Assessment and Analysis of the Reliability of Insulation System for High-Voltage Induction Motors Based on the Partial Discharge Level

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***Abstract* — The object of the paper is an experimental study and analysis of the reliability of the stator winding insulation of high voltage induction motors that have been in continuous operation for more than 30 years. The analysis is based on experimental results of measurements of the dissipation factor values and partial discharges, performed on a number of induction motors in several consecutive years. They give an information to asses the current condition of the stator insulation, the trend of insulations deterioration and allow forecasting its residual life.**

Keywords—high voltage induction motors, stator winding, insulation, dissipation factor, partial discharges, residual life

I. INTRODUCTION

The reliable and smooth operation of technological equipment used in various responsible industry processes depends largely on the sustainable operation of their electric motors. The production processes in which they are involved usually do not allow emergency shutdown due to defects occurred in them. To a large extent, this applies to high-voltage (HV) induction motors with power from hundreds kW to several MW. The operating condition under which these motors operate is characterized by continuous duty cycle at high ambient temperatures - in the range of 40-47 °C. Irreversible changes can occur in various motor components under such condition, especially when the service life is in the order of 30 years or more [1, 2]. The most vulnerable in this regard is the stator winding insulation. Over time and depending on the operating conditions - overload, pollution, moisture, vibration and other factors, the characteristics of the windings insulation deteriorate [1, 3, 4, 5]. For this reason, periodic stator winding tests need to be carried out, which include the measurement of: insulation resistance, polarization index, absorption coefficient, dissipation factor (tan δ) and partial discharge level [3, 7, 8, 9, 10, 11]. The results of these measurements make it possible to estimate the current state of the insulation, to assign reparation activities or to predict its residual life. The most significant information from the tests could be obtained from the measurements of the dissipation factor and the partial discharges as the successive partial discharges destroy the insulation slowly. The presence of a system for online monitoring of partial discharges allows to monitor in real time the occurrence, number and type of partial discharges, analyze them, record information in a database and provide the user with information about the state of the insulation and the trends of the processes in it. The system issues automatically warnings in case of persistent trends for increasing partial discharges that the necessary repair actions should be anticipated before fault or breakdown occurs. Existing standards [12, 13, 14, 15, 16] describe the methods and conditions for performing these tests, but do not define admissible (acceptable) limits for continued operation of high-voltage motors without repairing the isolation or pointing to the need to replace it with more efficient new one.

The aim of this article is to present possible criteria that will allow us to estimate the residual life of high-voltage motors' insulation that have been used for a long time. Experimental results of tests performed on high voltage induction motors, after their long-term operation in responsible technological processes, are used to obtain acceptable criteria.

II. CONDITIONS FOR PARTIAL DISCHARGES OCCURRENCE

The stator winding insulation system for high-voltage machines has multi-layer structure formed from insulating tapes consisting inorganic materials (such as mica) and impregnating resins. The characteristics of the stator winding insulations differ depending on the materials used and the fabrication technology. Technology is widely used in which insulating tapes are wound over the coil manually or mechanically in overlapping layers. Then each coil is subject of impregnation with epoxy resins, molding, pressing and baking to form a solid stator coil. The penetration of the resin into the insulation strips and into the space around them is different depending on the impregnation technology used and on the characteristics of the impregnation resin. This fact determines the possibility of having more or less gas caverns in the volume of insulation of the stator winding.

The insulation system of the stator windings manufactured about 25-30 years ago is made by varnish method of materials with relatively low heat resistance and mechanical endurance. During the term of operation of the motor, the stator winding is repeatedly influenced by various factors such as: overheating due to short-term overload; change in ambient temperature; abrupt mechanical stress in start-up mode during heavy starting processes; surface contamination of stator coils. After long-term operation, these effects lead to an accelerated change in the structure and features of the insulation system – thermal ageing and deterioration of the insulating characteristics of the materials and occurrence of gas caverns. The areas where gas caverns are present are usually located at the boundary surfaces between the conductors and the insulation; the boundary surfaces between the laminated steel core and insulation; inside the insulation or between its individual layers – Fig.1.

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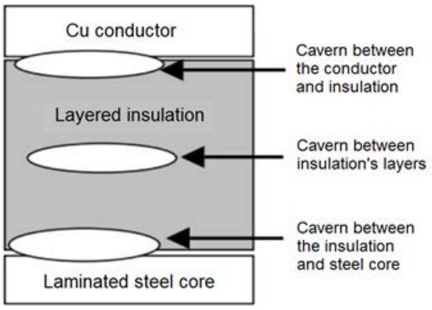

Fig. 1. Typical cavern locations

Particularly sensitive to the influence of the above factors are the areas of the stator windings at the points of their outlet from the magnetic core. Under the high voltage applied to the stator winding, ionization process and charge redistribution occur in the gas caverns. In essence, these caverns are micro-capacitors in the volume of insulation. When the potential difference between the sides of the caverns becomes greater than the dielectric strength of the gas in them, a discharge occurs in the cavern. The discharge is a current impulse through the insulation with duration of about several nanoseconds. Initially, the number and volume of the caverns is small and partial discharges (if any) are practically insignificant. Due to the different cooling conditions in these zones, the temperatures in the slot part and in the end part of the coil are different, which results in additional mechanical stress of the insulation and helps expand gas caverns and create new ones. The number of gas caverns is increasing, which in turn is a prerequisite to more intensive partial discharges.

Similar processes occur in insulation systems made with newer technologies - for example, VPI (Vacuum Pressure Impregnation). In general, VPI insulation systems are much more resistant to the effects of temperature, humidity, mechanical pollution and the gases contained in the environment. They have a sufficiently high rigidity, but are sensitive to mechanical stress due to the thermal expansion or to the electrodynamic force produced of the currents in the coil. As a result, this type of insulation produces micro-cracks in which partial discharges occur [9].

Partial discharges usually occur at high voltages and are closely related to dielectric losses, and therefore the measurement of partial discharges in the stator winding insulation is usually combined with the measurement of the dissipation factor. If the dissipation factor does not increase significantly over time, this allows it to be judged that there is no deterioration of the insulation due to thermal aging or coarse contamination. If there is a high rate of increase over time, this is a signal of its deterioration due to systemic overheating, cavities in the insulation, moisture absorption or contamination with conductive particles.

III. EXPERIMENTAL RESULTS

A number of experimental studies have been performed on the insulation of the stator windings of a number of HV induction motors for several consecutive years. The results of measuring the dissipation factor and partial discharges over the motors lifetime have been considered and analyzed to assess the reliability of the insulation system and to predict its residual life.

A. Dissipation factor tests

The measured values of the dissipation factor vs. test voltage for 3 induction motors with voltage and power ratings 6 kV and 4 MW respectively after their 32 years of continuous operation are shown in Fig. 2. The test voltage was varied from 1.5 to 7.5 kV in the 1.5 kV step. The lowest values of the dissipation factor have been measured for the IM1 induction motor, where a small, almost linear increase depending on the test voltage was obtained. This gives reason to believe that the motor can be operated without having to replace the stator winding insulation.

Higher values for the dissipation factor were measured for the IM2 compared to those of IM1. The increased values can be due to two reasons - either to the greater dielectric loss of the insulation materials used in the production or to the structural changes in the insulation of this motor due to its thermal aging, leading to insulation resistance decrease and polarization processes increase. The fact that the rise of the dissipation factor is relatively small with increasing the test voltage indicates that the reason is more likely in the characteristics of the materials used. This motor may be operated, but further control tests need to be carried out to determine its residual life.

The experiments for the IM3 induction motor showed high values of the dissipation factor that rapidly increase with the increase of the test voltage over 4 kV. This is an indication that significant structural changes have occurred in the insulation materials, leading to a significant increase in the polarization processes and a decrease in the insulation resistance. The residual life of this motor is minimal. To be used in the future, it is necessary to carry out very frequent control tests - at least twice a year, but eventually the best solution is to replace its insulation.

Measurements of the dissipation factor of stator windings' insulation of IM4 and IM5 induction motors for consecutive years have been performed. The comparison of results obtained for a test period of two years is shown in Fig. 3 and Fig.4.

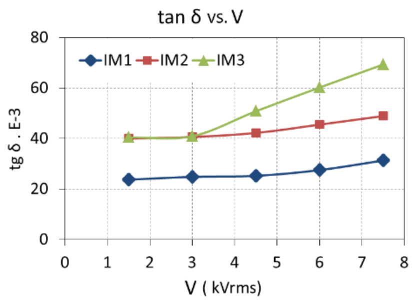

Fig. 2. Dissipation factor vs. test voltage after 32 years continuous operation

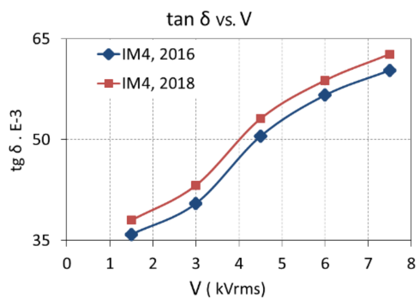

Fig. 3. Dissipation factor measured in 2 years interval

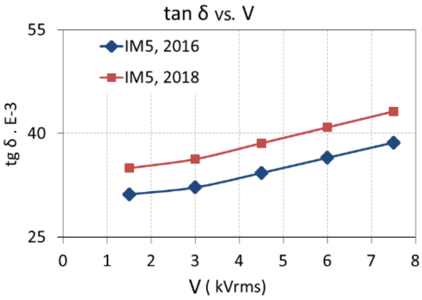

Fig. 4. Dissipation factor measured in 2 years interval

An increase in the measured values is observed for both motors. The results show about 5% average increase for IM4 two years after the first measurement but a rapid increase depending on the test voltage – approximately 68%. For IM5 motor the increase in the dissipation factor with the test voltage is 24%, while 12% increase is obtained of the values measured after two years. From the results it could be concluded that an accelerated thermal aging processes have begun, leading to a reduction in the residual life. Provided that the motors are to be operated in this state, continuous test measurements must be made to monitor the trends in the dissipation factor change.

B. *Partial discharge tests*

Measurements of the partial discharges in the stator winding's insulation of some induction motors for consecutive years have been performed also. The diagrams showing the quantity and level of the partial discharges in the stator coil of the IM5 motor in 2016 and 2018 respectively are shown in Fig. 5 and Fig. 6. The number of registered discharges in the second measurement is significantly higher. Some increase in the charge level than those registered at the first measurement was registered also. This is most likely due to the expansion of the gas cavities with the thermal aging of the insulation, which has led to an increase in their capacity.

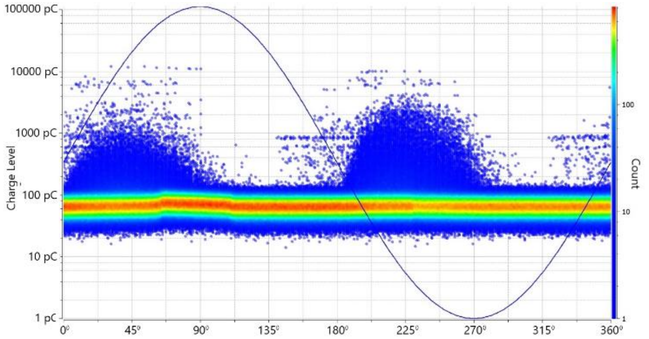

Fig. 5. Partial discharge diagram of IM5 (2016)

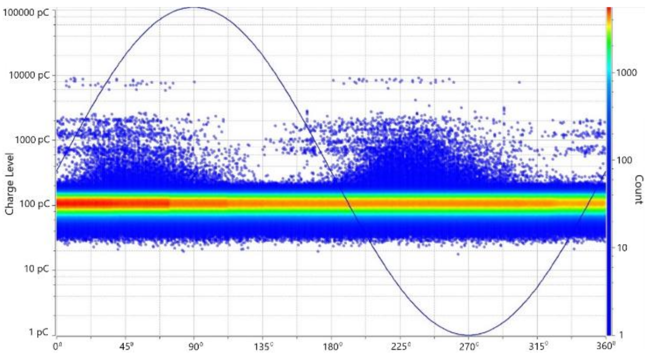

Fig. 6. Partial discharge diagram of IM5 (2018)

Further experiments, statistical processing and analysis of the results are required for assessment of the residual resource of the motors' insulation.

The IM6 induction motor has been used in continuous operation for 32 years. Its duty cycle was characterized by long periods of work (in the order of 80%) combined with short downtime when switched off. Diagrams for the partial discharge level in the stator coil insulation obtained from measurements made over three consecutive years are shown in Fig. 7, Fig. 8 and Fig. 9. The peak values of the partial discharges obtained from measurements made in the first year are 8.5 nC (Nano Coulomb), in the second year - 10 nC, and in the third year - 12.2 nC.

Using these results and assuming the same trend of increasing the maximum value of partial discharges during the next years, it is possible to forecast the residual life of the insulation of its stator coils, which is shown in Fig. 10. If the obtained trend is maintained, the level of 30 nC will be reached after approximately 4 years. According to the recommendations of world-renowned companies with extensive experience in the field of electrical insulation monitoring at partial discharge values above 30 nC, the insulation status is classified as "critical", in which case rapid action must be taken for its replacement.

In this sense a conclusion could be made that the estimated value of the residual insulation life of an IM6 motor is no more

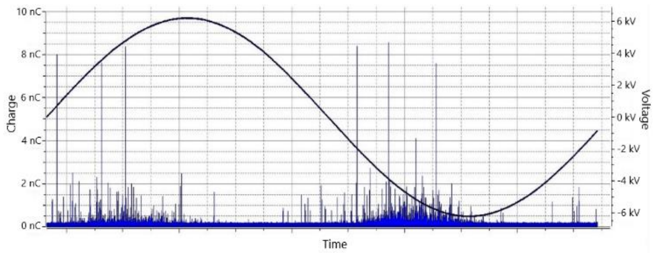

Fig. 7. Partial discharge level diagram - first test (after 32 years operation)

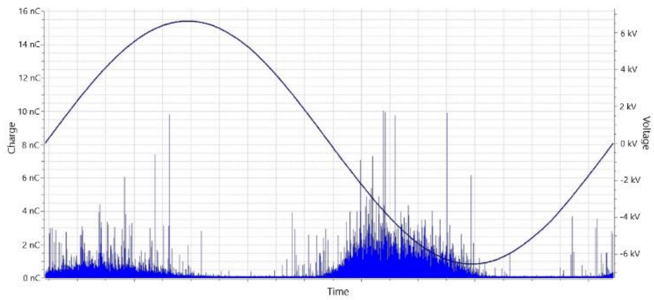

Fig. 8. Partial discharge level diagram - second test

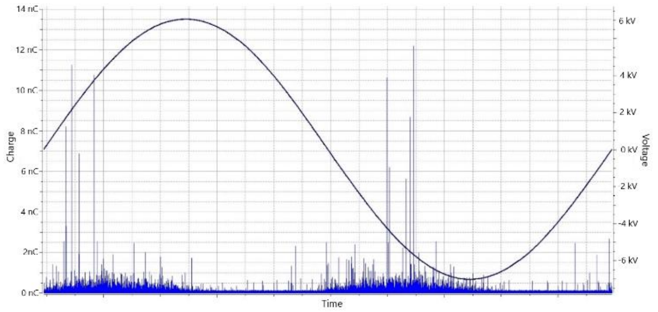

Fig. 9. Partial discharge level diagram - third test

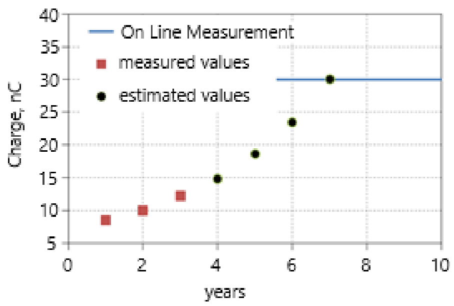

Fig. 10. Forecast residual resource

than 4 years. If the nature of the technological processes does not allow immediate replacement or repair of the insulation system, it is necessary to proceed to continuous measurement of the level of partial discharges therein, using the method "On Line Measurement".

IV. Conclusion

The dissipation factor and partial discharge tests conducted on the insulation of the high voltage induction motors and the subsequent analysis of the obtained results make it possible to draw up a strategy for future actions for evaluating the residual life of the induction motors, operated in responsible technological processes in the field of electricity, chemical and oil industry. This provides the opportunity for: reliable and trouble-free operation of industrial facilities; reduction of losses from unplanned interruptions of the production processes; reducing the cost of repair and restoration activities in the event of an emergency shutdown of production facilities; drawing up a schedule for replacement the insulations of those machines that have spent their residual resource.

Acknowledgment

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