INVESTIGATION ON CORRELATION BETWEEN BREAKDOWN VOLTAGE AND DIAGNOSTIC MEASURING RESULTS OF SOME IN SERVICE AGED MOTORS

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Abstract: In order to check how the results of the breakdown voltage tests can correlate with the results of different non-destructive diagnostic measurements, a series of diagnostic investigations as partial discharge, dissipation factor and insulation resistance measurements were firstly conducted on the insulation of some in service aged medium voltage motors. After that the remaining electrical strength of the motor insulation were determined by breakdown voltage tests and the potential correlation between the results of the breakdown voltage tests and the non-destructive test methods were investigated. In the contribution the results of the measurements and tests will be reported and the correlation between the breakdown voltage tests and the diagnostic measuring results analyzed.

1. INTRODUCTION

The winding insulation is one of the most important parts of rotating machines and its electrical and dielectric properties may change due to combined thermal, mechanical, electrical and environmental stresses during machine operation. In long term, these multiple stresses cause insulation aging which leads to final insulation failure. In order to minimize the technical risk of a breakdown and to make an economical decision of further operation or renewal of electrical machine the condition evaluation and estimation of the remaining electrical strength of the insulation is a very important part in asset management.

The remaining electrical strength of the insulation can be determined by destructive test methods as breakdown voltage tests, but it is of great importance that the aging condition and remaining electrical strength of insulation can be evaluated based on non-destructive characteristic parameters. This will be possible if there is a correlation between results of the destructive and non-destructive test methods. Unfortunately, it is very difficult to establish such correlations because of the fact that for most insulation the scatter involved in the experimental results of the diagnostic properties with time are very large [1]. Today, the estimation of the aging state of the insulating system and remaining lifetime of a machine is based on experience and empirical laws found by extensive testing and dielectric measurements on machines and on model insulators [2].

To evaluate the condition of insulation system of rotating machines different electrical and dielectric methods as non-destructive measuring methods can be used. The diagnosis based on insulation parameters such as insulation resistance, dc leakage current, polarization index (PI), dissipation factor at low voltage (tan δ), tip-up dissipation factor (Δtan δ), capacitance, maximum partial discharge (PD), partial discharge inception voltage (PDIV), partial discharge extinction voltage (PDEV) and dielectric spectroscopy in time (PDC) and frequency domain (FDS).

Each diagnostic parameter is considered to reflect a different aspect of the condition of stator insulation. Therefore it is preferable to monitor as many diagnostic parameters as possible in order to obtain reliable and complete information regarding the state, quality and trend in ageing of the insulation [3], [4]. Some methods as dissipation factor measurement (tan δ) provide integral information about condition of insulation system and other as partial discharge (PD) measurement reflect the locally confined insulation defects that often can not be found by other dielectric methods.

In this paper the measuring results of non-destructive parameters such as dissipation factors (tan δ), insulation resistance and partial discharge of three in service aged medium voltage motors have been investigated in relation with their breakdown voltage values.

2. TEST DETAILS

2.1. Test objects

The investigation is conducted on stator winding insulation system of three in service aged medium voltage motors, which are labelled as motor A, B und C. They are three phase oil filled motors with a rated voltage of $U_N = 3.0 \text{kV}$, which were for a long time at approximately 90 to 95 °C ambient temperature in service. The motors are the same type and were manufactured based on the epoxy VPI (Vacuum Pressure Impregnation) technology.

All motors were tested from the terminals with removing the rotors. Before the measurements the stators were stored in a plastic container filled with a mineral oil. The diagnostic measurements and breakdown voltage test were performed on individual phase windings (U, V, W) of the motors A and B separately. In the case of the motor C the diagnostic
measurements and breakdown voltage test were done at all three windings of the stator connected together, because the disconnecting of the phases windings from other in the star point was difficult and could damage the insulation system. All measurements and tests were done at room temperature (RT~21°C).

2.2. Diagnostic measuring methods

The insulation resistance measurement was conducted at DC voltage 1.0 kV. The readings of the insulation resistance are taken after the test voltage has been applied for 1 and 10 minutes. The polarisation index (PI) was then calculated from insulation resistance measuring results. The polarization index is normally defined as the ratio of the 10 minutes resistance value (IR₁₀) to the 1 minute resistance value (IR₁).

The dissipation factor (\(\tan \delta\)) was measured as a function of the voltage at five different voltage levels 0.6, 1.2, 1.8, 2.4 and 3.0 kV (representing 0.2, 0.4, 0.6, 0.8 and 1.0 \(U_N\)). For stator A and B the non measured phase were guarded during the dissipation factor und insulation resistance measurements on one winding.

The used PD measuring system performs a quasi integration with lower and upper frequency of 100 kHz and 400 kHz. For stator A and B the non measured phase were grounded during the PD measurement on one winding. The PD measurement was conducted at two different voltages 1.7 kV and 3.0 kV, representing \(U_N/1.7\) und 1.0 \(U_N\). The results are presented in form of the PD patterns with PD inception voltage (PDIV).

2.3. Breakdown voltage test

For breakdown voltage test the applied voltage (AC, 50 Hz) on the windings is raised gradually (step test) up to the breakdown of the tested winding. The voltage was increased by 3 kV per step and remains constant on each step for one minute. The transition from one to the other voltage step took place with a rate of approximately 500 V/s. For stator A and B the non measured phase were grounded during the test on one winding.

3. EXPERIMENTAL RESULTS

3.1. Insulation resistance

The results of the insulation resistance measurement on stator windings of the investigated motors at 1.0 kV after 1 (IR₁) and 10 (IR₁₀) minutes as well as the polarization index (PI) are listed in Table 1. It must be pointed out that in the case of motor C the insulation resistance of all three phase windings was measured together, that means that the insulation resistance of each phase can be about 3 times the reported value.

The comparison of the insulation resistance values of the three motors shows that the insulation system of the motor A is clearly higher than other motors. The insulation resistance of this motor is about 3 times higher than other motors. That means that this motor is in a better condition concerning the insulation resistance.

The comparison of polarization indexes of the three motors shows however no meaningful difference between them. This confirms the statement that when the IR₁ is higher than 5 G\(\Omega\), the PI may or may not be an indication of the insulation condition and is therefore not recommended as an assessment tool [5].

Table 1: Insulation resistance and polarization index of stator windings of investigated motors after 1 and 10 min at 1 kV and RT

<table>
<thead>
<tr>
<th>Motor</th>
<th>Phase</th>
<th>IR₁ (G(\Omega))</th>
<th>IR₁₀ (G(\Omega))</th>
<th>PI</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>U</td>
<td>98</td>
<td>330</td>
<td>3.36</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>130</td>
<td>420</td>
<td>3.27</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>138</td>
<td>450</td>
<td>3.38</td>
</tr>
<tr>
<td>B</td>
<td>U</td>
<td>36</td>
<td>127</td>
<td>3.52</td>
</tr>
<tr>
<td></td>
<td>V</td>
<td>57</td>
<td>169</td>
<td>2.96</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>55</td>
<td>168</td>
<td>3.03</td>
</tr>
<tr>
<td>C</td>
<td>UVW</td>
<td>17</td>
<td>59</td>
<td>3.47</td>
</tr>
</tbody>
</table>

3.2. Dissipation factor

Figure 1 presents the results of the dissipation factor measurements as a function of voltage for the stator windings of the investigated motors. The results show that the insulation system of the motor A has the lowest absolute value of \(\tan \delta\) and small increase with applied voltage. Motor B shows higher absolute values and higher increase with increasing voltage. Motor C has the highest absolute value of \(\tan \delta\) and shows also an increase with increasing voltage.

The results of dissipation factor measurements confirm the results of the insulation resistance measurements that the insulation system of motor A is in a better condition compared to other motors.
3.3. Partial discharge

The PD measurement was done for charges $\geq 10$ pC at two different voltages 1.7 kV and 3.0 kV, representing $U_{N}/1.7$ und 1.0 $U_{N}$. At 1.7 kV all stators were PD free for charges $\geq 10$ pC while at 3.0 kV they present different PD behaviours. The PD-patterns for the investigated motors at 3.0 kV are shown in Figure 2, 3 and 4. All PD patterns were developed by integrating the PD activity over a fixed period of time (30 seconds). The colours in the PD-patterns represent the repetition rate of the PD pulses with the relevant charge value and at the relevant phase angle. Figure 5 shows the PD-inception voltage values of the investigated motors.

![PD-pattern of the phase windings of motor A, measured at 3 kV](image)

**Figure 2**: PD-pattern of the phase windings of motor A, measured at 3 kV

For motor A the phase windings V and W are at 3.0 kV PD free for charges $\geq 10$ pC and only the phase winding U showed PD pulses below 200 pC with low repetition. In comparison with motor A the motors B and C have lower PD inception voltages and higher PD amplitude and repetition at 3 kV. Especially in the case of motor C the amplitude of the PD is very high, about 10 times higher than for motor B. As shown in Figures 3 and 4, the amplitude of the PD of the phase windings of motor B is up to 5 nC, while in the case of motor C it is up to 50 nC.

![PD-pattern of the phase windings of motor B, measured at 3 kV](image)

**Figure 4**: PD-pattern of the phase windings of motor B, measured at 3 kV

![PD-inception voltage of stator windings](image)

**Figure 5**: PD-inception voltage of stator windings

3.4. Breakdown voltage test

Figure 6 presents the results of breakdown tests for the stator windings of investigated motors. The breakdown voltage of the phase windings of motor A lies within the range of $11U_{N}$ to $13U_{N}$, while for the phase windings of motor B at about $8U_{N}$ and for motor C at about $4U_{N}$.
4. DISCUSSION OF RESULTS

The reported investigations demonstrate that the insulation condition can be assessed by comparing the diagnostic test results between different machines with similar insulation systems. The results of all three used diagnostic measuring methods show that the insulation system of motor A stands in better condition as for motors B and C. The acceptable PD activities, high insulation resistance and low dissipation factor of motor A indicate that all three phase windings of this motor are in serviceable condition. This fact was confirmed later by the results of the breakdown voltage test, whereby breakdown voltages of the phase windings of motor A up to 13 $U_N$ could be reached.

A comparison of diagnostic measurement results of motor B and C also shows that motor C is in worse condition than motor B. Especially the partial discharge activities in motor C are unacceptable, because the value of PD magnitude is very high up to 50 nC and the PD inception voltage relatively low. The PD patterns of motors B and C are relatively symmetric regarding to the positive and negative half cycle of test voltage, which is a typical PD pattern for internal discharge in voids and delaminations within the main insulation [6]. The dominance of PD pattern amplitude in negative half cycle could indicate the presence of voids or delaminations within the groundwall insulation at interfaces of copper conductor and the main insulation, probably due to debinding of the conductor stack from the groundwall or creation of delaminations near the conductor.

The results of the breakdown voltage tests also confirm the critical condition of motor C, whereby the breakdown voltage of motor C is only about 4 $U_N$. The breakdown voltage of motor B shows values between motor A and C concerning the results of the non-destructive diagnostic measurements.

The comparison of the results of diagnostic measuring results and the breakdown voltage test of investigated motors show a clear correlation between the breakdown voltage of the motors and their diagnostic measured values. This correlation is clearer between the breakdown voltage and PD measuring results, which means that the insulation problems are more due to local defects.

It should be considered that such clear correlation does not always exist, and if the differences between diagnostic measurements are small, the interpretation may lead to wrong conclusion. As an example phase W of motor A shows no PD about 10 pC and has the highest PD inception voltage, but the lowest breakdown voltage.

5. CONCLUSION

Diagnostic non-destructive measurements of dissipation factor, insulation resistance and PD are useful tools to determine and diagnose the insulation condition.

The correlation between the breakdown voltage and diagnosis measurement is good and the investigated methods can be used for the evaluation of the insulation condition.

The correlation is based on comparative measurements which mean that similar insulation systems can be evaluated and classified, but this can not be transferred to any other insulation system without care.

The interpretation of the diagnostic measurements should also be carefully done, if the differences in the measured values are small.

6. REFERENCES


