A Survey on Testing and Monitoring Methods for Stator Insulation Systems of Low-Voltage Induction Machines Focusing on Turn Insulation Problems

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***Abstract*—A breakdown of the electrical insulation system causes catastrophic failure of the electrical machine and brings large process downtime losses. To determine the conditions of the stator insulation system of motor drive systems, various testing and monitoring methods have been developed. This paper presents an in-depth literature review of testing and monitoring methods, categorizing them into online and offline methods, each of which is further grouped into specific areas according to their physical nature. The main focus of this paper is on testing and monitoring techniques that diagnose the condition of the turn-to-turn insulation of low-voltage machines, which is a rapidly expanding area for both research and product development efforts. In order to give a compact overview, the results are summarized in two tables. In addition to monitoring methods on turn-to-turn insulation, some of the most common methods to assess the stator's phase-to-ground and phase-to-phase insulation conditions are included in the tables as well.**

***Index Terms*—Induction motors, interturn shorts, motor diagnostics, stator faults, winding insulation.**

I. Introduction

MOTOR DRIVE systems are an important component in industrial applications. One of the most critical components of these systems and also one of the main sources for their failures is the stator winding insulation system [1]–[4]. Various surveys on motor reliability have been carried out over the years. In [1], [2], the percentage of motor failures due to problems with the insulation is about 26%. In [4], it is even 36%.

The unscheduled process downtime caused by a failure of the insulation system can cause enormous costs. Thus, it is desirable that a weakness in the insulation system, which can result in a severe failure, is identified in the early stages in order to perform a scheduled machine service or replacement. The economical losses of the process downtime caused by an unexpected outage of the machine exceed the machine maintenance costs considerably. For example, in an offshore oil plant, the downtime losses caused by motor failures can be as high as $25 000/h.

It is well realized by the industries that degraded energy efficiency of the motor causes increased energy losses and results in more economical losses. However, more energy losses actually come from the unscheduled downtime caused by the unexpected motor failures, which, for some certain industries, can be catastrophic and intolerable. The average downtime cost of different industries is summarized in Fig. 1 [5].

There are several different mechanisms that cause the breakdown of the insulation system. The main reasons of winding insulation deterioration as described in [6] and [7] are thermal, electrical, mechanical, or environmental stress. Moreover, the class of insulation and the application of the motor have a strong influence on the condition and aging of the insulation system.

The recent technology advances in sensors, integrated circuits, digital signal processing, and communications enabled engineers to develop more advanced methods to test and monitor the conditions of the machine [8]. Many approaches have been proposed to detect the faults and even the early deterioration of the primary insulation system (phase-to-ground or phase-to-phase) and the secondary insulation system (turn-to-turn). Numerous standards [10]–[22] concerning the testing and maintenance of electrical machinery have been developed. Various surveys [23]–[35] made on motor diagnostics show the research trend and the need for further development in this area.

The testing and monitoring methods can be generally divided into two different categories. The first one is offline testing [6], [8], [37]–[52], which requires the motor to be removed from service, while the second one is online monitoring [6], [24], [59]–[125], which can be performed while the machine is operating. An important aspect of each method is whether it is invasive or noninvasive to the machine's normal operation. Nonintrusive methods are always preferred because they only use voltage and current measurements from the motor terminals and do not require additional sensors.

Most of the insulation system faults are caused by the deterioration and failure of the turn-to-turn insulation [8], [9]. Therefore, the monitoring of the turn-to-turn insulation's condition is of special interest. For this reason, the main focus of this survey—in contrast to other surveys related to motor diagnostics [23]–[35]—is on methods that can be used to detect faults or deterioration in the turn-to-turn insulation of low-voltage machines. Some popular methods related to

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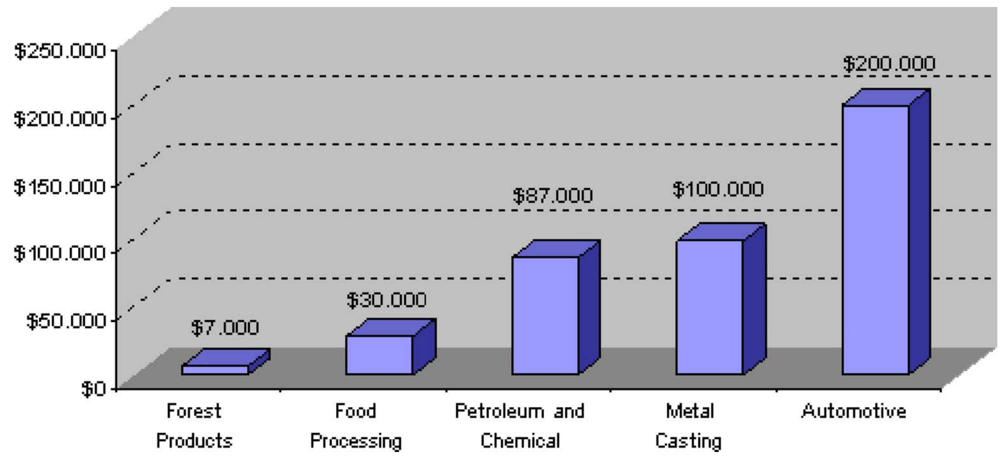

Fig. 1. Average downtime cost of different industries.

medium- and high-voltage machines are also briefly mentioned. The most common methods to test and monitor the ground-wall and phase-to-phase insulation are also included in this survey.

First, the insulation–failure mechanisms are analyzed briefly. Then, several offline tests are introduced. Finally, a general approach of developing online methods is discussed, and conclusions are drawn considering the need for future development in this area.

II. Stator Faults and Their Root Cause

As mentioned earlier, the main cause for stator failures can be divided into four groups [6], [7], [36]: thermal, electrical, mechanical, and environmental stress. Before describing the different causes for the breakdown of the insulation system, a brief overview over the possible nature of the fault and a way to analyze it is given.

A. Analysis and Nature of the Stator Insulation Failure

There are different failure modes and patterns associated with stator insulation failures [36]. The most severe failure mode is a phase-to-ground fault. Other modes are turn-to-turn, coil-to-coil, phase-to-phase short-circuits, or an open-circuit of the stator windings. Those faults can occur in a single phase, can be symmetrical, nonsymmetrical with grounding, or nonsymmetrical excluding grounding. Analyzing the mode and pattern of the fault helps to find its cause.

In a turn-to-turn fault, two or more turns of a coil are short-circuited. The current in the shorted turns will be substantially higher than the operating current and therefore increases the winding's temperature to a level where severe damage or even the breakdown of the insulation is the result. A great percentage of the insulation failures start with a turn-to-turn insulation problem and subsequently develop into more severe insulation faults.

One of the faults developing from a turn-to-turn fault might be a coil-to-coil short circuit, where coils from the same phase get shorted, or a phase-to-phase short circuit, where two or more of the different phases get shorted. These faults again can develop into phase-to-ground faults, which can cause substantial damage to the motor.

A different kind of fault is the open-circuit of a stator winding. As the short-circuit faults, the open-circuit introduces a strong asymmetry and, thus, malfunction of the motor. Compared to the short-circuit faults, this kind of fault rarely occurs.

Aside from analyzing the mode and pattern of the failure, the examination of the appearance of the motor is helpful to identify the cause of the fault. This includes aspects like the cleanness of the motor, the presence of foreign material, signs of moisture, and the condition of the rotor. The operating conditions under which the motor fails, as well as the general operating conditions, should also be taken into consideration. Furthermore, the maintenance history can be consulted to determine the problems that lead to failure.

Considering all these aspects, a methodology can be developed in order to analyze and classify insulation failures [36].

B. Root Causes for the Failures of the Stator Insulation System

1) Thermal Stress: One of the thermal stresses the insulation is subject to is the thermal aging process. An increase in temperature accelerates the aging process and thus reduces the lifetime of the insulation significantly. As a rule of thumb, a 10° increase in temperature decreases the insulation life by 50%. Under normal operating conditions, the aging process itself does not cause a failure but makes the insulation more vulnerable to other stresses, which then produce the actual failure. In order to ensure a longer lifetime and reduce the influence of the aging process, one can either work at low operating temperatures or use an insulation of higher quality, i.e., use a higher insulation class.

Another thermal stress that has a negative effect on the insulation lifetime is thermal overloading, which occurs due to voltage variations, unbalanced phase voltages, cycling, overloading, obstructed ventilation, or ambient temperature.

For example, even a small increase in the voltage unbalance has an enormous effect on the winding temperature. As a rule of thumb, the temperature in the phase with the highest current will increase by 25% for a voltage unbalance of 3.5% per phase.

It should be ensured that the flow of air through the motor is not obstructed since the heat cannot be dissipated otherwise and that the winding temperature will increase. If this is not possible, however, this should be taken into account by upgrading the insulation system or restricting the winding temperature.

2) Electrical Stress: There are different reasons why electrical stresses lead to failure of the stator insulation. These can usually be broken down into problems with the dielectric material, the phenomena of tracking and corona and the transient voltages, that a machine is exposed to.

The type of dielectric material that is used for phase-to-ground, phase-to-phase, and turn-to-turn insulation, as well as the voltage stresses applied to the insulating materials, influences the lifetime of the insulation significantly. Thus, the materials for the insulation have to be chosen adequately in order to assure flawless operation and desired design life.

Tracking and corona are phenomena that only occur at operating voltages above 600 V and 5 kV, respectively.

The negative influence of transient voltage conditions on the winding life has been observed in recent years. These transients, which either cause deterioration of the insulation or even turn-to-turn or turn-to-ground failures, can be caused by line-to-line, line-to-ground, or multiphase line-to-ground faults in the supply; repetitive restriking; current limiting fuses; rapid bus transfer; opening and closing of the circuit breakers; capacitor switching (power factor improvement); insulation failure in the power system; or lightning strike. Variable frequency drives are subject to permanent voltage transients. In particular, during the starting and stopping process, high-voltage transients can occur.

3) Mechanical Stress: The main causes for insulation failure due to mechanical stresses are coil movement and strikes from the rotor.

The force on the winding coils is proportional to the square of the motor current and reaches its maximum value during the startup of the motor. This force causes the coils to move and vibrate. The movement of the coils again can cause severe damage to the coil insulation or the conductor.

There are different reasons that will cause the rotor to strike the stator. The most common are bearing failures, shaft deflection, and rotor-to-stator misalignment. Sometimes, the contact is only made during the start, but it can also happen that there will be a contact made at full speed of the motor. Both contacts can result in a grounded coil.

There are other mechanical stresses, which the windings are exposed to, like loose rotor balancing weights, loose rotor fan blades, loose nuts or bolts striking the motor, or foreign particles that enter the motor.

4) Environmental Stress: Stresses stemming from contamination, high humidity, aggressive chemicals, radiation in nuclear plants, or the salt level in seashore applications can be categorized as environmental or ambient stress [6].

For example, the presence of foreign material by contamination can lead to reduction in the heat dissipation, increasing the thermal deterioration. A thin layer of conducting material on the surface of the insulation is another possible result of contamination. Surface currents and electrical tracking can occur due to this layer applying additional electrical stress. Aggressive chemicals can degrade the insulation and make it more vulnerable to mechanical stresses. If possible, the motor should be kept clean and dry internally, as well as externally, to avoid the influence of moisture, chemicals, and foreign particles on the insulation condition.

Radiation is a stress that only occurs in nuclear power plants or nuclear-powered ships. The aging process is comparable to thermal aging.

III. Offline Testing

The condition of the stator winding is critical for the overall motor wellness. To ensure the flawless operation of a motor system, various offline tests can be performed. These tests allow the user to assess the condition of the motor under test. Offline methods are normally more direct and accurate. The user does not need to be an expert of motor drives to perform the tests. However, most of these tests can only be applied to motors that are disconnected from service. This is one of the main drawbacks compared to the online-monitoring methods. An advantage to online monitoring is that meaningful tests can be performed after fabrication of the motor and that a test device can be used for several different machines, which saves costs.

The offline tests are summarized in Table I, [6], [8], [37]–[52]. Evaluating the table, it becomes obvious that there are not many offline techniques available to diagnose the turn insulation condition of low-voltage machines. The most common techniques to assess the stator turn-to-turn insulation are the surge test and the offline partial discharge (PD) test. Since the PD test is not applicable to low-voltage machines, it is not further described here.

Common methods used to test the phase-to-ground insulation [6], [37]–[39] are the insulation resistance (IR) test, the polarization index test, the dc and ac high potential test, and the dissipation factor test. Recently, a new method was developed to apply some of those offline tests (IR, dissipation factor, and capacitance tests) to inverter-fed machines while they are not operating [40], [41]. Since the tests can be conducted on a frequent basis without using additional equipment, ground-wall insulation problems can be diagnosed at an early stage.

A. Signature Analysis After Switch-Off

A technique that uses motor, the signature analysis of the terminal voltage immediately after switch-off to diagnose turn faults, is introduced in [42]. The advantage, compared to online techniques using current signature analysis, is that the voltage unbalance of the source does not influence the result since the supply is off. The faulty machine model used for simulation is also included in the paper.

B. Surge Test

About 80% of all electrical failures in the stator originate from a weak turn-to-turn insulation [9]. None of the other tests summarized in Table I is capable to directly measure the integrity of the turn insulation though. By applying a high voltage between the turns, the surge test is able to overcome this limitation and provides precious insight into the condition of the turn-to-turn insulation [6], [8], [9], [37], [43]–[46].

The principle of surge testing is to apply a short current pulse with a fast rise time to the windings of the stator. By Lenz's law,

TABLE I
DIFFERENT METHODS TO TEST THE STATOR INSULATION SYSTEM OF ELECTRICAL DRIVES

Method	References	Standards	Insulation Tested & Diagnostic Value	Attributes
Winding Resistance/ DC Conductivity Test	[6], [8] [37]		detects shorted turns, no predictive value	(+)easy to perform, (-)only detects faults
Insulation Resistance (IR)/ Megohm	[6], [37]- [41]	IEEE 43, NEMA MG1,	finds contaminations and defects in phase-to-ground insulation	(+)easy to perform, (+)applicable to all windings except for the rotor of a squirrel cage IM, (-)result is strongly temperature dependent
Polarization Index (PI)	[6], [37]- [39]	IEEE 43	finds contaminations and defects in phase-to-ground insulation	(+)easy to perform, (+)less sensitve to temperature than IR-test
DC High Potential Test (DC HighPot)	[6], [37]- [39]	IEEE 95, IEC 34.1, NEMA MG1	finds contaminations and defects in phase-to-ground insulation	(+)easy to perform, (+)if test does not fail, the insulation is likely to work flawlessly until the next maintenance period → more predictive character than IR and PI, (-)in case of failure repair required (destructive)
AC High Potential Test (AC HighPot)	[6], [38] [39]	IEC 60034 NEMA MG1	finds contaminations and defects in phase-to-ground insulation	(+)more effective than DC HighPot, (-)not as easy to perform as DC HighPot
Signature Analysis of Terminal Voltage after Switch-Off	[42]		detects turn-to-turn faults	(+)signature analysis without influence of supply voltage unbalance, (-) test can only be conducted directly after switch-off
Surge Test	[6], [8], [9], [37] [43]- [50]	IEEE 522 NEMA MG1	detects deterioration of the turn-to-turn insulation	(+)only offline test that measures the integrity of the turn insulation, (-)test can be destructive
Offline Partial Discharge	[6], [51]	IEEE 1434	detects deterioration of the phase-to-ground and turn-to-turn insulation	(+)good practical results, (-)not applicable to low-voltage machines, (-) difficulty in interpretation of the data
Dissipation-Factor	[6], [40] [41], [52]	IEEE 286 IEC 60894	detects deterioration of the phase-to-ground and phase-to-phase insulation	(-)measurements on a regular basis required in order to trend the data over time, (+)able to determine the cause of deterioration
Inductive Impedance	[6]		detects shorted turns, no predictive value	(-)undesired foreign influence on result, (-)not as easy to perform as the Winding Resistance test

there is a voltage induced between the adjacent loops of the winding. If the voltage is too high for the insulation, there will be arc developing. This process can be detected by observing the impulse response of the motor, which is also called "surge waveform."

In practical application, a capacitor is charged up to a specified voltage level and subsequently discharged in one of the motor windings. In the first-order approximation, the capacitor and the motor present an RLC-series circuit. If there is a short between the turns of the insulation due to a deteriorated winding, a change in the frequency and the magnitude of the impulse response can be observed.

By applying voltages that are significantly higher than during operation, a weakness in the insulation can be found that is not apparent under rated conditions. The recommended test voltages can be found in IEEE 522, NEMA MG-1.

There have been a lot of controversies about the risk of surge testing [47]–[49]. A comprehensive study about this issue disproves the statement that surge testing significantly reduces the lifetime of a machine [45], [46]. The effect of the surge rise time is also a topic that has been widely discussed [50].

IV. ONLINE MONITORING

Various monitoring methods have been developed using different physical quantities to detect the health condition of the stator insulation system [6], [7]. These methods utilize different motor parameters like magnetic flux, temperature, stator current, or input power for the monitoring purpose. The induction motor model with a turn-to-turn fault, introduced in [53]–[57], is required for some of the methods.

Online condition monitoring is usually preferred in the applications, which have a continuous process, such as petro/chem, water treatment, material handling, etc. The major advantage is that the machine does not have to be taken out of service. As a result, the health condition while the motor is operating can be assessed. Predictive maintenance is made easier because the machine is under constant monitoring, an incipient failure can immediately be detected, and actions can be scheduled to avoid more severe process downtime. A disadvantage is that the online-monitoring techniques often require the installation of additional equipment, which has to be installed on every machine. Compared to the offline tests, it is more difficult or even impossible to detect some failure processes [6]. However, many sensorless and nonintrusive methods have been recently developed using the electrical signatures, e.g., current and voltage, such that the monitoring algorithm can reside in the motor control center or even inside of motor control devices, such as the drives [58]. Therefore, the online monitoring can become nonintrusive without the need of additional sensors and installations. The online-monitoring techniques described in the survey are summarized in Table II [59]–[112].

A. Temperature Monitoring

The constant monitoring of the temperature and trending over time can be used by maintenance personnel to draw conclusions about the insulation condition [6]. In many motors,

TABLE II
DIFFERENT METHODS TO MONITOR THE STATOR INSULATION SYSTEM OF ELECTRICAL DRIVES

Method	References	Insulation Monitored & Diagnostic Value	Attributes
Temperature Monitoring	[6], [24], [59]- [63]	detects deterioration in phase-to-ground and faults in turn-to-turn insulation	(-)invasive if sensors are required, (-)a lot of data and additional information like ambient temperature required
Condition Monitors and Tagging Compounds	[6], [24]	detects faults and problems with phase-to-ground and turn-to-turn insulation	(-)invasive (equipment for detection of particles required and chemicals have to be applied to machine)
Leakage Currents	[64], [65]	detects deterioration of the phase-to-ground and phase-to-phase insulation	(+)non-invasive, (+)capable of determining the cause of deterioration
High Frequency Impedance/ Turn-to-Turn Capacitance	[66]- [68]	detects deterioration of the turn-to-turn insulation	(-)invasive (search coil), (-)not tested widely yet, (++)capable of monitoring the deterioration of turn-to-turn insulation
Negative Sequence Current	[34], [69]- [76]	detects turn-to-turn faults	(+)non-invasive, (-/+)non-idealities that complicate fault detection / methods available to take non-idealities into account
Sequence Impedance Matrix	[77]- [82]	detects turn-to-turn faults	(+)non-invasive, (-/+)non-idealities that complicate fault detection / methods available to take non-idealities into account
Zero Sequence Voltage	[83]	detects turn-to-turn faults	(+)non-invasive, (-/+)non-idealities that complicate fault detection / methods available to take non-idealities into account, (-)neutral of the machine has to be accessible
Pendulous Oscillation Phenomenon	[86]	detects turn-to-turn faults	(+)non-invasive, (+)able to compensate for non-idealities
Axial Leakage Flux, Airgap Flux Signature	[88]–[90]	detects turn-to-turn faults	(-)invasive (search coils), (-)results strongly depend on the load
Current Signature Analysis	[94]- [103]	detects turn-to-turn faults	(+)non-invasive, (-)interpretation of results subjective, (-)further research advised to generalize results
Vibration Signature Analysis	[104], [105]	detects turn-to-turn faults	(-)invasive (accelerometer), (-)further research advised to generalize results
AI-based	[71]–[73], [106]- [111]	detects turn-to-turn faults	(+)no model for fault or system required, (+)automation of diagnostic process, (+/-)can be non-invasive/invasive based on required input quantities
Online Partial Discharge	[7], [112]- [119]	detects deterioration of the phase-to-ground and turn-to-turn insulation system	(-)additional equipment required, (-)not applicable to low-voltage machines, (-)difficulty in interpretation of the data, (+)good practical results
Ozone	[6]	detects deterioration of the phase-to-ground and turn-to-turn insulation system	by-product of PD, (-)invasive (gas analysis tube or electronic instrument)

the temperature is monitored and the motor is turned off if a certain temperature is exceeded. Temperature sensors can be embedded within the stator windings, the stator core, or frame or even be part of the cooling system. There are different types of temperature sensors employed like resistance temperature detectors or thermocouples. Recently, there has also been a lot of work done on temperature estimation techniques [59]–[63], which are nonintrusive and, thus, do not require the installation of temperature sensors. The ability to measure even small excursions in temperature enables the detection of possible problems in the insulation at an early stage and can thus be used to plan maintenance before a major breakdown occurs [24].

B. HF Impedance/Turn-to-Turn Capacitance

A nonintrusive condition monitoring system using the high-frequency (HF) response of the motor is introduced in [66]. It is able to observe the aging and, thus, the deterioration of the turn-to-turn insulation by detecting small changes in the stator winding's turn-to-turn capacitance.

It is shown that the turn-to-turn capacitance of the stator winding and, thus, its impedance spectrum are changing under the influence of different aging processes. Since it is not possible to use an impedance analyzer for the purpose of an online test, it is suggested to inject a small HF signal into the stator winding. Its frequency has to be close to the series resonance frequency of the system. The flux of the machine caused by the injected HF signal can be measured by a magnetic probe in the vicinity of the machine. The change in the phase lag between the injected signal and the measured flux will be used as an indicator of a change in the resonance frequency and, thus, in the turn-to-turn capacitance, which is caused by the deterioration of the insulation. If there is some prior knowledge or data of the system available, it can even be deduced how likely a failure of the insulation system is in the near future.

A similar technique is introduced in two different patents [67], [68]. Two different methods to determine the insulation condition and how close it is to failure are listed. The first one requires the comparison of the impedance response to a response that is recorded after the fabrication of the motor, which can be called its "birth certificate." Another method is to calculate the power that is dissipated in the insulation by either measuring current or voltage across the winding and using the broadband impedance response. This power is then compared to a target value which can be determined by historical data from similar motors.

In contrast to the claim in [66], the use of an impedance meter is suggested in [67]. However, in [68], the measurement of the broadband impedance is accomplished by measuring voltage and current at the machines' terminals and by using Ohm's law.

C. Sequence Components

Several methods based on the sequence components of the machine's impedance, currents, or voltages have been developed for the online detection of turn-to-turn faults in the stator insulation system [34], [69]–[87].

One of the drawbacks of the methods utilizing sequence components is that only a fault, but not the change of the overall condition and thus the deterioration of the insulation system, is monitored.

1) Negative-Sequence Current: The monitoring of the negative sequence current for fault detection is the subject of several papers [34], [69]–[76].

If there is an asymmetry introduced by a turn-to-turn fault, the negative-sequence current will change and can thus be used as an indicator for a fault. The major problem with this method is that not only a turn-to-turn fault contributes to the negative-sequence component of the current but also supply voltage imbalances, motor and load inherent asymmetries, and measurement errors have an effect on this quantity.

The methods suggested in [69] and [70] account for those nonidealities by using the negative-sequence voltage and impedance and a database.

Another way to consider the nonidealities is the use of artificial neural networks (ANNs). A method to determine the negative-sequence current due to a turn fault with the help of those ANNs is proposed in [71]–[73]. The neural network is trained offline over the entire range of operating conditions. Thus, the ANN learns to estimate the negative-sequence current of the healthy machine considering all sources of asymmetry except for the asymmetry due to a turn fault. During the monitoring process, the ANN estimates the negative-sequence current based on the training under healthy condition. This value is compared to the measured negative-sequence current. The deviation of the measured value from the estimated value is an indicator of a turn fault and even indicates the severity of the fault. Another approach using negative-sequence current and an ANN to detect the fault, which is implemented in a LABVIEW environment, is proposed in [74].

The injection of an HF signal superposed to the fundamental excitation in inverter-fed machines has been suggested and examined in [75]. By using reference frame theory and digital filters, the authors show that the negative-sequence component does not depend on the frequency of the injected signal. Thus, it is possible to use a frequency that is substantially higher than the one of the fundamental excitation. The application of an HF signal also minimizes the influence on the machine's operation. To compensate for nonidealities, a commissioning process during the first operation of the machine is suggested.

2) Sequence Impedance Matrix: The calculation of the sequence impedance matrix under healthy conditions is the basis of an approach that is presented in [77]–[81]. A library of the sequence impedance matrix as a function of the motor speed for a healthy machine is used during the monitoring process. The method is not sensitive to construction imperfections and supply unbalances, since they have been taken into account during the construction of the library.

Another robust method with high sensitivity using the sequence component impedance matrix is introduced in [82]. It uses an off-diagonal term of the sequence component impedance matrix and is immune against supply voltage unbalance, the slip-dependent influence of inherent motor asymmetry, and measurement errors.

3) Zero Sequence Voltage: A method utilizing the zero sequence voltage is proposed in [83]. The algebraic sum of the line-neutral voltages is used as an indicator for a turn fault. Ideally, this sum should be zero. The sensitivity is improved by filtering the voltage sum to get rid of higher order harmonics. It is pointed out that the method is not sensitive to supply or load unbalances. In order to take inherent machine imbalances into account, different procedures are suggested. The main drawback of this procedure is that the neutral of the machine has to be accessible.

D. Signature Analysis

1) Axial Leakage Flux: If an induction machine is in perfectly balanced condition, there should be no axial leakage flux present. Due to production imperfection, there is always a small asymmetry in the motor that causes an axial leakage flux. Since a turn fault also creates some asymmetry in the machine and thus some axial leakage flux, the monitoring of this flux can be used for detecting turn faults. This technique has been the topic of several publications [88], [89].

The theoretical and practical analyses carried out show that certain frequency components of the axial leakage flux are sensitive to interturn short circuits. One of the main disadvantages of this method is the strong dependence on the load driven by the motor. The highest sensitivity can be reached under full-load conditions. Another drawback is that a search coil to detect the axial flux has to be installed.

Another publication [90] not only detects turn-to-turn faults but also uses the axial leakage flux to find broken rotor bars and end rings.

2) Current Signature Analysis: Motor current signature analysis is a popular method to detect broken rotor bars and airgap eccentricity [91]–[93]. In [94]–[103], it has been shown that it is also possible to use this technique to detect turn faults. This approach is based on the fact that the magnitude of the stator current harmonics changes after a turn fault developed. The method for detecting a turn fault seems to be subjective though. The various approaches use different frequency harmonics to detect a fault.

For example, in [94], it is suggested to observe the change in the third harmonic and some other frequency components. Unfortunately, the sensitivity of those components under loaded conditions is not very high, and they are also sensitive to inherent motor asymmetry and supply unbalance.

3) Vibration Signature Analysis: Another quantity whose signature analysis can be used to get information about the condition of the insulation system is the electrically excited vibration. This topic has been examined in [104] and [105].

The results show that deteriorated and faulted windings can be identified. It is indicated that the method is good to provide additional information supplementary to other monitoring techniques. Further research has to be made in order to gain full access to the potential of this method. An obvious disadvantage is the required installation of vibration sensors.

E. AI-Based Methods

As mentioned earlier, ANNs can be used to detect stator turn faults in combination with the negative-sequence current [71]–[73]. Recently, several other methods based on artificial intelligence (AI) have been developed to detect turn faults in the stator of induction machines [106]–[111]. The methods use different techniques to identify the faults. The most common ones are expert systems, ANNs, fuzzy logic, or a combination of the latter.

According to Filippetti *et al.* [27], the diagnostic procedure using AI-based methods can be divided into the signature extraction, the fault identification, and the fault severity evaluation.

An advantage of the AI systems compared to traditional diagnosis techniques is that only minimum *a priori* knowledge is required to implement the diagnosis tool. Neither a detailed model of the system to be analyzed nor the modeling of the fault is required. Furthermore, the automation of the diagnostic process is improved by using AI-based systems.

F. PD

A popular, reliable, and very frequently used method for finding problems with the insulation system of medium- and high-voltage machines is the PD method [6], [7], [112]–[115] that can be applied online as well as offline. Unfortunately, it requires the installation of costly additional equipment. For various reasons, the method has not been widely applied to low-voltage machines yet. However, the occurrence of PD in low-voltage motors under application of voltage surges has been subject to several investigations [116], [117], and the possible use of the PD method for low-voltage motors has been recently reported in [118] and [119]. Since the voltage level in low-voltage mains-fed machines is too low to induce PDs, the method is only applied to inverter-fed machines that are subject to repetitive voltage surges. The main problem in this application is that the PDs are overlapped by the voltage surges and thus are difficult to detect. Different methods are suggested, which all entail large complexity and cost. For example, the detection using optical sensors is suggested. However, this method does not seem to be very useful for the application in motors since the windings are at least partially invisible (hidden) and some discharges will therefore be “hidden” from the optical sensor. The cost and complexity of this or other methods seem to be too high to justify the use on comparatively cheap low-voltage motors on a big scale.

A by-product of the PD that can also be used for monitoring the insulation condition is ozone [6].

G. Motor Diagnostics in Specific Environments

Several papers are investigating the possibility of applying various motor diagnosis tools under certain operating conditions [97], [120]–[125]. These operating conditions include mains- or inverter-fed [97], [120]–[122] and torque- or vector-controlled [123]–[125] induction machines.

V. Conclusion

The main objective of this paper is to evaluate existing offline and online-monitoring methods for the stator winding insulation of low-voltage induction machines in order to give researchers and application engineers a broad overview over recent developments in this area, to show the capability and boundaries of those methods, and to point out possible directions for future research activities.

A comprehensive literature survey on the existing methods for low-voltage induction motor winding insulation condition monitoring and fault detection has been presented, and it has been identified that turn-to-turn faults count most for induction motor winding insulation faults [8], [9]. Various online methods have been developed that are capable of identifying a turn fault even in the presence of nonidealities. The offline surge test is not only able to identify a fault but also capable of revealing a weakness in the turn insulation prior to a fault.

Despite all progress made in the field of monitoring motor drive systems, there is still no online-monitoring method widely applied in industries and accepted in the diagnosis community, which is capable of monitoring the deterioration of the turn-to-turn insulation of low-voltage machines.

Thus, based on the survey results, the authors suggest the development of an online-monitoring method applicable to low-voltage machines, which is capable of diagnosing the deterioration of the turn-to-turn insulation prior to a fault and is also reasonable from a cost standpoint.

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