Detection of Stator Winding Insulation Failures: On-line and Off-line Tests

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***Abstract*--Insulation faults in electrical rotating machines are a matter of great industrial interest since the economic losses associated with these events are usually equal or even higher than the cost of the machine itself. For this reason, the development of monitoring and diagnostic techniques to detect this failure during its earliest stages has been a subject of great interest. On the other hand, the accuracy of the quality controls applied to the manufacturing of insulation systems is an essential issue to reduce fault rate and increase machine life. The aim of this paper is to present a comprehensive review of the scientific literature in this field, including not only research papers but also existing standards for off-line tests. A critical review of their diagnosis capability, especially on low voltage machines, is essential to clarify the reliability of these techniques as well as the convenience of its generalized industrial use.**

***Index Terms*--Electrical machines, fault diagnosis, insulation, insulation testing, maintenance, rotating machines, stators.**

I. Introduction

THE lifetime of the insulation system of a rotating electrical machine, defined as the maximum time prior to the rewinding of the stator, is above 30 years in most industrial applications. In fact, a certain number of cases are found where this time surpasses 40 years. Nowadays the rewinding of motors with rated output not larger than some hundreds of kW may be higher than the cost of a new machine. For higher powered motors the ratio between the cost of machine rewinding and the cost of a new machine is not so unfavorable, although it is, without any doubt, the most expensive repair that a rotating machine must deal with during its lifetime. For this reason, both manufacturers and final users give the greatest attention to prevent a generalized degradation or even an early breakdown of the insulation system of the machine. Obviously, the consequence of this concern has been the attempt to develop all kind of techniques for machine condition monitoring and diagnosis oriented to the early detection of insulation faults.

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Since the initial state of the insulation system is critical in terms of the later development of incipient faults in the machine, the quality control techniques applied during manufacturing have been also improved and modified during the last decades. Thus, it is now possible to detect minor defects that might be the source of later failures capable to evolve to the final breakdown of the system.

In order to define a criterion in the development of this bibliographic survey, those publications considered relevant to the study have been classified into two groups: on-line condition monitoring and fault detection; and off-line tests for fault detection. Considering that in specific cases these publications address both issues, some of the references can be found in more than one of the following sections where the two groups of studies are reviewed.

II. On-line Fault Detection

From an industrial point of view the ideal situation for the early detection and diagnosis of insulation faults in the stator winding of rotating machines is the application of on-line diagnosis methods. This type of techniques must provide the user with enough information about the actual status of the machine in order to allow the scheduling of corrective actions if a breakdown might be forecasted.

A. Inter-turn Short-circuit Detection

Initial research studies proved that inter-turn short-circuits were one of the main root causes for insulation breakdown. As a consequence, since the early 80s a large number of researchers have focused their efforts in the early detection and diagnosis of this type of failure. In 1985 the use of the negative-sequence component of motor supply current was first proposed for the detection of this type of failure, [1]. The use of this current component as fault indicator was studied later by other researchers [2]-[9] using different approaches.

Spectral analysis of the electromagnetic torque, [10], instantaneous power, [11] and leakage flux, [12] were also proposed as valid techniques for inter-turn short-circuit detection and analysis.

Other methods, similar to certain extent to the use of the negative-sequence component of the supply current, were also developed for other machine variables. Thus, voltage

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zero-sequence component, [13], negative-sequence impedance, [14]-[16], or the impedances matrix, [17]-[19], have been successfully applied.

A different approach was developed by Nandi, [20], who proposed the use of the induced electromotive force at the disconnection of the machine from the power grid as a diagnostic parameter.

Later studies were especially designed for fault diagnosis in electrical drives under closed-loop operation, [21]-[23].

Even if showing different sensitivities to the level of fault in the machine, or dealing with specific limitations for its industrial use, most of the above methods have demonstrated their reliability when experimentally applied to test benches based on low voltage (LV) motors. In these test benches the stator windings have been modified *ad hoc* to install leads, usually soldered to different points of the winding and extracted outside the machine housing (see Fig. 1). The use of these leads allows the user to force different levels of failure by the external connection of resistors.

Since this type of modification in the stator windings cannot be easily applied to large medium voltage (MV) motors with form-wound stator coils the successful application of these methods to this type of machines and its reliability for the early detection of insulation defects has not been completely proved.

Another factor that limits the widespread application of these diagnosis procedures is that none of them allows the user to obtain any indication about the current degree of degradation of the insulation system. In fact, only the severity of an existing fault can be roughly estimated.

It is well known that the time elapsed between the first inter-turn short-circuit and the global breakdown of the stator insulation system that puts the machine out of service is quite short. Therefore, a method capable of detecting the progressive degradation of the insulation system that leads to the appearance of inter-turn faults, instead of using diagnosis procedures that detect this fault once it has happened, would be extremely important from the industrial point of view since it could allow stopping the machine before an imminent catastrophic fault, [24].

B. Insulation System Condition Monitoring

Condition monitoring of the stator insulation system provides the machine user with information on the extent of aging of the insulation, serving as an evaluation of the degradation caused by time and environmental factors. The most widely applied method for this purpose is partial discharge analysis (PDA). However, an important number of studies, [25]-[27], that can be grouped into 13 categories, [28], depending on the variables used for diagnosis, have already been developed.

These less extended diagnosis procedures must be also considered, since its contribution to the characterization of the status of the insulation is relevant, and even in some

Fig. 1. Left) 11kW low voltage motor used in a test bench for the analysis of inter-turn short-circuits. Right) Stator end-windings showing the leads connected to the stator to cause the fault.

cases may be complementary to PDA. Among these methods three of them seem to produce the most significant results: temperature monitoring, chemical analyses and vibration analyses. In all three cases, the diagnosis variables can be measured on-line, on the basis of a continuous monitoring system, or periodically, by means of punctual analyses spaced in time according to the previous experience, or taking into account the relevance of the machine for the production process.

These techniques imply a much higher economic cost than those considered in the previous subsection, as well as the installation of sensors and pieces of equipment that require specialized staff for the correct interpretation of the results. For this reason, its application is restricted to high cost or critical machines whose sudden fault might produce unaffordable production costs.

1) Temperature Condition Monitoring

Temperature Condition Monitoring and the analysis of its tendency may, in many instances, detect the existence of a fault or anomaly in the behavior of the machine.

In order to apply this analysis temperature probes must be installed in the machine. The installation as well as the type of probe may change from one type of machine to another. In some cases the probes are embedded in the windings of the machine, frequently located between the upper and lower coils into the same stator slot. In water-cooled and hydrogen-cooled machines, probes are usually installed closed to the output of the cooling ducts, where the refrigerant fluid flows after absorbing the heat of the machine stator windings.

A certain number of attempts have been made to estimate the temperature of machine windings by means of mathematical models, [29]-[32], however thermal parameters of the models are extremely difficult to measure or estimate, and cannot be adapted to changes in the cooling conditions of the machine, [33]. Therefore, temperature monitoring based on models is still strongly limited today.

2) Chemical Compounds Analysis

The monitoring of the formation of chemical compounds in electrical machines is based on the detection of particles or gases formed as a direct consequence of the degradation process of the insulation, or the presence of electrical discharges in the machine. When the epoxy resin used in the manufacturing of stator insulation systems of electrical machines is overheated, particles are issued and thus mixed with the cooling air or hydrogen. The detection of these particles and the analysis of their concentration can be related to the loss of insulating properties of the machine insulation system, [25]. The presence of gases, such as CO, also indicates insulation wear. Therefore, different procedures have been developed for the detection of this gas in the cooling circuits of the machine, [34].

Formation of particles and CO can be produced by degradation of the stator insulation system, rotor insulation system, when it exists, or by damage in lamination insulation of the magnetic cores. For this reason, neither the detection of particles nor the detection of CO in the refrigeration fluid is able to identify the part of the machine that has been damaged. On the contrary, the detection of ozone, formed by air ionization caused by partial discharges, is a clear indicator of the existence of this phenomenon on the surface of bars or stator coils. It may also indicate the slackening of the windings inside the stator slots or damage in the semiconductive layer of the coils, [25].

3) Vibration Monitoring

Regarding stator faults, vibration analysis, applied to the housing of the machines can be correlated with the presence of inter-turn short-circuits and voltage unbalance, [33], although both of these circumstances are not usually detected by means of this technique.

Vibration monitoring is usually focused on the diagnosis of slackening and looseness of the bars of the stator windings, [25]. This technique is almost exclusively applied to large turbogenerators where accelerometers for vibration monitoring are installed at the end-windings of the stator coils. These accelerometers are not conventional sensors, since to avoid any alteration in the electrical field distribution they do not contain metal components and are connected to measuring instrumentation through optical fiber, [35].

4) Partial Discharges Monitoring

A partial discharge is a small electrical arcing that appears in the air gaps that are present inside the insulation systems of electrical machines or medium or high voltage apparatus. Imperfections that can appear during the manufacturing process of the coils and the stress caused by vibration, thermal expansion or electrical anomalies, give rise to air vacuoles in the insulating ground-wall of the stator windings. When these vacuoles, immersed in the electrical field of the machine, are subjected to electrical field strengths higher than their dielectric strength, arcing appears through the air inside them. For this reason, partial discharge analysis is the only method that correlates directly the internal status of the insulation system with the magnitude that is being measured, and allows the evaluation of the level of degradation of the stator insulation system both in running machine tests, through on-line monitoring, and stopped machine tests, through off-line measures, [36].

First commercial pieces of equipment for the measurement of partial discharges were developed during the 70s and used in the diagnosis of hydraulic generators. Since this date, PDA has been the diagnosis method for insulation systems that has experienced the greatest expansion and refinement, taking advantage of the advances in electronics and digital signal processing. Nowadays, it is clearly the most widely used method for the diagnosis of large motors and generators, [37].

Partial discharge activity (PDA) can be measured by means of different types of sensors, [38], which must be permanently installed in the machine if a continuous monitoring system is desired. Therefore, the installation of one of these systems starts during a scheduled stop or even during the manufacturing process of the machine, [36], [39]. Two types of sensors are commonly used for the diagnosis of large MV motors: capacitors with capacities around 80pF, [36], [39], and high frequency current transformers, [25].

The antenna effect of the wiring of temperature probes embedded in the stator windings has occasionally been used for partial discharge detection. The advantage of this procedure is the pre-existence of these sensors in the machine; however this practice has been abandoned nowadays since the signal produced by the discharge must propagate from the point where it is generated to the slot where the temperature probe is installed. This propagation produces a strong damping of the signal level that strongly complicates its measurement and interpretation [25], [40].

On-line partial discharge analysis presents a number of drawbacks that do not appear when the test is applied off-line. When the machine is operating connected to the power grid the presence of electromagnetic pollution caused by the power system is unavoidable. This electromagnetic interference presents a pulse type nature, similar to PDA, and therefore, the measurements can be corrupted and the extraction of the partial discharge pattern from the record of electrical activity registered by the instrumentation becomes complex or even impossible.

For this reason, different methods have been developed to suppress or at least reduce electromagnetic interference, [36], [38], [39], [41]. For the diagnosis of large motors the most common technique, [40], is the use of capacitors, connected to the supply terminals of the machine. Thus, PDA can be isolated from the electromagnetic interference if the shape of the registered pulses is now considered: those with a very fast slew rate can be classified as actual machine partial discharges while those entering from the power system can be discarded taking advantage of their slower slew rates, normally greater than 10 ns. The slowness of the interference is caused by its propagation through the power grid that produces damping and thus a lower slew rate at the measuring point.

The determination of the admissible level of PDA in an electric machine is a complex issue, since this value should take into account the specific internal characteristics of the insulation system, [38], the type of materials, and other constructive and functional aspects. Moreover, PDA in an electrical machine is also dependent on these factors:

- Supply voltage; the PDA in the insulation system is higher at higher supply voltage levels.
- Humidity and/or pollution; the PDA is increased by these factors due to the so-called tracking effect.
- Temperature; an increase in temperature can reduce PDA due to the size reduction of the vacuoles in the ground-wall caused by the compression derived from the thermal expansion of the materials.
- Load level of the machine; higher load levels are usually associated to a higher vibration level of the machine. Vibration produces movement and displacement of stator coils inside the stator slots leading to a higher PDA.

For all the above reasons, a correct interpretation of the data acquired from partial discharge monitoring can only be correctly done by using the tendency of PDA derived from continuous monitoring or periodic measurements. In order to analyze tendencies in this type of tests, obtaining the PDA records at similar conditions is crucial, i.e. the voltage supply level, temperature, load level, etc. should remain as constant as possible during all the set of measurements. Additionally, the comparison between different tests is only reliable for the same type of winding and if the same measurement procedure and the same electronic instrument are used. Electronic instruments from different marketers usually employ different bandwidths and data acquisition processes.

If all these constraints are taken into account, the observation of a progressive increase in the magnitude of partial discharges can be clearly assumed as a process of degradation of the insulation system. The comparison between the results of tests carried out under the same conditions on identical machines can also be used for the detection of progressive wear in the insulation system of one of them. In order to evaluate if the PDA measured in an insulation system is within the normal limits, databases have been created to compare specific test results with those obtained from numerous groups of stators of similar characteristics, [42].

Tallam and Maughan, [40], [43], showed the level of PDA that must be considered as abnormal as a function of the machine rated voltage. Moreover, even in absence of specific limit values some empirical rules have been suggested for monitoring purposes:

- If the maximum level of PDA is doubled in 6 months it can be considered as an indicator of fast degradation of the insulation system, [25].
- The PDA of a strongly damaged winding is 30 or even more times higher than the one shown by the same winding in a healthy status, [28].

In spite of the limitations inherent to partial discharge analysis as a diagnosis procedure, its effectiveness has been frequently pointed out. Nevertheless, some factors must be also taken into account regarding the range of voltage applied during the test. IEEE Std. 1434-2000 (R2005), [38], is a guide for partial discharge analysis in rotating electric machinery. This document is the most detailed reference that can be found for this type of test since it includes all the aspects concerning both on-line and off-line tests as well as the application of the method to individual bars and coils. However, the lowest rated voltage level that allows the application of the test is not mentioned in the standard. Stone, [25], suggests that the test can be applied for machines with rated voltages higher than 4 kV. However, to the authors' aware only one study has been found where this type of test is applied for the monitoring of machines of voltages lower than 6 kV, [44]. This study presents the results of partial discharge analysis in 4 kV motors, clearly pointing out the complexity of applying the method in this voltage range: PDA is the consequence of the dielectric breakdown in a small air gap within the insulation system and a minimum dielectric stress around 3 kV/mm is needed for this to happen. Since in 4 kV machines rated phase-to-ground voltage is just 2.3 kV it is quite difficult to surpass the above limit unless the degradation of the insulation system is really deep. Therefore, before a significant level of partial discharge appears, the insulation system is already seriously degraded, [44]. Moreover, as the ground-wall insulation of this type of machines is much thinner than the one used in higher voltage motors, when the test is capable of detecting the presence of PDA the machine is usually close to its final breakdown. In fact, in these cases it is even possible not to find any relevant PDA even under strong degradation levels, [25]. Therefore, it can be clearly concluded that partial discharge analysis is strongly limited for the diagnosis of machines whose rated voltage is below 6 kV and thus its natural field of use are large motors with rated voltages of 6 kV and above.

III. Off-Line Fault Detection

Off-line analysis of stator insulation systems in rotating machines is performed by means of a set of tests that imply the machine disconnection from the power grid. These techniques have been applied for decades, and the experience achieved in this field is nowadays important. This high level of maturity allows these methods to be standardized and thus applied in predictive maintenance programs, [45] or as a part of the protocols for quality control during the manufacturing processes.

Although some IEC standards exist, the main references in this field can be found in IEEE standards. Most of them were created in the 50s and have since undergone numerous revisions, [46]. IEEE Standards deeply review all the technical aspects concerning every test than can be applied to the insulation system of electric rotating machinery. These are the most relevant ones:

IEEE 43-2000: measurement of insulation resistance and polarization index, [47].
IEEE 56-1977: AC Hipot tests, [48].
IEEE 95-2002: DC Hipot tests, [49].
IEEE 286-2000: power factor tests, [50].
IEEE 522-2004: turn-to-turn insulation tests, [51].
IEEE 1434-2000: partial discharge analysis, [38].

A. Insulation Resistance and Polarization Index

In spite of being the most commonly used test procedure, the conclusions extracted from the results of these methods are considerably limited, [46]. Both, insulation resistance and polarization index, allow the detection of reversible faults, i.e. those caused by pollution or humidity capable of being removed by means of a suitable cleaning or drying process that turn back the insulation system to its original status. Nevertheless, some cases have been reported, where ground-wall insulation faults have been detected, [52], from the measurement of low values of insulation resistance and polarization index.

Standard IEEE 43-2000, [47], pays more attention to insulation resistance and polarization index than to polarization and depolarization currents. These currents can be measured during the same test and have the advantage of providing certain information about irreversible faults, [45]. Since 2002, [53], publications on the advantages of these currents as diagnosis parameter have considerably increased in the USA, [53]-[56], while in Europe this interest had formerly arisen, [57].

These methods can be applied to all type of machines regardless of their rated voltages, being the voltage level for the test clearly established by the aforementioned standard [47].

B. AC Hipot Tests

Among other methods, AC Hipot Tests are included in the Standard IEEE 56 (for machines with rated power above 10,000 kVA) [48] and in the Standard IEEE 432 (for motors with rated power within the range 5 to 10,000 hp) [58]. Both standards are comprehensive guides for the practical application of tests for inspection and maintenance that can be done on the rotor and stator windings of electrical rotating machinery.

This method is a pass/fail test that reveals whether the insulation system is able to withstand the applied overvoltage or not. No direct additional information is obtained from this exam. The main idea of this diagnosis procedure lies on assuming that if a winding passes the test, an insulation fault caused by degradation is not likely to occur in the near future. Obviously, if the winding does not pass the test it becomes damaged and must be repaired.

The need for large equipment, due to the power and high voltage levels that must be handled by the voltage source applied in this test, makes this method more suitable for laboratory surveys than for field work. An alternative procedure that reduces the difficulties derived of using large and heavy instrumentation consist of performing the test at a very low frequency, usually around 0.1 Hz, instead of using industrial frequency, [59]. Thus, the size of the equipment is markedly reduced, while the results have been proven to be similar enough to those obtained from the standard test.

Another important drawback of this type of tests is that they cause insulation ageing. In most of the cases, the voltage applied during the test is high enough to induce the formation of partial discharges and, as it is well known, this phenomenon entails degradation in the organic compounds of the insulation systems, [25]. In fact, this type of methods has been widely used in studies aiming to determine the ageing level suffered by an insulation system. This test is known as “AC breakdown test” and differs with the conventional Hipot test in the fact that the voltage is now increased above the rated value until reaching the breakdown of the insulation, [60]-[61].

Both Standard IEEE 56 [48] and IEEE 432 [58] differ from other aforementioned Standards since they focus exclusively on the maintenance of the stator insulation system. Therefore, these documents do not make any recommendations on voltage levels to accept or reject a bar, a coil or a complete winding during their manufacturing process. For these other purposes the Standard IEC 60034-1 [62] may be used.

C. DC Hipot Tests

The standard IEEE 95-2002 [49] describes the operating procedure, as well as the voltage levels, suitable for a DC Hipot test. Although this test is also of the type “pass – not pass” and shares most of its specifications with the AC Hipot test, certain differences should be pointed out. On one hand, the voltage levels that must be applied are significantly higher, on the other, the voltage distribution throughout the ground-wall insulation system during the test, i.e the dielectric effort applied on the insulation, is also different.

Relatively old studies concluded that if an equivalent dielectric stress is desired, the voltage level applied during DC Hipot tests should be 1.7 times higher than the one used in the AC Hipot test, [25], [49]. More recent surveys, carried out with epoxy-mica insulation systems, [63], have demonstrated that this ratio should be increased to an average of 4.3 times. Therefore, the old 1.7 factor cannot be supposed to induce the same dielectric stresses in modern insulation systems. However, since no value has been found capable of equalizing the dielectric effort suffered by the insulation in both tests, this ratio is still used even in newer version of the Standard, in spite of the decreasing of reliability that this implies.

The DC Hipot test gives three different application alternatives:

1. Direct application of the maximum voltage level during 1 or 5 minutes.
2. Discrete incremental application of voltage in 1 kV steps during 1 minute.
3. Continuous incremental application of voltage with a ratio of around 1 or 2 kV/min (ramp test).

Studies have demonstrated that the third method displays the higher sensitivity for the detection of weak points inside the insulation system, [64]-[66].

D. Power Factor Tests

Power factor tests allow the user to obtain information, in an indirect way, about the PDA in the bosom of the insulation system. As partial discharges produce a certain consumption of active power, this demand will be reflected in the current absorbed during the test, and is shown as a variation in the phase angle between voltage and current. Under ideal conditions this angle should be 90º, however, as a consequence of the PDA it becomes smaller. Since PDA is related to the level of degradation of the insulation, this test allows estimating the degradation level and tracking its evolution over time.

Standard IEEE 286 [50] describes the test procedure. This test was applied in the past to the quality control of bars and stator coils. In fact, its results provide useful information about the reliability of the resin impregnation after the heating and pressing processes. For this reason, it is widely used nowadays. In fact, a European Standard exists, [67], where limits are established for the maximum values of power factor and power factor increments when the test is carried out by increasing the voltage applied to the specimen under test.

During the 50s this test was extended to complete windings to determine the ground-wall insulation status. Nowadays, it is one of the main tests for both purposes [25]: quality control during manufacturing, and diagnosis of complete windings. Moreover, it is part of the essential tools used in any study focused on the analysis of the ageing process of all kind of insulation systems, [68]-[73].

Nevertheless, this test shows two significant limitations. The first is related with the semiconductive protective layers located close to the output of the slots in the bars or individual coils that form the stator winding. These layers are commonly used in machines with rated voltages equal or higher than 6 kV in order to prevent the formation of partial discharges in this sensitive region. In this case, the increase of voltage applied to the specimen during the test produces a decrease in its resistance because of the semiconductive nature of the varnishes used for this purpose. Therefore, the current through the semiconductive layer increases, and thus, Joule effect losses appear in this region that give rise to an increase in the power factor that may hide the actual presence of partial discharges caused by insulation degradation, preventing a reliable diagnosis of the insulation system, [46]. When individual bars or coils are tested this problem can be minimized by using guard terminals [50] (see Fig. 2), however, when the test is carried out on a complete machine this solution is not feasible.

The second limitation has to do with the minimum machine rated voltage from which this test can be applied. According to IEEE Standards, [50] this test is suitable for any bar or stator coil, although it is usually applied to components or machines whose rated voltage is equal or higher than 6 kV. According to the European Standard, [67], the test allows the user to analyze the dielectric behavior of the insulation systems of rotating electrical machinery whose rated voltage is between 5 and 24 kV. Some studies affirm that this test only produces relevant results when it is applied to stator coils whose rated voltage is higher than 2.3 kV, [25]. Tetrault developed a study, [44], that demonstrates the inactivity of partial discharges in machines rated at voltages below 4 kV unless the internal status of the insulation is really poor. If this is the case, PDA is a clear indicator of an imminent fault, [44], [74]. Therefore, it can be concluded that for voltages below 6 kV reasonable doubts exist about the reliability of this method to make a proper diagnosis of the internal status of the insulation system. The different criteria observed by the various standards and the disagreements between them and different research studies point out the existence of doubts about the effectiveness of the method when applied at the lower voltage levels.

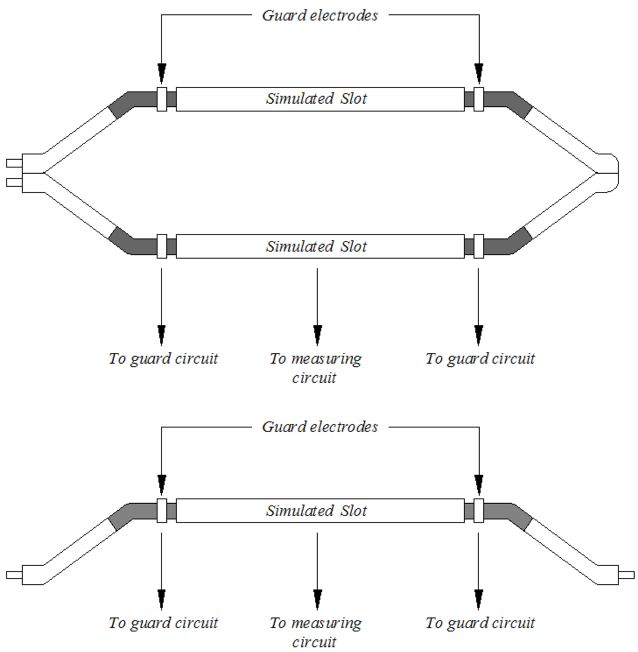

Fig. 2: Power factor measurement, using guard terminals in bar (below) and in an individual coil (above.)

E. Turn-to-turn Insulation Test

This is the only one of the tests referred to in this section that provides the capability to stress turn-to-turn insulation, [51]. To achieve this, a surge-type voltage waveform is applied to individual coils or to whole phases of the insulation system. This wave is propagated through the different turns, and thus, their individual insulation can be stressed and tested. The nature of information given by this test is identical to the one obtained from the Hipot test, i.e. pass/fail type. The turn-to-turn insulation preserves its integrity during the test, or is led to a permanent fault. In fact, no diagnosis variable is obtained, although the simultaneous combination of this test with partial discharge analysis is capable to detect small gaps in the turn-to-turn insulation that can estimate its level of degradation, [75].

If its consideration as a potentially destructive test is neglected, which is always a controversial issue for off-line tests, the main limitation of this method is its inability to detect a single shorted turn when the winding is formed by coils with a large number of turns [25]. Stone suggests, [46], that a ratio of approximately one shorted turn per 50 healthy turns is undetectable for this method. Modern digital instruments allow a partial solution for this drawback. The presence of a shorted turn modifies the inductance of the winding or coil to be tested, and leads to a change in the frequency of the waveform obtained during the propagation of the surge. The evaluation of this change can be detected by taking advantage of the storage capabilities of modern measurement instruments. In order to do so, the waveform obtained during the test is compared with other waveforms corresponding to the application of the same voltage surge to other coil or winding taken as reference of a healthy insulation, [46]. Since changes in the waveform caused by the fault of a single turn may be especially subtle, different mathematical procedures have been developed to carry out a numerical evaluation of this comparison, [76], [77]. Nevertheless, this improvement only partially solves the problem since the winding inductance may also change for other reasons such us constructive asymmetries, asymmetrical connections between coils or asymmetrical couplings with the rotor windings. These spurious effects can lead to a wrong evaluation of the turn-to-turn insulation. In fact, a method to detect rotor asymmetries by means of this test and the effects caused by the asymmetrical coupling between rotor and stator has been developed, [78], [79].

F. Partial Discharges Tests

Standard IEEE 1434 [38], as well as IEC 60034-27 [80], are the most specific guides for the development of off-line partial discharge analysis. Off-line tests are essentially different from off-line monitoring of partial discharges because of the following reasons:

- The machine must be completely disconnected from the power grid and from all the measurement and protection devices (transformers, capacitors and surge arresters).
- A power source without internal partial discharges is needed to energize the insulation system.
- Since the temperature of the machine is lower than the operating temperature and no vibration exists, the PDA of the slot region, caused by vibration or slackening, will be lower.
- The regions of the windings close to the neutral point are subjected to higher voltages than the ones they withstand under normal operating conditions.
- The electromagnetic interferences are lower since the machine is not connected to the power grid or any other electrical device more than the partial discharge analyzer.
- The inception and extinction voltages of the PDA can be measured.
- A per-phase analysis of the machine can be done if the connection of the winding makes it possible.

All the above reasons make off-line tests an essential complement to on-line tests, even if the scheduling of the former can be difficult [25], [38], [44].

Regarding the limitations of this method, they can be considered the same than those associated to partial discharge monitoring: a correct interpretation of the results can only be achieved if periodic measurements are taken and their tendency is observed.

When tendencies are studied, it is extremely important to assure identical conditions during the tests. Furthermore, in order to compare successive measurements they must be carried out by using the same instrumentation and exactly the same measurement procedure. If these restrictions are taken into account, the detection of an increase in the magnitude of PDA and a reduction in the inception and extinction voltages can be clearly considered as the indication of an actual degradation of the insulation system, [25], [38].

Because of the above reasons, the comparison of results between machines of different constructive characteristics and specifications, or even identical machines of different manufacturers, may lead to a wrong interpretation of the results. Comparison between PDA for the same machine or for identical windings is also only valid if the same test equipment and test procedure have been used.

Standard IEEE 1434 [38] does not specify the rated voltage values suitable for its application while the standard IEC 60034-27 [80] is intended for machines rated at 6 kV or higher voltages. In fact, again a high degree of uncertainty exists in the application of this test to machines whose rated voltage is below 6 kV since in this range the detection of PDA is linked to an extremely high level of wear in the insulation system, making the fault imminent.

IV. CONCLUSIONS

The review of previous research work and standards on the detection of stator winding insulation failures allows extracting the following conclusions:

- A great number of studies about the detection of turn-to-turn short-circuits exist that can be applied to operating machines. However, the usefulness of these methods in MV machines has not been proved or it is, at least, questionable since no experimental validation has ever been presented.
- The most widely used method for the condition monitoring of insulation systems of electrical machines is partial discharge analysis. Other methods are available, but partial discharge analysis is the only one capable of determining the internal status of the insulation system.
- The correct interpretation of the results of partial discharge tests can only be performed if periodic measurements are taken and its tendency is analyzed. To achieve this, the uniformity of test conditions is an essential issue: temperature, humidity, load level, supply voltage, test instrument and measurement procedure should remain unchanged. Comparing results from machines with different constructive characteristics or specifications, or even identical machines from different manufacturers may lead to wrong conclusions.
- Experimental results show that it is almost impossible to detect PDA in machines with rated voltage below 6 kV. Moreover, when PDA is detected in this type of machines, the degree of wear of the insulation system is unrecoverable.

Off-line techniques have been used for decades; however, their major drawbacks, quite evident in the case of power factor and partial discharge tests, are the disparity of criteria, even between different standards, as well as the gaps demonstrated by research studies about their reliability when applied to machine rated at lower voltages.

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