Online insulation condition monitoring of ac machines using ultra-fast inverter switching transition based on new semi-conductor materials

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Abstract

In modern propulsion applications of tractions drives, voltage source inverter-fed three phase AC machines are preferred due to their flexibility and high dynamic torque properties. However, the fast switching of the inverter (high dv/dt rates) causes increased stress for the motor windings and leads to insulation degradation. Thus, insulation condition monitoring is getting more and more important to ensure reliability.

The proposed online insulation monitoring method is able to detect incipient insulation defects by evaluation of the motor current's transient response on voltage pulses injected by inverter switching. Experimental results are presented to prove the method's performance in case of application of voltage source inverters with very high dv/dt rates as will appear for, e.g., inverters equipped by SiC semi-conductors.

1. Introduction

Availability and reliability today are key factors to be considered for all modern safe and efficient transportation systems. Although in general electrical machines are highly reliable, the increased electrical stress on the machine's insulation system in case of inverter-fed operation leads to additional insulation strain. The main reasons for machine breakdown have been analysed in [1], [2] (25% of all failures are caused by the insulation system). Insulation breakdown is usually a slowly developing process starting with deterioration of the insulation material itself and then leading to severe turn-to-turn, phase-to-phase or phase-to-ground short circuit cf. Fig.1. Hence online insulation condition monitoring assists to ensure a detection of insulation degradation in an early stage. This provides the possibility to react timely on an incipient insulation's defect without the risk of a sudden breakdown usually resulting in high economic losses – strategic maintenance.

The deterioration of the insulation condition is accelerated by different causes. As well known, major causes for insulation degradation are high thermal stress followed by other environmental influences (moisture, dust, debris). However, concerning inverter-fed drives increased electrical stress of the insulation system is added, as analyzed in [3].

The fast rise times of voltage pulses applied by modern standard switching devices like IGBTs and beyond that, by using upcoming wide-bandgap semiconductors (SiC-MOS-FET/diode combinations) resulting in low switching losses but ultra high dv/dt rates in combination with impedance mismatch (machine versus cabling & surge) lead to transient overvoltages (typically up to twice the DC-link voltage) and thus highest strain for the machine's insulation. Several different techniques (online and offline methods) to detect insulation faults therefore have been proposed in literature [4]–[8].

To overcome the drawbacks of the already existing techniques is the aim of the proposed online insulation monitoring method. The online applicability for voltage source inverter (VSI) -fed drives, the usage of the already existing sensors only, and the detection of insulation deterioration, i.e., developing fault (degradation of the insulation prior the actual short circuit) are key requirements of the proposed online insulation monitoring method [11],[12].

The technique is based on evaluating the signal information detectable in the transient current response on inverter voltage pulses to detect changes in the machine's insulation system.





Fig. 1. Root causes of insulation deterioration and resulting failure.

Fig. 2. Transient phase current response/ringing resulting from inverter switching transition of a healthy machine and degraded winding insulation.



Fig. 3. Basic scheme of drives equivalent circuit – including high frequency behaviour determining parasitic components

2. High Frequency Behaviour of Inverter Fed Drives

In principle an inverter-fed drive system consists of three main components (inverter, cabling, machine), which define a complex impedance system. The impedance elements can be divided into characteristic electrical parameters like stator resistance/inductance, the cables' resistance/inductance and on the other hand parasitic components like the machine's winding-to-ground, winding-to-winding and turn-to-turn capacitances and others. In Fig. 3 a basic scheme of the drive's equivalent circuit (complex impedance system – including the mentioned parasitic components) is depicted. Most of these parasitic high-frequency-components are defined by the machine insulation system and its actual status (insulation degradation leads to a change of insulation capacitance) [2], [9], [10]. Hence, these components strongly influence the voltage ringing and the corresponding transient current response. Changes in the machine's insulation system (e.g. due to insulation degradation, insulation fault) therefore lead to changes in the characteristic hf-current oscillation and can thus be used to analyse the machine's insulation status.

3. Insulation State Indicator

As first processing step, the current response caused by an applied voltage step (inverter switching) must be sampled with sufficient resolution in time (cf. Fig. 2). A key task of the proposed method therefore is to accurately resolve the current response including the high-frequency oscillation by using oversampling. In the measured current signal the mentioned high-frequency oscillation is clearly visible decaying together with the final mean derivative. As only the hf-oscillation is of interest and contains the insulation state information, the mean slope in the current signal has to be eliminated. Next the transient current oscillation signal will be transformed to the frequency domain by fast Fourier transformation. The amplitude spectrum |Y| will then be used for insulation state characterization.

To achieve a diagnose strategy it is important to perform reference measurements on a healthy machine to determine the original insulation state (in the correlated amplitude spectrum). This serves as a reference and is compared to later measurements in operation (condition monitoring measurement) to assess the machine's actual insulation condition.

In the next step an Insulation State Indicator (ISI) for each individual phase will be introduced for the continuous monitoring of the insulation condition by applying the Root Mean Square Deviation (RMSD) to the amplitude spectra.

It should be noted that the Insulation State Indicator (ISI) magnitude correlates with the severity of insulation degradation, and is hence suited to act as the final monitoring value.

To detect the spatial location of the insulation degradation, in a final step of the signal processing, by linear combination of the previous calculated ISI-phase values (1) a Spatial Insulation State Indicator (SISI) can be defined (cf. Fig. 6).

$$SISI = ISI_U + ISI_V \cdot e^{j\frac{2\pi}{3}} + ISI_W \cdot e^{j\frac{4\pi}{3}}$$
(1)

By this linear combination symmetrical changes of the high-frequency behavior (e.g. due to temperature variation, moisture,...) are eliminated as these would lead to zero-sequence components.

In [3] a detailed description of the fundamentals, theory as well as mathematic calculation of the proposed condition monitoring technique and the ISI are given.

4. Experimental Setup

The main focus in this paper is to test and verify the applicability of the proposed online insulation condition monitoring method on a three phase AC machine with the boundary condition of a converter voltage with very high dv/dt-rate. This is to be expected for future developments of drive converters based on new wide-bandgap semi-conductor materials like, e.g., silicon carbide (SiC) which probably will allow the application of fast MOSFET devices at high operating voltages giving the advantage of reduced switching losses and/or higher switching frequencies. For testing the proposed drive monitoring, therefore a test pulse generator has been designed and implemented featuring test pulse signals with dv/dtrates of >25kV/µs at amplitudes of up to 800V (Fig. 4). As indicated in the circuit diagram Fig.5, the pulse generator in fact is a half-bridge stage of two SiC-MOSFETs with additional external free-wheeling diodes (also in SiC technology). All semiconductor devices are grouped on a power printed circuit board containing two electrolytic DC link capacitors which is characterized by an ultra-low-inductive bi-planar power plane routing. The MOSFETs are equipped with a fully isolated bipolar drive (-5V/+19V) using standard opto couplers with additional dv/dt improving circuitry. As shown in Fig. 6 the developed test system generates steep output voltage pulses at negligible ringing.

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stage of two SiC-MOSFETs with external pulse generator in SiC technology. SiC- free-wheeling diodes.

Fig. 4. Test pulse generator; half-bridge Fig. 5. Circuit diagram of designed and implemented test



Fig. 6. Inverter/Generator rising and falling edge switching transition; Ch1 (red): output voltage pulse (amplitude: 800V; $dv/dt \approx 25kV/\mu s$); Ch2 (light blue): switching stage output current (10A).

Furthermore, an extension to 1200V pulses is planned. The experimental investigations are carried out on a 4-pole 1.4MW squirrel-cage induction machine with fibre-insulation wires. To perform the alteration of the machine's high-frequency behaviour the test machine is equipped with several tapped windings accessible at a terminal connection block (cf. Fig. 7). This enables the possibility to insert additional capacitors between the different taps to change the machine's hf-behavior, which is used for emulating the insulation degradation without damaging or destruction of the winding [11], [12], [13]. The signal processing and measurement unit consists of a combined National Instruments data acquisition/processing system with fast ADC and a Field Programmable Gate Array programmable under LabView.

Investigation Results 5.

First measurements are presented in following paragraph. Concerning the test scenario of an emulated insulation degradation by insertion of a 15nF capacitor in parallel to full phase winding U. A testing voltage pulse of 800V amplitude and dv/dt rate of 25kV/µs gives a current response depicted in Fig. 2 leading to the evaluation results of Figs. 8-10.

As clearly visible from the amplitude spectrum (Fig. 8), the dominant frequency response in case of a modified hf-behavior (i.e., insulation status) is changed according the planned forecast model.

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Fig. 7. Additional capacitor C_{fault} inserted in parallel to the full phase winding U (schematically drawing).

Fig. 8. Reference amplitude spectrum (healthy: blue) and in case of a fault condition (green); also shown: calculated square deviation of both traces (red, dashed; amplitude 800V, dv/dt rate: 25 kV/µsec.

A statistic analysis (box plots) of the ISI_U (insulation state indicator calculated for phase U) is depicted in Fig. 9 for two scenarios (healthy state & emulated insulation degradation). The red horizontal lines in the center of the box-plots correspond to the median of the calculated ISI-values, the lower and upper limits represents the 25th and 75th percentile of the 30 repetitive measurements, respectively.



Fig. 9. Box plots of insulation state indicator calculated for monitoring of phase U, for two investigation scenarios (healthy and emulated insulation degradation).

Fig. 10. Normalized spatial insulation state indicator (SISI) for different investigated machine conditions (see Fig. 5); Healthy machine (blue *) and condition assessment (red +).

The two investigation scenarios can be distinguished clearly, and due to the not overlap of the box plots the separation of different conditions can be guaranteed. Fig. 10 depicts the calculated Spatial Insulation State indicator (SISI) in the Gaussian plane (normalized values) for different investigated machine conditions (healthy machine and insulation deterioration scenarios).

The experimental results point out, that the SISI for unchanged machine condition (healthy machine) is always located very close to the origin of the Gaussian plane. In addition, the results show that for all examined insulation deterioration scenarios the changed machine condition (locus of SISI) is clearly different to the unchanged (healthy) one. As can be seen, the spatial insulation state indicator for a faulty condition is pointing in the direction of the phase in which the capacitor (used for emulating an insulation degradation) has been inserted. Hence the phase location of the alteration can be clearly identified. In addition, the distance between origin of the plane and the locus of the SISI-pointer represents the severity of the insulation deterioration.

It can thus be concluded that the proposed online insulation condition monitoring method is well working and applicable to inverter fed AC machines with highly increased dv/dt-rate of the converter output voltage.

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