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Correlation between Capacitance and Dissipation Factor used for Assessment of Stator Insulation

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***Abstract*—**Measurements of capacitance *C* and dissipation factor $tan\delta$ of the stator insulation system provide useful information about internal defects within the insulation. The index *k* is defined as the proportionality constant between the changes at high voltage of capacitance ΔC and of the dissipation factor $\Delta tan\delta$. ΔC and $\Delta tan\delta$ values were highly correlated when small flat defects were within the insulation and that correlation was lost in the presence of large narrow defects like electrical treeing. The discrimination between small and large defects is made resorting to partial discharge *PD* phase angle analysis. For the validation of the results, *C* and $tan\delta$ measurements were carried out in a 15MVA 4160V steam turbine turbogenerator placed in a sugar mill. In addition, laboratory test results obtained by other authors were analyzed jointly. In such laboratory tests, model coil bars subjected to thermal cycling resulted highly degraded and ΔC and $\Delta tan\delta$ values were not correlated. Thus, the index *k* could not be calculated.

***Keywords*—**Aging, capacitance, dissipation factor, electrical treeing, insulation condition, partial discharge.

I. Introduction

The integrity of Stator Insulation System of electrical machines is responsible for reliability of service. In operation, stator coil bars are subjected to continuous thermal, electrical, ambient and mechanical stresses (TEAM stresses) which cause internal defects like voids, holes, cracks, delamination, and electrical treeing. The movement of the coil inside the slot can erode gradient/semiconductive layers and groundwall insulation, leading eventually to an insulation failure.50-60% of unscheduled outages of generation units are due to insulation failure [1] so the diagnosis and condition-based maintenance of stator groundwall insulation is of great concern for avoiding such in-service failures.Measurements of capacitance *C*, dissipation factor $tan\delta$ and partial discharges *PD* along with their change with time and with applied test voltage allow detecting and qualifying defects within the groundwall insulation. To distinguish flat and small defects (normal defects) from delamination and narrow defects, like electrical treeing (dangerous defects), this paper will compute the correlation between the changes at high voltage of capacitance ΔC and of the dissipation factor $\Delta \tan\delta$ by using accelerated aging cycles data.

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The proportionality constant is related with the discharge phase angle and in turn, this phase angle is a function of the type of defect. The theoretical relationship between discharge phase angle and ΔC and $\Delta tan\delta$ values was derived from Dakin´s research [2]. Hereafter, the proportionality constant will be referred as the index *k*.

The index *k* was computed from test results obtained by different authors who subjected coil bars to various types of aging cycles. Coil bars aged by thermal cycles resulted more degraded than those subjected to thermoelectric stress. In the first case, there was no correlation between ΔC and $\Delta tan\delta$ values and the index *k* was undefined. However, in the second case the index *k* ranged from 0.1 to 9. T he meaning of the former values will be discussed in a later paper.

Additionally, measurements were carried out in a 15MVA 4160V steam turbine turbogenerator placed in a sugar mill which resulted severely aged by excessive slot discharges and leakage currents. As a consequent, the index *k* was undefined.

Although the breakdown voltage *BDV* is still the dielectric parameter most related to actual insulation condition, after *BDV* measurements, machines become unserviceable. So the index *k* is a suitable non-destructive diagnostic tool.

II. Methodology

A. The Relation of Phase Angle in Void Discharge to the Increase of C and $tan\delta$

In 1959, Thomas Dakin [2] researched the capacitance changes due to internal discharges at high voltages and he also published an analysis relating the transfer charge by individual discharges to the increment in dissipation factor $tan\delta$ and in capacitance *C*, which can be measured on a high-voltage bridge.

The correlation between *PD* and the increase of *C* and $tan\delta$ according to Dakin´s research will be show briefly due to space constraints as follows:

The conductance *G* of the insulation at high voltage is the contribution of the intrinsic conductance G_0 of the insulation at low voltage and the equivalent conductance G_{dis} due to discharge of void inclusions as show in (1).

$$G = G_0 + G_{dis} \tag{1}$$

where

$$G_0 = \omega C_0 \tan \delta_0 \tag{2}$$

$$G_{dis} = \frac{2f}{V_m} \sum_0^{2\pi} \left(\Delta Q_i \sin \omega t_i \right) \tag{3}$$

$$G = \omega C_o \tan \delta_0 + \frac{2f}{V_m} \sum_0^{2\pi} \left(\Delta Q_i \sin \omega t_i \right. \tag{4}$$

ΔQ_i is the transfer charge due to the i-th *PD* occurred at the time t_i, $tan\delta_0$ and C_0 is the dissipation factor and the capacitance at low voltage where no *PD* occurs, V_m is the maximum amplitude of the applied test voltage, and ω and f are the angular and power frequency respectively.

When a *PD* occurs, a small area of the void inclusion is short-circuiting instantaneously and the amount of charge on the electrodes or conductors increase and as a result the capacitance of the insulation increases. The insulation reactance X considering the increase of capacitance C_{dis} due to *PD* is defined in (5).

$$X = \omega(C_0 + C_{dis}) \tag{5}$$

$$C_{dis} = \frac{1}{\pi V_m} \sum_0^{2\pi} \Delta Q_i \cos \omega t_i \tag{6}$$

Theoretically, the tangent of the dielectric loss angle $tan\delta'$ at high voltage when *PDs* occur is defined as in (7).

$$tan\,\delta' = \frac{G}{\omega C} = \frac{G}{X} \tag{7}$$

The effect of *PD* in the dielectric loss angles is quantified by replacing (4) and (5) in (7) as following:

$$tan\,\delta' = \frac{\frac{2f}{V_m} \sum_0^{2\pi} \left(\Delta Q_i \, sin\, \omega t_i \right) + \omega C_0 \, tan\, \delta_0}{\omega \left[C_0 + \frac{1}{\pi V_m} \sum_0^{2\pi} \left(\Delta Q_i \, cos\, \omega t_i \right) \right]} \tag{8}$$

Equation (9) is obtained by simplification of (8).

$$tan\,\delta' = \frac{\alpha \sum_0^{2\pi} \left(\Delta Q_i \, sin\, \omega t_i \right) + tan\, \delta_0}{1 + \alpha \sum_0^{2\pi} \left(\Delta Q_i \, cos\, \omega t_i \right)} \tag{9}$$

$$\alpha = \frac{1}{\pi V_m C_o}$$

Dakin concluded that when *PDs* occur near the applied voltage peak, the term $\sum_0^{2\pi} \Delta Q_i \sin \omega t_i$ in (9) tends to its maximum and thus, *PDs* contribute to the increase of $tan\delta'$ and in turns of $\Delta tan\delta$. On the other hand, when *PDs* occur near the applied voltage zero the term $\sum_0^{2\pi} \Delta Q_i \, cos\, \omega t_i$ in (9) tends to its maximum and thus, *PDs* contribute more to the increase of the capacitance C_{dis} and in turns of ΔC.

From the foregoing conclusion, it can be seen that both ΔC and $\Delta tan\delta$ are affected by the discharge phase angle.

B. Hypothesis of Work

Firstly, let us consider that the discharge angle is a function of the shape of void inclusions only.

According to Paschen´s law [3] the *BDV* of a void inclusion decreases as the product of distance *d* along the electric field and the internal pressure *p* of the void increases until certain value. After that value, the *BDV* increases again as show schematically in Fig (1).

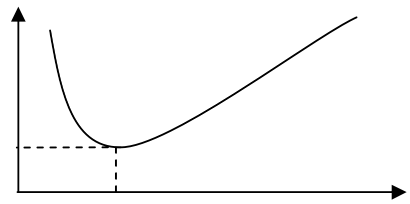

Fig. 1 Schematic behavior of the *BDV* as a function of *pd* product in a air gap.

By taking in consideration Paschen´s law and Dakin´s research jointly, *PD* within narrow and large void inclusions, like delamination and electrical treeing, would occur near the applied voltage zero contributing to the capacitance increase. *PD* within flat and small void inclusions would occur near the applied voltage peak, due to a higher voltage is required to discharge the void inclusions, contributing more to the dissipation factor increase.

Additionally, assuming that ΔC and $\Delta tan\delta$ are linearly correlated, the index *k* is defined as the slope of the straight line fitting the ΔC vs $\Delta tan\delta$ curve.

$$k = \frac{(\Delta C)}{(\Delta \tan \delta)} \tag{10}$$

If the hypothesis of work considered in this paper is a valid one, it is expected that $\Delta C > \Delta tan\delta$ and $k>1$ in coil bars with narrow and large defects like delamination, and $\Delta C < \Delta tan\delta$ and $0<k<1$ in coil bars with only small and flat defects distributed in the volume of the groundwall insulation..

In severely degraded insulation, delaminations can grow until become into electrical treeing. In such case, the treeing shortens the insulation thickness and the capacitance at low voltage increases largely, as a result, the correlation between ΔC and $\Delta \tan\delta$ is lost and it is not possible to compute the index *k*.

Before validating this hypothesis of work, it is necessary to review how the TEAM stresses affect the insulation condition.

C. TEAM Stresses Affecting the Insulation Condition

The groundwall insulation starts to develop changes in its chemical and physical structure because of TEAM stresses even so if the machine has been operated within design limits. New mica-epoxy insulation systems undergo less annual deterioration than thermoplastic resin based insulations, but even so, deterioration can occur and lead insulation to failure.

With years of service or during accelerated aging tests, thermal stress splits high-molecular-weight chains of epoxy insulation into lower-molecular-weight chains, activates oxidation reactions and hydrolysis, forms polar molecules and makes the insulation brittle [4]. Oxidation reaction encourages formation of some byproducts like, CO, CO2, H2O vapor and HCl [5]. As a result, during the machine service, void inclusions form inside the insulation apart from those formed in the manufacturing process. These initially small voids worsen with electrical and mechanical stresses until become in large defects.

The coefficients of thermal expansion in core stacks (steel), copper, and insulating material may differ by a factor of 10 or more resulting in shear stresses at the copper insulation interface and tensile stresses inside the insulation volume. The cyclic shear stresses weaken the bond between the conductor strands and the groundwall insulation and can eventually result in delaminations at the conductor insulation interface and between the laminated mica tape layers in the groundwall. Once the voids caused by delaminations and fatigue cracks have grown large enough, *PD* sets in and erodes the epoxy resin through oxidation of the polymer chains. Eventually the PD will bore a hole through the organic parts of the insulation and cause failure [6,7].

Growth of delaminations can lead to electrical treeing formation which shortens the effective insulation thickness. In such condition, the insulation is likely to fail.

Loose coils (vibration) in the slot can abrade the semiconductive layer of the coil and then abrade the groundwall insulation. Once the semicon coating is abraded, *PDs* occur between the coil surface and the core, further increasing the rate of deterioration [8].

Between all stresses, ambient stress can be kept as low as possible and even, moisture and contamination can be avoided with a proper maintenance.

Thermal cycling seems to be the hardest operation mode of the machine, which can become small voids (from normal insulation degradation) into large delamination and even electrical treeing. Theoretically, coil bars subjected to thermal cycling are expected to undergone greater degradation than those subjected to thermoelectrical stresses and show a greater increase of ΔC than of $\Delta tan\delta$

D. Computation of the Index k

Firstly, the increase of capacitance and dissipation factor at high voltage is computed as shown in (11) and (12). Sometime those increases are referred as capacitance and power factor "tip-up".

$$\Delta C_i = \frac{C_{HV} - C_{LV}}{C_{LV}} \tag{11}$$

$$\Delta \tan \delta_i = \tan \delta_{HV} - \tan \delta_{LV} \tag{12}$$

Subscripts HV and LV correspond to measurements at high and low voltage respectively. ΔC and Δtanδ are dimensionless.

Equations (11) and (12) should be computed in time intervals throughout the aging cycles or from the maintenance reports when available.

Then, every ordered pair $(\Delta tan\delta, \Delta C)$ is plotted in a Cartesian plane and by lineal regressions the slope of the resultant straight line (index *k)* is obtained.

III. Experimental Set-up

4 poles, 15MVA, 4160V steam turbogenerator placed in a sugar mill was used for the measurements. The coil bars were not provided with semiconductive layer or gradient tape and were in service for 5 year after rewinding. We have been carrying out tests measurements of *C* and $tan\delta$ every year since 2008 for diagnostic purpose using a balanced bridge DOBLE M4000. Phase C failed to ground on February 2011.

Additionally, results of accelerated aging tests published by M. Farahani y J. Zhidong were used for the aim of this paper. Table I shows types of stresses applied in each aging cycle and the actual case of an 11000HP and 6.6kV reported by Stone G. All machines had windings of mica and epoxy resin insulation ranged from 3.3 to 18kV. Measurements were made using guard electrode over gradient tape.

TABLE I
TEAM Stresses Applied to the Coil Bars for Each Case of Study

Case of study	Stress	Time elapse [Hour h]	Cycles [Hour h]
1	TE-M-TC	2100	300h-7 cycles
2A	TC	5000	1h-5000 cycles
2B	TE	7000	7000h-1 cycles
3	T-A-M	21625	865h-25 cycles
4	T-A-M	25950	865h-30 cycles
5	T-A-M	30275	865h-35 cycles
6	TC	1000	2h-500 cycles
7	Actual service	56000	--

TC= thermal cycling
TE= thermoelectric stress
T= thermal stress
A= ambient stress
M= mechanical stress (vibrations)

IV. Results and Discussion

A. Steam Turbogenerator

Fig. 2 shows the results of the measurements of ΔC and $\Delta tan\delta$ on each phase of the steam turbogenerator from 2008 to 2011. As seen, the values are not correlated, so the index *k* cannot be computed.

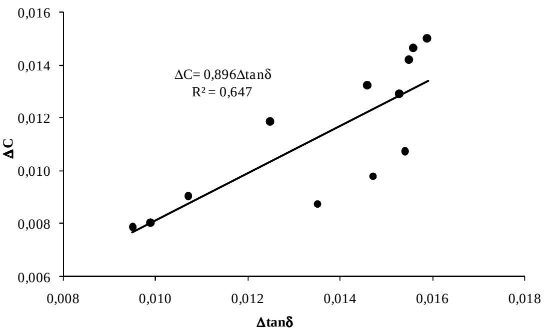

Fig. 2 ΔC vs Δtanδ curve for the steam turbogenerator. Measurements were done at 0.5 and 2.4kV

The former result suggests that severe defects are formed within the insulation. The diagnostic tests and visual inspection done in 2011 allowed proving this conclusion.

After extraction of the rotor, it was found several zones with finishing varnish shedding and overtemperature operation mode symptoms as depicted in Fig. 3.

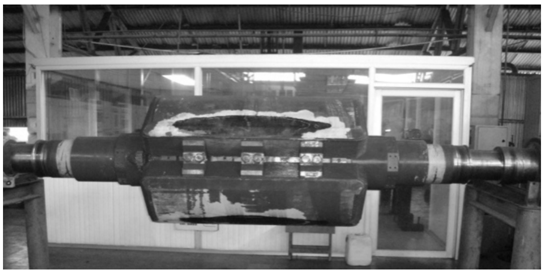

Fig. 3 Finishing varnish shedding as a symptoms of overtemperature operation mode of the steam turbogenerator. The affected zones showed bluish coloration.

The values of polarization index (*PI*) were about 6 in average. Although, the *PI* value was greater than the minimum value recommended by the standard IEEE-43, it is a high value compared with similar machines suggesting crystallization of the insulation because of over temperature operation mode (embrittlement).

A deeper intervention of the endwindings and of its mechanical lashing system showed total carbonization of the resin and conformable material placed between coils which prevent coil bars from vibrating. Samples of the material (plush) in Fig. 4 shows charring due to excessive leakage current.

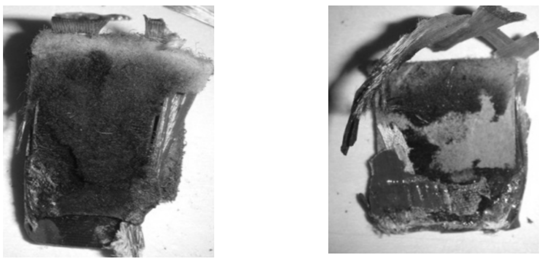

Fig. 4 Excessive leakage current throughout conformable material and evaporation of resin

Additionally, large amount of slot discharges near clamping fingers were observed in the whole stator as shown in Fig. 5.

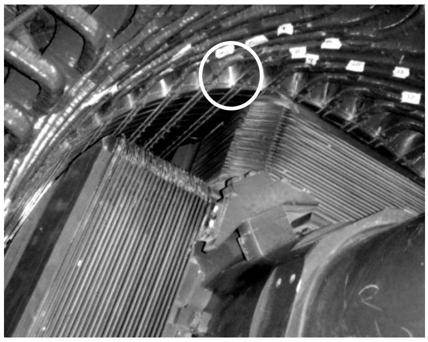

Fig. 5 Slot discharge at the end of the stator core.

B. Accelerating Aging Tests

Similar to the case of the steam turbogenerator, the coil bars of case of study 1 were exposed to TC-M-TE stresses and resulted highly aged. That was confirmed by the fact that values of ΔC and $\Delta tan\delta$ were not correlated. The index *k* could not be computed as shown in Fig. (6).

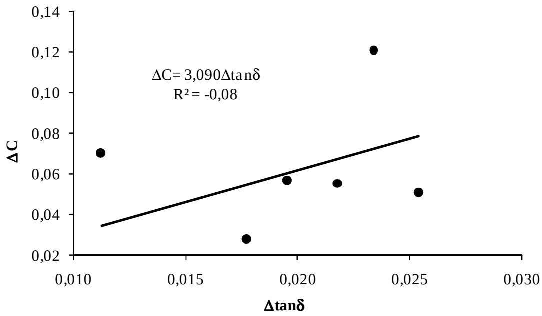

Fig. 6 ΔC vs Δtanδ curve for case of study 1. Measurements were done at 2 and 10.4kV [9].

In new coil bars, the capacitance at low voltage decreases somewhat with time from its initial value due to post-curing process and remains decreasing as a result of void inclusions. As opposed to that, in the two earlier cases, the capacitance at low voltage increased with time as depicted in Fig. 7 and 8. From Fig. 7, it can be seen that failed phase C showed the biggest increase of capacitance at low voltage.

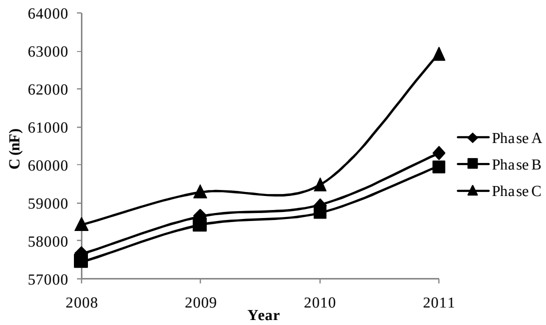

Fig. 7 Behavior of the capacitance as a function of year of service at 0.5kV for the steam turbogenerator.

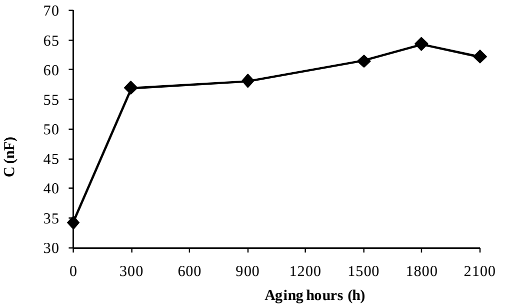

Fig. 8 Behavior of the capacitance as a function of aging time at 1kV for the case of study 1.

The increasing behavior of the capacitance at low voltage can be attributed to electrical treeing growth which, decrease the insulation thickness [10]. This behavior was reported by Sorenud in 2009 who observed the capacitance increase as a function of tree length after carrying out measurements on samples of cross-linked polyethylene (XLPE) [11].

The increase of the capacitance due to electrical treeing growth prevails over the effect of void inclusions which decrease the capacitance. In [12], a detail study of the behavior of such electrical treeing forming high conductivity path is described.

From the *PD* tests in case of study 1, it was found that the values of skewness for positive halfwave S_{k+} decreased down progressively from 0.44 to -0.44. According to [9], negative values of S_{k+} indicate that the shape of voids in groundwall insulation changes from flat to narrow, and even exhibits treeing. Values of S_{k+} between [-0,1, -0,2] have been proposed as a criterion for highly degraded insulations [13].

As a conclusion, neither in the steam turbogenerator case nor the case of study 1 was possible to compute any index *k* due to large delamination which became into electrical treeing inside the groundwall insulation. Both insulation systems are in a dangerous condition.

ΔC vs $\Delta tan\delta$ curves for cases of study 2A to 7 are shown in Fig. 9 to 13.

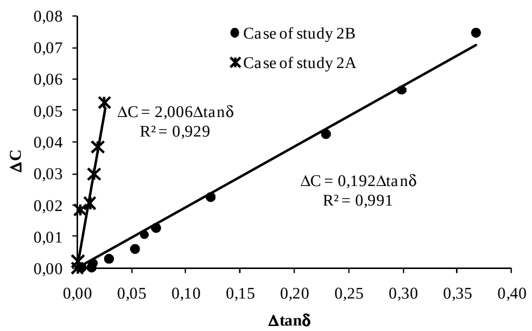

Fig. 9 ΔC vs $\Delta tan\delta$ curve for case of study 2A and 2B. Measurements were done at 2 and 12 kV [14].

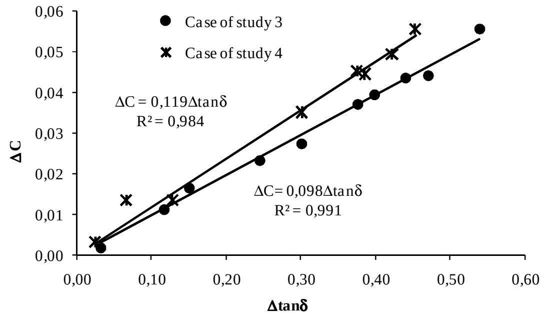

Fig. 10 ΔC vs $\Delta tan\delta$ curve for case of study 3 and 4. Measurements were done at 0,66 and 3,3kV [15].

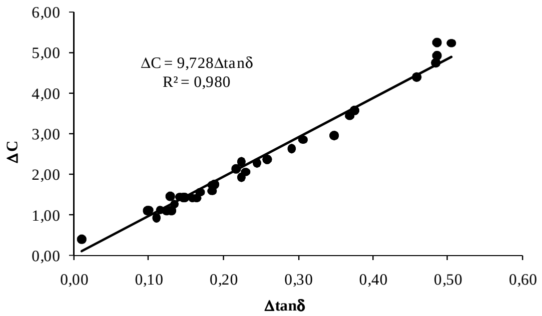

Fig. 11 ΔC vs $\Delta tan\delta$ curve for case of study 5. Measurements were done at 0,66 and 3,3kV [16].

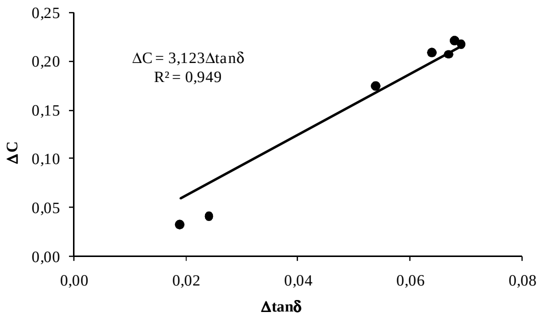

Fig. 12 ΔC vs $\Delta tan\delta$ curve for case of study 6. Measurements were done at 2 and 16kV [17].

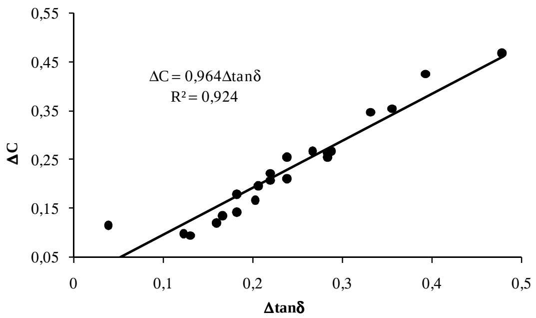

Fig. 13 ΔC vs $\Delta tan\delta$ curve for case of study 7, 11000HP induction motor [18].

From Fig. 9 to 13, it is shown that ΔC and Δtanδ values are high correlated with correlation factors greater than 0.9 and with indexes *k* different for each case of study as shown in TABLE II.

TABLE II
SUMMARIZING OF INDEX K

Case of study	Stress	Index k	T_{max} °C	Relationship
1	TE-M-TC	--	130	Electrical treeing
2A	TC	2	175	ΔC > Δtanδ
2B	TE	0.192	175	ΔC < Δtanδ
3	T-A-M	0.098	175	ΔC < Δtanδ
4	T-A-M	0.119	175	ΔC < Δtanδ
5	T-A-M	9.72	215	ΔC > Δtanδ
6	TC	3.123	155	ΔC > Δtanδ
7	Actual service	0.964	--	ΔC = Δtanδ

Coil bars in cases of study 2A to 7 resulted degraded but not until reach a dangerous condition (as the case of study 1) according to the diagnostic reported by each author.

Cases of study 2B to 4 which were not subjected to thermal cycling, showed indexes 0< *k* <1, and the insulation was characterized by normal degradation with small and distributed void inclusions, whereas those were subjected to thermal cycling like cases of study 2A and 6, resulted more degraded and the groundwall insulation was characterized by large void inclusions and delamination, and therefore their index *k* were greater than 1. Those results are in agreement with hypothesis of work (item 2B).

Although coil bars in the case of study 5 were not subjected to thermal cycling, their indexes *k* were greater than 1, which can be explained by the high aging temperature (215 ºC) so much over their thermal class F (155 °C) accelerating the rate of degradation.

For the 11000HP induction motor the index *k* was near 1 indicating that the degradation of the insulation is normal. This agrees with the diagnostic reported by Stone, G. who stated that the machine was able to remain in service after years of service.

Finally, for all the cases of study in which coil bars resulted aged but not showed electrical treeing (cases 2A to 7), the index *k* remained constant from the beginning to the end of the aging procedure.

V. CONCLUSION

After conducting test measurements in a steam turbogenerator in actual service and analyzing the results of accelerated aging tests carried out by different authors, it can be stated that the correlation between the changes of capacitance and of dissipation factor can be used to detect the type of defects inside the groundwall insulation.

The index *k* was proposed as a criterion for detecting electrical treeing, delamination and flat void inclusions.

When ΔC and $\Delta tan\delta$ values are high correlated, the index *k* can be computed as the proportionality constant of the straight line fitting data values. If *k*> 1, the groundwall insulation is characterized by large void inclusions and even delamination. If 0<k<1, the groundwall insulation shows normal degradation with small and distributed void inclusions. On the other hand, if ΔC and $\Delta tan\delta$ values are no correlated, large delamination and electrical treeing are present inside the groundwall insulation and the machine should be scheduled for a deep maintenance or replacement.

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