

Practical experiences on condition assessment of Stator insulation using Polarisation / Depolarisation Current technique

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SUMMARY

The introduction of dielectric response diagnoses in time domain based on Polarisation / Depolarisation Current (PDC) technique for transformers at the start of this 21st century allows the insulation aging of other power apparatus such as rotating machines, etc. to be assessed and identified on site non-destructively as well. Its ability to distinguish between conduction phenomena (due to moisture, carbon dust, metal dust, etc.) from polarisation phenomena (due to aging products at the material interface caused by oxidation or heat, mixture of spilled oil and dust, by-products of partial discharges, corrosive contaminants from chemical plants, salt or hydrogen sulphide, etc.) provides a clue to maintenance people how to solve the problem and to manage the life of the apparatus. While the depolarisation current over serviced years increases due to aging of insulating materials (e.g. resin, varnish, etc.) and may decrease due to formation of voids or gaps e.g. caused by delamination, the shape of polarisation and depolarisation currents in time domain reveals the type and cause of insulation aging.

This paper provides a proposal of the methodology for interpretation of PDC results through a number of case studies, by which the most probable cause of global trouble in stator insulation may be diagnosed when the effective PDC measurement is carried out according to the early publication, see [1]. The input of PDC interpretation includes both time-domain PDC measurement results and frequency-domain PDC evaluation results. It is demonstrated in this paper that the majority of insulation trouble in rotating machines described in these case studies can be identified independently by time-domain PDC measurement results but cannot be identified by the frequency-domain dielectric responses alone. Nevertheless the frequency-domain PDC evaluation results facilitate the decision on acceptability for continued operation.

KEYWORDS

Polarisation – Depolarisation – Current – Dielectric – Dissipation factor – Capacitance - Stator.

1. INTRODUCTION

This paper is intended to be the continuation of the article in [1] which provided details how to apply effectively the Polarisation Depolarisation Current (PDC) technique from the analyser introduced in [2], to obtain reliable, accurate and best measurement results for conclusive diagnosis of stator insulation. Reference [1] also described how to analyse fault and trouble through a failed machine in the case study. Conductive contaminants like copper particles, carbon dust, etc. increased the polarisation currents (which consist of absorption and conduction currents) but did not increase the depolarisation currents (which consist of absorption currents only). Products of spilled lubricating oil and dust contaminants caused the pattern of charge reversal in both the polarisation and the depolarisation currents of phase-to-phase insulation. The PDC shape itself provided information about the weakness of insulation system. Then the PDC evaluation results of both frequency domain (capacitance & $\tan \delta$) and time domain (insulation resistance, recovery voltage polarisation spectrum) told the severity of weakness. Details of the fundamentals for dielectric spectroscopy in time and frequency domain are published in [3]-[4]. Authors in [5]-[6] also applied dielectric responses on rotating machines.

For this paper, more case studies with different types of insulation aging are presented in Section 2. The purpose is to propose a methodology for the interpretation of PDC results in both time and frequency domain, as well as to suggest acceptable in-service criteria as a guideline for the judgement of aging status or severity level. These suggested criteria are based on practical on-site experiences with 44 stators of rotating machines in New Zealand, Australia and Thailand from 2002 to 2007. Special conditions apply to the suggested in-service criteria as described in Section 3.

2. CASE STUDIES

In most of the case studies below, four charts are used to describe the dominant symptoms of insulation trouble – PDC, Insulation resistance and polarization index (R & P.I.), Capacitance ratio (C ratio) and $\tan \delta$. These are PDC measurement and evaluation results which details were presented in Section 3 of [1]. In addition, L-L in this document means phase-to-phase insulation and L-G means phase-to-ground insulation. When the term “moisture” is used e.g. in Case 1, it means moisture which absorbed in the insulating materials, rather than humidity on the insulation surface. The latter is considered as surface contaminants or surface leakage.

Case 1: Moisture

- Stators: 79 MVA, 11 kV, G-01A and G-01B were twins. G-01A fell in the sea during transport and was refurbished. G-01B had fire accident but was rescued in time.
- PDC (Fig.1a): G-01A, L-G has normal PDC shape, quite straight lines in log-log scale and no pronounced crook.
G-01A, L-L has normal PDC shape, but amplitude is much higher than G-01B (L-L)
G-01B, L-L has slightly high amplitude before 10 seconds.
Note: Because G-01A was refurbished after failing into the sea, the PDC shape does not show the pattern of surface leakage (will be mentioned later in Case 2).
- R & P.I. (Fig. 1b): P.I. (between 1 and 10 min.) of G1-01A (L-G) is > 2 and < 7 .
- C ratio (Fig.1c): G-01A (L-L) is unacceptably high towards very low frequencies.
- Tan δ (Fig.1d): Only G-01A (L-L) is higher than suggested limit
- Conclusion: G-01A, L-L had moisture in the insulation system, due to the normal PDC shape but high current amplitude and high C ratio especially. The results are unacceptable, as C ratio and $\tan \delta$ exceed the suggested limits for L-L. G-01A, L-G and G-01B, L-L are both acceptable.

[Note: G-01A was tested 1 & 2 years later but the results had only slight change, so no action has been taken.]

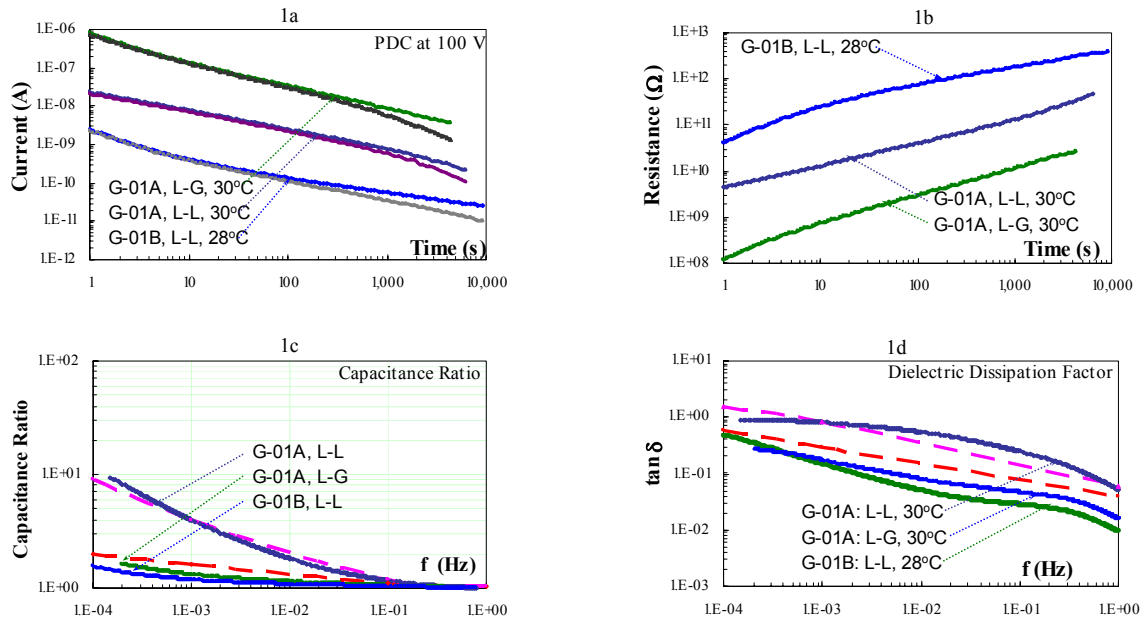


Figure 1: PDC measurement results (1a) and evaluation results (1b)-(1d) of ground insulation (L-G) and phase-to-phase insulation (L-L) of wet stator G-01A and dry stator G-01B. The suggested limits are marked with pink dotted line (for L-L) and red dotted line (for L-G)

Case 2: Moisture plus conductive contaminants

Stator: 21 MVA 11 kV, 32-year-old G-02 suffered from a flood but has not yet been refurbished.

PDC (Fig.2a): For both L-L and L-G, the polarization current (I pol.) shows pronounced deviation from a straight line as well as from the depolarization current (I depol.). This is the pattern of surface leakage or conductive contaminants. The pattern can clearly be seen in the PDC shape of L-L in Figure 2a:

- I pol. (+) is quite flat or constant after 15 seconds.
- I depol. (-) separated from I pol. (+) at the initial time of 1 second.

Whether the current amplitude is high is not known, as there is no past record or other unit to compare.

R & P.I. (Fig. 2b): P.I. (between 1 and 10 min.) of L-L is 1.35 which is quite low.

C ratio (Fig.2c): C ratio of L-L is unacceptably high towards very low frequencies and it exceeds suggested limit. C ratio of L-G is approaching the suggested limit.

Tan δ (Fig.2d): Tan δ of L-G is high, but L-L is very high

Conclusion: Conductive contaminants or surface contaminants are identified by the pattern of PDC shape as mentioned above, which also decrease P.I., increase tan δ but not C ratio. Because C ratio is also high in this case, moisture as mentioned in Case 1 is also one of the trouble. The results are unacceptable because C ratio and tan δ of phase-to-phase insulation exceed suggested limits.

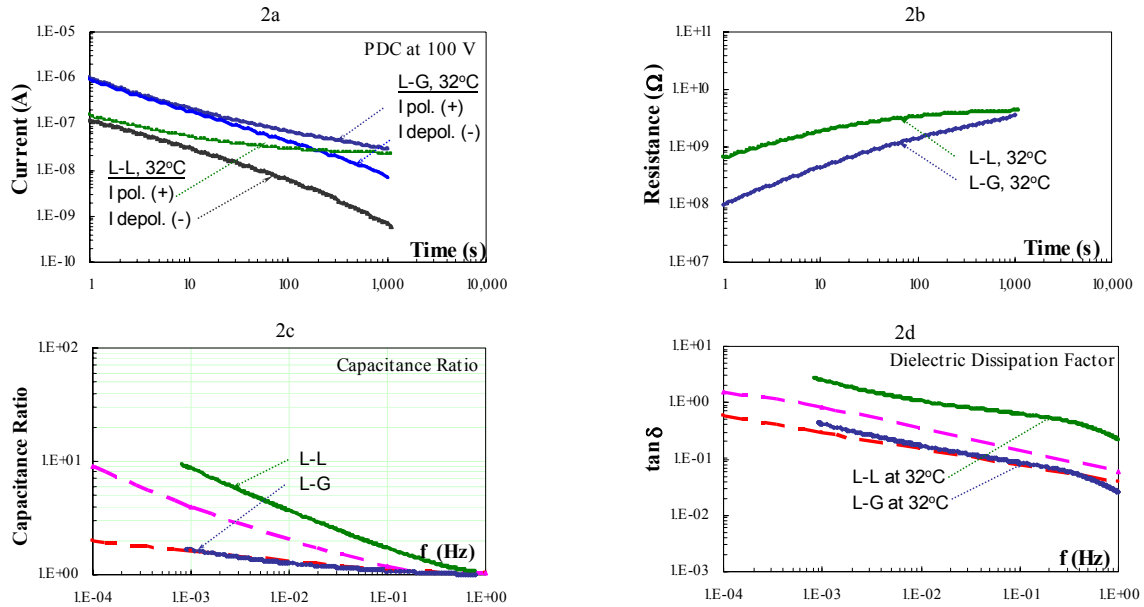


Figure 2: PDC measurement results (2a) and evaluation results (2b)-(2d) of ground insulation (L-G) and phase-to-phase insulation (L-L) of stator G-02. The suggested limits are marked with pink dotted line (for L-L) and red dotted line (for L-G)

Case 3: Thermal trouble

Stator G-03A: 5 MVA 11 kV, stator G-03A was installed in a room with poor ventilation while operated at rather high load. The star point of this machine could not be isolated, so the insulation of all three-phases to ground was assessed.

Stator G-03B: 20 MVA, 11 kV, indoor stator G-03B operated at rated load all the time.

PDC (Fig.3a): This pattern of crook shape (or bending shape) of ground insulation of G-03A (obvious) as well as G-03B (slightly) characterizes thermal trouble. For G-03B, L-L; both polarisation and depolarisation currents show deviation from straight lines which reflect the activities of polarisation phenomena. Whether the current amplitude is high or not is not known, as there is no past record to compare.

R & P.I. (Fig. 3b): Thermal aging is identified by high P.I. (between 1 and 10 min.) e.g. > 7 of ground insulation, both G-03A and G-03B. The P.I. for G-03B, L-L is 2.3.

C ratio (Fig.3c): C ratio of ground insulation is low in case of thermal aging. The low C-ratio of G-03B, L-L confirms no moisture trouble.

Tan δ (Fig.3d): Within limits for ground insulation (L-G). G-03B, L-L shows a sharp increase at < 10^{-2} Hz and has a trend to exceed suggested limit at very low frequencies.

Conclusion: Thermal aging or thermal trouble of ground insulation is identified by the crook shape as shown and the very high P.I. Polarisation phenomena (e.g. aging of insulating materials at interfaces) is the major cause of aging in phase-to-phase insulation which increase PDC amplitude after about 30 seconds. The sharp increase in tan δ of G-03B, L-L at < 10^{-2} Hz, without the increase of C-ratio, indicates conductive contaminants (e.g. carbon dust) are also involved in the insulation aging.

Though C ratio & tan δ of ground insulation of G-03A are within suggested limits, improvement of cooling system was recommended to the client. In a crook shape (or bending shape), there are both increase and decrease in current amplitude. The increase of absorption currents is normally caused by the aging of insulating materials at the interfaces which can be a kind of normal aging. The decrease of absorption currents can be caused by the formation of gaps or delamination which is dangerous.

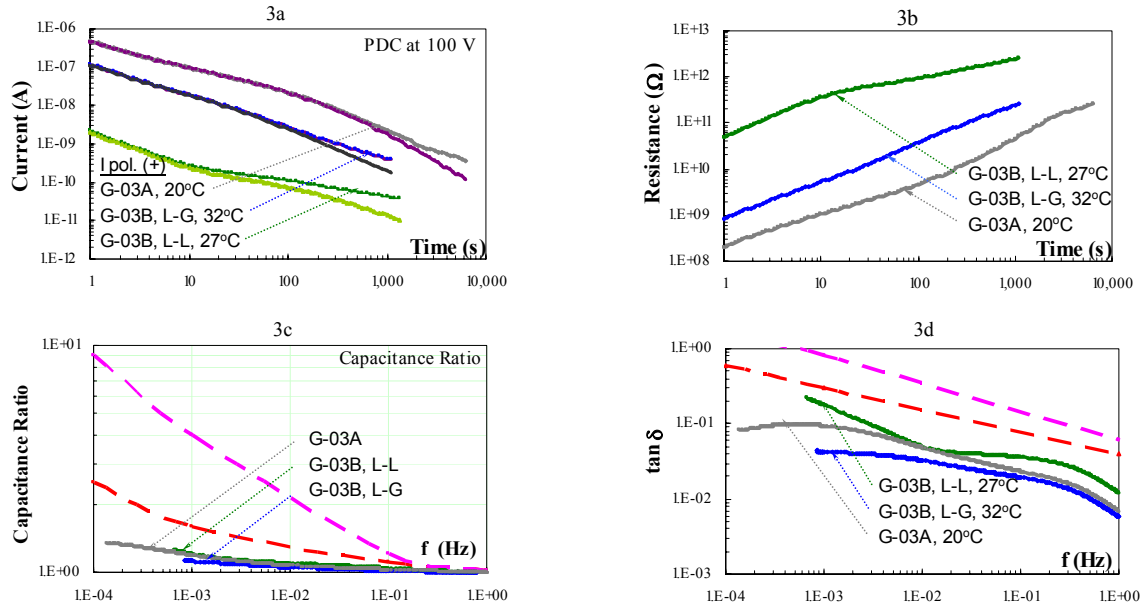


Figure 3: PDC measurement results (3a) and evaluation results (3b)-(3d) of 3-phase-to-ground insulation of stator G-03A and ground insulation (L-G) as well as phase-to-phase insulation (L-L) of stator G-03B. The suggested limits are marked with pink dotted line (for L-L) and red dotted line (for L-G)

Case 4: Trouble with corrosive dust

Stator G-04: 5 MW, 11 kV, 10-year-old stator G-04 was operated in an area with high corrosive dust. The test was carried out before and after refurbishment.

PDC (Fig. 4): Pattern of charges reversal appeared on phase-to-phase insulation (L-L) before refurbishment. With effective cleaning by special solvent, the PDC shape of L-L was back to normal.

PDC (Fig. 5a): Pattern of charges reversal did not occur on ground insulation, though corrosive dust was also found. The successful refurbishment caused the decrease of PDC amplitude, although temperature difference had some influence as well.

R & P.I. (Fig. 5b): Insulation resistance was improved. Not much change for P.I., since conductive surface contaminants was not the big issue before refurbishment.

C ratio (Fig. 5c): The decrease in C ratio means the refurbishment process also removed moisture.

Tan δ (Fig. 5d): The very high tan δ before refurbishment especially 10^{-2} Hz to 1 Hz was much reduced and the shape was back to normal.

Conclusion: As the charges reversal occurred in both polarisation and depolarisation currents of phase-to-phase insulation, polarisation phenomena were the major cause, which in this case refers to corrosive dust. PDC shape of ground insulation was normal before refurbishment but both C ratio and tan δ were about the suggested limits.

Note: The suggested limits are not applicable to judge the acceptability after refurbishment.

Case 5: An unusual PDC shape

The PDC shape of phase-to-phase insulation of a 42 MVA, 11 kV, G-05 stator as shown in Figure 6 may have local trouble. Both polarisation and depolarisation currents in 2003 and 2004 show bending from straight lines but the results in both years are quite similar. The PDC shape in 2006 twists around the past results before about 15 seconds. There are two areas which had quite big change, which may not have been caused by the somewhat higher temperature. Confirmation a month later revealed more or less similar results. These are:-

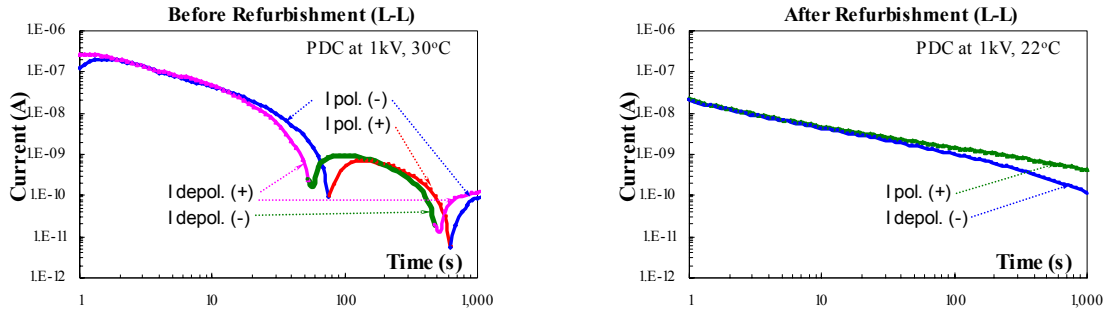


Figure 4: PDC measurement results of G-04 phase-to-phase insulation (L-L) before and after refurbishment.

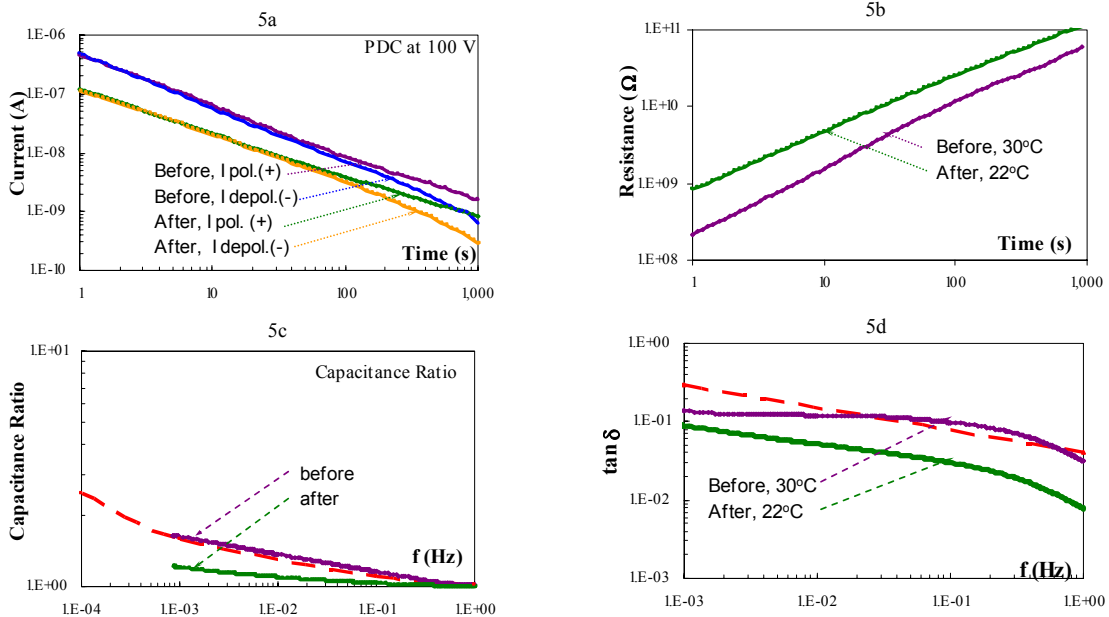


Figure 5: PDC measurement results and evaluation results of G-04 ground insulation (L-G) before and after refurbishment. The suggested limits are marked with pink dotted line (for L-L) and red dotted line (for L-G)

- a. Absorption currents decrease obviously in the initial 3 seconds. The decrease in absorption current can be caused by the formation of voids / gap in ground wall insulation due to partial discharges or thermal cycling. Delamination can be a case.
- b. PDC shape twists after the initial decrease mentioned in item (a) and absorption currents increase after that. The shape looks like a small hump between 3-15 seconds (approximately). The difference in temperature can have some influence on the increase of absorption currents but not much. The increase of absorption current is due to polarization phenomena which can be the products of partial discharges, polar molecules caused by the aging of bond at mica / bond interface, etc.

So far there is no opportunity for internal inspection, as the plant runs continuously. The purpose to present Figure 6 is essentially to show only an unusual shape of PDC measurement results.

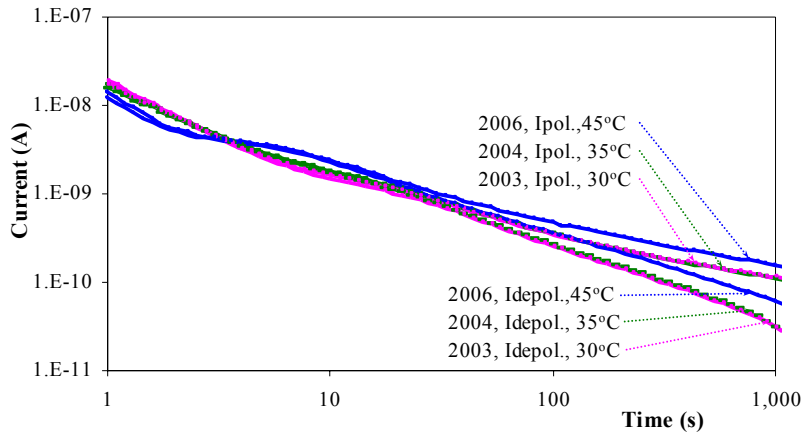


Figure 6: PDC measurement results of G-06 phase-to-phase insulation in 2003, 2004 and 2006

3. CONDITION IN APPLYING SUGGESTED CRITERIA

The shape of PDC measurement results itself describes the difficulties in the insulation system of rotating machines. Many types of insulation deterioration such as surface contaminants in Case 2, thermal trouble in Case 3, corrosive dust in Case 4 and some unidentified changes in Case 5 can be identified by the time-domain PDC measurement results but not the capacitance & $\tan \delta$ which are dielectric response in frequency domain. So the suggested criteria as indicated in the chart of capacitance ratio and $\tan \delta$ of Figure 1-3, Figure 5 and Figure 7 below shall be applied only when the type of insulation aging is known or identified by PDC shape, with the knowledge whether or not the capacitance ratio and $\tan \delta$ are sensitive to that trouble. This means action may need to be taken in some cases even though the capacitance ratio or $\tan \delta$ has not reached the suggested limits.

Suggested in-service criteria for ground insulation (L-G) are different from phase-to-phase insulation (L-L). In each chart of Figure 7, the stator is unacceptable for continued operation if the responses in any frequency range are above the limit line. These charts are applicable for winding temperature of about 20-35°C.

In spite of the suggested criteria, the rate of change in insulation properties is the most important to be considered.

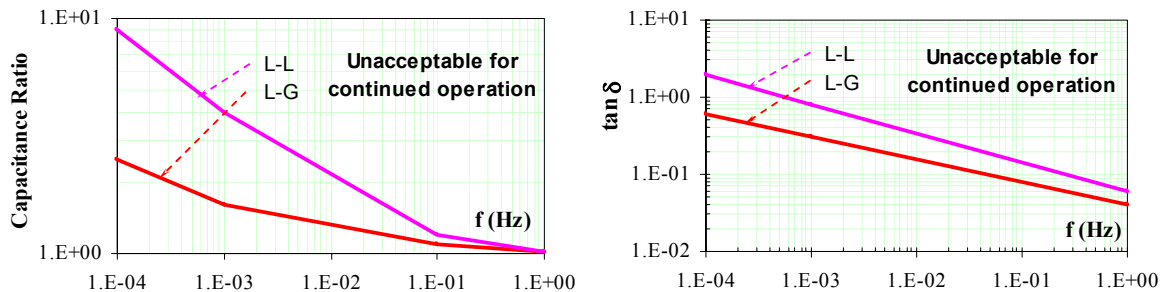


Figure 7: Suggested in-service criteria for phase-to-phase (L-L) and phase-to-ground (L-G) insulation of stator. Special conditions apply. (see item 3)

4. CONCLUSION

The case studies in this paper and in the first part of the article [1] demonstrate that the PDC technique is the most reliable and easiest diagnostic tool in the analysis of trouble and fault in rotating machine insulation. While the time-domain PDC measurement results identify various types of insulation aging, the frequency-domain PDC evaluation results assist in the judgement of acceptable status for continued operation.

The description and procedures for performing healthy PDC measurement in [1] combined with the methodology for PDC interpretation presented in this paper provide the practical instruction in the application of PDC technique for condition assessment of stator insulation.

5. ACKNOWLEDGEMENT

The author gratefully acknowledges the contribution of Walter S. Zaengl, Prof. Em. Dr.-Ing., Swiss Federal Institute of Technology (ETH), Zurich, Switzerland, for the review of the original document.

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