Surge Testing in Low-Voltage Three-Phase Motors with Random Winding: A Case Study Demonstrating Its Effectiveness.

Gonzalo G. Gómez
Fabrifor | Ingeniería Electromecánica
Rosario, Argentina
gonzalogomez@fabrifor.com

Abstract - There is a lot of experience and regulations linked to dielectric testing of electric motors of 2.3kV or higher for field maintenance, leaving low voltage motors limited to measurements of insulation resistance and winding resistance. However, tests such as the surge test or continuous overvoltage test are powerful tools for field diagnosis of low voltage electric motors, which despite being economical, in many cases represent logistical difficulties for their replacement and large economic losses due to loss of profits. This article presents a case study that shows the usefulness of carrying out impulse tests on low voltage motors, applying the criteria that the regulations recommend for motors of 2.3kV or higher.

Keywords: surge, test, winding, turn insulation.

I. INTRODUCTION

Three-phase induction motors for industrial applications are responsible for approximately 70% of industrial energy demand [1] and of that percentage the vast majority are random-winding low-voltage motors. It would therefore be reasonable to consider that a good alternative to improve the reliability of industrial processes is to carry out controlled overvoltage tests on the windings of these assets, to evaluate the suitability of their insulation systems. The controlled overvoltage tests for main insulation evaluation presented in [2] and impulse tests for inter-turn insulation evaluation in [3] cover preformed winding machines of 2.3kV or higher. However, there are numerous manufacturers on the market that offer instruments capable of controlling voltage from levels low enough to be able to carry out tests on low voltage motors, extrapolating the same criteria that apply to medium voltage motors. Taking this into account, the application of controlled overvoltage tests became an efficient alternative for preventive maintenance of low voltage electric motors in industrial plants. This is because the insulation system of these machines is much less robust than in the case of form wound stators, so the thermal, mechanical and environmental aging mechanisms are more effective in degrading rapidly the insulation of its random windings. When carrying out controlled overvoltage tests, the aim is to stress the insulation system at voltage levels where the occurrence of transient overvoltage impulses is likely [4], and consequently evaluate the performance of the insulation system at these levels, taking into account the different mechanisms aging present in normal operation that can cause different points of weakness in both the main insulation and between turns.

II. INTER - TURN INSULATION

In the particular case of low voltage motors, the insulation between turns and between strands of the same section is provided by a layer of polyester enamel based on hydroxyethyl isocyanurate (PEI-THEIC) and polyamides (PAI). These conductors, whose technical specifications are established [5], must be able to withstand without problems the nominal voltage of the motor they will constitute. This standard tabulates standardized properties of enameled copper wires. The thickness of the insulating layer is a function of the grade of the conductor, with grade 2 being the most widely used in industrial motors. It can be considered that on average the insulation layer has a thickness of 80 μm for grade 2 enameled wires. In the standard it can be seen that the dielectric strength of two enameled wires in contact can reach 5000V AC at room temperature, which far exceeds the requirements of a low-voltage three-phase motor. Such dielectric capacities with respect to the nominal voltage are necessary because the random nature of the coils makes it impossible to respect an ordered sequence of turns, which gives rise to the possibility that in a given coil the first and the last turn are in contact. If it is considered that in the worst scenario two turns in contact can be subjected to the line voltage it would be reasonable to think that an insulation defect between turns is unlikely, given that the standard breakdown voltage is more than ten times higher than the values that can be presented in service. Therefore, the fact that short circuits between turns are one of the most common causes of low voltage motor failures [6] suggests that the insulation system between turns is

susceptible to losing its dielectric properties in a pronounced manner due to different factors.

III. SURGE TEST

When a high voltage impulse occurs between a terminal of a machine and ground, the winding cannot adopt the same potential instantaneously at all its points. As a result, two types of potential differences are formed in the winding: the potential difference between the conductor and ground (transverse voltage) and the potential difference along the conductor (longitudinal voltage) [7]. While the transverse voltage stresses the ground insulation system, the longitudinal voltage also stresses the insulation between turns. Overvoltage impulses that appear due to load switching can have wave fronts as fast as 0.1 μs, which will mainly stress the turns closest to the connection point to the winding line.

In order to evaluate the capacity of the insulation system between turns, a test method was developed that consists of the injection of a train of fast wavefront pulses (0.1 to 0.2 μs) of increasing amplitude, which will allow, If it exists, detect insulation weakness between turns, causing a perforation of the insulation in the affected area. This test is the only one capable of detecting this type of weakness, which is responsible for most of the failures in the windings of electric motors and generators due to their low thickness and their constant subjection to electrodynamic stresses of vibration and attraction between turns.

The result of these tests consists of obtaining a damped sinusoidal waveform, which results from considering the RLC series circuit formed by the resistance and inductance of the winding under test and the capacitance of the capacitor available internally in the equipment to generate high-voltage unipolar impulses.

To quantify the results of these tests, two main calculations [8] are performed based on the following equation:

$$EAR = \frac{\sum_{i=1}^{N} \left| F_i^{(1)} - F_i^{(2)} \right|}{\sum_{j=1}^{N} \left| F_j^{(1)} \right|} \qquad (1)$$

where $F_i^{(1)}$ represents the ith point of the reference waveform, $F_i^{(2)}$ is the ith point of the test waveform, and N is the total number of points of each waveform.

Line-to-Line Area Error (LL EAR): This value arises from comparing the waveforms of different windings obtained by applying the same test in each of them. The areas of the damped sinusoidal waveform obtained by the maximum voltage impulse applied to each winding phase are obtained and compared. Based on the values obtained, constructive asymmetries of the winding or defects can be detected.

Pulse-to-Pulse Area Error (PP EAR): This value involves comparing the winding response produced by the last applied impulse versus the previous impulse. The acquisition system compares in real time the area of the damped sinusoidal waveform produced by each impulse, and using equation (1), the area difference between the waveforms produced by the last applied impulse and its predecessor is obtained. If this difference remains stable throughout the test, the inter-turn insulation system does not present anomalies. If erratic behavior is detected in this PP error or if it spikes to values considered critical, it can be considered that there is an insulation defect that allows the formation of an electrical arc between turns.

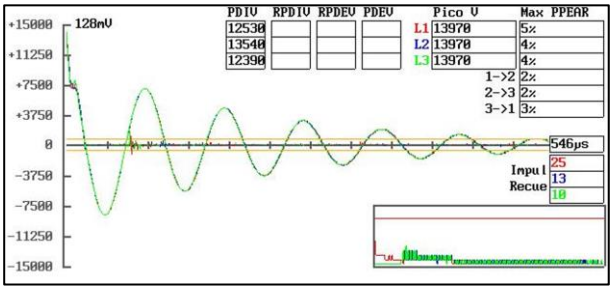

Fig.1. Surge test result for a 6.6kV motor. The box in the lower right corner represents the evolution of the PP EAR error during the test.

Regardless of the indicator obtained, the fundamental principle of these tests is that the minimum inter-turn voltage must not be less than 327V peak, a value that Paschen's law establishes as the minimum for the formation of an electrical arc in the air. Therefore, to confirm the existence of inter-turn insulation weakness, a maximum impulse voltage must be applied such that it allows reaching Paschen's minimum as far as possible from the voltage injection point without compromising the insulation integrity of the first turns that will receive the largest proportion of the applied impulse amplitude.

IV. MECHANICAL STRESS ON THE WINDING

The mechanical aging of insulation systems of rotating machines occurs when significant electrodynamic stresses occur due to starting currents in service regimes with repetitive starting and stopping, short circuits in the vicinity of the reference motor or generator, or when winding elements become free due to different factors. An extremely influential factor in this process for low voltage motors is the formation of fractures and fissures facilitated by thermal aging processes [9] that mechanically weaken the insulation system and reduce its dielectric strength.

Electromechanical stresses are based on Lorentz's magnetic force law, which relates a current to an applied

magnetic field. The magnetic force for two conductors through which a current flows in the same direction is:

$$F = \frac{\mu_o l\, I^2}{2\pi r}\,(1 - \cos 2\omega t) \qquad (2)$$

This force, which depends on the square of the current, implies that in instances where the current is much higher than the nominal, the force will increase quadratically. For example, if the starting current in a motor is seven times the nominal, the magnetic force on the conductors will be 49 times higher than in normal operation. In the case of generators, a short circuit on a nearby line can bring the subtransient short-circuit current to ten times the nominal current, so the force would be multiplied by 100. These stresses can compromise the integrity of the insulation system since abrupt forces in some cases can fracture the insulator in areas free of mechanical containment, such as the winding ends, or produce interface detachment between insulators, thus resulting in the coils gaining some degree of movement freedom. If a coil (or a segment of it) gains movement freedom, the alternating component of the magnetic force will make it vibrate at twice the grid frequency (100Hz for a 50Hz grid frequency), leading to a friction process between static and moving parts (or relatively moving parts), allowing the development of abrasion on the insulation wall, whether primary or inter-turn. As logically thought, this abrasion process will reduce the insulator thickness, and consequently, the insulation system's breakdown voltage will be lower. Additionally, the area where abrasion exists will have an operating temperature higher than that of other areas, and it will thus be subjected to a much more aggressive thermal cycle than a healthy insulation area. This is because areas with abrasion will have a significantly lower thermal dissipation capacity than healthy insulation.

V. TEST PROCEEDURE

Prior to the execution of any test, the safe work procedure detailed in [10] is followed. Historic information on the equipment to be tested is obtained and the atmospheric and temperature conditions are evaluated.

The instrument used for the case presented in this article was a Baker DX15 rotating machine static analyzer, which integrates the following functions in a single device:

- Measurement of winding resistance and unbalance.
- Measurement of winding inductance, impedance, dissipation factor and quality.
- Measurement of insulation system capacitance, dissipation factor and quality at very low voltage.
- Insulation resistance, absorption and polarization index.
- DC voltage jumps (step voltage test).
- Direct current Hipot test.
- Surge test.
- Partial discharges under repetitive impulses.

The tests are carried out in the detailed sequence, the condition for carrying out each stage being the acceptance of the result of the preceding test. In the case study presented in this paper, all tests prior to the impulse test were satisfactory. The maximum voltage to be applied during the impulse test in low voltage motors is $2U_n + 1000\,V$, as recommended [11].

VI. TEST RESULTS

This study corresponds to a sequence of tests carried out on a low voltage motor, 550kW, 400V, 940A, 1490 n/min, used in a sunflower press. For this application, the service regime is continuous, however given the production characteristics and availability of raw material, the motor may suffer several start and stop events within a month. The motor is used at 100% of its nominal load, so it achieves thermal stability during its production cycles.

The first test on the reference equipment was carried out in November 2022. During it, satisfactory results were obtained for the main insulation system, both for the insulation resistance and polarization index test and for the subsequent voltage jump test. continuous tension in steps.

During the surge test, a slight instability of the PP EAR error was detected for one of the phases, at 1100V applied voltage.

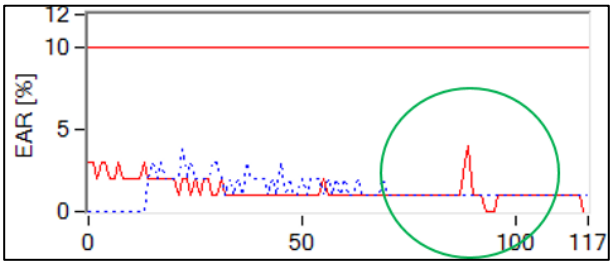

Fig. 2. PP EAR graph of one of the winding phases, where the disturbance can be seen highlighted in the green circle.

Since this behavior did not manifest again for higher voltages, the anomaly was observed without recommending actions other than follow-up through new tests within a maximum period of one year.

The subsequent test was carried out in November 2023, during the plant's next scheduled maintenance

outage. At this stop, tests were repeated on all the engines tested during the previous year. For the reference engine, all tests of the main insulation system were again satisfactory, with no negative trends detected. However, during the impulse test, electric arcs were detected between turns for the three phases of the winding, evident by pulse-to-pulse error triggers. This result exposed a highly negative trend regarding the results obtained in 2022.

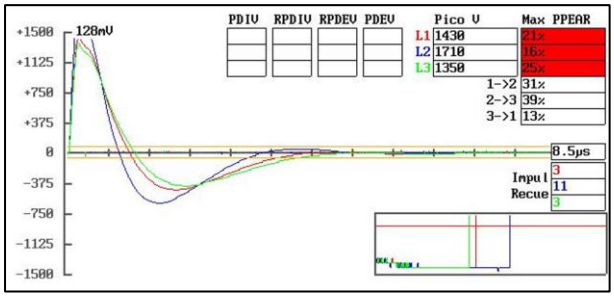

Fig. 3. Result of impulse test carried out in November 2023. The voltage levels at which electric arcs between turns were detected for each of the three phases and the evolution of the PP error can be seen in the lower right corner.

After observing the results obtained, a visual inspection of the winding was carried out using boroscopy, entering through an inspection opening in the motor casing. During this procedure, lubricant deposits were observed in winding heads, which can contribute to the interfacial separation of conductors with subsequent abrasion due to electrodynamic vibration in service, a process that can degrade the insulating coating of the enameled wire and facilitate short circuits between turns.

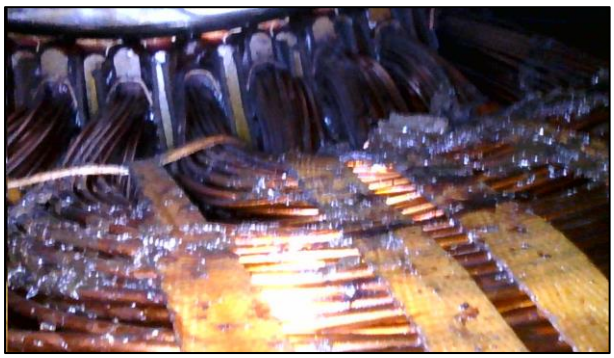

Fig. 4. Image of accessible winding head obtained by boroscopy.

Taking into account the detections made and the results of the visual inspections, the client was recommended to remove the engine in the next window of opportunity, given that it is not possible to predict the remaining useful life of the asset taking into account that external factors that can lead to a failure in service are of a stochastic nature.

The asset was removed from service in April 2024, about 130 days after the recommendations were issued. The motor was received for inspection and diagnosis, where it was disassembled and its winding was subjected to a washing process with dielectric solvent and drying at 120°C for 6 hours, in order to evacuate any type of surface contamination and moisture.

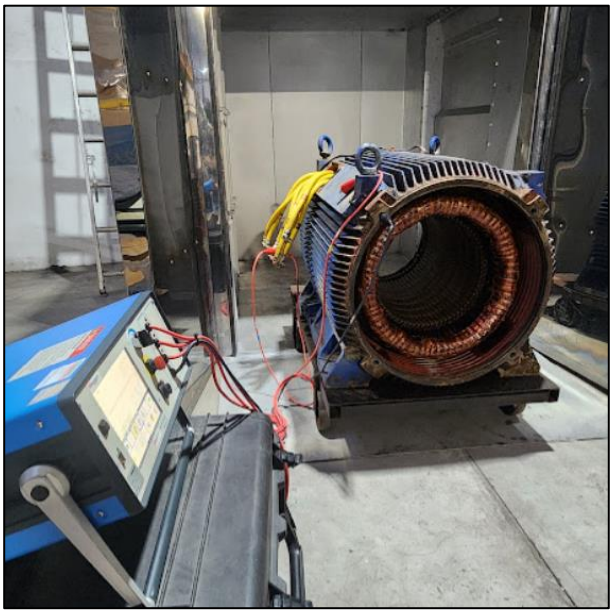

Fig. 5. Test after the cleaning and oven drying process of the winding.

Once the winding temperature stabilized at 40°C after drying, an impulse test was performed again to check the evolution of the previously detected defects. They gave even more negative results than in previous instances, detecting insulation defects between turns from 800V of applied voltage. This detection indicates that the negative trend had concluded in an insulation collapse with subsequent short circuit between turns.

Comparación entre líneas y pulsos				Límite entre impulsos
Comparar	Tensión máxima [V]	Número pulsos	Estado	EAR PP [%]
1-2 (1)	940	1	FALLA	19
2-1 (2)	800	3	FALLA	22
3-1 (3)	1010	4	FALLA	17

Fig. 6. Capture of the table obtained from the Megger Surveyor DX software.

Considering the results obtained, detailed visual inspections were carried out, which revealed as the origin of the defects numerous enamel detachments from the conductors on the winding heads, added to deep fractures that even affected the solid insulation between phases in some points.

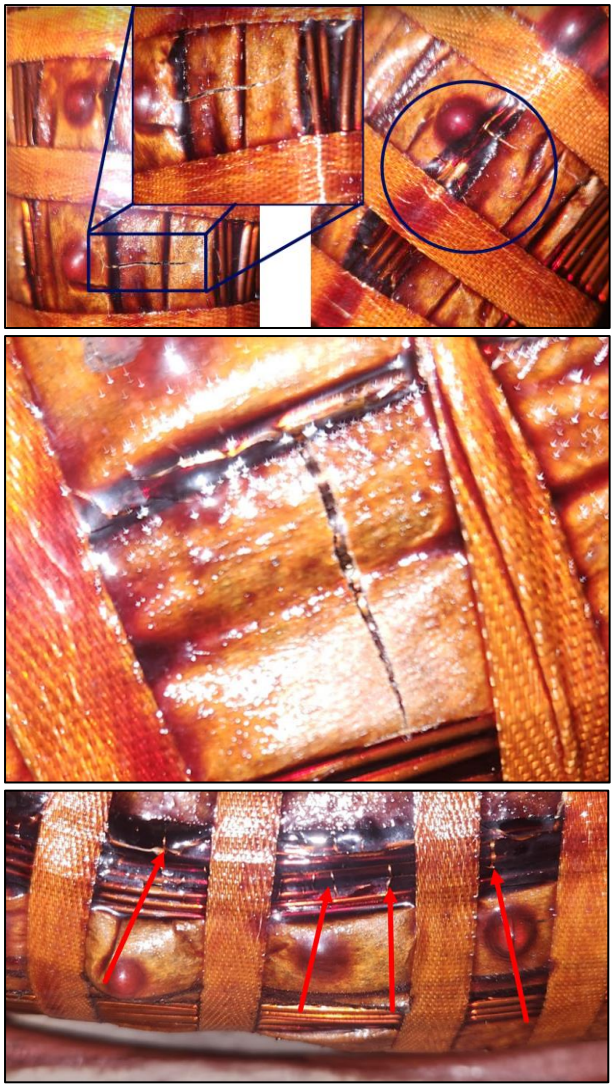

Fig. 7. Images of fractures in winding heads, affecting the insulation system between turns and between phases.

These observations allowed to conclude that the origin of the insulation defects detected were the fractures produced on the surface of the winding, which affected the insulation system between phases on headers and the enamelling of the conductors.

Considering the historical information of the motor and the detected defects, the root causes of the deviations are attributed to a combination of mechanical and thermal aging: the service regime of the analyzed motor suggests that eventual starts and stops produce thermal cycles in the winding, which lead to asymmetric expansion and contraction processes of its different components. The thermal inertia of the copper volume is vastly greater than that of the head surface impregnation resins taking into account that these heads have a large heat exchange surface with the surrounding air, so in the case of cooling processes the surface resin contracts at a greater rate than the volume of copper coil heads. Given the high adhesion capacity of the resin, the contraction processes generate tensile stresses on the surfaces in contact with it, forcing the detachment of enamel from the conductors and causing fractures in the insulating material between phases, as observed in the images. This process exposes the bare conductors and limits the dielectric strength between them to that of air, in the absence of coating enamel. Added to this phenomenon, the lubricants deposited on the surfaces contributes to the abrasion process by facilitating the loss of interfacial adhesion, accentuating the degradation mechanisms described.

VII. CONCLUSIONS

The surge test is the only one capable of detecting the defects exposed in this article, which inevitably end in short circuits in winding heads with high damage, mainly considering the power of the network at the connection point of the asset evaluated. This type of aging process is not detectable by insulation resistance tests (or other evaluation methods of the main insulation system) or measurements of RL parameters of the winding, considering that an insulation defect between turns does not influence the resistance or inductance of the coils until the short circuit instance is reached.

The results obtained during this study show the usefulness of incorporating impulse tests in preventive maintenance routines of low voltage machines, given that these are sensitive to damage to the insulation system between turns due to their low robustness compared to form wound motors, added to different aging mechanisms that may occur in service depending on the operating regime, environmental conditions, construction characteristics, among others.

VIII. BIBLIOGRAPHY

[[1] MarketsandMarkets, "Electric Motors Market by Type, Voltage, End-User, and Region - Global Forecast to 2025," MarketsandMarkets, 2023.

[2] IEEE 95 – 2002, Recommended Practice for Insulation Testing of AC Electric Machinery with High Direct Voltage.

[3] IEEE Std 522 – 2023, IEEE Guide for Testing Turn Insulation of Form-Wound Stator Coils for Alternating-Current Electric Machines

[4] Bal Gupta, “Risk In Surge Testing Of Turn Insulation In Windings Of Rotating Machines”, Proceedings: Electrical Insulation Conference and Electrical Manufacturing and Coil Winding Technology Conference, 2003.

[5] IEC 60317 – 2013, Specifications for particular types of winding wires – Part 0-1: General requirements – Enamelled round copper wire

[6] J. Geiman, “DC step-voltage and surge testing of motors,” Maint. Technol., vol. 20, no. 3, pp. 32–39, 2007.

[7] G. C. Stone, I. Culbert, E. A. Boulter and H. Dhirani, “Electrical Insulation for Rotating Machines – Design, Evaluation, Aging, Testing and Repair, IEEE Press, 2004.

[8] S. Grubic; R. Harley, T.G. Habetler, J. Restrepo “- Sensitivity analysis of the surge test applied to AC machines“. 2011 IEEE International Electric Machines & Drives Conference (IEMDC)

[9] N. Fernando, P. Romanazzi and M. D. McCulloch, "Degradation of mechanical properties of class-H winding insulation," 2017 IEEE International Electric Machines and Drives Conference (IEMDC), Miami, FL, USA, 2017, pp. 1-7

[10] IEEE 62.2 – 2004, IEEE Guide for Diagnostic Field Testing of Electric Power Apparatus— Electrical Machinery.

[11] EASA Standard AR100 – 2020. Recommended Practice For The Repair Of Rotating Electrical Apparatus.