A New Concept for Online Surge Testing for the Detection of Winding Insulation Deterioration in Low-Voltage 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. Preventive maintenance and online monitoring are some of the methods to improve the reliability and to reduce unscheduled downtime. One of the main reasons for the failure of the machine is the breakdown of the stator turn insulation. The offline surge test is the most commonly used offline test to assess the condition of the turn insulation. There is no online monitoring method that is applicable to low-voltage machines and has the same capabilities as the surge test. This paper introduces new concepts to implement an online surge test. The possibilities and limitations of the online surge test are presented, as well as the simulation and experimental results, to validate the concepts.**

***Index Terms*—Induction machine, motor diagnostics, online testing, surge test, turn insulation failure.**

I. Introduction

ELECTRICAL machines are an important component in industrial applications. It is estimated that more than 60% of the electrical energy in industry is consumed by electric machines [1]. The unscheduled process downtime caused by a failure of an electrical machine can cause enormous costs. In some settings, an electrical machine failure can cause entire assembly lines to stop and thus interrupt the production process. It is therefore desirable that a problem with the critical components of the motor like the bearing or the stator insulation system is identified at an early stage in order to perform a scheduled machine service or replacement. The economic losses of the process downtime caused by an unexpected outage of the machine exceed the machine maintenance costs to a considerable extent. On an offshore oil plant, for example, the downtime losses caused by motor failures can be as high as \$25 000/h [2].

The most common reasons for a breakdown of electrical machines are bearing failures and failures related to the stator insulation [3]–[5]. Stator faults account for a large percentage of the machine failures. About 80% of all electrical failures in the stator originate from a weak turn-to-turn insulation [6]. A turn fault can propagate and quickly develop into a ground fault. This may result in significant damage to the machine stator core, which will require it to be repaired or replaced before a stator rewind can be completed. Thus, the turn insulation is one of the most critical components to be monitored. There are several online methods that are capable of detecting solid turn faults which are most commonly based on the signature analysis of a suitable motor quantity like the current or the analysis of a sequence component of the motor impedance matrix or the current [7], [8]. Despite all the progress made in the field of stator monitoring, there is still no commonly used method that is able to not only diagnose a solid turn fault but also detect the deterioration of the turn insulation. The only test that is capable of finding a weakness prior to the breakdown of the stator insulation and applicable to low-voltage machines is the surge test, which is conducted when the machine is not operating [7], [9].

This paper proposes a method of how to apply the surge test to an operating machine. The criteria used for the evaluation of the online results are briefly introduced, and some of the practical challenges are described. Simulation and experimental results are presented to validate the proposed technique. A brief synopsis of the offline surge test is given as well.

II. Offline Surge Test

The surge test is a very commonly used offline test to assess the integrity of the turn-to-turn insulation of the stator. The benefits and dangers of the surge test have been discussed elaborately in the literature, and the methods to conduct and evaluate the measurements have continually been improved over the years [6], [7], [9]–[17]. There is no other offline or online test that is applicable to low-voltage machines with a similar capability. For example, the partial discharge test is

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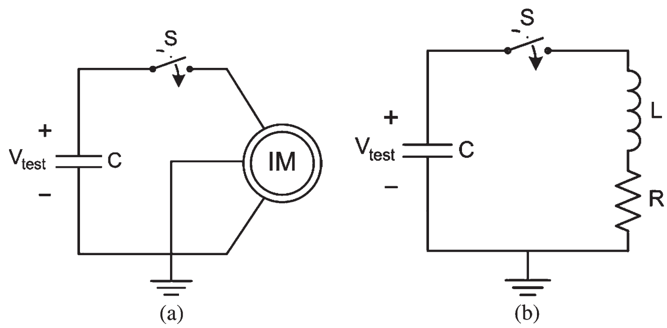


Fig. 1. Offline surge test schematic. (a) Surge test setup. (b) Equivalent circuit for the surge test.

applicable to medium- and high-voltage machines only, and other methods like the winding resistance test or the inductive impedance test can detect a solid turn fault only due to the imbalances in the resistance or inductance, respectively.

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 exceeds the maximum voltage that the insulation can withstand, there will be an arc developing, and the inductance of the coil will be modified for a short time. This process can be detected by observing the impulse response of the motor, which is also called the surge waveform. In a practical application, a capacitor is charged up to a specified voltage level and subsequently discharged in one of the motor's windings. The schematic is shown in Fig. 1(a) and (b).

In a first-order approximation, the capacitor and the motor present an RLC series circuit. If there is a short circuit 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. The ringing frequency of the damped sinusoidal waveform can be determined by solving the RLC series circuit shown in Fig. 1(b) for the damped resonance frequency [15]

$$f = \frac{1}{2\pi}\sqrt{\left(\frac{1}{LC} - \frac{R^2}{4L^2}\right)} \tag{1}$$

where R is the overall resistance, L is the motor's inductance, and C is the surge capacitance.

By applying voltages that are significantly higher than the rated voltage of the machine, a weakness in the insulation that is not apparent under rated conditions can be found. The recommended test voltages can be found in IEEE 522 [15] and NEMA MG1 [16]. As a rule of thumb, the maximum test voltage can be determined by [11]

$$V_{\max} = 1000\ \mathrm{V} + 2 * V_{\mathrm{rated}}. \tag{2}$$

Some of the topics investigated in the research related to the surge test are the risk of performing a surge test [14], [18]–[20], the analysis of the voltage distribution, and the effect of the surge rise time [21]–[23].

In recent years, different methods to conduct and evaluate the surge test have been developed, as well as reliable test equipment that makes it easy to perform the surge test. A common method to evaluate the surge test is the error area ratio (EAR). It is very sensitive and detects a difference between two waveforms that is difficult to observe visually. The EAR is determined by the following equation [14]:

$$\mathrm{EAR} = \frac{\sum_{i=1}^{N}\left|F_i^{(1)} - F_i^{(2)}\right|}{\sum_{j=1}^{N}\left|F_j^{(1)}\right|} * 100 \tag{3}$$

where $F_i^{(1)}$ is the ith point of the first waveform (reference waveform), $F_i^{(2)}$ is the corresponding point of the second waveform (test waveform), and N is the number of data points that are compared. Two identical waveforms will have an EAR of 0%.

The EAR can be applied in different ways. A method called the pulse-to-pulse EAR (P–P EAR) that is immune to the effects of rotor position, rotor condition, winding configuration, motor connection, iron condition, and saturation is the most robust and reliable evaluation method for the surge test. During the test using the P–P EAR, the voltage is increased in well-defined steps. Successive waveforms are evaluated by using the EAR. Since the test voltage level is increased, the EAR will be $> 0\%$. If the EAR changes by more than the value expected, this is an indicator for arcing and, thus, for a weak turn-to-turn insulation.

III. Online Surge Test

A comprehensive literature survey has shown that there is no equivalent to the offline surge test in online applications [8]. In order to overcome this limitation, an investigation on the applicability of the surge test to an operating machine is investigated. A rather general schematic of the online test configuration is shown in Fig. 2. The surge capacitors are connected at the phase terminals of the motor under test through insulated-gate bipolar transistor (IGBT) switches. The device must be able to test each phase of the motor. This can be accomplished by the configuration depicted, for example, yet other configurations are conceivable, too. Since only a single capacitor is needed at a time, multiple switches to connect this capacitor to the phase under investigation can be used to conduct the test. In an online test, the capacitor discharges not only through the investigated coils of the motor but rather through the line leads, i.e., the energy-supplying circuit. The impedance of the line leads at the frequencies of interest is well depicted by a serial combination of a resistor and an inductor. Looking into the network from the side of the surge capacitor, the mains output impedance is placed in parallel to the motor impedance. For simplicity, the mains output impedance will be called the supply impedance in the following discussion. Similarly, the resistive part and the inductive part of this impedance will be called the supply resistance and supply inductance, respectively.

A simplified one-phase equivalent circuit is shown in Fig. 3, where L_1 and R_1 are the supply inductance and resistance, L_2 and R_2 are the equivalent motor inductance and resistance, C is the capacitance of the surge tester, and S is the IGBT switch.

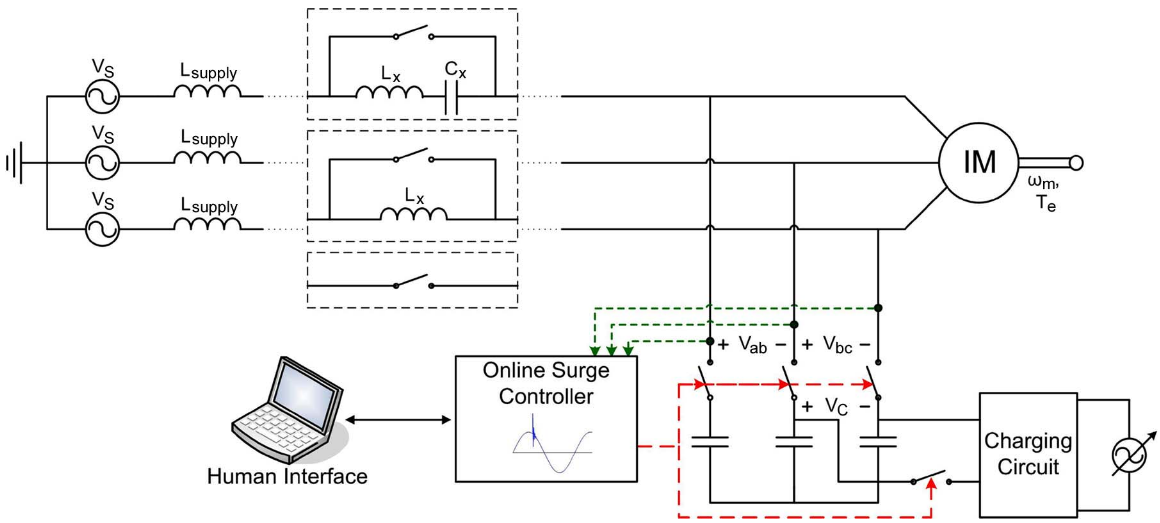


Fig. 2. Basic online surge schematic with additional supply impedance.

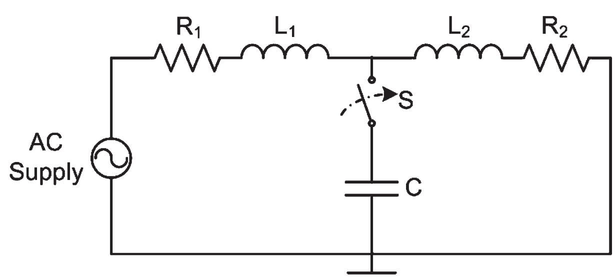


Fig. 3. Single-phase equivalent circuit of the online surge test.

If all resistance is neglected, the frequency of the surge waveform can be determined as

$$f_n = \frac{1}{2\pi\sqrt{C\frac{L_1 L_2}{L_1+L_2}}} \tag{4}$$

where L_1 is the supply inductance, C is the surge capacitance, and L_2 is the equivalent motor inductance, as shown in Fig. 3. The equivalent motor inductance is approximately equal to the combined leakage inductance of the motor in the vicinity of the surge test frequency.

From (4), it can be shown that, for a supply inductance much smaller than the equivalent motor inductance $(L_1 \ll L_2)$, the resonance frequency is mainly determined by the supply inductance

$$f_n \approx \frac{1}{2\pi\sqrt{CL_1}}. \tag{5}$$

A comparison to the offline test can be made to show the impact of the supply inductance on the test result. The equation for the oscillatory frequency of the offline test can be obtained from (4) by letting L_1 grow to infinity. The frequency is then $f_n = 1/(2\pi\sqrt{CL_2})$. Thus, the frequency is determined only by the motor's equivalent inductance L_2. However, in the online configuration, the frequency is determined mainly by the smaller equivalent supply inductance L_1 as shown in (5). Therefore, a modification of the motor's inductance (L_2) in the online configuration due to a breakdown of the turn insulation will have an impact on the surge waveform much smaller than in the offline test. A decrease of the ratio between the supply inductance and the motor leakage inductance results in a decrease of the test sensitivity. If no provisions are taken, a weakness in the turn insulation of the motor cannot be detected due to the small supply impedance.

One option to realize the application of the online surge test is to increase the supply impedance. Of course, the disruptive effect of this impedance enhancement on the operation of the machine has to be kept to a minimum. This requires a method of turning the impedance "on and off" in such a way that it is only present during the test and has almost no influence on the steady-state operation of the motor. The transients during the insertion and removal of the impedance should not be disruptive. The frequency of the surge test waveform can be adjusted to be more than two orders of magnitude higher than the operating frequency. An ideal supply impedance under these conditions would be zero around the fundamental operating frequency and infinitely large around the frequency of the surge transient.

Such an ideal supply impedance is physically not realizable, although some implementation can exhibit features close to those required. For the realizable impedances, there will always be a tradeoff between how much the operation of the machine will be affected and how high the sensitivity of the test will be. In addition, there is a practical limit on the components of this hypothetical impedance determined by the current and the voltage ratings of the motor.

Fig. 4 shows the frequency characteristics of the ideal supply impedance and the three realizations that can be used to separate the motor from the supply during the test. The basic schematic of the online test configuration is shown in Fig. 2, where only one of the different impedances shown in the dashed boxes is added to all three phases. The impedances investigated are as follows:

1) a series LC resonant circuit with a resonance at 60 Hz;
2) the disconnection of the motor;
3) an additional inductive impedance.

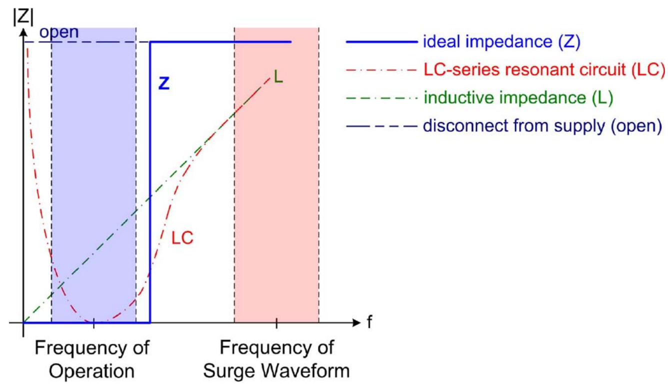


Fig. 4. Frequency characteristics of supply impedances suggested to separate the motor from the supply.

Clearly, the series LC resonant circuit comes closest to the ideal impedance around the frequencies of interest. However, the analysis shows that this impedance can introduce motor instability and is therefore unsuitable. The phenomenon leading to instability is called subsynchronous resonance and has been investigated in [24].

Disconnecting the motor for a short time offers the most auspicious test conditions due to the infinite impedance in the supply line but also poses the biggest disturbance to the operation of the machine. To avoid voltage spikes, the motor can be disconnected only when the current is zero. The duration of the disconnection has to be kept short in order to avoid a large drop-off in speed and large transients when the motor is reconnected to the supply after the application of the surge.

More details, as well as simulation results for the insertion of a series LC resonant circuit and the disconnection of the machine, are shown in [25].

The simplest choice of performing an online test is the insertion of an additional inductance, which is also the most suitable method for a practical application. The sensitivity of the test will be lower than that for a machine disconnected or for the offline test, respectively, but it will still be high enough to detect a turn insulation problem for an appropriate impedance. The reduction in frequency sensitivity can be determined as follows. The frequency of the surge waveform will approximately be determined by (4). The frequency sensitivity is given by the following equation:

$$S_\omega = \frac{\Delta\omega/\omega}{\Delta L/L} = -\frac{1}{2}\frac{L_2}{L_1 + L_2} \tag{6}$$

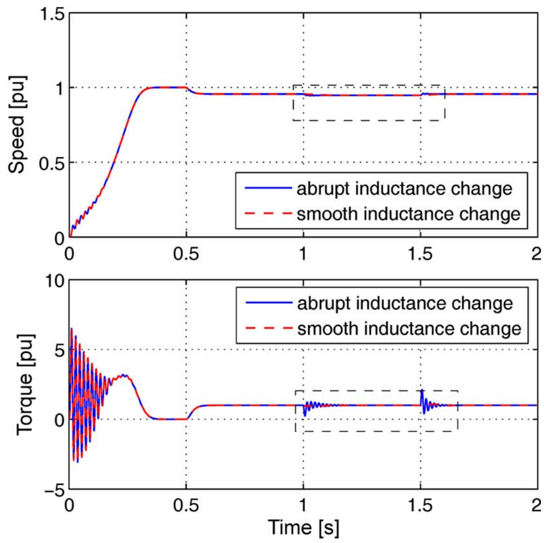
where L_1 is the equivalent inductance of the motor and L_2 is the supply inductance. The thorough derivation of the frequency and EAR sensitivity is beyond the scope of this paper and will be discussed in more detail in future publications. If, for example, the supply inductance chosen is equal to the equivalent motor inductance $(L_1 = L_2)$, the frequency of the surge waveform will increase by a factor of $\sqrt{2}$, and the frequency sensitivity will decrease by a factor of two, compared to the offline test $(S_\omega = -1/4)$. A bigger supply inductance results in a higher sensitivity of the test. The disadvantage of a bigger inductance is the increase in the voltage drop across the inductor. For high currents and voltages, the geometrical size of the proper inductor might be an additional drawback.

There are different options for inserting the additional supply inductor, i.e., for how to switch it on and off. Two different approaches are to be distinguished here: an abrupt inductance transition and a smooth inductance transition. The abrupt inductance transition refers to a supply inductance that is changed in a stepwise fashion. This can be achieved by installing a switch in parallel to the supply inductance that is closed during normal operation (bypass mode) and open during the test (test mode). Another solution is to use a transformer with a switch on the secondary that is closed during operation and open during the test. If the switch is closed, the leakage inductance, which is negligibly small, is seen on the primary. When the switch is open, the sum of primary leakage and magnetizing inductances is seen on the primary. The switching of the inductor has to be synchronized with the zero crossings of the line current to mitigate voltage spikes.

A smooth inductance transition refers to a supply inductance with a gradual transition between a low value, that it assumes during operation, and a high value, which is suitable for the test. The advantage of this method is that the transients in current, torque, and speed during the modification of the inductance are significantly smaller than for an abrupt change of the inductance. Even if the inductance is increased when the current is nonzero, there will be no voltage spikes. In order to illustrate the difference between the transients in torque and speed for the abrupt and the smooth inductance transitions, a simulation has been implemented in MATLAB. The inductance simulated changes linearly between its minimum $(10^{-5}$ p.u.) and maximum values (0.2 p.u.). The transition time between the lowest and highest inductance values for the smooth change is 0.1 s. The machine is operated at rated load and has a combined leakage inductance of 0.2 p.u. The results are shown in Fig. 5.

The oscillations in torque and speed for the smooth inductor change are negligible compared to the oscillations caused by the abrupt inductor change. The disadvantage of the smooth inductor change is a significant increase in hardware requirements and control complexity. An example for an inductor that can perform a smooth change in inductance is given in [26].

A simulation of the online surge test has been implemented in MATLAB/Simulink to show the influence of the supply inductance on the surge waveform. Fig. 6 shows the surge waveform for an initial capacitor voltage of 4.34 p.u. (equivalent to 2000 V for a 460-V line–line voltage). The supply inductance is chosen equal to the combined leakage inductance of the motor. For comparison, the offline surge waveform is depicted, as well as the test results without an additional supply inductance (i.e., the supply impedance switch is closed during normal operation and during the test). The addition of the supply inductance only makes it possible to conduct the surge test online. Without the additional supply inductance, the frequency of the waveform is significantly higher while the influence of the motor inductance on the waveform becomes negligible.



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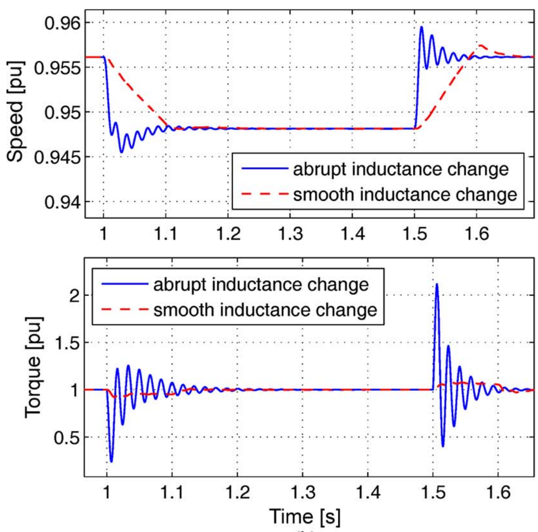
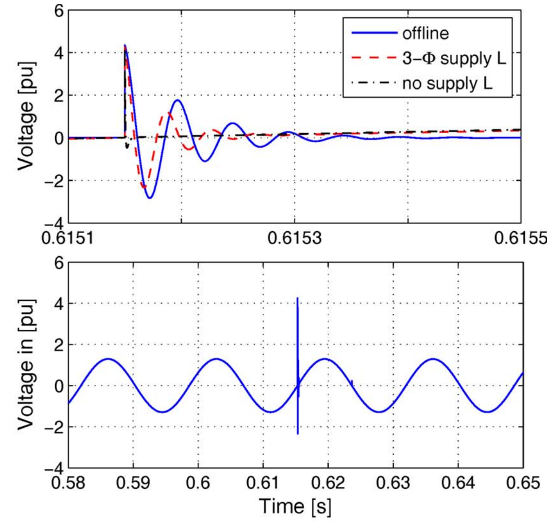


(b)

Fig. 5. Simulation results for the abrupt and smooth inductance changes of the additional supply inductor. (a) Torque and speed transients for the abrupt and smooth inductance changes. (b) Close-up of (a).



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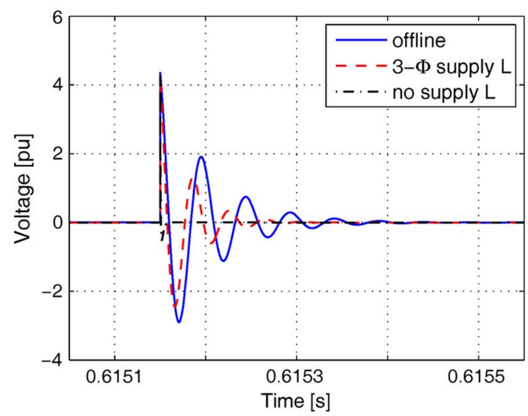


(b)

Fig. 6. Simulation results for the online surge test with an additional supply inductance in all three phases. (a) Online surge waveform for the additional supply inductance in all three phases compared to the offline waveform and the online waveform without additional supply impedance. (b) Online surge waveform for the additional supply inductance in all three phases with fundamental removed.

IV. Execution and Evaluation of the Online Surge Test

The execution of the surge test requires the application of multiple impulses to the motor at increasing voltage levels. The voltage is increased in well-defined increments of ΔV (e.g., 50 V) up to a maximum test voltage or to the level where insulation breakdown is detected. In the offline test, there is no restriction to the point of time when the capacitor can be discharged since no other voltage is applied to the machine. In the online test, the discharge of the capacitor has to be synchronized with the operating voltage. In order to have a well-defined test voltage, the moment that is the most suitable for the discharge of the capacitor is the zero crossing of the line–line voltage. If a different point of time is chosen for the capacitor discharge, the line–line voltage at that point has to be determined and taken into account, which increases the control complexity.

The surge test requires the capacitor to be discharged multiple times. If the supply impedance is increased by disconnecting the motor, transients as shown in [25] occur each time the capacitor is discharged. However, if an additional impedance is used, the operation of the motor is hampered by the transients as shown in Fig. 5 and [25] during the test only once. The impedance can be turned on before the first capacitor discharge and turned off after the last capacitor discharge and does not have to be switched on and off continually, i.e., the supply impedance will be in the test mode until the final test voltage is reached. This feature makes the use of an additional supply inductance more practical than the temporary disconnection of the motor.

A major drawback of the online test compared to the offline test is the change of the rotor position. In [27], it is shown that a change in inductance due to a change in the rotor position is reflected in the surge waveform. During the offline test, the rotor does not change its position, and thus, the test result is not affected by rotor eccentricity or rotor slotting. The most suitable moment to conduct the online test is at the zero crossing of the line–line voltage. If the motor is operated at no load, the slip is close to zero, and the rotor position does not change significantly with respect to the zero crossings of the line–line

TABLE I
PARAMETERS OF THE MOTOR UNDER TEST

P_{rated}	5 (hp)
$poles$	4
V_{rated}	230 (V)
I_{rated}	12.4 (A)
N_{rated}	1745 (rpm)
R_s	0.47 (Ω)
R_r	0.33 (Ω)
L_m	73.1 (mH)
L_{ls}	2.5 (mH)
L_{lr}	3.8 (mH)
Number of turns per phase	Two parallel windings each with 108 turns

voltage. On the contrary, if the motor drives some load and the slip is considerably different from zero, the zero crossing of the line–line voltage and the particular rotor position change during operation. If the test is only synchronized with the line–line voltage and not with the rotor position, the test result can be influenced by the change in inductance, and a false alarm might be triggered. Therefore, the effect of the rotor eccentricity or rotor slotting has to be taken into account when the test is conducted. More investigations will have to be made on the effect of eccentricity on the surge waveform compared to the effect of a turn fault. A solution based on some statistical method is conceivable. Another way to take into account the nonidealities like rotor eccentricity or rotor slotting is the use of a rotor position sensor or a position estimation. The test is only conducted when the zero crossing of the test voltage coincides with a particular rotor position during the test.

The evaluation of the waveform is similar to the evaluation of the offline test. A high-pass filter can remove the fundamental of the line–line voltage, and consecutive waveforms will be compared via EAR or zero crossings. An increase in the EAR above a certain value or a shift in the waveform indicates a turn insulation problem.

V. EXPERIMENTAL SETUP AND RESULTS

In [28], the application of the surge test to a machine operating under no load was shown. For simplicity and to avoid the effects of rotor eccentricity and rotor slotting on the surge waveform [27], the experimental validation is performed with a machine that is not rotating, i.e., the supply voltage is zero, but has additional inductors connected on the supply side. One terminal of the supply inductors is connected to the machine under test, and the other terminals are connected in wye. To distinguish this test configuration from an offline test and a real online test, this test setup is labeled online configuration.

A circuit for the online application of the surge test has been developed to verify the effect of the supply inductance on the waveform. The IGBT switches are controlled by a microcontroller. For the verification of the prototype, its results have been compared to the results obtained with a commercial test device. The machine under test has been rewound and can simulate a turn fault of one, two, or three consecutive turns. The machine parameters are given in Table I. The combined leakage inductance of the motor is $L_l = L_{ls} + L_{lr} = 6.3$ mH.

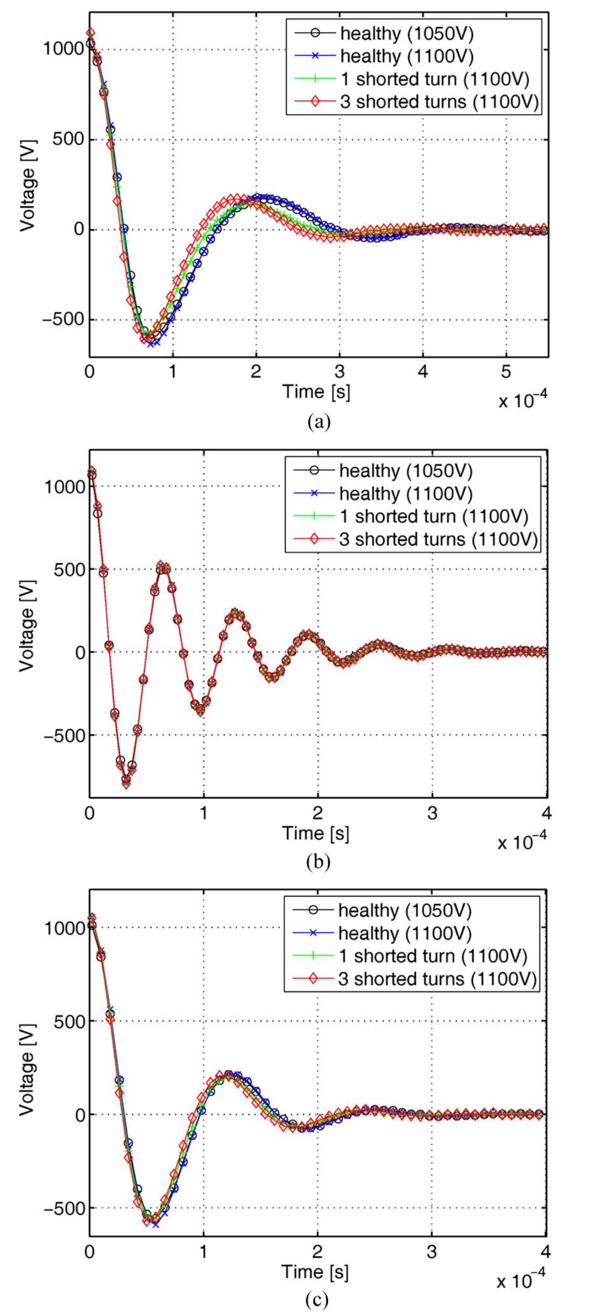
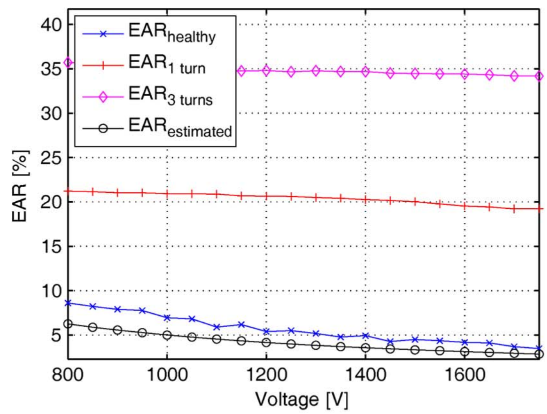


Fig. 7. Experimental results for a surge test applied to a healthy motor and a motor with one shorted turn and three shorted turns, respectively. (a) Offline surge test. (b) Surge test in the online configuration with 250-μH supply inductance. (c) Surge test in the online configuration with 9-mH supply inductance.

Two different sets of inductors are used as supply inductors. Each inductor of the first set has an inductance of 250 μH, and the inductors of the second set have an inductance of 9 mH each. The capacitance of the prototype circuit is 33 nF. To evaluate the test, the EAR is used as defined in (3). The test is performed offline and in the online configuration with 250 μH and 9 mH as supply inductances, respectively. The physical dimensions of the inductors are 4 in $\times$ 3 in $\times$ 3.5 in. The EAR is calculated between surge waveforms received for consecutive test voltage levels, e.g., for $V_1 = 1050$ V and $V_2 = 1100$ V. The plot labeled EAR_{healthy} is obtained for consecutive surge



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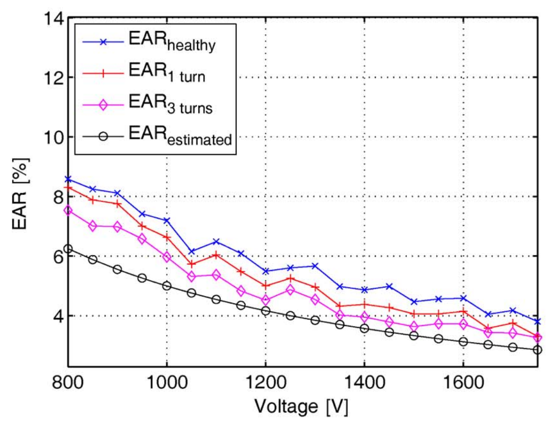

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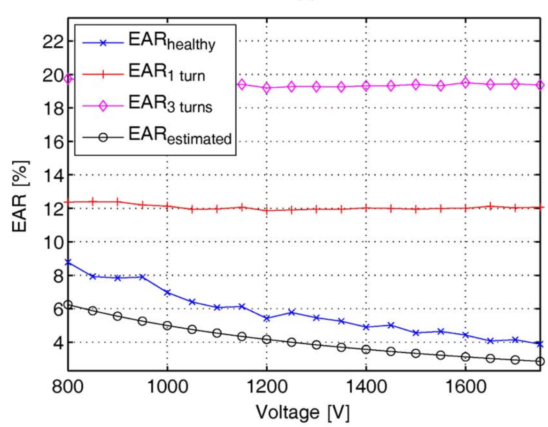

(c)

Fig. 8. EAR for the surge test applied to a healthy motor and a motor with one shorted turn and three shorted turns, respectively. (a) EAR obtained for an offline surge test. (b) EAR obtained for a surge test in the online configuration with 250-μH supply inductance. (c) EAR obtained for a surge test in the online configuration with 9-mH supply inductance.

waveforms obtained with the healthy machine. The curves $EAR_{1\,\mathrm{turn}}$ and $EAR_{3\,\mathrm{turns}}$ are acquired for V_1 measured with the healthy machine and V_2 measured with the faulty machine. Fig. 7 shows the surge waveforms for an initial test voltage of $V_1 = 1050$ V and for a voltage increase of $\Delta V = 50$ V. The EAR values obtained from the surge waveforms of the healthy machine and a machine with one shorted turn and three shorted turns, respectively, are shown in Fig. 8. The expected EAR of the healthy motor for the test voltages is determined by $\Delta V / V_1 \cdot 100$. The derivation of this equation is beyond the scope of this paper and will be subject of a future publication. Due to the measurement noise, the EAR obtained by (3) will be larger than the EAR expected. Even though the EAR removes some of the measurement noise, the measurement noise cannot be eliminated completely. Two surge waveforms with the same initial voltage can result in an EAR of up to 2%. The experimental results clearly show that the detection of a turn fault with one or three shorted turns out of 108 turns is not possible for the supply inductance of 250 μH, whereas for a supply inductance of 9 mH, both faults can clearly be identified.

VI. Conclusion and Future Work

Online surge testing has been investigated in order to improve the diagnostic capabilities for the stator insulation condition. This paper shows how to overcome the drawback of the test sensitivity reduced due to a small mains output impedance. Different approaches are suggested, and the most practical approach is implemented. Through the temporary insertion of an additional inductance between the motor and the supply, even one shorted turn out of 108 turns can clearly be identified.

However, there are still several challenges that need to be addressed. In [27], it has been shown that machine imperfections like rotor eccentricity and rotor slotting have an influence on the surge waveform. Since, in an online test, the rotor position changes with respect to the zero crossings of the line–line voltage $(slip > 0)$, this has to be taken into account. A simple solution to this problem is the use of a position sensor. The test is only conducted when the zero crossing of the test voltage coincides with a particular rotor position during the test. Because of practicality, this particular rotor position is restricted not only to one particular rotor angle but also to a small zone around the particular rotor position. To avoid the use of a position sensor, a solution based on some statistical method is conceivable.

Even though the basic concepts can be validated by the use of a machine with a solid turn fault, it is desirable to create a more realistic test condition, i.e., to simulate the breakdown of the insulation at a certain voltage level. At present, several approaches for an experimental simulation of arcing between stator turns are being investigated.

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