Application of Polarisation Depolarisation Current (PDC) technique on fault and trouble analysis of stator insulation

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SUMMARY

This paper presents the application of high-precision, reliable and practical on-site off-line non-destructive diagnostic technique, Polarisation Depolarisation Current (PDC) analysis for the assessment of fault and trouble in stator insulation. The most advantage is its ability in easy identification of absorption current and conduction current non-stressfully. The ground insulation of a large machine can be tested at the voltage as low as 50 V. In addition, its function in fault assessment without any voltage application ensures the original fault is not modified by diagnostic tests.

PDC measurement is the dielectric spectroscopy in time domain. The evaluation results include capacitance and dielectric dissipation factor (or tan δ) in frequency domain, in addition to the time-domain results of insulation resistance and recovery voltage polarisation spectrum. The analysis of trouble and fault in rotating machine require information from all PDC measurement results (from initial measurement to main measurement) as well as the evaluation results, which means dielectric response in both time and frequency domain. While PDC main measurement results identify the type of insulation aging or the cause of trouble, its evaluation results give decisive keys on degree of insulation aging. The case study on a faulty machine presented in this paper describes how.

Furthermore, the paper provides details how to perform healthy and accurate PDC measurement on rotating machines, starting from isolation and discharging, temperature and humidity influence, test connection, ground reference and measurement procedures. The interpretation of PDC measurement results and evaluation results are presented through the case study of faulty machine.

KEYWORDS


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1. INTRODUCTION

The on-site, off-line, non-destructive diagnostic technique discussed in this paper is based on, Polarisation Depolarisation Current (PDC) analyser, which was introduced at the start of this millennium for electrical power apparatus [1]. Its ability in measuring current as low as $10^{-12}$ A (pA) permits the high voltage insulation to be tested non-stressfully and accurately at low voltage, e.g. the ground insulation of a stator to be tested at 50 V. The most advantage of this technique is its easy identification between “conduction” and “polarisation” phenomena, which allows the dielectric trouble to be solved correctly. Figure 1 presents the principle of test arrangement for PDC measurement on phase-to-phase and phase-to-ground insulation. More details of this dielectric response technique are in [2] and [3].

Though up to now the PDC analysis has been performed worldwide mostly on a power transformer, due to its special evaluation of moisture in pressboard as verified by CIGRE Task Force D1.01.09; the author has tested 36 generator stators with the largest size of 80 MVA by means of this technique. The faulty machine picked up for case study in this paper is the smallest one of only 1 MW, 6.6 kV but the variety of trouble / fault in this machine allows more PDC applications to be discussed.

Before the story of faulty machine, description of PDC measurement which includes preparation, connection, procedures and influenced factors to achieve healthy measurement data for conclusive diagnosis of stator insulation will be presented.

![Diagram of PDC measurement](image_url)

Figure 1: Principle of test arrangement for PDC measurement of phase-to-phase insulation (left) and phase-to-ground insulation (right)

2. DESCRIPTION FOR PERFORMING HEALTHY PDC MEASUREMENT

2.1 Discharging before PDC measurement

When a generator is switched off from operation, all line terminals of its stator are brought to earth for discharging. The time taken for stator winding temperature to be stabilized is normally longer than the time required for discharging. This means by the time all line and neutral terminals of a stator are disconnected and isolated from all connected devices, remaining charges in the stator insulation will be low enough (e.g. $< 10$ pA) to start the first test. It is expected that PDC measurement be the first test, before any other high voltage tests which can introduce charges into the stator insulation. In the situation that other high voltage tests are carried out before PDC, suggest having all stator terminals earthed overnight, in preparation of the PDC test in the morning.

2.2 Temperature influence and waiting time before PDC measurement

PDC measurement is more or less temperature dependent, so it shall be carried out when stator winding temperature is as stabilized as possible. Normally when a machine is shutdown, heaters inside will be automatically switched on, in order to prevent moisture ingress. The winding temperature will be controlled and stabilized by means of thermostat. Waiting time before PDC measurement depends on the winding temperature at shutdown and the time taken for the winding temperature to decrease and stabilize. Temperature-controlled heaters shall be switched on throughout the PDC measurement.
2.3 Influence of surface leakage and ambient humidity

Both line and neutral terminals of a stator are normally indoors or at least inside an enclosure which has a built-in heater. This means air humidity and contaminants are minimized. So many tests both phase-to-phase and ground insulation were successfully carried out overnight. Although the internal-guard design of PDC-Analyser always allows the test in the rain of insulation between windings of a power transformer, this is not the case for a stator. When all stator terminals are wet or heavily polluted, no test instrument will be able to assess its internal condition.

2.4 Test connection and Ground reference

As PDC analysis is a DC test, the test can be applied to either line or neutral terminal of the stator. The line and neutral terminal of each phase under test do not need bonding like AC diagnostic tests. Both line and neutral terminals of the stator shall be isolated from bus, instrument transformers and any connected means. The neutral of all three phases shall be also isolated and disconnected from earth.

For PDC test on phase-to-phase insulation, the voltage is applied to one phase while the current is sensed from another phase. The non-tested phase is connected to the earthed frame. The ground reference of PDC shall be connected to exactly the point where the stator frame is earthed, in order to obtain healthy measurement. Care shall be taken in case of machine after refurbishment, as new paint may prevent good grounding path.

For PDC test on phase-to-ground insulation (or “ground insulation”), the accessory of PDC Analyser called “Phantom” is required. The voltage from Phantom source is then applied to the phase under test, phase by phase, while the other two non-tested phases are isolated from earth. The ground of phantom shall be connected to exactly the point where the stator frame is earthed. The main PDC-Analser is not connected to earth in this case, as it is bonded to the Phantom through its control cable.

2.5 Test procedures

Suggest performing PDC measurement on phase-to-phase insulation before ground insulation, as the capacitance of phase-to-phase insulation is much smaller than the capacitance of ground insulation. This means it will take less time for discharging before the second test on ground insulation, if the first test is on phase-to-phase insulation.

There are three procedures in performing PDC measurement, as instructed by the manufacturer of the instrument in order to obtain accurate measurement – initial measurement, control measurement and the main measurement. The purpose of initial measurement is to determine initial condition of the test object before any application of test voltage. By setting the polarization duration to zero seconds (or in another words, no charging voltage is applied), the PDC instrument monitors the depolarization currents which give information of magnitude and polarity of remaining charges inside the insulation system under test. The remaining currents are normally in the range of pA. If the stator insulation is well discharged to earth before test, the values of remaining currents can be only a few pA. The quite constant values from some tens nA to the level of µA indicates either permanent ground fault of the insulation or externally very wet.

The control measurement is done by setting the short polarization time e.g. 5 seconds and measuring the depolarization currents. Suggest setting the voltage in this procedure 100 - 500 V for phase-to-phase insulation of the stator and only 50 V for ground insulation. The purpose of this procedure is to verify the amplitude of measured currents and the value of the capacitance. It is essential to wait until the depolarization currents decrease to minimum level or at least the same level of initial remaining currents in the previous procedures before starting the main measurement. (In case the remaining currents influence the main measurement results, the correction shall be made by means of “offset” function before starting the evaluation).
Due to the large capacitance of stator ground insulation, the test voltage of 50 V in many cases is appropriate to test the ground insulation. Though the test duration of 10,000 seconds polarisation and 10,000 seconds can be automatically carried out overnight as a full reference, the test duration of 1,100 seconds polarisation and 1,100 seconds depolarization is recommended as minimum duration.

3. RESULTS OF PDC MEASUREMENT AND PDC EVALUATION

3.1 PDC measurement results

The main measurement results include polarisation currents and depolarisation currents in time domain and they are in log-log scales. The polarisation currents consist of absorption currents due to polarisation phenomena (e.g. aging molecules at the dielectric interface caused by oxidation or heat, mixture of spilled lubricating oil and dust, by-products of partial discharges, corrosive contaminants from chemical plants, sea salt or hydrogen sulphide, etc.) plus conduction currents due to conduction phenomena (mostly moisture) plus, in some cases (see item 2.3), surface leakage currents (due to conductive contaminants e.g. free water, carbon dust, metal debris, etc.). The depolarisation currents consist of absorption currents only. The absorption currents over serviced years increase due to aging of dielectric which bonds the mica together (e.g. resin, varnish, etc.), oxidation aging and thermal aging. Absorption currents may decrease due to formation of voids or gap due to delamination. While conductive contaminants increase only the polarisation currents but not the depolarisation currents (see item 4.3), moisture in the stator insulation raises the whole polarisation and depolarisation currents (like the PDC shape of bushing with the presence of moisture [4]).

3.2 PDC evaluation of insulation resistance and polarisation index (P.I.)

PDC shape itself identifies the type of insulation trouble. The PDC measurement results depend not only on insulation condition but also the geometry or capacitance of the insulation system. Insulation resistance is the result of constant applied voltage divided by the measurement results of polarisation currents. So the insulation resistance is also influenced by the capacitance. The comparison of insulation resistance can only be made among similar insulation having similar design. The resistance of phase-to-phase stator insulation shall not be compared or judged with the resistance of ground insulation, since their capacitance values are much different. The PDC evaluation results of insulation resistance of stator ground insulation are comparable with the results from conventional test. Since PDC measures continuously the currents up to the preset duration which includes the time of 60 and 600 seconds, the actual meaning of polarisation index (P.I.) can be easily explained. The higher P.I. does not always mean good insulation, as thermal aging can lead to very high P.I. as well.

3.3 PDC evaluation of capacitance and tan δ in frequency domain

By measuring the polarisation and depolarisation currents in time domain, PDC evaluation results include also capacitance and dielectric dissipation factor, tan δ, in frequency domain. It is based on these evaluation results that the insulation condition is judged. The diagnostic keys are the evaluated frequency-domain results of tan δ and capacitance ratio (C ratio), which is the ratio of capacitance at very low frequencies e.g. at 1 mHz to capacitance at 50 Hz. An example of C ratio and tan δ for good stator insulation: C ratio is close to 1 e.g. C ratio [1mHz/50Hz] = 1.1, tan δ of ground insulation is < 0.005 at 1 Hz and < 0.05 at 1 mHz while tan δ of phase-to-phase insulation is < 0.015 at 1 Hz and < 0.3 at 1 mHz. From experience up to now, moisture in stator insulation (not free water at surface) increases both C ratio and tan δ at low frequencies (< 0.01 Hz), but conductive contaminants including free water increase tan δ but have little influence on C ratio in the same range of low frequencies.

3.4 PDC evaluation of recovery voltage polarisation spectrum

This function does not give diagnostic data for stator insulation in good condition due to the very high time constant of stator insulation. The calculation time of 20,000 seconds is run out before producing
any useful values. However, when the insulation is in moderate to bad condition such as the case of faulty machine which will be presented in item 4.7, the inferior quality of insulation is represented by the appearance of the first peak of recovery voltage polarisation spectrum at shorter charging time.

4. CASE STUDY

4.1 Brief event and initial assessment

The fault at the 1 MW, 6.6 kV air-cooled generator stator caused differential tripping shortly after the machine started to run, before reaching the rated speed and frequency. The machine was transported to the workshop for repair. It was raining during transport and the machine was not covered well. PDC initial measurement during zero polarisation duration revealed very high and constant depolarisation currents (I depol.) of about $10^{-5}$ A (instead of a few pA in normal condition), both phase-to-phase and ground insulation as shown in figure 2. This can mean either the insulation had very high conduction to earth (e.g. very wet) or the fault led to permanent short-circuiting of all phases. In order to verify what happened, the damaged areas were cut off and fuse wires were used for bypassing. The stator insulation without damaged parts was then reassessed. The results were still around $10^{-5}$ A, which convinced that the stator was very wet. The drying was then applied before further assessment.

![Figure 2: Depolarisation currents during initial measurement of phase-to-phase and phase-to-ground insulation.](image)

4.2 Visual inspection

Figure 3 presents one view of visible fault area after drying, which occurred at the end-winding between the coil of phase A and a series-joint lead of the same phase. The short-circuiting to the support ring of this phase was not visible from general inspection. Partial discharges obviously occurred before the breakdown, with power arc followed. Damages can be zoomed into this figure.

![Figure 3: Fault area after drying](image)

Apart from the infected area as mentioned, neither deformed coils nor loose coils were found in this stator. However, the overall stator including coil-to-coil and phase-to-phase was polluted by black sticky compounds which were the products (also oxidation products) of spilled lubricating oil and dust contaminants. These compounds are polar molecules which had strong influence on the absorption currents during PDC measurement of phase-to-phase insulation.

4.3 PDC measurement results of ground insulation after drying

After drying, the depolarisation currents (I depol.) during PDC initial measurement of phase A ground insulation were about 1 µA (figure 4, top-left) which were still very high. This gave the conclusion that phase A had direct ground fault, likely through the support ring. Without damaged parts, the bottom-right of figure 4 shows phase A had higher polarisation currents than the other phases but
similar depolarization currents; which means phase A had higher conduction currents than the others. Some conductive contaminants still remained.

For phase B, in spite of damaged parts, the remaining currents before voltage application was only 1 pA which confirms that phase B had no ground fault or any connection to ground. However, the PDC measurement results at 50V (figure 4, top-right) show the flat shape of polarisation currents as well as the huge difference between polarisation currents (I pol.) and depolarization currents (I depol.). It reflects the very high conductive path to ground of this phase. The wound, though severe, had not yet occupied the whole insulation between this phase and the support ring. In addition, the very high depolarization currents compared to the results without damaged parts at the same voltage (figure 4, bottom-right) are the evidence that contaminants from the fault contains not only conductive materials (e.g. copper debris, carbon dust, etc.), but also polar molecules, which are by-products (chemically) from the burning of insulating materials (such as epoxy, paint, etc.) as well as those sticky compounds mentioned in item 4.2.

The bottom-left of figure 4 shows the PDC measurement results of phase C ground insulation. Conductive contaminants influenced the polarisation currents when damaged parts were included.

![Figure 4: Measurement results of polarisation currents (I pol.) and depolarisation currents (I depol.) of ground insulation of all three phases, with and without damaged parts](image)

**Figure 4**: Measurement results of polarisation currents (I pol.) and depolarisation currents (I depol.) of ground insulation of all three phases, with and without damaged parts

### 4.4 PDC measurement results of phase-to-phase insulation after drying

The top-left of figure 5 shows the measurement results of phase-to-phase insulation when damaged parts were included. Since phase A had direct ground fault, high remaining currents (depolarisation currents) appeared when assessing the insulation A-B and C-A in spite of no voltage application during initial measurement. For PDC tests on B-C, the main measurement results show conduction disturbance during polarisation, likely from arc contaminants which polluted the damaged area.

When the damaged parts were excluded, polarization phenomena due to polar aging molecules in the form of sticky compounds, as mentioned in item 4.2, had stronger influence than conduction phenomena from arc contaminants. The normal PDC pattern of phase-to-phase insulation was then modified by the opposite charges or reversed charges as shown in figure 5, top-right, bottom-left and
bottom-right. The spikes in these 3 charts occurred due to the balance of positive and negative charges but because zero does not exist in log-log scale. The spikes at the time < 50 seconds would be caused by the sticky compounds (products of spilled lubricating oil) while the spikes at the time > 300 seconds would be caused by conductive contaminants. Of course the sticky compounds existed before the fault. (From experience with other machines having similar trouble with compounds from spilled lubricating oil, the behaviour disappeared after effective cleaning with special solvent).

Figure 5: Measurement results of polarisation currents (I pol.) and depolarisation currents (I depol.) of phase-to-phase insulation, with and without damaged parts

4.5 PDC evaluation results of insulation resistance

As mentioned in item 3.1, the resistance of phase-to-phase insulation cannot be compared with the resistance of ground insulation because their capacitance values are much different. For resistance of ground insulation in figure 6, insulation of phase B was very poor and unacceptable when damaged parts were included, due to the very low resistance, even < 1 MΩ. When damaged parts were isolated, ground insulation of phase A had lower resistance than the others. The value at 60 seconds or 1 minute was only 0.94 GΩ while 2.2 GΩ for the other two phases. For this faulty machine which polarisation currents of phase-to-phase insulation were modified (as mentioned in item 4.4), no phase-to-phase insulation resistance will be presented.

Figure 6: Resistance of phase-to-ground insulation

4.6 PDC evaluation results of capacitance and tan δ in frequency domain
Even without damaged parts, the C ratio [1 mHz / 50 Hz] of ground insulation of all three phases increased at the frequency > 0.1 Hz towards low and very low frequencies, as shown in figure 7. The C ratio [1mHz / 50 Hz] was about 2 which is considered high for stator ground insulation. This indicates rather high level of moisture in the ground insulation, which also increased the tan δ of all phases above the unacceptable level (e.g. suggested values of tan δ at 1 Hz < 0.04 and at 1 mHz < 0.3 for in-service ground insulation). Since the results of phase C with and without damaged parts were more or less similar e.g. in the range of 0.05 - 1 Hz, it means the stator insulation had rather high moisture before the fault.

Conductive contaminants in the form of surface leakage increase tan δ at low and very low frequencies (depending on the severity) but not the C ratio. An example can be seen on the results of phase A ground insulation without damaged parts in figure 7.

4.7 PDC evaluation results of recovery voltage polarisation spectrum

Figure 8 presents the PDC evaluation results of recovery voltage polarization spectrum without damaged parts. Obviously (as mentioned in item 3.4), phase A ground insulation was inferior to the other phases since the charging time at the first peak of recovery voltage polarisation spectrum appeared at shorter charging time than the others.

4.8 Summary of PDC analysis results on the faulty machine

For ground insulation, PDC initial measurement results confirmed the ground fault of phase A but neither phase B nor C. PDC main measurement results revealed the very high conductive path of phase B. It shows phase C was slightly influenced by conductive contaminants from the fault. With the damaged path isolated, some conductive contaminants from the arc still remained at phase A but not the other two. PDC evaluation results of tan δ and capacitance revealed moisture in the insulation was
also quite high before the fault. The results of insulation resistance and recovery voltage polarisation spectrum gave the support.

For phase-to-phase insulation, the ground fault of phase A influenced the PDC initial measurement of A-B and C-A. The PDC main measurement results of insulation B-C was influenced by conductive contaminants from the arc. When the damaged parts were isolated, sticky compounds which were the products of spilled lubricating oil and dust contaminants were dominant and modified the normal shape of PDC main measurement results.

At present, the machine enjoys its new life. The stator was rewound. Actually the machine was rebuilt ten years ago after the former fault.

5. CONCLUSION

The paper provides details how to apply the PDC technique for the reliable and accurate assessment of fault and trouble in rotating machine insulation. Some tips are:-
- Good preparation yields good measurement. So what to prepare – well discharging, stabilized temperature and good ground reference are the most important keys.
- Right connection provides meaningful results. What to analyse – phase-to-phase insulation test requires non-tested phase to be earthed, ground insulation test requires other phases to be isolated.
- Complete all three procedures ensure safe and accurate measurement. Initial assessment and control measurement before actual or main measurement.

The case study of faulty machine provided guidelines how to interpret PDC measurement and evaluation results. The variety of fault / trouble of machine in this case study allow various diagnostic functions of PDC analyser to be verified. Some advantages are:
- Easy identification of trouble between “conduction” and “polarisation” in the dielectric.
- Identification of fault without voltage application.
- The multifunction in both time domain and frequency domain of the PDC analyser allows type of insulation aging to be identified and its degree/severity to be assessed.
- PDC analysis is a DC test. So any part of stator insulation from line to neutral receives equal stresses and similar accuracy in the diagnosis. There is no distortion of measurement results such as AC test.
- Remaining charges are known before and after PDC test.
- Minimum detectable current of 1 pA allows stator insulation to be tested at voltage as low as 50 V.
- Constant voltage source of the instrument produces reliable measurement results.

In spite of the off-line test and time consumption, it is worth for a machine life to have this reference.

BIBLIOGRAPHY