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REVIEW OF TEMPERATURE-RISE TESTING METHODS FOR ELECTRICAL ROTATING MACHINES

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ABSTRACT

The need for temperature-rise measurement is relevant for companies that provide or service electrical machines, and especially for users. The manufacturing or repair must satisfy thermal limits of the electrical machine's insulation, since exceeding such limits compromises the useful life of the equipment. In addition to temperature-rise, the test can identify potential failures in design, manufacturing and refrigeration circuits. Such conditions are only possible to assess with full-load tests. If this is not possible, at least as close as possible to nominal conditions, even if equivalent methodologies and extrapolations must be used for said purpose. The article contains a review of the methods and techniques for temperature-rise tests on rotating electrical machines, demonstrating the importance and necessity to perform such tests to ensure the integrity of this kind of equipment, for both repairs and new electrical machines.

Keywords: Electrical Machines; insulation class; temperature rise.

INTRODUCTION

Heat is a form of energy that, in the case of electrical machines, is not used to produce work. It is wasted energy. The higher the losses, the lower the efficiency of the electrical machine. The heat generated inside ends up producing an internal temperature rise. Due to the temperature difference established between the inside and the outside of the electrical machine, a heat-transfer process occurs [1].

The electromechanical conversion of energy in electrical machines generates is partially composed of losses that turn into heat. One of the causes of these losses is the joule effect of the current flowing in the stator and rotor windings. The interaction between the stator and the rotating part, the rotor, is made by the magnetic flux induced between the components. This flux circulates through the stator and rotor cores, inducing undesirable Eddy currents or Foucault currents, which also generate heat from iron losses. These iron losses are minimized because of the cores made of insulated silicon steel plates. The lamination core is influenced by winding failures or removal of the coils at repairs, as these insulated plates may short-circuit and generate hot spots. Also in the composition of the main losses are the mechanical losses due to the friction of shaft and bearings and the ventilation [1]; [6] and [9].

Temperature rise is a determining factor for assessing conditions and characteristics of electrical machines, as it is usually limited by the thermal properties of the materials. Load testing is essential as it approximates factory-testing conditions to those of the final application in the field and serves mainly to evaluate the temperature in operation. The bigger the laboratory structures, the better the results. However, even if these nominal characteristics are not met, standardized equivalent methodologies enable these assessments. This is also relevant for customers seeking to restore equipment to factory conditions, ensuring their operation for a few more years.

Machines that operate at a temperature rise above specifications will have a shorter service life. Building new laboratories with higher power capacity and larger load-simulation equipment requires huge investments in machines, robust power circuits, electronic panels, computer programs and more. Labs with a capacity around 10 MW satisfy the requirements of a wide range of machines. However, methods simulating equivalent load are employed to determine the temperature rise of motors that exceed the nominal power installed in the laboratories.

There are innumerous advantages in performing tests at nominal conditions, including vibration analysis after thermal stabilization. This check is important to identify if there are any mass displacement imbalances and possible cracked or broken rotor bars. For machines with voltages below 1000 V, testing is indispensable to assess stator and rotor cable temperatures. This is because the currents for these electrical machines are high, and several cables are required to meet this current density. The testing at nominal capacity guarantees the features of these projects. Laboratories with a capacity around 2500 A satisfy the requirements of most tests when it comes to induction motors.

The nominal-load test will also show that the replacement of some cooling-system components such as fan, heat exchanger, radiator was effective. On machines with fixed brushes, we can

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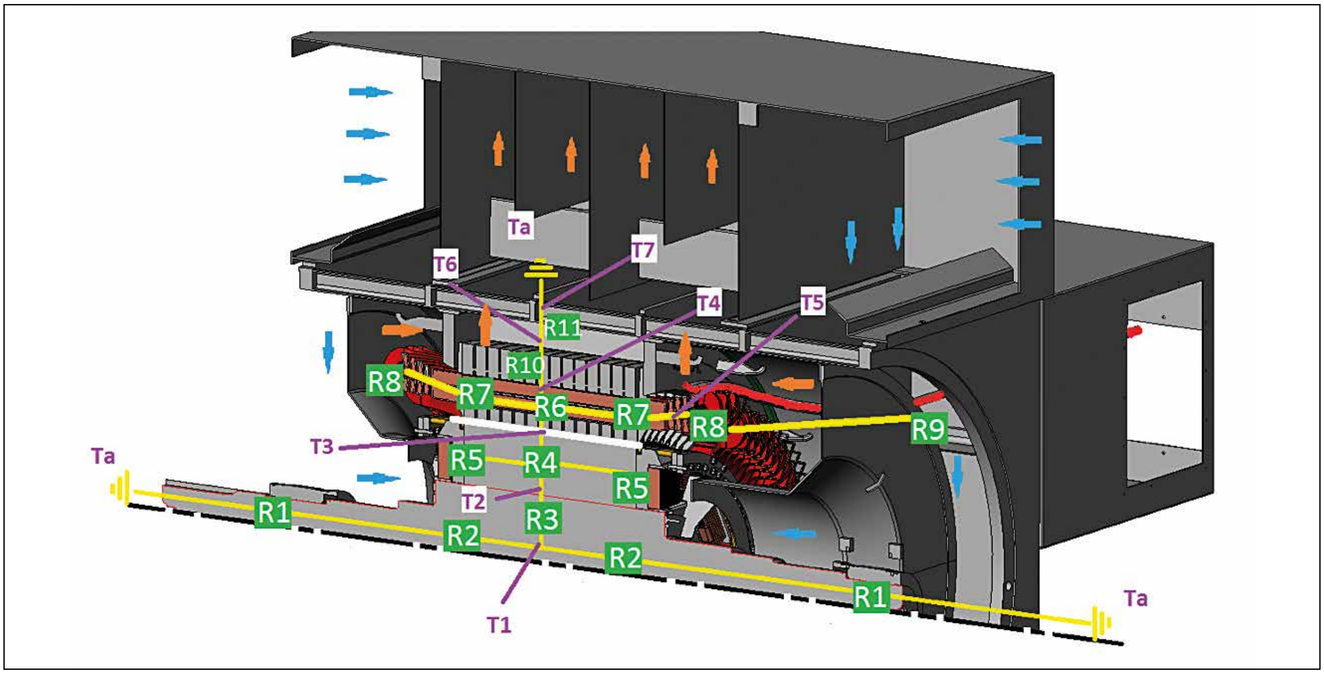

Figure 1. Thermal circuit of an electrical machine

prove that the replacement or adaptation of the brush meets the standard or brush manufacturer's criteria, when provided. For DC machines, in addition to the items already mentioned like cable temperature, brushes and windings, it is also possible to check the sparking level in brushes and make adjustments if necessary, ensuring that the motor will operate without requiring new adjustments.

Figure 1 shows a thermal model of an electrical machine. Based on this figure, it is possible to see the complexity and parts involved in a thermal analysis. The good operation of all these components must be guaranteed to avoid compromising the life of the equipment [6].

STANDARD TEST METHODS

Test method for temperature rise in induction motors

There are several methods for temperature rise. The direct load application method may be the most conventional, but it requires large structures and high costs. Another method, which is also well-known is Forward Short Circuit, which consists of coupling the machine to be tested to another machine with similar characteristics as load. This method also presents limitations and difficulties because similar machines are required for the load and the entire structure to couple one to the other. Most methods require coupling, have a high cost and demand extra machines for load application. The coupling condition is complex, especially in the case of vertical machines.

The most dynamic and feasible method for temperature-rise testing on large electric motors is the two-frequency method. This method does not require extra machines or mechanical loads. Two-frequency temperature rise requires only two variable voltage and frequency sources. The test can be applied to any type of induction motor with the advantage of faster execution and lower costs, in addition to consuming around 40% of the power of the machine to be tested.

The two-frequency temperature rise test was already proposed by Ytterberg in 1921. The motor is not mechanically coupled; it rotates freely. The main power supply provides voltage and frequency to the motor under test. The auxiliary power supply has a lower frequency, around 60 to 95% of the frequency and voltage between 5 and 25%, both referring to the main power supply. The auxiliary power supply voltage and frequency are adjusted until the rated current of the motor under test is reached. The rotor will oscillate around the synchronous speed, operating between motor and generator [4].

There are two possibilities for applying the two-frequency method. The method shown in Figure 2 consists of two power supplies with a transformer. The main power supply is connected in series with one of the transformer windings. The

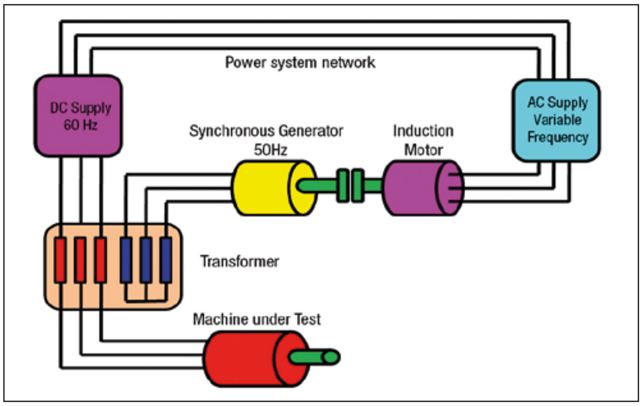

Figure 2: Interconnections between the two-frequency circuit and the transformer

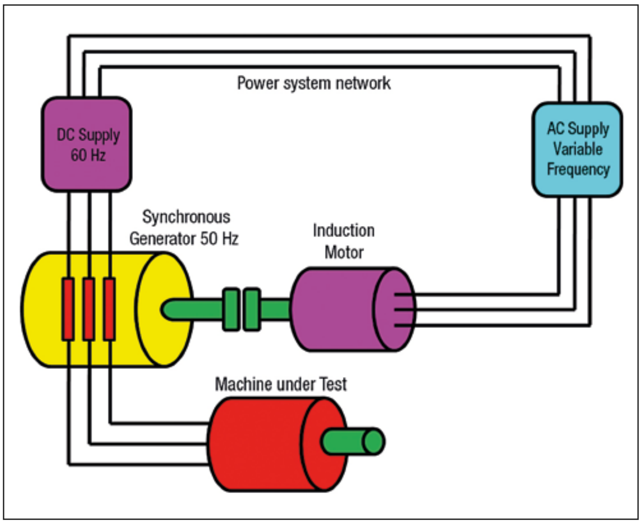

Figure 3. Two-frequency circuit interconnections through the auxiliary generator

input is connected to the source generator and the transformer winding output is connected to the motor under test. The second auxiliary power supply controls the current of the motor under test. This auxiliary power supply is connected to the input of the other winding of the transformer and the output of this winding is closed in a star connection [3].

The second possibility is the serial interconnection of the main power supply circuit connected to the motor under test pass through the winding of the auxiliary power supply generator. The adjustments and controls are the same as the first methodology. The interconnections are shown in Figure 3.

The possibility of carrying out the test under rated voltage and current conditions depends on the capacity of the two power supplies that make up the two-frequency laboratory. Generating sources with larger capacities meet the requirements of most machines. Even so, in case of electric motors to be tested for temperature assessment with powers above the laboratory capacity, two graphical methodologies can be used to extrapolate the results.

The temperature-rise test should be preferably at rated conditions in two frequencies, as this is just a fast, accurate and straightforward test. If there are limitations, you can apply this same method to a reduced extent. For example, the motor to be tested is set at rated voltage and reduced current by the current capacity of the laboratory source, and a further test makes up the result. Or reduced voltage and current of the motor to be tested, in which case the method requires three tests in the composition of the final temperature rise results.

The graphical extrapolation method with the two tests at rated voltage consists of one no-load test and one on-load test with at least 70% of the rated power of the machine to be tested. With the results of these two tests, we obtain the two points of the straight line for extrapolation, considering the x axis by the quadratic relationship of the current and the Y axis the results of the temperature rises of the two tests, as shown in Figure 4.

The graphical extrapolation method with the three tests, two of which with reduced voltage, consists of a no-load test and an on-load test with the same reduced voltage and rated current. It is also possible to consider a reduced current with a minimum of 70% of the rated current. And a third no-load test at rated voltage is required for adjusting the reduced voltage difference in the on-load test at the rated motor voltage. Figure 5 illustrates the extrapolation, showing that the voltage difference is compensated by a line parallel to the two reduced voltage tests.

Thus, the description presented shows the feasibility of performing the two-frequency test to evaluate the thermal characteristics of an induction electric motor. The only limitation in this method is the vibration and noise assessment

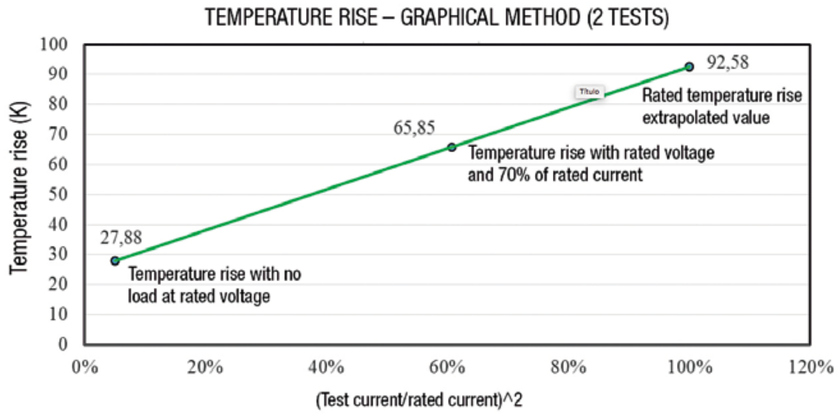

Figure 4. Extrapolation by the graphical method with two tests at rated voltage

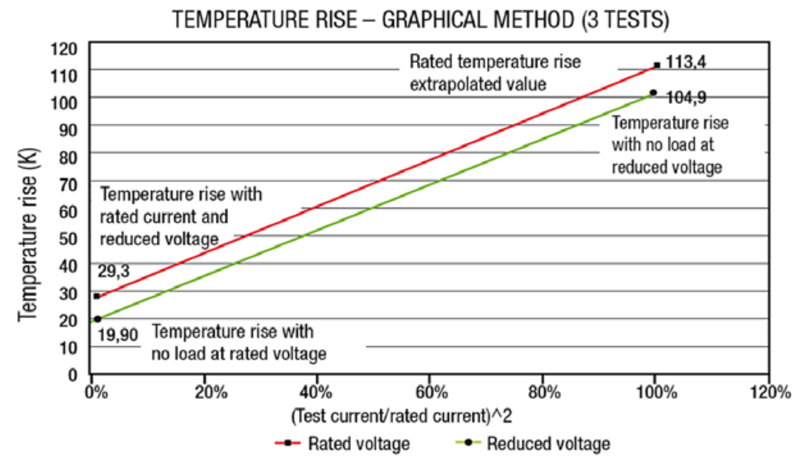

Figure 5. Extrapolation by graphical method with reduced voltage and three temperatures

during the test, as the effect of load simulation causes the tested motor to increase these parameters. An additional test is required at the end of the temperature rise: with the machine hot and thermally stabilized, drive the motor with a sinusoidal source for vibration and noise assessment.

Test method for temperature rise in synchronous machines

It is quite difficult to perform tests with load on large synchronous machines at production operating conditions. This includes both machines operating as a generator as well as a motor. Therefore, to perform this type of test and determine the actual temperature rise of these machines, standard equivalent methods need to be used. However, to reach the rated values, it is necessary to extrapolate the values found in such methods, and due to numerous design and manufacturing process variables, the results may present some inaccuracies.

According to the standards, there are three methods for this type of test, namely: applying the rated load directly (which will not be addressed in this study due to execution unfeasibility) and the two equivalent methods of the sum of short circuit plus no-load and no-excitation and the null power factor test. The document clearly defines the inaccuracy of each method and the adjustments that can be made to reduce these errors. The results must ensure compliance with the thermal class criteria and feed back the design data, and thus optimize new projects.

The major advantage in performing the test using the temperature method of sum of short circuit and no-load and no-excitation is that there is no power limitation for the tests. In the no-load test, the machine is driven at rated voltage and basically generates the heat of the iron losses until thermal stability. Iron losses are basically composed of two phenomena: the hysteresis of the stator ferromagnetic core material when subjected to a field variable in time (alternate voltage generated by the generator), and the currents induced on the stator laminations that produce heat (Joule effect), giving rise to losses by Foucault currents.

Then the short-circuit test is carried out, in which the rated current is applied, raising its temperature due to Joule losses. This thermal effect expresses the relationship of the heat generated by an electric current at a given time. The stator temperature rise is the sum of the temperature rise of these two tests minus the temperature rise of the no-excitation test. This subtraction is necessary because of the duplication of the friction and ventilation losses that are contained in both short circuit and no-load tests. However, in these two cases the rated field current is not reached. Therefore, in this case, extrapolations of the rotor temperature rise according to IEC 60034-29 [11] or IEEE 115 [12] are required.

In the case of the null power factor test, the field current can be imposed as needed, achieving the rated values and thus increasing the rotor temperature accuracy. The main difficulty is to know the field current for the rated conditions. It is not simply using the designed value, because these values vary due to many factors intrinsic to the production process. Another aggravating factor is the capacity of the source that will power the machine for testing, which should be about 50% higher than that of the machine under test, which may often limit conditions.

For large machines, especially with high polarity, it can be considered that to reduce errors in rotor temperature tests (in the field windings), you should start by performing the no-load saturation, short circuit and "V" curve tests to calculate the excitation current by the Potier reactance; therefore, use the calculated value for the temperature test.

The "V" curve test determines the excitation current point for the generator rated conditions at null power factor. In this

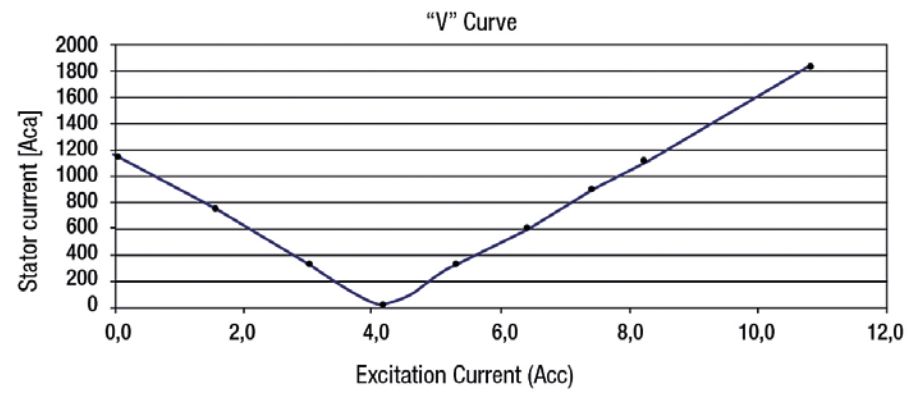

Figure 6. "V" curve test for determining the Potier reactance point A

test, the generator operates as a motor and the excitation current is varied, measuring the stator current. The points are recorded and plotted according to Figure 6. The nominal point may be tested; if this is not possible, the value is linearly extrapolated. This excitation point at null power factor is referred to as "A" in the Potier reactance determination curve of Figure 7. The test to determine this point is usually the saturation at null power factor, but for large machines, it is not feasible. Therefore, it is replaced by the "V" curve.

The curves characteristic of saturation with no load, short circuit and point "A" corresponding to the stator rated voltage and current at null power factor are included in the same Figure 7. Point "A", which ordinate is the machine rated voltage (pu), and the abscissa is the measured excitation current, corresponding to the rated armature current at null power factor with overexcitation. Due to limitations of laboratory test sources, the rated point at null power factor is taken by extrapolating the "V" curve from the values tested.

On the parallel to the abscissa axis (x-axis) at point "A", we take, to its left, a length equal to the excitation current i_{fk} which is equivalent to the excitation current corresponding to the stator rated current in the short-circuit saturation test, which is located on the abscissa axis i_f, identifying point "F".

The no-load saturation curve, before entering the saturation region, has a linear part; a line is drawn parallel to the linear region of the no-load saturation curve at the distance of point "F". At the intersection of this parallel line with the saturation curve is point "H".

The length of the perpendicular line HG lowered from point "H" over the straight line AF represents the voltage drop in resistance XP under the rated armature current. In values per unit XP = HG. Figure 7 was taken from ABNT NBR5052 standard.

On the abscissa axis the rated armature current vector (i_N) of the machine under test and, by the origin, forming with the abscissa axis an angle φn (considering positive in the case of the over-excited generator) the rated voltage vector U_N corresponding to the load power factor for the desired excitation current value. From the free end of the voltage vector, a line perpendicular to the armature current vector is drawn, which represents the voltage drop vector ($i_{N.}Xp$) of the Potier XP reactance, as shown in Figure 8.

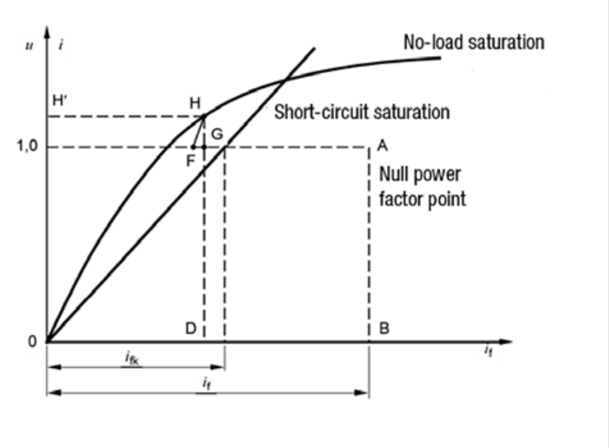

Figure 7. Determination of Potier reactance based on IEC60034-4 standard

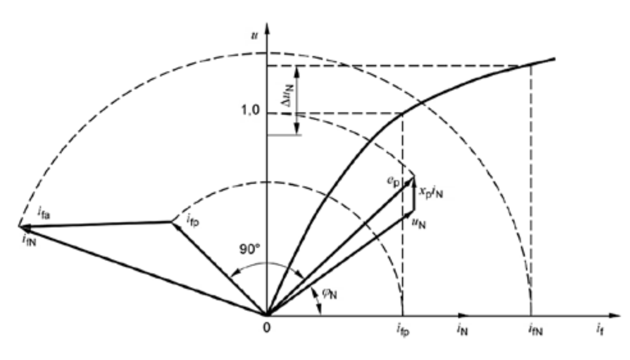

Figure 8. Determination of the rated excitation current through the Potier chart, based on IEC60034-4 standard

The vector sum of rated voltage and voltage drop in reactance XP produces the electromotive force vector ep. The excitation current i_{fp}, corresponding to this force, is determined in the characteristic with no load and is plotted on the chart from the origin, 90° from the electromotive force vector. The excitation current component that compensates for the armature reaction under the rated current (i_{fa}) is determined as the difference between the excitation current, corresponding to the rated armature current at short-circuit saturation, and the excitation current, corresponding to the voltage drop in XP due to the rated armature current in the characteristic with no load.

Vector i_{fa} is drawn from the end of vector i_{fp} parallel to the armature current vector. The rated excitation current i_{fN} is the vector sum of i_{fp} and i_{fa}, as shown in Figure 8, which was taken from IEC60034-4 standard.

With the determination of the rotor excitation current for the synchronous machine operating at rated load, the rotor temperature-rise test to be extrapolated in the case of the short circuit plus no-load test or imposed for the null power factor.

Test methods for temperature rise on direct current machines

The most common methodology for large direct current machines is back-to-back. However, it depends largely on the structural limitations of laboratories. On smaller machines, test with load is possible. For direct current machines, the equivalent methodology of short circuit, no-load and no-excitation is applicable – the same method used on synchronous machines.

A specific characteristic to be observed in direct current machines at temperature rise and with load is the sparking. The condition with no sparking or little sparking confirms the perfect operation of the machine. The adjustment of the brushes in the neutral zone causes the switching without voltage between the plates, not producing small short circuits that are the sources of sparking. This adjustment in practice is not that simple, as there are influences of distorted fields in the air-gap.

Neutral zone adjustment is possible by four methods: Rough adjustment: Energize the armature between 50% and 80% of the rated current for a maximum of 30 seconds using a low dc voltage source, such as a battery. If the neutral zone is out of alignment, the rotor will tend to spin. To adjust the neutral position, turn the brush holder ring opposite the motor direction of rotation. The neutral zone will be adjusted when the rotor is still. The fine adjustment is made by applying load at rated voltage and current to both directions of rotation. The difference in speed between both sides may not exceed 1%.

There are two other possibilities for fine adjustment: Operating the dc motor as a generator for both the open circuit (generating voltage) and the dc generator with the output short-circuited (circulating current). By adjusting the parameter (short circuit or output voltage), the difference cannot be greater than 1% between the parameter for both directions of rotation. For the three fine adjustment methods, also turn the brush holder ring opposite the motor direction of rotation to adjust the neutral position.

In the case of the no-load plus short circuit and no-excitation temperature rise test, the field will not be tested at rated conditions either. A specific test applying rated voltage in the field with the ventilation system running will be enough to determine the temperature rise of this winding. Normally, only the no-load test is performed with the machine operating as a motor, so the field is tested at rated conditions and the temperature rise without load can be determined.

DISCUSSION AND COMPARISON BETWEEN METHODS

An electrical machine in use within the specified characteristics keeps its components warm and free of moisture absorption. On the other hand, parameters not complied with compromise performance. If this parameter results in increased winding temperatures, the degradation of the insulators is exponentially enhanced with the temperature rise and may lead to premature burns.

Precise temperature rise testing in the manufacture or repair of an electrical machine is required to ensure perfect operation in the application. That ensures the estimated life of an electrical machine. There are many factors that lead to overtemperature, not just overload. Therefore, the refrigeration circuit requires careful attention, as it can reduce efficiency during operation due to contaminants.

This is so important that the IEC standard, more precisely IEC60034-29, was developed to specifically address the subject of temperature-rise testing for large electrical machines, induction motors, synchronous machines and direct current motors. Applying direct load to determine the temperature rise for these machines is only possible for low powers. Therefore, IEC developed this standard that describes only indirect methodologies for determining temperature rise. IEC 60034-29 provides a table with the methods, the laboratory equipment for the equivalent method, machine type preference and inaccuracies. The following descriptions are based on this table.

The two-frequency test is called by IEC "*Mixed-frequency or Bi-frequency method*" and IEEE122, "*Primary-superposed equivalent loading method*" The IEC standard considers an inaccuracy in the method of +/-5%. IEEE does not mention inaccuracies. Thus, it can be considered that the two-frequency method is the most common because of its versatility and for being standardized worldwide.

Synchronous machines are addressed in unique standards for operation as both motor and generator. In the case of a synchronous motor, the dynamometric test option may be considered if it has a suitable structure for that. However, it requires mechanical care for the pulsating torque characteristic of this machine design. That means reinforced and different couplings, base and fixings. Therefore, this test may only be feasible at low power, and indirect methodologies are more commonly used. Even the standards focus more on these methodologies.

The short circuit, no-load and no-excitation method is undoubtedly highly accurate for determining the stator temperature rise of synchronous machines. This methodology comprises all the losses that generate the temperatures at nominal conditions. In addition to this method, the other one is the null power factor, which is also common but depends on laboratory structure. An ideal source to meet the rated characteristics of the machine to be tested must have a higher output. Or choose only one parameter for the test - only the rotor (excitation as a whole) or only the stator.

As for the rotor, there are two difficulties: The first is to know the actual excitation current value that the machine will need to meet the rated load conditions, and the second is how to achieve such current value and, hence, temperature. The excitation current value is difficult to project because the rotor manufacturing processes may contain variables disregarded in the design that result in design deviations from those required to meet load conditions. The possibility in this case is Potier reactance, which can indirectly determine the excitation current at full load.

Once the excitation current is determined, the difficulty is how to impose this parameter. Three methodologies apply: drive the synchronous machine as a motor (even if it works as a generator), at null power factor and adjust the Potier excitation current. However, this condition depends on the capacity of the laboratory, which must be greater than the machine to be tested. A second option would be to use the delta connection and work on the machine saturation curve, overexciting it. In this condition, it is necessary to pay attention to the heating of the bars that hold the lamination core, as they may overheat. That happens because of the stator core saturation, and these bars are induced by the magnetic field generated by the rotor. In addition, the insulation of the voltage between turns must also be analyzed. The output voltage is limited by the delta connection, but the machine is overexcited, and this voltage is higher between turns. These two factors may limit the imposition of the Potier excitation current. A third possibility is the linear extrapolation of the three temperatures of the short circuit, no-load and no-excitation temperature rise tests.

As for direct current machines, the back-to-back and short circuit plus no-load and no-excitation techniques are commonly used. The back-to-back depends on the structure, coupling and another machine with characteristics similar to or above for the testing. If these requirements are met, it is the most recommended. The other possibility, the short circuit plus no-load and no-excitation, has no limitation and can meet any power as long as it has a driving motor that can supply the losses generated by the test conditions, plus friction and ventilation of the machine to be tested. The field cannot be tested by this method, but as these machines are usually designed with forced ventilation because of the possibility of operation at various speeds, the field can have an independent test.

In addition to temperature rise, sparking characteristic should be monitored and evaluated. The sparking condition under load or full current shall be tested, both cold and hot. Sparking can be caused by design problems in the case of new machines, connection errors, weak or strong commutation or brush seating. Thus, functionality of the application is guaranteed.

CONCLUSION

Temperature rise is the test to evaluate the thermal characteristics of electrical rotating machines. This can be considered for both new and repaired machines. The test aims to evaluate if temperatures meet the thermal class of the materials used in the manufacture of the machine. However, in addition to this, manufacturing errors such as number of turns, assembling of fans, heat exchangers and possible components that reduce the efficiency of the heat exchange circuit can be detected. Machine vibration is also influenced by temperature and is evaluated in this test. The components that make up the rotor can accommodate because of thermal expansion and influence the vibration values with the machine hot. The review focused on induction motors, synchronous and direct current machines. For induction motors, among the several possibilities already studied, the two-frequency test is the most feasible, since it does not require coupling the equipment, and the structures are less complex, even though two sources are needed for the test.

In synchronous machines, applying direct load is only possible on small generators. The two possibilities are the tests of sum of short circuit plus no-load and no-excitation and the null power factor test. The short circuit plus no-load and no-excitation test is the most feasible as there are no power limitations. The difficulty lies in correcting rotor temperature as it calls for corrections and extrapolations, which are standardized. The null power factor, even being a test in which the synchronous machine is tested as a motor, is the test where nominal conditions can be imposed, even being a generator. It only depends on the power of the source available for the tests.

In direct current machines, the load test is fundamental to evaluate the main characteristic, which is sparking. The rise in temperature can also be determined by the short circuit plus no-load and no-excitation methodology, the same as for synchronous machines. ■

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