conditioning of five minutes of each connection before the PD tests. Along with these tests, the PD magnitude was recorded after the PDIV was observed, with a voltage of 10 % higher than the measured PDIV. At this higher voltage, first 5 seconds was waiting time, and then 5 seconds when the value was recorded.

First, the basic motor tests were done before any PD tests or conditioning. The results of those are presented in Table 2.

Table 2. Results of basic motor tests on the stator by Schleich MotorAnalyzer2.

Phases	**Resistance [Ω]**	**Inductance [mH]**	**IR [GΩ]**	**DAR [-]**	**Capacitance [nF]**
U-V	1.192	23.156	122.3	2.55	5.6
U-W	1.193	23.181			
V-W	1.192	23.086			

The insulation resistance is much higher than the minimum values defined in the standard, and thus also suitable for continuing onto PD tests. DAR was measured using the usual 30 second and 60 second IR values and shows also excellent results. Resistance and inductance of the stator winding are measured between two phases and without the rotor. Those values show that the stator winding is very much symmetrical. Capacitance measured is the capacitance between the phases and the frame.

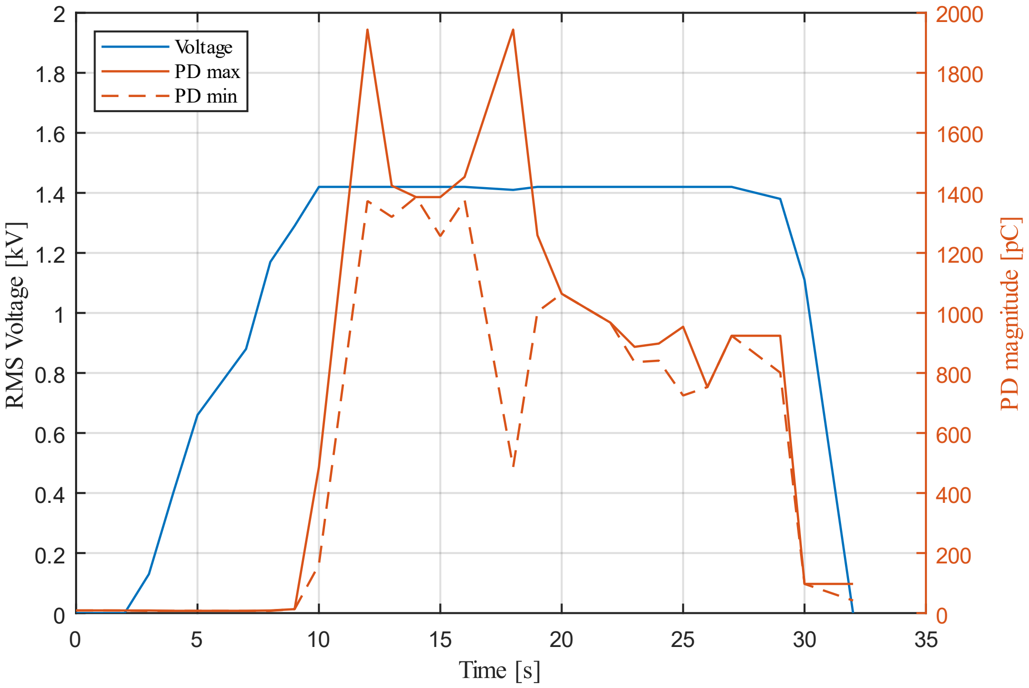


Figure 13. Example graph of one PD test. Test voltage RMS value is shown in blue, and maximum PD magnitude in solid orange, and minimum PD magnitude with dashed line.

Figure 13 shows an example graph from one of the PD tests. It shows the RMS value of the test voltage, and the maximum and minimum values of the detected PD pulse magnitudes. As the voltage increases, partial discharges begin to occur. As can be seen in the figure, the PD magnitude does not stay on the same level, even though the voltage is kept constant. This shows the inconsistent nature of the partial discharges. Even though this figure shows a pattern of decreasing magnitude after a high peak in the beginning, graphs from other tests do not replicate the same pattern.

The results from the first measurement on the unused stator, before stressing, are presented in Table 3. Some measurements produced a ‘none’ for the PDEV, so those measurements are excluded, and replacement measurements were done. Total amount of successful measurements is six for all test connections. The results can also be found in Appendix 1.

For tests 1, 2 and 3 the correction factor or scale factor *k* obtained by normalization was 1.29. Background noise for these measurements was around 7 pC. For connection 4, the correction factor *k* was 1.65. Background noise was also higher, hovering around 15 pC. These background noise values are also multiplied by the correction factor set in the measuring unit. When considering that, background noise picked up by the measuring unit was higher with all phases connected to it. The stator winding acts as an antenna, picking up electromagnetic disturbances from the environment, which are produced by various equipment inside the facilities where these tests were conducted. The background noise had significantly lower levels when measuring cables were disconnected from the test object. This also implies that the test chamber, where the test object was placed inside of, was not a perfect Faraday cage.

Table 3. Measurement results from the first PD measurements, with the standard deviation calculated for 95 % confidence level, assuming normal distribution. Voltages are presented as RMS values.

Test connection	**Average PDIV [kV]**	**Average PDEV [kV]**	**Average test voltage [kV]**	**Average PD magnitude [pC]**
1, U phase	1.19 ± 13.0 %	0.94 ± 13.7 %	1.35 ± 9.3 %	905 ± 65.6 %
2, V phase	1.31 ± 5.3 %	1.03 ± 11.1 %	1.47 ± 5.3 %	902 ± 28.7 %
3, W phase	1.25 ± 4.2 %	1.13 ± 14.2 %	1.41 ± 3.9 %	181 ± 88.5 %
4, all phases	1.24 ± 4.0 %	1.11 ± 7.3 %	1.40 ± 2.9 %	573 ± 72.3 %

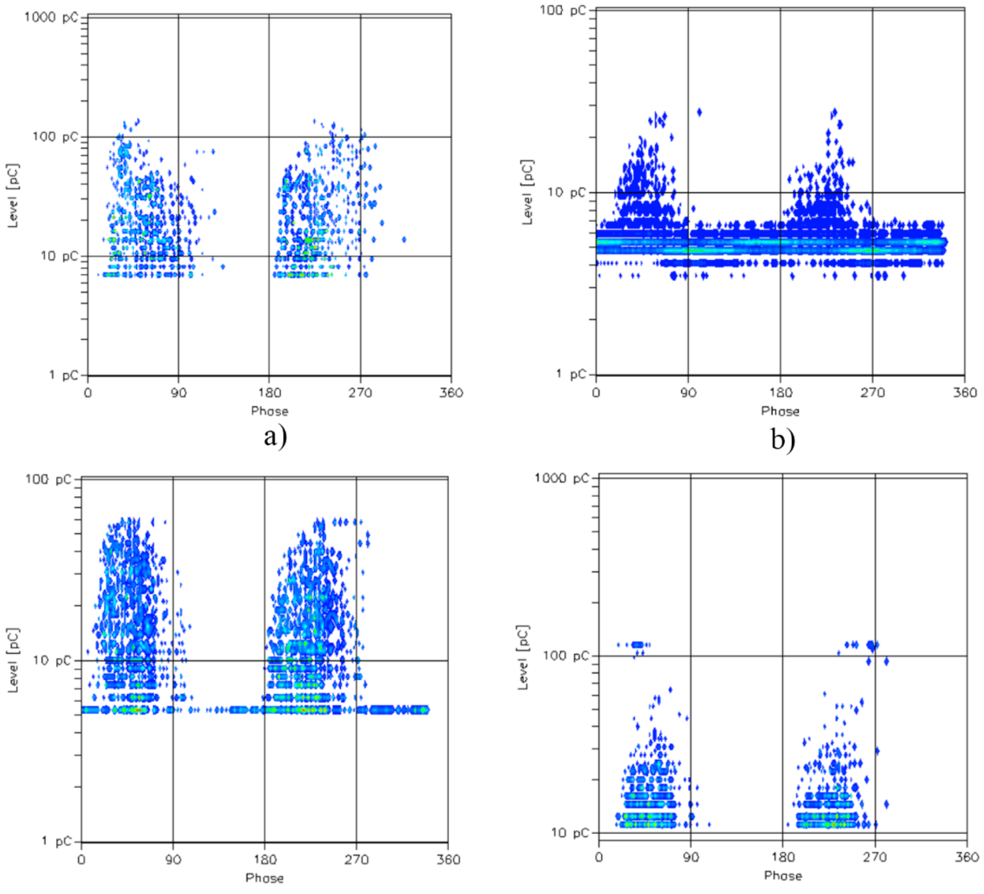
The average value of measurements is presented as arithmetic mean value. From the measured values, standard deviation was calculated, and then that was expanded to correspond to 95 % confidence level. Assuming normal distribution of these measurement results, the standard deviation was multiplied by a factor of 2, to achieve 95 % confidence level. The relative deviation was then calculated in relation to the average value and is presented in the table.

The measurements were conducted in the same order as they appear in Table 3. The deviation in measured PDIV and PDEV values decreases as the measurements go on. This could imply that the conditioning that was done, was not completely sufficient to stabilize the PD activity. With all measurements other than for U phase, the first measured PD charge magnitude was higher than the rest of the measured values. However, the PD charge magnitudes have significant variation, between 65 % and 89 %, except for phase V, which has only 29 % of variation.

When looking at the PD magnitudes, PDs seem to be occurring more somewhere along the U and V phase winding. On average, their magnitudes are much higher than for W phase, and with all phases the magnitude is in between the magnitudes of those phases. Practically all the partial discharges are between the phase and ground, as the phases are in the same potential due to the star connection.

PRPD patterns were recorded for all connections with a voltage of 1.3 kV RMS. This voltage level was selected as it is above the PDIV, and thus PDs will occur, and they can be recorded.

The PRPD patterns consist of three measuring periods of three seconds each, and thus containing nine seconds worth of PD pulses.



a) b) c) d)

Figure 14. The PRPD patterns from initial measurements. a) Phase U, b) phase V, c) phase W and d) all phases together. PD magnitude is shown on the vertical axis in pC and the phase in degrees on the horizontal axis.

Figure 14 presents the PRPD patterns for all four test connections from the initial tests, with a test voltage of 1.3 kV RMS. As can be seen especially in Figures 14b) and 14c), the background noise is still visible in these patterns, and the magnitude of PDs is not as high as in Table 3. This is due to the lower test voltage compared to the test voltage used to acquire the values in Table 3.

Despite that, it can be clearly seen in Figure 14, that almost all PD pulses happen in between 15° to 105°, and between 180° to 280°, so within the first and third quadrant of the sinusoidal test voltage cycle. This means that partial discharges occur only on the rising edge of the sine wave, in both positive and negative directions, when the potential difference over the insulation is increasing. The PD pulses are highly symmetrical. The shape and the magnitude of the PRPD pattern are similar on both positive and negative half-cycles of the applied voltage.

Even though the interpretation guidelines in different standards, such as IEC 60034-27-2 and IEC 60034-27-1, are said not being valid for these types of machines, some hints can be taken from them. Both standards state that this shape of PRPD pattern implies that there are cavities or internal voids in the main insulation. According to IEC 60034-27-2, the PRPD patterns would be asymmetric between the positive and negative half-cycle if there was for example delamination between the conductor and insulation. The patterns being symmetrical on positive and negative half-cycle indicates that the partial discharges occur between two insulating materials. Asymmetric magnitude could imply the PDs are between copper and insulating material.

In Figure 14, the PRPD pattern a), for U phase, shows a total of 1320 detected PD pulses. For b) V phase 17316 pulses, for c) W phase 2424 pulses and for d) all phases 1159 pulses. The number of detected pulses is hugely bigger for phase V, which can be explained by looking at the PRPD pattern b). There is a large amount of background noise, which is detected due to the low magnitude of the PD pulses from the stator. If the test voltage were higher, the PD pulse magnitude would be higher too and thus the measuring range would render the background noise practically undetectable. The detection of background noise can also be seen in the figure, as there are pulses detected at all phases, from 0° up to almost 360°. Some background noise can also be seen on phase W in c), but as the PD magnitude is higher, the background noise detected is also less. This indicates that the V phase insulation is from the PD point of view better than the other phases, as the PD magnitude on V phase is not as high as on the other phases. On the other hand, no background noise is detected on the U phase, as there the PD magnitude is the highest. This indicates that the U phase insulation is weaker than on the other phases.

PRPD patterns in Figures 14a) and 14d) contain practically no background noise. Their pulse counts are 1320 and 1159, respectively. The number of pulses per cycle can be calculated, as the graph includes data over a period of 9 seconds, and the frequency of the sinusoidal voltage is 50 Hz. This corresponds to about 2.93 and 2.58 PD pulses in one cycle of the sinusoidal test voltage. As there are two spots where the PDs occur, on the first and third quadrant, this means that on average at least one partial discharge occurs every time the potential over the insulation increases.

5.1.1 After stressing

For measurements after stressing, the PD measurements were repeated six times for all connections. Extra measurement was taken in one case where the PDIV was lower than the PDEV, as that result was discarded. Reason for that result is unknown, there might have been for example a single disturbance which caused the PD meter reading to spike over the threshold value. Before the PD tests, same basic motor tests were taken as with the initial measurement before stressing period. The results of the basic tests after stressing are presented in Table 4.

Table 4. Results of basic motor tests after stressing

Phases	**Resistance [Ω]**	**Inductance [mH]**	**IR [GΩ]**	**DAR [-]**	**Capacitance [nF]**
U-V	1.196	23.123	183.2	2.98	5.3
U-W	1.196	23.159			
V-W	1.195	23.065			

Comparing the values from Table 4 to those acquired with the initial tests, values are mostly similar. Resistance values are slightly different, but symmetrical. They have changed from 1.192 Ω and 1.193 Ω, to 1.195 Ω and 1.196 Ω. The difference in resistance is insignificant and can for example be a result of different measurement temperature. Inductances have decreased slightly, by 0.14 % at maximum. Capacitance also decreased from 5.6 nF to 5.3 nF. Every difference between the measured values may fall within measurement uncertainty.

Insulation resistance has increased significantly from 122.3 GΩ to 183.2 GΩ. This also clearly exceeds the minimum value set in the standards. DAR has also increased from 2.55 to 2.98. The increase in IR could indicate that the varnishing had not yet cured completely, and there might have been some moisture in the insulation. Also, leftover flux substances might have evaporated, while the machine was stressed, and the winding temperature reached 100 °C regularly.

The values from the PD tests after stressing are presented in Table 5. With normalization of every test connection, a correction factor of 1.28 was achieved for connections 1, 2, and 3. It remained very similar compared to the initial measurements, where the correction factor for these connections was 1.29. For test connection 4, the correction factor was 1.62. That is slightly lower than the correction factor on initial tests, which was 1.65.

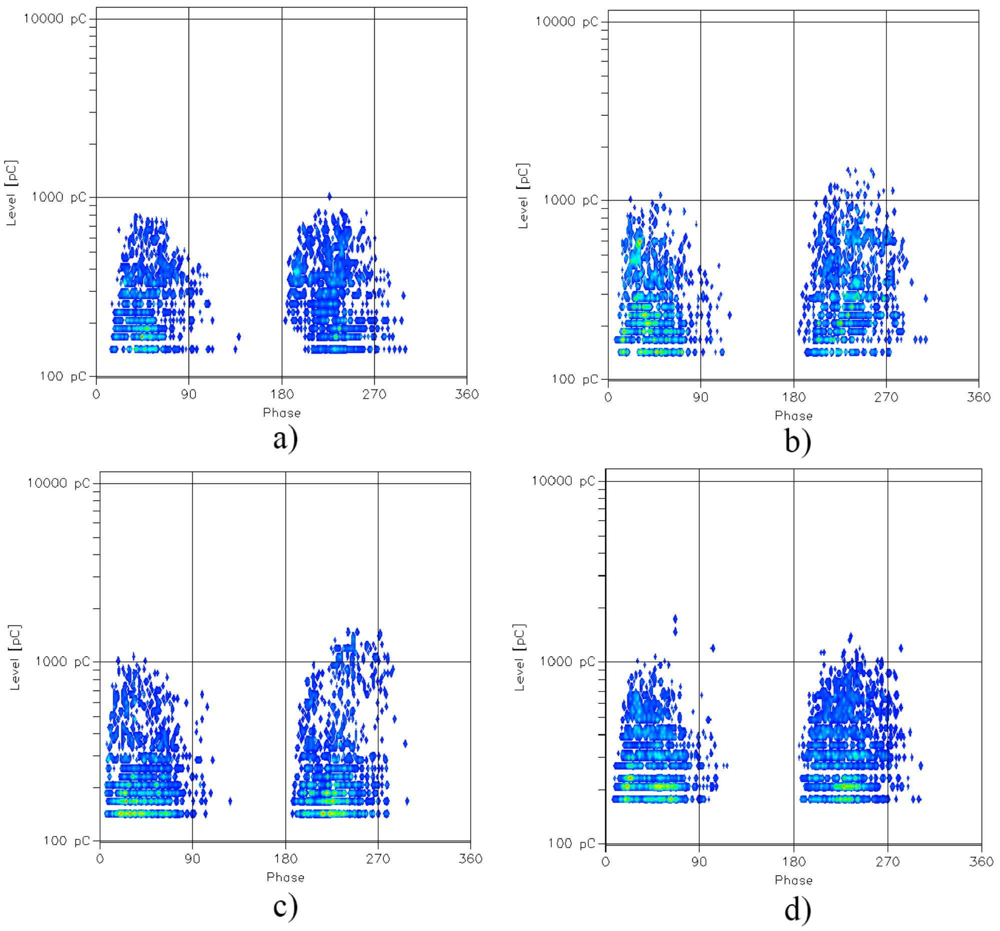
Background noise detected by the PD measuring unit was between 4 pC and 5 pC with connections 1 to 3. With connection 4, it again increased, to about 8.5 pC. These readings are somewhat lower than the ones when conducting the initial measurements, those being 7 pC and 15 pC, respectively. There might have been less devices running that create electromagnetic disturbance, at the day of these measurements. However, as the PD magnitude limit for PDIV and PDEV was still 25 pC, these lower disturbance values should not affect the results and detection of inception and extinction voltages.

Table 5. Results of the PD tests on the stator winding after stressing, with the standard deviation calculated for 95 % confidence level, assuming normal distribution. Voltages are presented as RMS values.

Test connection	**Average PDIV [kV]**	**Average PDEV [kV]**	**Average test voltage [kV]**	**Average PD magnitude [pC]**
1, U phase	1.16 ± 13.4 %	0.95 ± 14.9 %	1.31 ± 13.9 %	482 ± 94.4 %
2, V phase	1.28 ± 7.5 %	0.97 ± 15.9 %	1.43 ± 7.9 %	1082 ± 53.4 %
3, W phase	1.24 ± 12.1 %	0.96 ± 8.0 %	1.39 ± 9.8 %	650 ± 129.2 %
4, All phases	1.22 ± 12.5 %	1.00 ± 10.0 %	1.33 ± 16.7 %	1077 ± 82.9 %

As shown in Table 5, the average values of PDIV and PDEV are different compared to the initial measurements. They are mostly lower values, but the variability has also increased in most cases. The standard deviations of PD magnitude values contain especially large variations, up to over 100 % with 95 % confidence level on the W phase. Here the PD magnitudes are the highest on W phase and on all phases, in contrast to the initial measurements, where the highest magnitudes were on phases U and V. The results are also presented in Appendix 1, alongside the results from initial measurements. The measurement results from before and after stressing are compared in more detail in section 5.1.2, including graphical presentation.

The PRPD figures from these tests were acquired automatically with the test voltage, which was also used to measure the PD magnitude, thus the voltages being different from the initial PRPD patterns. The test voltage was 10 % higher than the inception voltage for each measurement, so in these PRPD patterns the partial discharges are initiated properly. PRPD patterns for all four test connections are provided in Figure 15.



a) b) c) d)

Figure 15. PRPD patterns from all test connections after the stressing period. a) U phase, b) V phase, c) W phase and d) all phases. PD magnitude in pC on vertical axis and phase of pulses in degrees on horizontal axis.

As these patterns in Figure 15 were acquired automatically during the PD measurement, the voltages are slightly different between them, depending on the PDIV. The RMS voltage of the applied sinusoidal test voltage for these presented PRPD patterns are 1.39 kV for a), 1.43 kV for b), 1.44 kV for c) and 1.41 kV for d). As the voltages are higher than with the initial PRPD patterns, these patterns do not include any of the background noise below 10 pC. The PD magnitude is higher, so the lower magnitude pulses are not detected due to the decreased sensitivity.

The PRPD patterns look very similar compared to the ones captured during initial measurements. The phases where the pulses are located are the same, mainly between 0° to

90° and between 180° to 270°. The magnitudes of the patterns b) and c) are slightly different between the positive and negative half-cycles.

The PRPD patterns in Figure 15 contain the pulses of four measuring periods, each three seconds long. In total, the patterns show pulses over a period of 12 seconds. The number of pulses was also recorded, and for phase U it is 2308 pulses, for V phase 2337 detected pulses, for W phase 2803 pulses and for all phases 3673 pulses. This corresponds to 3.85, 3.90, 4.67 and 6.12 pulses, respectively, per one cycle of the 50 Hz sinusoidal test voltage. On average with single phase connected, this means that about two partial discharges occur every time the potential over the insulation increases. With all phases connected, on average three pulses occur on every rising edge. The number of pulses per cycle is higher than with the initial measurements, those being 2.93 and 2.58. This can be due to ageing or weakening of the insulation, or due to the higher test voltage, which was used to capture these PRPD patterns. Measurements with the same test voltage could be done, to also follow the trend in the amount of PD pulses.

5.1.2 Comparison of PDIV and PDEV results

Here the results from PDIV and PDEV tests are presented visually in a graph. This provides an easy way to see the trend and interpret the results quickly. The graphs present the results from the initial tests on the brand-new test stator, and the results after the stressing period. The results and values presented in the following figures are from Tables 3 and 5.

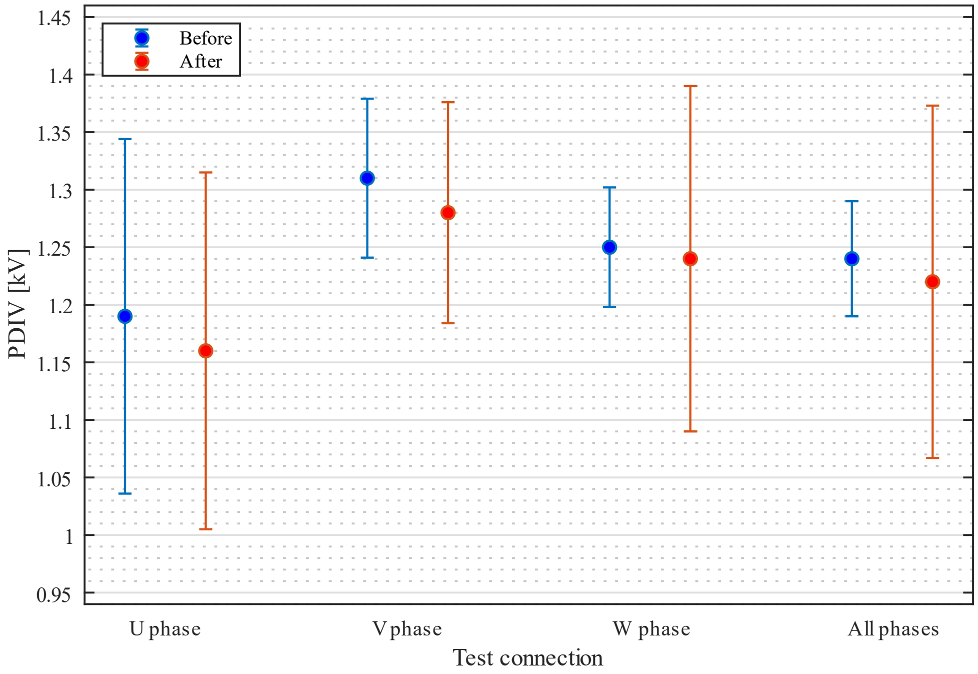


Figure 16. PDIV test results from before stressing (in blue) and after stressing (in orange). The dots present the average value, while the error bars present the 95 % confidence interval.

Figure 16 presents the results for PDIV visually. As can be seen in the figure, the average values of measured PDIV have slightly decreased with all of the test connections. Decrease is noticeable in phases U, V and for all phases, with a very slight decrease in phase W. Biggest decrease is in phases U and V, that being 30 V. The highest PDIV is on the V phase, in both measurements, before and after. This indicates, alongside the lowest PD magnitude of all phases in PRPD in Figure 14, that the V phase is better insulated than the other phases. The PDIV is lowest on the U phase, also in both measurements, before and after. In the PRPD pattern in Figure 14, the PD magnitude of U phase was the highest, so this supports the finding that U phase insulation is the weakest.

However, as can be also seen, the error bars representing the variation of the measured values show that variation is significant. With phase W and all phases, the variation is significantly increased compared to the initial measurements. The PDIV values acquired after stressing can practically also lie above the before values, as the confidence intervals are wide. With this much variation, these results cannot be used to draw definitive conclusions.

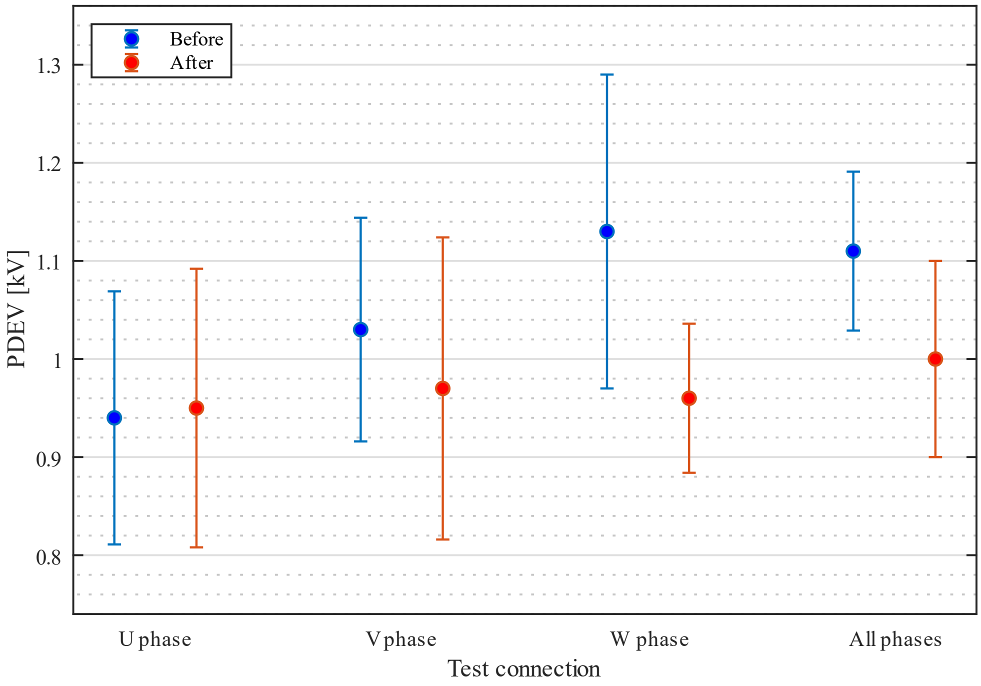


Figure 17. The PDEV values from the initial measurements (in blue) and after stressing (in orange). The dots represent the average value, while error bars present the 95 % confidence interval of the measurements.

Figure 17 shows the comparison of PDEV results visually. As can be seen in the figure, the trend with PDEV values is also showing a decrease. Except for phase U, all other phases show a reduction in the PDEV value. The decrease in phase W is the biggest, that being 170 V. Difference of PDEV value in phase U is 10 V increase compared to the initial value. Considering the test voltage regulation resolution of about 40 V, the difference between the before and after measurements can be deemed insignificant in phase U. Also, the limits of 95 % confidence interval are very similar.

In contrast to the PDIV results, the PDEV results after stressing have similar or even lower variability. Figure 17 shows more clearly that a trend in PDEV is a decreasing trend, unlike Figure 16 for the PDIV, as the variability is smaller, and the differences between the average values are larger.

In Appendix 1, in addition to the results of the official test stator, also test results of another stator are presented. That stator is the same type and size as the unit used for testing in this thesis. The unofficial stator has been stressed in a tester for significantly longer time than the official test stator had time, several years. As it is not the same unit, the results are not directly comparable. However, the results of that more used stator show generally PDIV values of around 100 V lower than with the official stator after stressing. Only one phase shows similar PDIV values. Two phases show similar PDEV values, and two show lower values on the unofficial stator, up to a difference of around 200 V.

This could indicate that as the insulation keeps ageing, it also becomes more vulnerable to PDs. PD activity might increase in machines during operation, as the inception and extinction voltages decrease over time. Partial discharges affect the lifetime of LV machines by deteriorating the insulation. If the decrease of PDIV and PDEV is observed to be increasingly faster, that could indicate that the insulation is reaching the end of its lifetime.

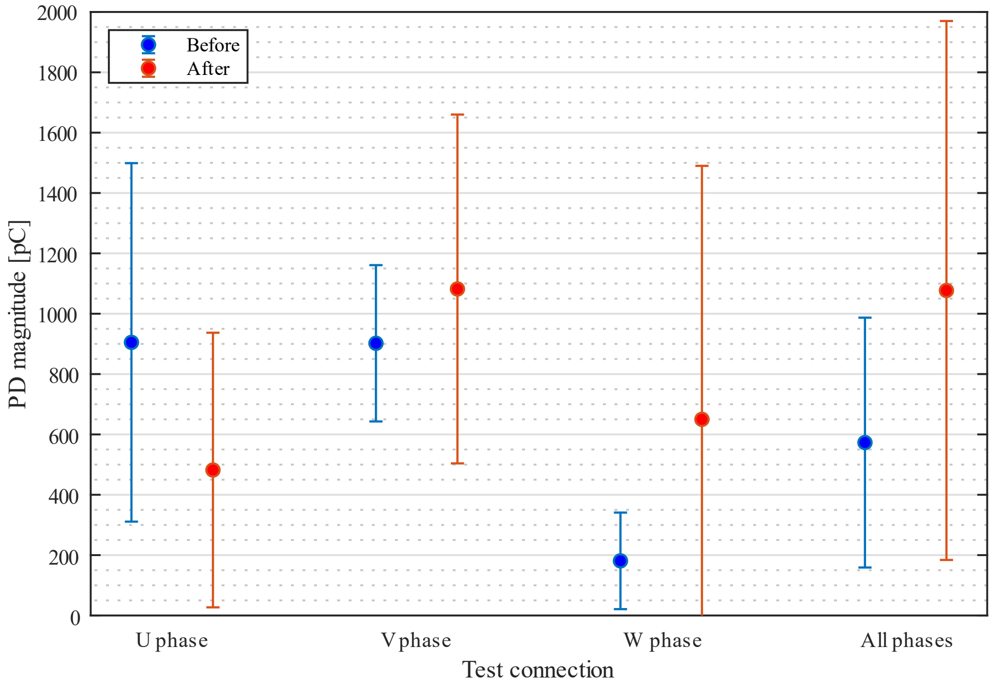


Figure 18. The measured PD magnitude of initial measurements (in blue) and for measurements after stressing (in orange). Dots show the average value of the corresponding measurement, and error bars show the 95 % confidence interval.

Figure 18 shows the measured PD magnitude values. As can be seen in the figure, there is a huge variability in the magnitude values. Except for the phase U, other phases show an increase in the average value, although there is a significant increase in the variability, too.

The test voltages were not the same for these PD magnitude measurements. However, they are tied to the measured PDIV in every case, being 10 % higher than the PDIV. The PD magnitude seems to have increased from the initial measurements. Measurements could be done also with the same test voltage, to follow the trending on PD magnitude at the same voltage level, in addition to the number of PD pulses.

When comparing the results with the unofficial stator test results (Appendix 1) no clear conclusions can be drawn from the PD magnitudes. With the more used stator, the variation in the measured PD magnitudes is as large as with the official stator. However, the average of the PD magnitude seems to be increasing as the tests go on from phase U to all phases. The PD magnitudes of the unofficial stator are of the same magnitude or higher, with lower test voltages, when compared to the official stator.

5.2 Implications

The results indicate that partial discharges are possible in low-voltage machines with the typical operating voltage level of 400 V line-to-line. Those machines are typically supplied by frequency converters with DC-link voltages greater than 600 V. As discussed in section 2.2.1, due to impedance mismatch and cable reflections with long enough supply cable, the voltage that the machine experiences at its terminals can be doubled from the DC-link voltage. With similar windings arrangement and insulation materials, it is likely that also other types of machines do experience PDs in a similar manner.

According to research papers by Lusuardi et al. (2021) and Fabiani et al. (2004), when testing twisted wire pairs of enamelled wires, the waveform does not affect PDIV. Both used 50 Hz sinusoidal voltage, and square voltage waveforms, with frequencies between 50 Hz and 10 kHz. Fabiani et al. (2004) showed, that the PDIV values for four different samples stayed almost identical between the 50 Hz sinusoidal and square wave with frequencies of 50 Hz, 1 kHz, and 10 kHz. The voltage slew rate used was below 5 kV/µs. Lusuardi et al. (2021) used only 10 kHz square wave, but with a voltage rise time of 7 ns. With voltage being 500

V, that leads to slew rate of around 60 kV/µs. With this test, the measured PDIV deviates slightly, but not significantly, while around normal pressure. When the pressure drops, the difference becomes larger.

In the standards, PDIV with sinusoidal voltage is defined as the RMS value of the voltage. However, in these studies by Lusuardi et al. (2021) and Fabiani et al. (2004), the PDIV expressed as the peak value of the sinusoidal waveform is the same as with an impulse waveform. This indicates that the PDIV only depends on the peak value of the applied voltage, and not on the waveform or RMS value. When comparing PDIV values for example between sinusoidal and impulse waveforms, the peak-to-peak values should be used in the comparison. The papers used twisted pairs of enamelled wire, which use different insulating material than phase-to-phase and phase-to-ground insulations. There might be a difference on how the waveforms affect different insulating materials, too.

In the light of these papers by Lusuardi et al. (2021) and Fabiani et al. (2004), the peak value of the sinusoidal test voltage should be considered in the case of PDIV and PDEV. As the lowest average PDIV measured in this thesis is 1.16 kV RMS, that means the peak value is about 1.64 kV. If the cable reflections are assumed to double the voltage seen at the machine terminals, it means that the DC link voltage corresponding to this PDIV would be about 818 V. As this machine type is supplied with a converter with a DC link voltage of 620 V, the voltage at machine terminals could be 1.24 kV when doubled. If considering the lowest PDIV which can be seen in Figure 16 with the confidence interval taken into account, it would correspond to a peak value of about 1.4 kV. This means that PDs should not be initiated in this machine in normal operation, at least not within the phase-to-ground insulation. The lower limit of PDEV in Figure 17 is 0.8 kV RMS, which translates to a peak value of 1.13 kV. This voltage level can be achieved during normal operation, so the voltage levels used could maintain the PD activity, if the inception voltage is exceeded with a higher voltage pulse.

However, these tests were conducted with a sinusoidal test voltage, while the supplying converter is a switching converter, which uses PWM to generate output voltage. The inception and extinction voltages can be different when applying voltage impulses, instead of sinusoidal voltage. With impulse voltages the rising edge of voltage is faster, which also means that the voltage distribution in the windings is significantly more uneven than with sinusoidal voltage. As the voltage distribution is uneven, large portion of the voltage drop occurs within the first few turns of the winding. This will lead to higher electrical stress of the turn-to-turn insulation. This could lead to overall lower PDIV values for the complete stator, as the turn-to-turn insulation is generally the weakest part of the insulation system. So, using impulse voltage to measure PDIV and PDEV on a complete stator can produce different results, not due to the different waveform impacting the mainwall insulation differently, but rather due to the PDs occurring in a different location. That location could very well be the turn-to-turn insulation, or phase-to-phase insulation. As the voltage supplied to this machine in operation is from a PWM converter, that could mean that PDs occur with lower voltage levels than 1.4 kV, if they occur within the turn-to-turn insulation or phase-to-phase insulation.

With sinusoidal voltage, the turn-to-turn insulation is not electrically stressed as much, and thus impulse voltage testing could find out weaknesses in the turn-to-turn insulation. With the stator that was tested in this thesis, the phases are connected to each other via the star point. This way all the phases are practically at the same potential, so no phase-to-phase insulation was stressed much electrically in the tests in this thesis.

Also, with impulse voltage testing, repetitive inception and extinction voltages can be found out. RPDIV and RPDEV will show whether the voltage impulses produce PDs above or below 50 % of the time. This can be a tool used to assess the level of PD activity, and thus also the severity of PD activity. Partial discharges generally deteriorate organic insulating materials, which are used in such LV machines.

6 Conclusions

The main research question was to find out whether there are partial discharges in the machinery or not. It was found out, that there are indeed partial discharges when the voltage is increased enough. The measured PDIVs are close to the voltage level that can be present during normal operation. However, as other research shows, the peak value of the sinusoidal voltage regarding PDIV and PDEV is comparable to the peak value of an impulse voltage. The peak values of average inception voltages are at such level, that with about 620 V DC link voltage and assumed doubling of the voltage due to reflections, PDs should not be initiated during normal operation, at least on the phase-to-ground insulation. As the inverters use PWM supply voltage, that could cause PDs at a lower voltage level, if they occur in different location, between the different turns in the winding, or in the phase-to-phase insulation.

When measuring the PD magnitudes, there were large variations, even with the same supply voltage. This shows that partial discharge is not a consistent phenomenon. It depends on many different factors. However, it was noted, that increasing the voltage generally increases the magnitude of the PD pulses significantly, when over the PDIV levels.

There are many factors and variables that affect the emergence of partial discharges in the machines, and also affect the measuring of PD activity. There can be differences between the instruments, and with the same instrument different settings can produce significantly different results. Thus, PDs should always be treated as relative, not absolute. When comparing the trend of PD activity, the used instrument and its settings should be the same to enable more accurate results. Also, environmental factors affect the phenomenon, and the measuring. For measuring, the environment should be as similar as possible between the measurements.

According to the research conducted in this thesis, no definite conclusions on the ageing of the insulation in this case can be drawn, as the variability of the measurements is quite significant. The trend of the two measurements shows that there might have been some sort of insulation weakening during this relatively short stressing period. However, the ageing of the insulation is rather improbable, due to the short stressing period. As the stator that was tested was brand new, it might also be the case that the insulation system has just now reached its steady state, meaning that the possible traces of flux have evaporated, and the varnishing has cured. More tests would be needed to verify this trend and observe how the PDIV and PDEV values behave after more stressing.

For future research, at least for enamelled twisted wire pairs, the use of sinusoidal or impulse test voltage does not affect the value of PDIV. As the tests in this thesis were conducted with complete stator windings and with sinusoidal voltage supply, the turn-to-turn insulation was not tested, in practice. Also, as the end windings were connected to a star point, the phase-to-phase insulation was not tested. With a complete winding or a stator, the phase-to-phase insulation could be tested with a test object where the star point is accessible, and the end windings can be disconnected from the star point.

If using twisted pair samples of the enamelled wire, those can be tested with the sinusoidal test voltage equipment to test the turn-to-turn insulation. If the turn-to-turn insulation is required to be tested with a complete winding or stator, a test set with impulse test voltage generator would be required.

Another interesting topic for research of partial discharges could be to study if acoustic detection by microphones integrated in the machinery would be able to detect partial discharges. This could be an economical mean to monitor the condition of the machines and identify the need for maintenance before failure.

All in all, the trend of these measurements in this thesis shows that some weakening of insulation has happened. However, the variability and therefore uncertainty caused by that is significant. Investigating this phenomenon requires more research to achieve reliable results, with more test samples, more stressing and more measurements with regular time intervals.

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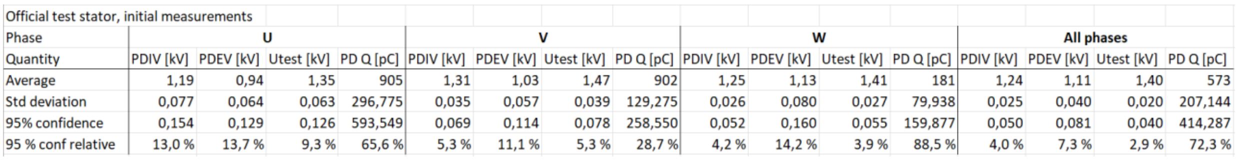
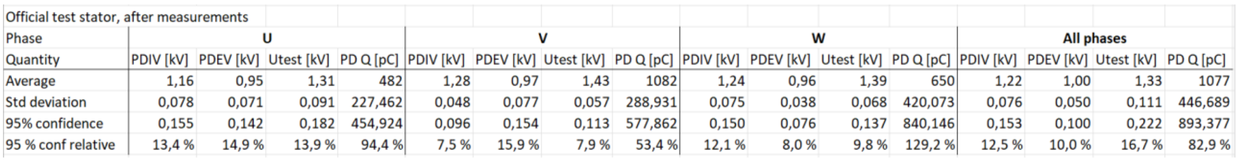
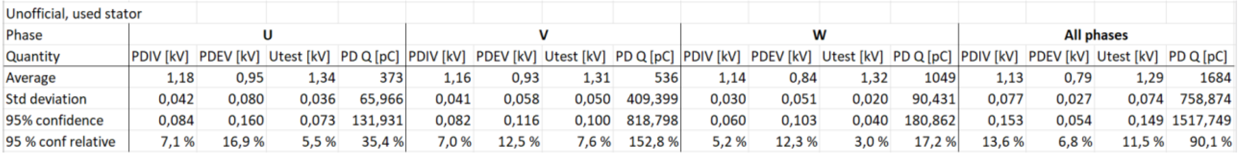
Appendix 1. Analysis results from the official test stator and from an unofficial stator.



Official test stator, initial measurements																
Phase	**U**				**V**				**W**				**All phases**			
Quantity	PDIV [kV]	PDEV [kV]	Utest [kV]	PD Q [pC]	PDIV [kV]	PDEV [kV]	Utest [kV]	PD Q [pC]	PDIV [kV]	PDEV [kV]	Utest [kV]	PD Q [pC]	PDIV [kV]	PDEV [kV]	Utest [kV]	PD Q [pC]
Average	1,19	0,94	1,35	905	1,31	1,03	1,47	902	1,25	1,13	1,41	181	1,24	1,11	1,40	573
Std deviation	0,077	0,064	0,063	296,775	0,035	0,057	0,039	129,275	0,026	0,080	0,027	79,938	0,025	0,040	0,020	207,144
95% confidence	0,154	0,129	0,126	593,549	0,069	0,114	0,078	258,550	0,052	0,160	0,055	159,877	0,050	0,081	0,040	414,287
95 % conf relative	13,0 %	13,7 %	9,3 %	65,6 %	5,3 %	11,1 %	5,3 %	28,7 %	4,2 %	14,2 %	3,9 %	88,5 %	4,0 %	7,3 %	2,9 %	72,3 %



Official test stator, after measurements																
Phase	**U**				**V**				**W**				**All phases**			
Quantity	PDIV [kV]	PDEV [kV]	Utest [kV]	PD Q [pC]	PDIV [kV]	PDEV [kV]	Utest [kV]	PD Q [pC]	PDIV [kV]	PDEV [kV]	Utest [kV]	PD Q [pC]	PDIV [kV]	PDEV [kV]	Utest [kV]	PD Q [pC]
Average	1,16	0,95	1,31	482	1,28	0,97	1,43	1082	1,24	0,96	1,39	650	1,22	1,00	1,33	1077
Std deviation	0,078	0,071	0,091	227,462	0,048	0,077	0,057	288,931	0,075	0,038	0,068	420,073	0,076	0,050	0,111	446,689
95% confidence	0,155	0,142	0,182	454,924	0,096	0,154	0,113	577,862	0,150	0,076	0,137	840,146	0,153	0,100	0,222	893,377
95 % conf relative	13,4 %	14,9 %	13,9 %	94,4 %	7,5 %	15,9 %	7,9 %	53,4 %	12,1 %	8,0 %	9,8 %	129,2 %	12,5 %	10,0 %	16,7 %	82,9 %



Unofficial, used stator																
Phase	**U**				**V**				**W**				**All phases**			
Quantity	PDIV [kV]	PDEV [kV]	Utest [kV]	PD Q [pC]	PDIV [kV]	PDEV [kV]	Utest [kV]	PD Q [pC]	PDIV [kV]	PDEV [kV]	Utest [kV]	PD Q [pC]	PDIV [kV]	PDEV [kV]	Utest [kV]	PD Q [pC]
Average	1,18	0,95	1,34	373	1,16	0,93	1,31	536	1,14	0,84	1,32	1049	1,13	0,79	1,29	1684
Std deviation	0,042	0,080	0,036	65,966	0,041	0,058	0,050	409,399	0,030	0,051	0,020	90,431	0,077	0,027	0,074	758,874
95% confidence	0,084	0,160	0,073	131,931	0,082	0,116	0,100	818,798	0,060	0,103	0,040	180,862	0,153	0,054	0,149	1517,749
95 % conf relative	7,1 %	16,9 %	5,5 %	35,4 %	7,0 %	12,5 %	7,6 %	152,8 %	5,2 %	12,3 %	3,0 %	17,2 %	13,6 %	6,8 %	11,5 %	90,1 %