TECHNICAL ARTICLE

ASSESSMENT CRITERIA FOR INSULATION SYSTEMS FOR ROTATING ELECTRICAL MACHINES MAINTENANCE

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ABSTRACT

Frequent maintenance on rotating electrical machines is essential for their flawless operation, and that is even more relevant for large machines due to the high values added to those machines and to the process in which they are inserted. Large machines, built with medium voltage windings, require specific technologies and special precautions in the manufacturing. Such precautions must be even more specific in operation and maintenance, as the electrical machines are subjected to severe conditions of electrical, mechanical, thermal and environmental stress. Periodic maintenance guarantees a longer service life, since it can detect failure trends. Tools, equipment and experiments used by the maintenance teams can identify such trends, the causes and respective corrections. For such assessments, the windings must often be subjected to stress levels that can compromise the machine, which has already suffered the operation stresses for many years. Thus, this article aims to present techniques to assess rotating electrical machines using the rated phase voltage +10%, that is, the same voltage levels applied to the windings in operation, a different approach from what is described in the standards.

Keywords: Electrical machines; insulation; maintenance.

1 INTRODUCTION

Electrical machines play an essential role in any production process, both in terms of driving force and as an energy source. Therefore, any stoppage of an electric machine will significantly affect the production process.

High levels of market competitiveness are leading industries to seek reliable and available equipment to minimize undesirable interruptions in production processes and reduce unplanned maintenance costs. Thus, the maintenance sectors play an essential role using management strategies for preventive and predictive maintenance. Every manufacturing process has machines in continuous depreciation or even on the way to becoming obsolete. Maintenance must guarantee the reliability of the equipment throughout the depreciation process [1].

The traditional “bathtub curve” of product failures, shown in figure 1 [1], illustrates the probability of failures in rotating electrical machines. At the start of operation, you may encounter flaws inherent in the application, in the transport or, occasionally, in the production. After that initial period, the equipment enters a stable operation stage, during which it may fail randomly, and it then reaches the limit of its service life. To reduce the number of failures due to production, which would occur after installation, several tests are performed by the manufacturer before the equipment is released. Such tests are not designed for the other periods of the equipment service life. This article proposes to deal with the assessments of the insulation system when the electrical machine is in the last period of the “bathtub curve”.

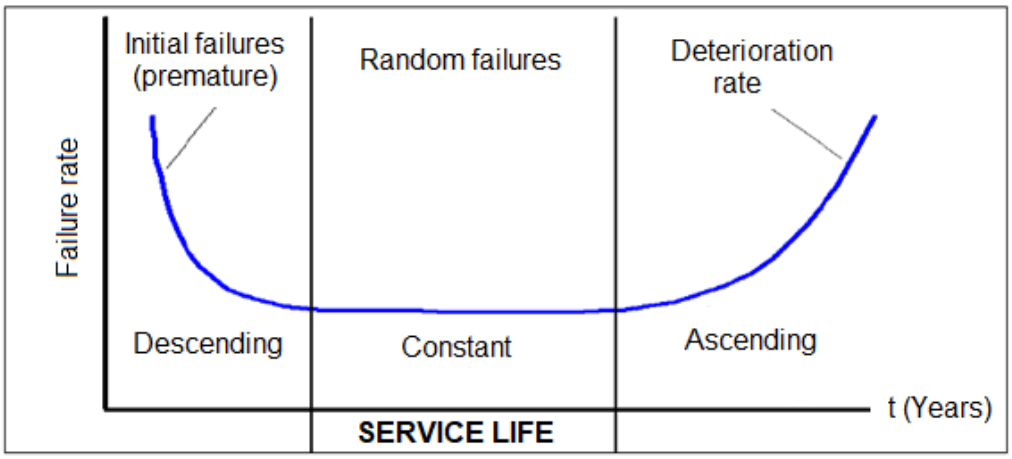


Figure 1: *Traditional "bathtub curve" for the failure probabilities over the equipment service life [1]*

Rotating electrical machines are continuously subjected to electrical, mechanical, thermal and environmental stresses, mainly caused by contaminants that degrade the machine components and compromise their service life. The main component that is degraded in an electrical machine is the winding insulation system. Such issue is even more complex in medium voltage machines. Figure 2 shows failures statistics in large generators, where the predominance of failures related to insulation is noticeable.

The life of the insulators usually defines the operating reliability of the electrical machine. The life expectancy of a good quality machine operating under the recommended conditions is around 25 years [2; 3]. Several factors may affect the insulation, such as moisture absorption, oxidation, thermal decomposition, electrolytic effects and leakage currents, electrical discharges and their chemical reactions, thermomechanical stresses, mechanical wear and abrasives. Such factors can accelerate degradation in the insulation and lead to premature and unexpected failures of the electrical machine.

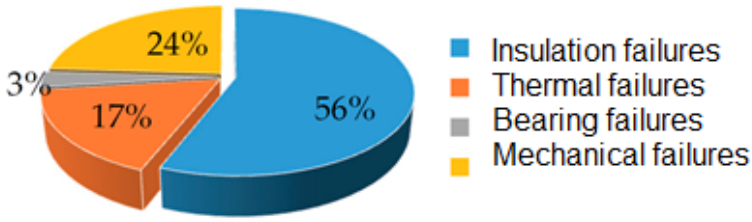


Figure 2: *Failure statistics on large medium voltage generators [2]*

Studies and equipment are constantly developed to monitor failure trends. The most common tests used to assess electrical machines are: measurement of the insulation resistance; polarization and absorption index; surge test, used to identify short circuits between turns; hipot test; current leakage measurement; corona effect inspection; dielectric losses (tangent of delta),used to identify the trend of losses in the capacitance associated with the insulation and partial discharge test, used to monitor small discharges that occur in the insulation systems and trace an evolution of such levels.

The stator and rotor of an electrical machine are basically composed of three types of materials: copper conductors (aluminum in some cases), the core (composed of ferromagnetic laminations) and insulators. Conductors conduct the current necessary to create the magnetic field and convert energy, the lamination core conducts the magnetic flux, and the insulators separate the electrically active parts, ensuring that the current follows the correct path.

Stator windings can be manufactured in three ways: random winding, used for high-current capacity coils with several conductors in parallel, common in machines with voltage below 1kV (low voltage). Form wound coil, normally used for machines with a voltage above 1kV. The coils are formed and insulated before the insertion into the machine slots. All coils

have the same shape with separations between each coil. Roebel bar windings, used formachines above 50 MW,which have large coils difficult to insertinto the slots, increasing the risks of damage during the winding process. This type of winding, with connections on both sides of the bars to form the turn, facilitates the insertion process.

The electrical machine winding insulation system contains several components which prevent short circuits in the active part. The basic components of an insulation system are the insulation between wires, insulation between turns and insulation to the ground. The design of the insulation must consider the vibration caused by the electromagnetic forces and the difficulty they cause to cool the windings.

Medium voltage electrical machines normally use the star connection with the neutral accessible to feed the stator. When the machine features that connection, the composition of the line voltage is given by the vector sum of the two phase voltages. As for the delta connection, the phase voltage is exactly the same as the line voltage, and the line current is given by the vector sum of the phase currents. Thus, there is a 1.73 times ratio (square root of 3) between the line and phase quantities in three-phase machines.

The design of the insulation system considers more than one century of experience of electromagnetic equipment manufacturers. However, new materials and the use of power electronics, both with a high update rate in the recent decades, require continuous improvement of knowledge on the subject. The standards consider the assessments of windings always using the machine line voltage. The voltage employed in the hipot test is standardized to 2 x U_{Line} + 1kV, a value well above the machine line voltage. Such high voltage produces concentrated stress for one minute and should only be applied to new machines.

Machines still within their service life cycle that have operated for a long time, subjected to the most diverse aggressive conditions, may have the properties of their insulation changed.Therefore, the hipot test is not suitable for such machines, since its concentrated stress may quickly age the insulation, reducing the machine service life [4].

The proposition of this article is to maintain the operating voltage levels for the general assessments of the insulation systems of machines to be repaired, and thus always use $U_{Line}/\sqrt{3}$+10% in all recommended tests. There is a 10% increase in voltage due to the possibility of voltage variation in the power supply systems.

2 CHARACTERISTICS OF THE INSULATIONS

2.1. Stator construction types

The stators of medium voltage electrical machines are composed of form wound coils, a ferromagneticlamination core with low losses and high permeability, and the insulation system. The insulation to the mass in form wound coils is applied to the coil itself, differently from the low voltage random windings, in which the insulation is made by insulating films inside the groove (which will not be discussed in this article).

The factors that define an insulation system are the operating temperatures when the electrical machine is running, the rated voltage, the resin used in the impregnation, the environment in which the machine will operate, and the machine application. Windings with form wound coils are generally used in electrical machines with power above 1000 kW and line voltage usually above 690 V. Figure 3 shows a stator with form wound coils, properly spaced, highlighting how the rectangular wires are arranged inside the groove.

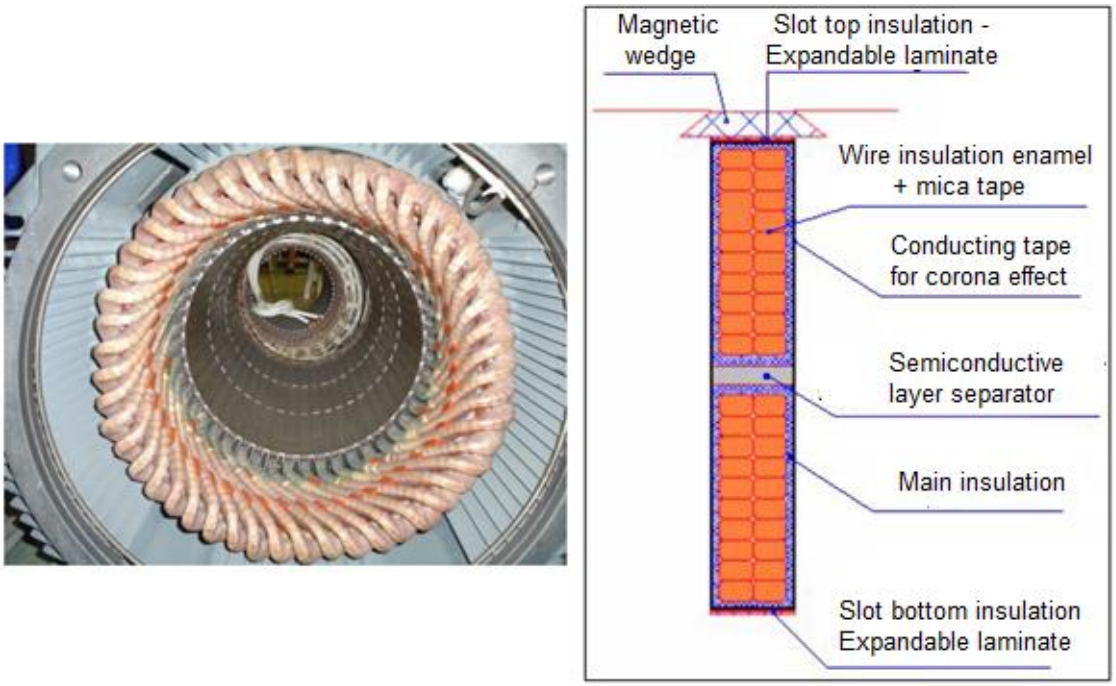
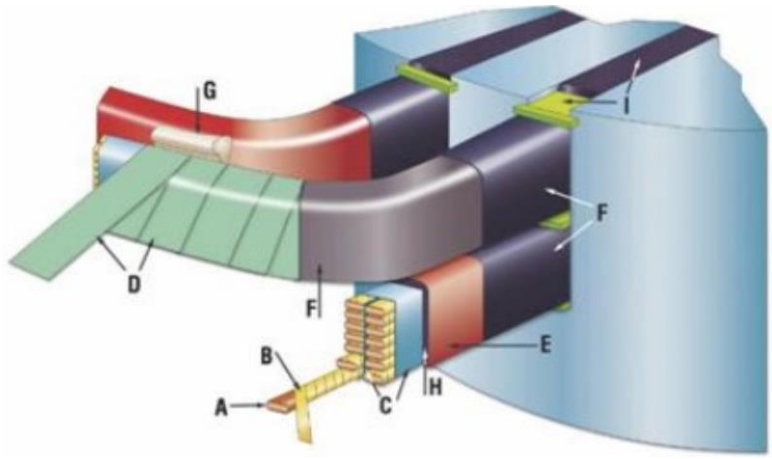


Figure 3: *Stator with form wound coils and groove with the layout of the conductors [13]*

The windings with form wound coils are composed of rectangular wires, which can be isolated from each other in four different ways, selected by the desired voltage level. Rectangular wires can be coated with a layer of polyester-based enamel. For higher voltages, this insulation is reinforced with one or two layers of fiberglass-based insulating wire. Another solution is a layer of polyester-based mica tape. Finally, the insulation with a layer of polyester enamel and another layer of mica tape is the most suitable option for higher voltages. Those methods have dielectric strengths in the range from 70 to 100 kV/mm [13].

A complete insulation system of a form wound coil for a medium voltage electrical machine is shown in figure 4.

After completing the entire process of coil insulation and forming, they are inserted into the slots of the magnetic lamination core and locked by the slot wedges. After the entire ferromagnetic core has been wound, coil connections made and output cables interconnected, the set is subjected to the vacuum and pressure impregnation (VPI). This process consists of dipping the windings into insulating resin under pressure to eliminate all air bubbles. The resin is cured in a heated oven, monitoring the winding temperature. When the windings reach the specific temperature, the machine remains in the oven for about 12 hours for curing. After curing, the impregnation process is over.



A) Conductor
B) Conductor insulation
C) Turn consolidation materials
D) Main insulation (mica tape)
E) Finishing and sealing tapes
F) Corona protection (conductive)
G) Binding materials
H) Impregnation resin
I) Slot filling materials

Figure 4: *Insulation system for medium voltage machines [13]*

Problems associated with insulation failure may be related to the movement of the coils due to vibration, usually as a result of improper operating conditions. Those vibrations reduce the clearance distance, increasing the stress on the dielectric. Load conditions or high variations in load cycles may lead to deformations and cracks in the insulating material. In contaminated environments, installation and maintenance, discharges are produced on the surface of the insulation by conductive particles (dust, water, oil, etc.). Periodic cleaning and proper maintenance can minimize the effects of contaminants.

3 INSULATION SYSTEM ASSESSMENTS AND TESTS

Over time and under the operation stress, the properties of the insulation system change, causing natural or even accelerated aging.That reduces the dielectric capacity of the insulators and contribute to their failure. Such failures may happen in the middle of important processes in which the electrical machine is inserted. Those undesirable events can be minimized with periodic preventive checkups, where specialists use techniques to determine trends and weak points in the insulation systems. In order to do so, standardized assessment techniques or even specific measurements that show such trend can be used.

The main assessments tests are insulation resistance, absorption index and polarization index, applied potential test, visual corona, voltage surge test, dielectric losses (tangent of delta) and partial discharges.

The insulation resistance measurement test on electrical machines is used to detect damages to the insulation system that produce direct short circuits or reduce the insulation resistance in comparison to the resistance of machines of the same type in good conditions or to previous measurements.

The absorption and polarization indices are related to the 30-second and 10-minute readings of the insulation.

The applied potential test (hipot test) assesses the dielectric capacity of the insulation system to withstand the stresses to which the electrical machine is submitted in operation. If the insulation system withstands the hipot test, it means that it will withstand the operation stresses with low risk. Figure 5 shows an example of a surge caused by a circuit breaker operation to which the 11 kV electric motor is subjected. It reaches 36.2 kV (the scale of the graph is 10 kV per division).There are two possibilities to perform the applied potential tests: AC or DC. The AC testing is preferred because it submits the insulation to operation-like conditions. In addition, it

can better detect possible defects and be used in other tests such as visual corona, tangent of delta and partial discharges. The advantages of the DC test are that the equipment is cheaper and portable, an important feature for field tests because of mobility. It also has the advantage of a better control to abort the test in a failure trend or diagnosis. The AC standardized applies 2 x U_{Line} + 1 kV; the DC test applies a value 70% higher than that.

The corona effect is present in medium voltage electrical machines (above 10 kV). The corona effect is caused by the ionization of the gas that is adjacent to windings with form wound coils. Such ionization is caused by the electric field around the conductors.

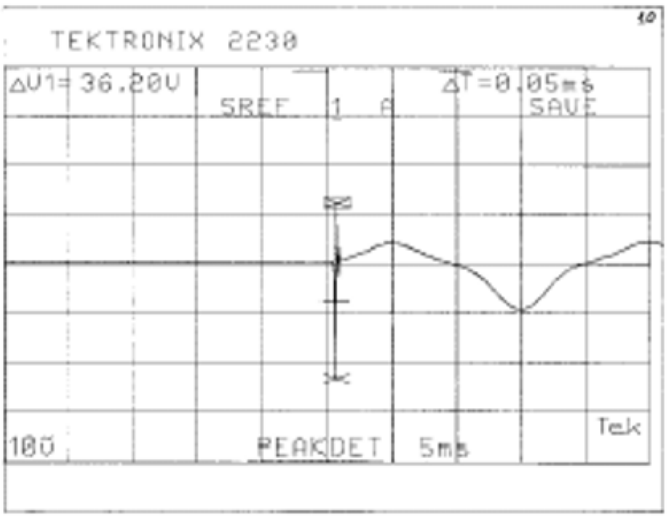


Figure 5: *Example of voltage surges caused by circuit breaker operations*

The voltage surge test is performed by applying a brief voltage surge to the coil, which responds by means of a damped sinusoidal waveform. The waveform that the instrument shows is directly related to the impedance of the coil, which has its own unique characteristic.

Insulation assessments hardly ever reveal the condition of the insulation with a single measurement, since changes in dielectric losses depend on the material of which they are made, the machine size, and environmental and operating conditions. However, monitoring the tangent of delta measurements, also known as a dissipation factor, shows trends throughout the electrical machine life cycle that can determine the trend of degradation of the insulation system. The tangent of delta test is also used to assess the quality of the insulation impregnation, drying and curing throughout the manufacturing process of the electrical machine [5].

The voltage applied to an insulation system submits the insulators to a potential difference that is distributed across the winding in relation to the ground. However, gaps and cavities can change the dielectric, reducing the dielectric strength due to the gases inside them. These faults can generate small sparks of partial discharges into the bubbles, causing a progressive process of material deterioration and possible failure of the insulation. Those gaps can be related to the winding impregnation, drying or curing processes, or also to aging and microcracks caused by operating conditions, mainly overtemperature.

Those tests, in general, were developed to detect flaws in the manufacturing process and provide a lot of important information; however, they cause extra stress on the insulators. Thus, testing may lead insulation systems weakened by a long life to failure. An example of an insulation system with the end of its life precipitated, and which could operate for a few more years, is shown in the next paragraph.

During the applied potential test, the entire winding (from the beginning to the end of the winding) is subjected to the same potential difference in relation to the ground, as shown in figure 5 (b). However, under normal operating conditions, the voltage level to which the coils are subjected in the surroundings of the neutral point is lower than at the phase output, as shown in figure 6 (a) [6].

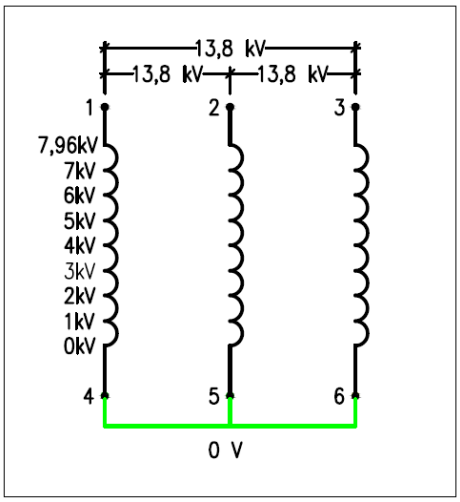


Figure 6 (a)

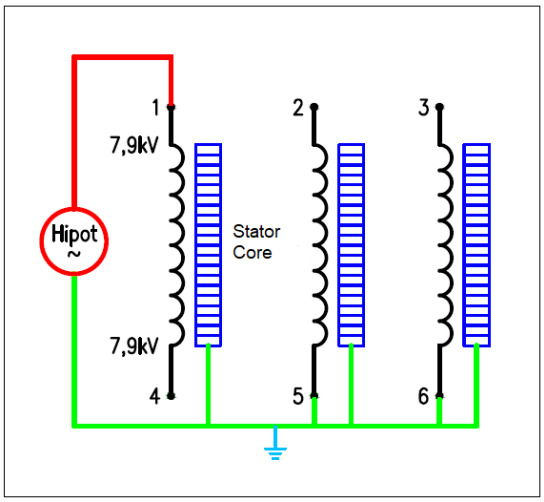


Figure 6 (b)

Figure 6: *(a) Illustrative example of the voltage distribution in the windings when the equipment is in operation. (b) Illustrative example of a winding being subjected to a hipot test*

3.1 Insulation resistance and polarization and absorption index

This test is performed with DC voltages, with an amplitude that depends on the magnitude of the rated voltage of the machine to be tested. The megohmmeter is the typical instrument for performing this test. Megohmmeters have scales from 500 to 15,000 V, and the ambient temperature and air relative humidity strongly influence the measurements. Therefore, it is especially important to always consider these two environmental factors in the measurement.

Table 1: *Guide for selecting DC voltage for measuring insulation resistance (IEEE43)*

Rated Voltage (VAC)	DC Test Voltage. (VDC)
< 1000	500
1000 - 2500	500 - 1000
2501 - 5000	1000 - 2500
5001 - 12000	2500 - 5000
> 12000	5000 - 10000

The total current flowing through the insulation is composed of three components: the conductive leakage current, the capacitive leakage current and the polarization absorption leakage current. The conductive leakage current (I_L) is a small amount of current (µA) that flows through the insulator. This current increases as the insulation deteriorates. The capacitive load leakage current (Ic) occurs through the insulation of the conductors due to their proximity. This current lasts only a few seconds until the insulation is charged with the DC voltage applied by the instrument. Finally, the polarization absorption leakage current (Ia) is caused by the displacement of charges within the dielectric material. In low-capacitance equipment, the current is high for the first few seconds and slowly decreases to almost zero. For equipment with high capacitance or contaminated insulation, there will be no decrease in the absorption current for a long period, as shown in figure 7, [14].

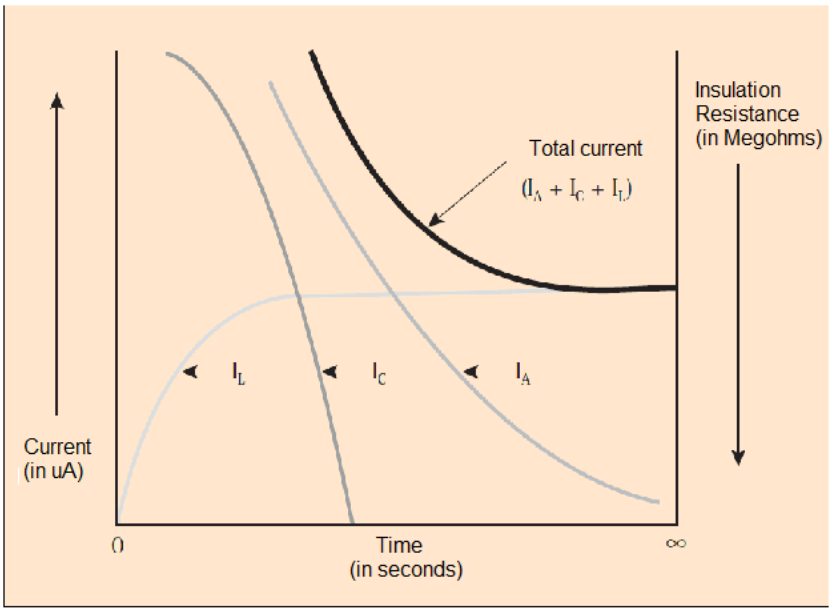


Figure 7: *Decomposition of the total current when measuring the insulation resistance [14] (scale to the left of the graph) and its corresponding isolation resistance (scale to the right of the graph, in the unit typically shown by the megohmmeter)*

The insulation resistance value is measured in 1 minute and corrected to the reference temperature (40 ºC) by equation 1, according to IEEE43. The acceptance criterion is 100 MΩ for form wound coils.

$$R_{Insul40°C} = K_{40°C}.R_{Measured} \qquad [1]$$

$$K_{40°C} = (0{,}50)^{\frac{(40-T_{Measured})}{10}}$$

The values of indexes I_P I_{Abs} are determined by equations 2 and 3, and it is necessaryto measure the isolation in 30 seconds and 10 minutes:

$$I_P = \frac{R_{10Minutes}}{R_{1Minute}} \qquad [2] \qquad\qquad I_{Abs} = \frac{R_{1Minute}}{R_{30seconds}} \qquad [3]$$

Table 2: *Assessment criteria to measure insulation resistance (IEEE43)*

Absorption index	Polarization index	Insulation assessment
----	1 or less	Bad
Below 1,1	<1,5	Dangerous
1,1 to 1,25	1,5 to 2,0	Regular
1,25 to 1,4	2,0 to 3,0	Good
1,4 to 1,6	3,0 to 4,0	Very Good
Above 1,6	>4,0	Excellent

The insulation resistance measurement test has no restrictions, respecting the values indicated in table 1. In addition, the instruments available on the market have DC voltage limited to 15k V and, mainly, insufficient power to maintain a leakage current harmful to the winding, automatically reducing the applied potential.

3.2 Voltage surge test

The voltage surge test is essential to detect short circuit between turns, but it also allows detecting faults such as: short circuit between coils, short circuit between phases, inverted connections and different number of turns. The inductance value of the coil (measured in henry) is basically determined by the number of turns, the shape of the turn and the geometric and physical properties of its core. When the inductance decreases, the circuit oscillation frequency increases according to equation 4.

$$f = \frac{1}{2\pi\sqrt{L*C}} \qquad [4]$$

The IEEE 522 standard, item 6.2 indicates the voltage level that should be used for the test, determined by equation 5.

$$V_2 = 3{,}5.\left[\left(\sqrt{2/3}\right).V_{Line}\right] \qquad [5]$$

Note: From the constants of the equation, it can be considered concisely as 2.85 x U_{Line}.

If the dielectric resistance does not withstand voltage V_2, the insulation will break and ~~or~~ some turns will short-circuit, reducing the inductance and, therefore, increasing the frequency, according to equation 4. The waveform changes when the current (i) varies according to the time of the pulse (t). When the insulation between turns is fragile, the result is a deformed small-amplitude oscillation. Such amplitude is determined by equation 6:

$$V = L.\frac{di}{dt} \qquad [6]$$

The measurement by the surge test is easy to control, as the applied voltage rise ramp is monitored and in case any event trend is detected, the operator can interrupt the test quickly. However, the voltage level recommended by the standard can subject insulators to considerably high values. For example, for a machine with a rated voltage of 13.8 kV, the voltage recommended by the standard for the surge test is 39.5 kV. For field machines, the IEEE522 standard suggests the test value of 0.75 x 2.85 x 13.8 kV, which corresponds to 29.5kV.

To assess machines to be repaired and with possible aged insulation, the suggestion is to use the phase voltage + 10%. As it is a voltage pulse tending to continuous voltage, multiply it by 1.7. For example, for a 13.8 kV rated voltage machine, the value to be used in the test is 14.91 kV.

3.3 Applied potential

Applied potential test are necessary to ensure that the insulation systems have the minimum capacity to withstand the stresses present during normal operation. For example, they must withstand the surges (dV/dt's) of circuit breaker operations as shown in figure 5.

The test for a new or rewound machine consists of applying an alternating voltage of 2 x U_{Line} + 1 kV (E.g.: for a 13.8 kV machine, 28.6 kV will be applied). For a machine in operation, IEC 60034-1 recommends applying U_{Line} x 1.5 (E.g.: for a 13.8 kV machine, 20.7kV will be applied). To apply DC voltage, multiply the alternating voltage values by 1.7. For both cases, the insulation must withstand this voltage level for 1 minute.

Basically, the acceptance criteria are approved or rejected (failure). Therefore, in principle, it can be considered that an insulation system that fails this test will fail in a short period of operation. Its function is to reduce the characteristic mortality rate of the initial phase of the bathtub curve. Experience shows that the hipot test reveals several weak points in the insulation system.

For electrical machines with long periods of operation, that is, with already stressed insulation, the hipot test may reduce the useful life of the equipment in a few years, leading to a failure due to the application of voltage in an insulation that is not new. Choosing whether to perform this test or not after an overhaul is always a difficult decision and should be made by any manufacturer or service provider for repairs or overhauls based on standard criteria.

The proposition of this article is to use phase voltage +10% for the hipot test, because, doing so, an assessment of the insulation system becomes similar to the electrical machine operating conditions, but measuring the leakage current of the insulation system instead. Based on figure 5, there may still be a possibility of failure in the hipot test, but with very low risk.

Table 3: *Voltage levels recommended by standard and proposed in the article*

Isolation conditions	Hipot AC voltage level	Hipot DC voltage level
New machines (standard)	2 x U_{Line} + 1000	2 x U_{Line} + 1000 x 1.7
Repaired machines (standard)	U_{Line} x 1.5	U_{Line} x 1.5 x 1.7
Repaired machines (proposition)	U_{phase} + 10%	(U_{phase} + 10%) x 1.7

3.4 Visual corona (blackout test)

The corona discharges are produced by the ionization of the gas between coils or the ground. The bluish aspect accompanied by noise is characteristic of the effect that partially ionizes the gas, forming ozone. This effect deteriorates the insulating material with a corresponding reduction in the insulation dielectric strength, causing electrical discharges that lead to subsequent insulation failure.

This test is applicable to machines with voltage above 10 kV. It is performed with 1.15 x U_{Line} (E.g.: for a 13.8 kV machine, 15.87 kV is used), according to IEEE 1799. This test identifies spots of electrical discharges between coils. Such corona spots, if not corrected, accelerate the deterioration of the insulators.

The proposition for this test is also to apply 10% above the phase voltage (E.g.: for a 13.8 kV machine, 8.76 kV is used), but in two windings, using two 120º displaced voltage application devices, as shown in figure 8 (b). This condition is exactly the same as the operating condition, as shown in the phasor distribution in figure 8 (a). The proposed test detected 60 to 70% of the spots detected by the same test using the voltage levels suggested by the standard (15.87 kV for the example of 13.8 kV).

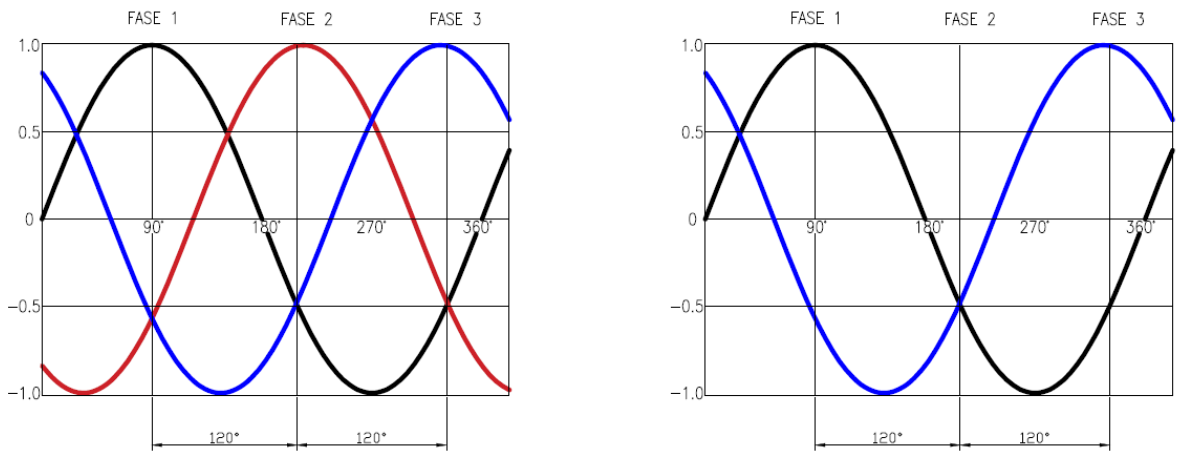


Figure 8 (a) Figure 8 (b)

Figure 8: (a) Phasor distribution of a three-phase voltage system. (b) Applied potential in two different phases and applied by two 120º displaced voltage application devices

3.5 Tangent of delta

The “tangent of delta” test is also applicable to machines with a voltage ≥ 6 kV. It is performed with 1.2 x U_{Line} (E.g.: for a 13.8 kV machine, 16.56 kV is used), according to IEEE286. In the test, the curve of standard dielectric losses is compared to the values measured on the machine. The results show possible insulation impairment trends. A new VPI impregnation, or even rewinding, may be recommended to restore the parameters.

The tangent of delta test is based on the fact that all insulating materials have dielectric losses. Thus, an insulation system can be modeled by a capacitor in parallel with a resistance that represents the dielectric losses. From this model, losses can be calculated using equation 9. The phasor diagram of the currents circulating in this model is shown in figure 9.

$$P_{Losses} = V.I.cos\varphi = V.I.sen\delta \qquad [7]$$

$$I.cos\delta = 2.\pi.f.C.V \qquad [8]$$

$$P_{Losses} = 2.\pi.f.C.V^2.\left(\frac{sen\delta}{cos\delta}\right) \qquad [9]$$

$$tan\delta = \frac{P_{Losses}}{2.\pi.f.C.V^2} \qquad [10]$$

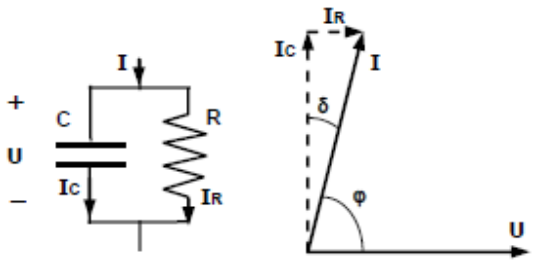


Figure 9: *Representation of the loss dissipation factor model and the vector diagram to calculate the tangent of delta [6]*

To measure the tangent of delta trend in machines in operation, it is also proposed the use of the phase voltage (+10%), as it is a trend measurement and, if the same measurement conditions are used for this assessment, the trend curve will have the same database and references.

3.6 Partial discharges

Partial discharges are small electric arcs in air cavities within or adjacent to the insulation. This phenomenon occurs because the 3 kV/mm dielectric strength of the air is smaller than the solid insulation, which is approximately 100 kV/mm.

The partial discharge test, as well as the tangent of delta, is treated as a trend for the assessment of insulation systems. For this test, there are two measurement options: the offline test, in which it is necessary to apply phase voltage +10%, according to IEC60034-27; and the online test, when measurements are made directly on the machine with rated voltage and running with no load, according to IEC60034-27-2, thus providing both periodic and continuous monitoring.

The test is used to detect conditions of the stator windings with a voltage above 3.3 kV. This test does not have an acceptance criterion, being used for monitoring trends over the operation time.

For the partial discharge test, in practice, the phase voltage +10% is already used for the offline test, and, when the equipment is already installed in the electrical machine for continuous monitoring, the system is energized like in the regular operation process.

4 CONCLUSION

The main objective of the article was to propose another option, in addition to those recommended by the standards, when deciding on the voltage levels to test aged insulation systems for repairs and services on electrical machines. Such decision is always complex, as all tests pose risks. The proposed option aims at testing the insulation systems using the same voltage levels to which electrical machines are subjected when in operation, minimizing the risk of failure during the tests. However, it is impossible to determine the remaining life time of the machine after the assessments and services performed. Most tests subject the insulation systems to voltage levels in order to verify the dielectric capacity of the insulators. For new machines, this process must be guaranteed by the electrical machine manufacturer, as the equipment is new. Those voltage levels are standardized and considerably high because electrical machines are subject to high dV/dt's in normal operation.

However, machines with a long period of operation and an aged insulation system naturally lose their dielectric capacity. Also, overhauls or repairs are expected to provide an additional period of operation, mitigating the occurrence failures. Nonetheless, in order to assess the integrity of this machine, tests energize it to check the insulation systems, which may lead to a failure in compromised insulations.

Voltage levels for dielectric tests that evidence the integrity of insulation systems are recommended by the specific standard. The article proposes to use the phase voltages of the windings +10%, but it also warns that the dielectric submitted to the assessment test is not exactly the same as the operation dielectric, as there are gradual voltage levels in the winding in operation. Therefore, the possibility of failure still exists.

The main tests were described in the article. The insulation resistance test does not present any risks. The surge test is also not quite critical due to the easy test control; however, the values were suggested considering the phase voltage +10% times 1.7, as it may be considered almost DC voltage (little variation), not having the same critical effect on the insulator.

The applied potential and visual corona tests are the most critical. The applied potential test is done with +10% of the phase voltage, monitoring the leakage current. The visual corona test uses the same voltage condition, but applying it to two phases, simulating the effect of the electric field imposed to ~~in~~ the coils in operation. The test detected 60% to 70% of the corona spots detected by the same test using the standard recommendations.

In the partial discharges and tangent of delta trend tests, it is possible to use the voltage proposed by the article, as they present reference levels that can be compared to previous measurements.

Therefore, the proposal of the article presents effective results in the detection of failure trends in the insulation system of machines for repairs and overhauls with phase voltage +10%, mitigating the possibility of failure in the tests.

The results presented in this article will be complemented with a research on the average time of additional life cycle based on the application of the proposed method. This future work will analyze the correlations between this time, the failures that caused the new stoppage and the test results.

THANKS

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BIBLIOGRAPHICAL REFERENCE

[1] SILVA, C. S. **Prescrição da modalidade de manutenção de motores elétricos considerando o custo de manutenção e depreciação do ativo**. Dissertação de mestrado da Universidade Tecnológica Federal do Paraná (Campus Ponta Grossa), 2012.

[2] RODENBURG, R. L. **Replacements, Units, Service Lives, Factors**. Prepared for U.S. Department of Energy, U.S. Department of the Interior and U.S. Bureau of Reclamation, 1995, PO No.AA-P0-12652-22503.

[3] STONE, G.C., H.G. SEDDING, B.A. LLLOYD, GUPTA, B.K. **The Ability of Diagnostic Tests to Estimate the Remaining Life of Stator Insulation.** IEEE Transactions on Energy Conversion. December 1988, Vol. 3, No. 4, pp. 833-840.

[4] 1. CIGRE WG A1.10. **Survey of Hydrogenerator Failures**. Cigre Report 392; CIGRE: Paris, France, 2009.

[5] GUEDES, A. S. **Estudo e proposição de técnicas para a avaliação do isolamento em motores de indução trifásicos de baixa e média tensão.** Tese de doutorado da Universidade Federal de Minas Gerais, 2018.

[6] MELERO, M. G.; CABANAS, M. F.; ROJAS, C. H.; NORNIELLA, J. PEDRAYES, F.; BARRERA, J. M. **Fault detection in the manufacturing process of form-wound coils by means of dissipation factor and hipot tests.** International Conference on Renewable Energies and Power Quality (ICREPQ 09), Valencia (Spain), 2009.

[7] GUPTA, B. K.; STONE, G. C.; STEIN, J. **Stator winding hipot (high potential) test.** IEEE Electrical Insulation Conference, Montreal, Canada. 2009.

[8] HENAO, H.; CAPOLINO, G. A.; CABANAS, M. F.; BRUZZESE, C.; STRANGAS, E.; PUSCA, R.; ESTIMA, J.; RIERA-GUASP, M. ; HEDAYATI-KIA, S. **Trends in fault diagnosis for electrical machines.** IEEE Industrial Electronics Magazine, 2014.

[9] BELKO, V. O.; KOSTELIOV, A. M.; PETRENYA, Y. K.; ANDREEV, A. M.; ROITGARZ, M. B.; **Numerical Simulation of discharge activity in HV rotating machine insulation**. Conference Paper, Saint Petersburg, Russia, 2014.

[10] SCHUELLER, M.; SENN, F.; LADSTAETTER, W. **Influences of the one minute withstand voltage test on the electrical endurance of insulation systems of rotating electrical machines.** Inductica, Berlin, Germany, 2009.

[11] RUX, L. M.; **The physical phenomena associated with stator winding insulation condition as detected by the ramped direct high-voltage method. Dissertation submitted to the Mississippi State University**. USA. 2004.

[12] STONE, G. C.; BOULTER, E. A.; CULBERT, I.; DHIRANI, H. **Electrical insulation for rotating machines. Design, Evaluation, Aging, Testing, and repair**. IEEE Press Series on Power Engineering, 2004.

[13] RÜNCOS, F. **Projeto e análise da máquina elétrica trifásica.** Editora OitoNoveTrês, 2º Edição, Volume 1, 2019.

[14] VORTEX Equipamentos. **Teste de resistência de isolação**. Fabricante Fluke. http://www.vortex.com.br

[15] FITZGERALD, A. E.; KINGSLEY JR, C.; KUSKO, A. **Máquinas Elétricas**. Editora McGraw-Hill do Brasil, Ltda, 1975.

[16] INSTITUTE OF ELECTRICAL AND ELETRONICS ENGINEERS. **Recommended Practice for Testing Insulation Resistance of Rotating Machinery**. IEEE Std 43 - 2000

[17] INSTITUTE OF ELECTRICAL AND ELETRONICS ENGINEERS. **Guide for Testing Turn Insulation of Form-Wound Stator Coils for Alternating-Current Electric Machines**. IEEE Std 522 – 2004.

[18] INTERNATIONAL ELECTROTECHNICAL COMISSION. **Rotating Electrical Machines – Part 1: Rating and Performance**. IEC 60034-1.Geneva, 2004.

[19] INSTITUTE OF ELECTRICAL AND ELETRONICS ENGINEERS. **Recommended Practice for Quality Control Testing of External Discharges on Stator Coils, Bars, and Windings**. IEEE Std 1799 - 2012

[20] INSTITUTE OF ELECTRICAL AND ELETRONICS ENGINEERS. **Recommended Practice for Measurement of Power Factor Tip-Up of Electric Machinery Stator Coil Insulation.** IEEE Std 286 - 2000

[21] INTERNATIONAL ELECTROTECHNICAL COMISSION. **On-line partial discharge measurements on the stator winding insulation of rotating electrical machines**.IEC 60034-27+2.Geneva, 2012.

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