A Survey of Testing and Monitoring Methods for Stator Insulation Systems in Induction Machines

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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 more than 20 existing methods, including the most common methods to assess the phase-to-ground, phase-to-phase, and turn-to-turn insulation conditions. The methods are categorized into as online and offline methods, each of which are further grouped into specific areas according to their physical nature. The paper focuses on turn-to-turn insulation testing and monitoring of low-voltage machines, which is a rapidly expanding area for both research and product development efforts. Finally, a new approach to online monitoring of turn-to-turn insulation faults for low-voltage induction motors is recommended.**

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]. Various surveys on motor reliability have been carried out over the years. In [1], the percentage of motor failures due to problems with the insulation is about 26%. In other surveys the percentage of insulation failures is even higher.

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 that 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 off-shore oil plant, the downtime losses caused by motor failures can be as high as $25,000/hour.

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 [2].

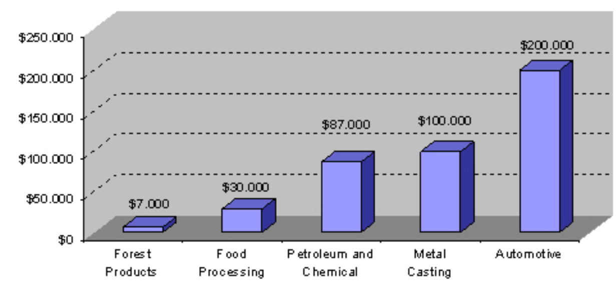

Fig. 1. Average Downtime Cost of Different Industries

There are several different mechanisms that cause the breakdown of the insulation system. The main reasons of winding insulation deterioration as described in [3], [4] are thermal, electrical, mechanical or environmental stress (contamination).

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 [5]. 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). These methods can be divided in two different categories. The first one is offline-testing, which requires the motor to be removed from service; while, the second one is online-monitoring, which can be performed while the machine is operating. An important aspect of each method is whether it is invasive or non-invasive to the machine's normal operation. Non-intrusive methods are always preferred because they only use voltage and current measurements from the

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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 [5], [6]. Therefore, the monitoring of the turn-to-turn insulation's condition is of special interest. For this reason, the main focus of this survey is on methods that can be used to detect faults or monitor the turn-to-turn insulation of low voltage machines. Some popular methods related to medium-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.

Firstly, the insulation-failure mechanisms are analysed briefly. Then, several offline-tests are introduced. Finally, a general approach of developing online methods is discussed and recommendation of future work is suggested.

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

As mentioned above the main cause for stator failures can be divided into four groups [3], [4], [7]: thermal-, electrical-, mechanical- and environmental-stress.

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^o 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 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, influence 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 $600V$ and $5kV$ respectively.

The negative influence of transient voltage conditions on the winding life has been observed in recent years. These transients, that either cause deterioration of the winding 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. Especially 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: Environmental stress can also be called contamination. The presence of foreign material can lead to reduction in the heat dissipation, premature bearing failure or even the breakdown of the insulation system by causing shorts. 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.

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 drive and that a test device can be used for several different machines which saves costs. The offline tests described in the survey are summarized in table I, [3]- [18].

A. Winding Resistance/DC Conductivity Test

With the coil resistance test it is simply checked if there is an unbalance between the resistances of the stator coils. Therefore a well defined DC current is injected and the voltage drop across the coil is measured. If the resistance in one of the coils is lower than in the other coils, this is an indicator of some shorted turns in the coil [5], [8].

This method has no predictive character since it can only detect a fault when it has already occurred.

B. Insulation Resistance (IR) / Megohm Test

The Insulation Resistance test, also called Megohm test, is probably the most widely used test for assessing the phase-to-ground insulation of the stator insulation system [3], [8]–[10]. It has been developed in and used since the early 20th century. The testing method can be applied to all machines and windings except for the rotor of a squirrel cage induction motor.

During the test the motor frame is grounded and a specified test voltage is applied to the motor terminals. Ideally, the measured resistance should be infinitely large. Since there is always a small leakage current present, the value of the insulation resistance can be determined by measuring the leakage current. If the value is too low this indicates that there might be a problem with the insulation.

The voltages to be applied and the insulation resistances to be expected are specified by different standards like IEEE 43-2000, NEMA MG-1-1993 and EASA technical manuals. One of the drawbacks of this method is that the measurement strongly depends on the temperature at which the test is done. In order to compensate for that there are methods for converting the IR value to a standard temperature [8].

C. Polarization Index (PI)

The PI test is a variation of the IR test and is performed at the same voltage level. The PI test measures the groundwall insulations ability to polarize. This is done by measuring the IR after one minute and after ten minutes and calculating the ratio of those two values. Usually the polarization index should be ”high” if the insulator is in a good condition [3], [8]–[10]. The minimum acceptable values of the PI are determined by different standards like IEEE 43-2000.

The current between the copper of the windings and the stator core consists of different components: a capacitive current, conduction current, surface leakage current and an absorption current. The ones that are of interest are the conductive and the leakage current. The capacitive current decays quickly. It has been shown empirically that the absorption current is first very high and vanishes after approximately ten minutes. Thus the PI value shows us how large the leakage and conductive currents are compared to the absorption current. If the PI ratio is close to one this indicates that there might be a problem with the insulation condition.

An advantage of the PI test compared to the IR test is its insensitivity to the temperature at which the test is performed.

D. DC High Potential Test (DC HiPot)

The DC High Potential Test shows the groundwall insulations ability to withstand high voltages without exhibiting large leakage currents or even breaking down. The voltages applied are substantially above the normal operation voltages. If the insulation is able to work under those conditions, it is very likely that under normal operating conditions there won’t be any major problems that will cause the insulation to fail in the near future [3], [8]–[10]. The magnitude of the test voltage and the way the test should be conducted are again described by various standards like IEEE 95, IEC 34.1 or NEMA MG-1.

The major problem with the HiPot test is, that it can be destructive in case of an insulation breakdown even though the machine might still have been able to operate for a long time. A breakdown usually results in a costly repair of the machine.

E. AC High Potential Test (AC HiPot)

The principle of the AC HiPot test is similar to the one in DC HiPot testing. Instead of a DC voltage an AC voltage of 50 or 60 Hz is applied to the groundwall insulation. Sometimes a test frequency of 0.1 Hz can be employed [3], [9], [10].

The AC Hipot test basically has all the features described in the DC Hipot test. The main difference between AC and DC is the voltage distribution. In the DC case the amount of voltage dropped across an element depends on its resistance (resistivity). In the AC case the voltage distribution depends on the capacitance of the element (dielectric constant).

F. Surge Test

About 80% of all electrical failures in the stator originate from a weak turn-to-turn insulation [6]. None of the tests described above 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 [3], [5], [6], [8], [11], [12].

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

In praxis a capacitor is charged up to a specified voltage level and subsequently discharged in one of the motor windings. In a first order approximation the capacitor and the motor present a 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 has been a lot of controversy about the risk of surge testing [13]–[15]. A comprehensive study about this issue disproves the statement that surge testing significantly reduces the lifetime of a machine [11], [12]. The effect of the surge rise time is also a topic that has been widely discussed [16].

G. Other Test Methods

Some other offline-tests that should just be mentioned here are the Offline-Partial-Discharge test [3], [17], which is only applicable to medium and high voltage machines, the Dissipation-Factor test [3], [18] and the Inductive-Impedance test [3].

IV. ONLINE-MONITORING

Various monitoring methods have been developed using different physical quantities to detect the health condition of the stator insulation system [3], [4]. 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 [19], [20], 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 [3]. However, many sensorless and non-intrusive 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 [21]. Therefore, the online monitoring can become non-intrusive without the need of additional sensors and installations. The online-monitoring techniques described in the survey are summarized in table II, [22]- [54].

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 [3]. In many motors 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 (RTD) or thermocouples. Recently there has also been a lot of work done on temperature estimation techniques [22]–[25]. 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 [26].

B. Condition Monitors and Tagging Compounds

Condition monitors and tagging compounds have been used in motor monitoring for over 30 years. The condition monitors can be described as ”smoke detectors” [3]. Basically they detect particles that develop when the windings are at a very high temperature and the insulation system is close to failure. In order to improve the sensitivity tagging compounds can be used in addition [26]. Tagging compounds are paints that emit particles with unique chemical signatures at specified high temperatures. These particles can easily be detected with the condition monitor and thus indicate if a certain motor temperature is reached.

C. Leakage Currents

This method was first suggested in [27] and examined in more detail in [28]. It is a non-invasive monitoring method based on the measurement of the differential leakage currents at the terminal box. A simple insulation system model is developed, that allows the calculation of an equivalent capacitance between phase-ground (PG) and phase-phase (PP) as well as the dissipation factor.

The continuous measurement and determination of those values allow to draw conclusions about the condition of the overall insulation system trended over time. An increase or a decrease of the capacitance and the dissipation factor even give us an idea of the cause of the deterioration. Even though this method is capable of detecting changes in the PG and PP insulation system it does not indicate a deterioration of the turn-to-turn insulation.

D. High Frequency Impedance/Turn-to-Turn Capacitance

A non-intrusive condition monitoring system using the high frequency response of the motor is introduced in [29]. It is able to observe the aging and thus the deterioration of turn-to-turn insulation by detecting small changes in the stator windings turn-to-turn capacitance.

It is shown that the turn-to-turn capacitance of the stator winding and thus its impedance spectrum is changing under the influence of different aging processes. Since it is not possible to use an impedance analyser for the purpose of an online-test it is suggested to inject a small high frequency (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 [30], [31]. Two different methods to determine the insulations 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

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

	References	Insulation Tested	Diagnostic Value	Advantages and Disadvantages
Winding Resistance/ DC Conductivity Test,	[3], [5], [8]	turn-to-turn	detects shorted turns	(+)easy to perform, (-)only detects faults, (-)no predictive value
Insulation Resistance (IR)/ Megohm,	[3], [8]- [10]	phase-to-ground	finds contaminations and major defects	(+)easy to perform, (-)result is strongly temperature dependent
Polarization Index (PI)	[3], [8]- [10]	phase-to-ground	finds contaminations and major defects	(+)easy to perform, (+)less sensitve to temperature than IR-test
DC High Potential Test (DC HighPot),	[3], [8]- [10]	phase-to-ground	finds contaminations and major defects	(+)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),	[3], [9], [10]	phase-to-ground	finds contaminations and major defects	(+)more effective than DC HighPot, (-)not as easy to perform as DC HighPot
Surge Test,	[3], [5], [6], [8], [11]- [16]	turn-to-turn	detects deterioration of the turn insulation	(+)only test that measures the integrity of the turn insulation
Offline Partial Discharge,	[3], [17]	phase-to-ground turn-to-turn	detects deterioration of the insulation system	(+)good practical results, (-)not applicable to low-voltage machines, (-) difficulty in interpretation of the data
Dissipation-Factor	[3], [18]	phase-to-ground phase-to-phase	detects deterioration of the phase and groundwall insulation	(-)measurements on a regular basis have to be made in order to trend the obtained data over time, (+)capable of determining the cause of deterioration
Inductive Impedance	[3]	turn-to-turn	detects shorted turns	(-)not as easy to perform as the Winding Resistance test, (-)no predictive value, (-)undesired foreign influence on result

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 [29] the use of an impedance meter is suggested in patent [30]. However, in patent [31] the measurement of the broadband impedance is accomplished by measuring voltage and current at the machines terminals and using Ohm’s Law.

E. 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 [32]- [45].

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 [32]- [38].

If there is an asymmetry introduced by a turn-to-turn fault the negative sequence component 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 components, but also supply voltage imbalances, motor and load inherent asymmetries and measurement errors have an effect on this quantity.

The methods suggested [34] and [35] account for those non-idealities by using the negative sequence voltage and impedance and a database.

The use of (ANN) in order to determine the negative sequence current due to a turn fault is proposed in [36]–[38]. 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 off 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.

2) Sequence Impedance Matrix: The calculation of the sequence impedance matrix under healthy conditions is the basis of an approach that is presented in [39]–[43]. 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 [44]. 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 [45]. 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.

F. 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 topic of several publications [46], [47].

The theoretical and practical analysis carried out show that certain frequency components of the axial leakage flux are sensitive to inter-turn short circuits. One of the main disadvantages of this method is the strong dependency 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.

2) Current Signature Analysis: Current signature analysis has been used to detect different motor problems like eccentricity. In [48]- [51] 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 change after a turn fault developed. The method for detecting a turn fault seems to be subjective though. The harmonics used in the different approaches use different frequency harmonics to detect a fault.

In [48] 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.

An approach that uses the rotor slot harmonics, which are reflected in the stator current, is shown in [49], [50].

In [51] the effect of interturn short circuits on the MMF reflected in the frequency spectrum of the line current has been investigated. Despite the ability to detect a turn fault, it is advised to carry out further investigations.

3) Vibration Signature Analysis: Another quantity whose signature analysis can be used to information about the condition of the insulation system is the electrically excited vibration. This topic has been examined in [52], [53]. 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.

G. Partial Discharge

A popular and reliable method for medium and high voltage machines is the partial discharge (PD) method [4], [54]. Unfortunately it requires the installation of additional sensors and is not applicable to low voltage machines. A by-product of the PD that can also be used for monitoring the insulation condition is ozone [3].

V. Recommendations for Future Work

The main objective of this work is to evaluate existing offline and online monitoring methods for motor winding insulation deterioration and suggest future research directions for incipient insulation fault detection. It has been identified that turn-to-turn faults count most for induction motor winding insulation faults [5], [6]. However, the existing methods applicable to low-voltage machines and widely accepted in industry are all based on offline tests.

Offline-testing is only done once in a while and problems that occur in the mean time cannot be predicted. Therefore, an online turn-to-turn fault detection method is needed, which is another focus of this work. Based on the survey results, some initial investigation has been performed. The approach introduced in [29]- [31] monitors the broadband impedance of the motor. This method seems to be promising, but has not been applied and tested widely. The surge-voltage test, on the other hand, is widely accepted and used in industry. However, it is only applicable when the motor is not in service.

The development of an online monitoring method based on the idea of the surge test would be a potential solution to the motor turn-to-turn fault monitoring. However, there are many things that have to be taken into consideration. The loading conditions while the motor is offline and that while the motor is in service are largely different. The influence of the supply also has to be taken into consideration. It has to be investigated if a change in the inductance induced by the surge can be monitored with an appropriate sensitivity. Another challenge is how to choose and generate a proper voltage level for the surge pulse. It is very likely that during an online-monitoring process the voltage level of the surge can be reduced significantly compared to the offline-test.

Further research and testing has to be done to verify and implement a concept, which is capable of diagnosing the deterioration of the turn-to-turn insulation at an early stage.

VI. Conclusions

A comprehensive literature survey on the existing methods for induction motor winding insulation condition monitoring and fault detection has been presented in this paper.

The only offline-test for low-voltage machines that is capable of detecting a turn-to-turn fault as well as the deterioration of the turn insulation is the surge test. There are several monitoring techniques that are able to detect turn faults but not to monitor the deterioration of the winding insulation. A promising approach that is capable of monitoring the condition of the turn insulation is suggested in [29]- [31]. It observes the broadband impedance of the motor and is able to diagnose problems with the turn insulation by detecting changes in the impedance before a failure occurs.

Despite all progress made in the field of monitoring motor drive systems there still is no online-monitoring method widely

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

	References	Insulation Monitored	Diagnostic Value	Advantages and Disadvantages
Temperature Monitoring	[3], [22]- [26]	phase-to-ground turn-to-turn	detects deterioration in groundwall and faults in turn insulation	(-)a lot of data and additional information like ambient temperature required, (-)invasive if sensors are required
Condition Monitors and Tagging Compounds	[3], [26]	phase-to-ground turn-to-turn	detects faults and problems with groundwall and turn insulation	(-)invasive → equipment for detection of particles required
Leakage Currents	[27], [28]	phase-to-ground phase-to-phase	detects deterioration of the phase and groundwall insulation	(+)non-invasive,(+)capable of determining the cause of deterioration
High Frequency Impedance/ Turn-toTurn Capacitance,	[29]- [31]	turn-to-turn	detects deterioration of the turn insulation	(+)only technique that monitors turn condition, (-)not testedwidely yet, (-)invasive (search coil)
Negative Sequence Current,	[32]- [38]	turn-to-turn	detects turn faults	(+)non-invasive, (+)compensation of non-idealities possible
Sequence Impedance Matrix	[39]- [44]	turn-to-turn	detects turn faults	(+)non-invasive, (+)compensation of non-idealities possible
Zero Sequence Voltage	[45]	turn-to-turn	detects turn faults	(+)non-invasive, (-)neutral of the machine has to be accessible, (+)compensation of non-idealities possible
Axial Leakage Flux	[46], [47]	turn-to-turn	detects turn faults	(-)invasive (search coils), (-)results strongly depend on the load
Current Signature Analysis	[48]- [51]	turn-to-turn	detects turn faults	(-)interpretation of results subjective, (-)further research required to generalize results
Vibration Signature Analysis	[52], [53]	turn-to-turn	detects turn faults	(-)invasive (accelerometer), (-)further research required to generalize results
Online Partial Discharge	[4], [54]	phase-to-ground turn-to-turn	detects deterioration of the insulation system	(-)not applicable to low-voltage machines, (-)difficulty in interpretation of the data, (+)good practical results
Ozone	[3]	phase-to-ground turn-to-turn	detects deterioration of the insulation system	by-product of PD, (-)invasive (gas analysis tube or electronic instrument)

applied in industry that is capable of monitoring the turn-to-turn insulation of low-voltage machines. Thus, based on the survey results, the authors suggest that an online surge testing method could be developed which is capable of monitoring the stator's turn-to-turn insulation condition and applicable to low-voltage machines.

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