# Separation of Disturbing Influences on Induction Machine's High-Frequency Behavior to Ensure Accurate Insulation Condition Monitoring

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Abstract—The range of industrial applications requiring adjustable speed drives (ASD) is continuously increasing. Although generally highly reliable, a breakdown of an electrical machine has to be prevented under any circumstance for certain applications like safety-critical devices or industrial systems with many drives installed. To increase efficiency and return-oninvestment the drives are operated at or near their rated values. High dynamics, overload and the fast switching of the inverter cause additional stress for the different drive components. One of the major causes for drive breakdown is insulation deterioration. Before an actual breakdown of the insulation system occurs, the machine's high-frequency behavior is altered. Therefore monitoring of the drive's hf-behavior can be employed to evaluate the insulation condition. However, other drive components like cabling, grounding or the inverter may change the drive's hf-behavior as well. The possibility to separate the different influences of the machine's hf-behavior is thus essential and will be shown by experimental results.

# I. INTRODUCTION

Due to their flexibility and high dynamic torque/speed properties inverter-fed drive systems are used in a broad field of applications as main or auxiliary drives. High reliability is a necessity in many applications like safety-critical devices (e.g. in the "more electric aircraft") or in industrial production lines and traction where outage of a single drive would lead to high costs. Therefore fault tolerant operation, predictive maintenance and continuous condition monitoring are required.

As analyzed in [1] and [2] with 25% of all failures, the machine's insulation system is one of the major sources leading to machine outage. Failures in the machine's insulation system usually do not occur suddenly but are slowly developing from degradation of the insulation leading to turn-to-turn fault that finally results in severe ground fault and thus machine breakdown [3]. To ensure high reliability and implement predictive maintenance continuous assessment of the insulation condition has to be aspired.

As analyzed in [4] the major cause for insulation degradation is thermal stress. However, the fast switching of the power electronics in combination with the mismatch of machine and surge impedance lead to transient overvoltage and additional strain for the insulation [3].

Many different approaches to detect insulation faults

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and/or degradation have been presented in literature. Basically all methods can be categorized into online and offline techniques. Most industrially accepted techniques can only be applied offline. The DC conductivity [5], the insulation resistance (IR) [6], DC/AC HiPot [7], polarization index (PI) [7] and offline surge test [8] are some examples all summarized in [7]. An industrially accepted online monitoring technique is the partial discharge (PD) test, however, only applicable for medium to high voltage machines [9] and linked with high efforts in sensors and costs.

Many other online techniques have been presented in literature like the application of motor current signature analysis (MCSA) in [10] and [11] or an enhancement of the surge test to online applicability [12]. Evaluation of the leakage current from conductor to ground can be used to assess the machine's phase-to-ground insulation as presented in [3]. This technique can be applied to inverter-fed drive systems also. A winding fault influences the machine's leakage induction. Application of voltage pulses by the voltage source inverter and measurements of the current's reaction can be used to calculate this transient leakage induction. Thus, such analysis can be implemented to detect winding faults as proposed in [13].

Before developing the proposed insulation condition monitoring technique the following requirements have been defined. The monitoring technique has to be applicable online on a voltage source inverter (VSI)-fed drive (no disassembling of drive required) with no additional sensors needed. Even a developing fault (degradation of the insulation) needs to be detectable.

The proposed technique is based on detecting small changes in the machine's high-frequency behavior by evaluating the signal ringing detectable in the transient current as a reaction on voltage switching. Experimental results will be presented to show the method's performance.

# II. FUNDAMENTALS OF PROPOSED MONITORING TECHNIQUE

Monitoring of the insulation in electrical machines fed by voltage source inverters is of special interest. The very short rise-times and thus high rate of voltage rise realizable with modern voltage source inverters in combination with the

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mismatch of the surge and machine impedance can lead to overvoltage of twice to four times (for sequential fast change of the switching state) the DC-link voltage. This has been investigated in [14] and [15] for instance. Despite thermal strains identified as the major cause of insulation degradation especially in mains-fed machines these overvoltages result in additional stress for the stator winding and an increased possibility of insulation breakdown.

The different components of modern variable speed drives form a complex impedance system consisting of characteristic electrical parameters like stator resistance  $r_s$  and inductance  $l_s$ , the cables' resistance and inductance per unit length and parasitic components like the machine's capacitances winding-to-ground, winding-to-winding and turn-to-turn, the cables' capacitive coupling to ground and the inverter's capacitance between power electronics and heat sink. Most of the parasitic parameters are defined by the cables' or machine's insulation and determine the drive's high-frequency behavior.

If a voltage pulse is applied by the VSI all these elements lead to a mismatch of surge and machine impedance and therefore – according to signal and systems theory – to reflections of the steep voltage pulse at the machine terminals. This reflections lead to transient overvoltage with decaying amplitude and frequencies in the range of several hundred kHz to MHz as analyzed in [14] for example. This high-frequency oscillation is visible in the current as well.

As in standard inverters phase current sensors are already available for control purposes, it is preferably to use the current signal for insulation condition monitoring. If this signal is recorded with sufficient resolution in time the machine's high-frequency behavior can be analyzed. A change in the machine insulation leads to a characteristic change in the current's high-frequency oscillation. This is resulting from the fact that degradation of the machine's insulation system leads to a change of the insulation capacitance as investigated in [16].

The proposed technique uses these coherences to assess the insulation condition and has been presented in [17] also. However, other properties of the drive's configuration like cabling, grounding and the inverter also influence the highfrequency behavior. Thus the proposed insulation condition monitoring technique has to be insensitive to these influences. This sensitivity will be investigated in the experimental results and is the main focus of this paper.

#### III. MEASURMENT PROCEDURE AND SIGNAL PROCESSING

The measurement procedure and signal processing begins with the measurement of the current reaction on a change of the switching state e.g. from lower short circuit (000) to positive active switching state (e.g. +U (001)). Standard industrial current sensors can be used. However, the sampling rate has to be high enough to resolve the interesting frequencies. In Figure 1 the current's reaction on such a change of switching state is depicted. The high-frequency oscillation is visible for about 7 $\mu$ s. The slope or derivative of the depicted current signal is determined by the machine's transient leakage induction. Inherent asymmetries like rotor slotting, saturation or anisotropy modulate this transient leakage induction in dependence of rotor or flux position. This clearly complicates the evaluation of the insulation condition. However, an elimination of these disturbing influences can be implemented in a simple but effective way. To eliminate rotor position and flux dependence the applied voltage pulse has to be long enough to ensure that the transient oscillation settles to a constant current derivative. This mean current derivative (green dotted line) is then subtracted from the current signal. Accurate elimination of the rotor position and flux dependence can be ensured with this simple approach.





Figure 1. Current signal with illustrated mean derivative (green, dotted line) and switching instant (red arrow).

The signal after subtraction of the mean current derivative is depicted in Figure 2. The red circles highlight the exemplary sampling instances. The accurate detection of the exact switching instant is very important to define the time window used for the investigations. The end of the time window is determined by the length of the high-frequency oscillation visible in the current. In the current investigation the window length is kept constant to  $6.4\mu$ s for the investigated machine. The current (after subtraction of the mean current derivative) shown in Figure 2 is cut to this time window



Figure 2. Current (mean current derivative subtracted) in phase U after switching transition from lower short circuit (000) to +U (001).

Theoretically the signal can be examined in the time or frequency domain. However the best results can be achieved in the latter. Therefore the recorded current signal as shown in Figure 2 is transformed to the frequency domain by Fast Fourier Transform (FFT). The mean value of this signal is subtracted before transformation to eliminate a possible DC-component in the frequency spectrum. The amplitude spectrum is depicted in Figure 3.

To assess the insulation condition an initial measurement at healthy machine condition has to be carried out. Then the signal processing is applied to this measurement. The amplitude spectrum at healthy machine condition serves as reference and is compared to later measurements (condition measurement).



Figure 3. Amplitude spectrum of measured current in phase U after switching transition from lower short circuit (000) to +U (001).

The measurements and signal processing is applied to all three phases. Thus it is possible to detect insulation deterioration individually for all phases. In the commissioning phase voltage pulses (positive active switching states; +U (001), +V (010), +W (100)) are sequentially applied. The current measurements are carried out in the respective phase and the signal processing is done for each as described above. In this investigations the number of current samples used for the calculation of the amplitude spectrum is chosen to 256. For a sampling rate of 40MS/s this results to a window length of 6.4 µs. The window length depends on the time duration of the high-frequency oscillation and thus on the investigated machine. A set of three amplitude spectra serves as the reference traces that are later compared to condition measurements.

Increased accuracy can be achieved with repetition of the measurements and signal processing. In the present investigation the measurements are repeated 140 times. The reference traces are calculated as the mean trace of all 140 amplitude spectra for each phase.

#### **IV.INSULATION STATE INDICATOR (ISI)**

A comparative value is then used to evaluate the difference between reference trace and condition measurement. The comparative value chosen is the root mean square deviation (RMSD). It serves as insulation state indicator (ISI) as described in (1).

$$ISI_{p,k} = RMSD_{p,k}(x_1, x_2) = \frac{\sqrt{\sum_{i=n_{low}}^{n_{logb}} (Y_{ref}(i) - |Y_{con, p,k}(i)|)^2}}{n_{high} - n_{low}}$$
(1)

The value of  $Y_{ref}$  is the mean trace of the 140 amplitude spectra recorded for healthy machine condition. It is calculated according to equation (2).

$$Y_{ref}(i) = \frac{\sum_{k=1}^{m} |Y_{ref,k}(i)|}{m}$$
(2)

The function  $Y_{con}$  represents the amplitude spectrum of a single condition measurement. The index *p* denotes the phase (U,V or W) that changes the switching state and *m* the number of sequential measurements. This number can be adapted to increase accuracy and is chosen to 140 as already mentioned above. The index *k* denotes the individual measurements (k=1,2,3,...). The parameters  $n_{low}$  and  $n_{high}$  depend on the frequency resolution and the frequency range chosen for the evaluation. The variable *i* is the discrete frequency. The actual frequency depends on the sampling rate  $f_s$  and the window length  $t_{win}$  (number of samples *N*). It is calculated according to equation (3).

$$f = \frac{i \cdot f_s}{N}; i = 0, 1, 2, 3, ...; N = t_{meas} \cdot f_s$$
 (3)

As mentioned above, accuracy can be increased by evaluating more than one measurement. The final insulation state indicator  $ISI_p$  for each phase is the mean value of all calculated root mean square deviations  $RMSD_{p,k}$  ( $ISI_{p,k}$ ).

$$ISI_{p} = \frac{\sum_{k=1}^{m} ISI_{p,k}}{m}$$
(4)

The value of  $ISI_p$  correlates with the severity of insulation degradation. Thus it quantifies the insulation condition or alteration of the machine's high-frequency properties.

To detect the location of the degradation (phase) the whole procedure including reference spectrum can be repeated for all three phases. By linear combination according to (5) a spatial insulation state indicator (SISI) can be defined.

$$SISI = ISI_U + ISI_V \cdot e^{j\frac{2\pi}{3}} + ISI_W \cdot e^{j\frac{4\pi}{3}}$$
(5)

This further increases the accuracy as symmetrical changes (not resulting from insulation degradation) result in a zero sequence component and are eliminated. The proposed method is thus independent of dirt effects equally influencing all three phases.

#### V. EXPERIMENTAL SETUP AND REALIZATION OF FAULT CONDITION

Experimental tests are carried out on an industrial 2-pole, 5.5kW squirrel-cage induction machine. Several windings in all three phases are tapped and accessible at the machine terminals. This configuration allows shortening different turns without destruction. Furthermore it is possible to alter the machine's high-frequency behavior by adding additional capacitors between the different taps of the stator winding. This additionally inserted capacitance will be further denoted as  $C_{fault}$ . This alteration can be interpreted with a degradation of the machine's insulation system, for instance. The machine winding with its parasitic capacitances (turn-to-turn  $C_{t-t}$ , phase-to-phase  $C_{ph-ph}$  and phase-to-ground capacitance  $C_{ph-gnd}$ ) is depicted in Figure 4, schematically. Furthermore an additional fault capacitance added in parallel to the full phase winding U is illustrated.



Figure 4. Additional capacitor  $C_{\text{fault}}$  inserted in parallel to the full phase winding U.

For the induction machine used, the phase-to-ground and phase-to-phase capacitances have been identified to 1.71nF and 742pF, respectively. The insertion of the fault capacitance in parallel to the turn-to-turn capacitances results in an increase of the insulation capacitance. This is in correlation with the investigations carried out in [16]. The capacitance of twisted pairs increases with the aging of insulation. However, the important fact is, that the machine's high-frequency properties are changed and can be detected and separated from alterations in other properties of the drive configuration.

Machine control and measurements are realized with a system by National Instruments combining a real-time processor for machine control, a FPGA (Field Programmable Gate Array) for inverter control and data preprocessing and fast sampling ADCs all programmable under LabVIEW.

# VI. EXPERIMENTAL RESULTS

As mentioned before, the high-frequency oscillation visible in the phase current due to fast inverter switching is not only influenced by the machine's capacitive coupling, but also depends strongly on the cabling and other properties of the drive configuration like grounding. To realize accurate detection of changes in the hf-behavior of the machine only, the influence of the different disturbing effects has to be identified to implement a separation from insulation degradation induced alterations. As the different disturbing effects result in changes of specific signal characteristics (e.g. specific frequency components) this separation can be implemented easily.

Tests are carried out with two different types of cables between inverter and machine– one with 3m (C3m) and another with 12m (C12m) in length. Furthermore, the cable with 3m in length consists of three wires for the machine phases and an additional grounding wire. The cable is shielded. The cable shield and grounding wire are both connected to the inverter's grounded heat sink on the one and the grounded machine housing on the other side in normal configuration. The cable with 12m in length consists of four wires (three phases plus grounding wire) as well. However, the cable is not shielded. Thus the hf-properties of the two cables are very different. The grounding wire is again connected to the grounded heat sink and machine housing in normal configuration.

## A. Separation of cable's and machine's influences on drive's hf-properties

In the following investigation it will be shown that a separation of the cable's and machine's influences on the drive's high-frequency behavior is possible with the proposed condition monitoring technique. The machine is analyzed for healthy condition and modified hf-behavior by adding a 1nF capacitor in parallel to phase winding U (emulating insulation degradation) at first. Figure 5 shows a comparison of the influences on the drive's hf-behavior due to different causes ((a) insulation degradation and (b) cabling).



Figure 5. Comparison of different influences due to insulation degradation and cabling on drive's hf-behavior.

The blue solid trace shows the reference amplitude spectrum recorded for healthy machine condition. This trace serves as reference for all comparisons during insulation condition assessment. The cable denoted as C3m connects the machine and the inverter during the reference measurements. The blue dashed traces show the amplitude spectra for condition measurements with (a) 1nF capacitor added in parallel to phase winding U (cable C3m connected) and (b) changed cabling from C3m to C12m. As can be seen, the drive's high frequency behavior is changed for both scenarios. However, the alteration happens in different frequency components. A change of the hf-behavior due to emulated insulation degradation is visible in a frequency component around 500kHz whereas a change due to replacement of the cables is visible around 1.7MHz. This is easily separable by applying a frequency filter during evaluation. Furthermore the change of cabling affects all three phases symmetrically. Therefore if evaluations are performed for all three phases and combined according to equation (5) the effect due to cabling is eliminated by the signal processing.

The chosen frequency range for the calculation of the insulation state indicator according to equation (1) is chosen from 0(DC) to ~1MHz. This leads to the parameter value of  $n_{low}$  and  $n_{high}$  equaling 0 and 7 for the used sampling rate of 40MS/s, respectively (see equation (3)). The calculated spatial insulation state indicators are depicted in Figure 6 in the Gaussian plane. During the acquisition of the reference trace the cable C3m was connected. This reference trace is used to calculate the spatial insulation state indicator for all other investigated scenarios according to equation (5). Figure 6 shows the SISI for the scenarios for healthy machine condition and the faulty condition with a 1nF capacitor added in parallel to full phase winding U ('U 1nF full'). The cables are changed for both scenarios.



Figure 6. Spatial insulation state indicator (SISI) for different investigated machine conditions and two types of cables.

It can be easily observed that for healthy machine condition the SISI for both cables does not leave the origin of the Gaussian plane. Thus, no alteration in the machine's highfrequency behavior is detected. For the second scenario with a 1nF capacitor added in parallel to machine phase winding U the alteration can be detected in severity and location. For both cases the SISI points in the direction of phase winding U with similar magnitude. Thus, the alteration is accurately detected for both cables. The calculated spatial insulation state indicators are summarized in Table I.

 
 TABLE I.
 Spatial Insulation State Indicators SISI Obtained for Different Machine Conditions and Cables.

Cable	SISI (·10 <sup>-2</sup> )	
Fault condition	C3m	C12m
Healthy	0.03	0.13
U 200pF partial	$0.28 \cdot e^{j \cdot 1.12^{\circ}}$	0.30·e <sup>j·22.08°</sup>
U 200pF full	0.30·e <sup>-j·2.80°</sup>	0.42·e <sup>j·15.79°</sup>
U 500pF partial	0.41·e <sup>-j·0.91°</sup>	0.59·e <sup>j·10.34°</sup>
U 500pF full	0.60·e <sup>-j·1.66°</sup>	0.75·e <sup>j·7.64°</sup>
U 1nF partial	0.96·e <sup>j·4.56°</sup>	1.25·e <sup>j·5.03°</sup>
U 1nF full	1.36·e <sup>-j·1.55°</sup>	$1.64 \cdot e^{j \cdot 2.47^{\circ}}$

In this table it can be seen that the different scenarios can be separated in both cases (for both cables). Thus, after identification of the interesting components the proposed method is able to eliminate factors influencing the drive's high-frequency behavior due to changes in the cabling from the ones resulting from alteration in the machine's hf-properties.

# *B.* Analysis of cable grounding and shielding influencing insulation state indicator

In the investigations presented in this section the influence of the drive's grounding concept on the insulation state indicator is analyzed. The normal configuration is that the cable's grounding wire and shielding (if available) is connected to the inverter's grounded heat sink on the one side and to the grounded machine housing on the other. If the grounding/shielding is disconnected on one or both sides, the drive's high-frequency behavior is changed. Thus the influence of the grounding concept on the insulation state indicator has to be investigated to ensure accurate assessment of the machine's high-frequency behavior.

All presented investigations have been carried out with the 3m long cable connecting inverter and machine. The worst case concerning the altered condition of grounding configuration is when both ends of the grounding wire and shielding are disconnected. The amplitude spectra for healthy machine condition and disconnected grounding and shielding (blue traces), as well as the square deviation between these two traces (green trace) is depicted in Figure 7.



Figure 7. Amplitude spectra for healthy machine condition (reference; blue solid trace) and disconnected grounding wire and shielding (blue dashed trace); Square deviation between these two traces (green trace).

The interesting frequency range in Figure 7 is between 0(DC) and ~1MHz as only this range is considered in the calculation of the insulation state indicator. It can be seen that an alteration of the frequency spectrum for the scenario with disconnected grounding wire and shielding ('gnd not connected') is visible. This alteration will disturb the insulation state indicator and could be misinterpreted as insulation degradation. The alteration visible around 2MHz is successfully eliminated. Due to the calculation of the spatial insulation state indicator according to equation (5) the disturbing influence is attenuated, however, not completely eliminated as can be seen in Figure 8 and Table II. Figure 8 depicts the SISI in the Gaussian plane for the two scenarios (healthy machine condition and 1nF capacitor added in parallel to full phase winding U 'U 1nF full) and different grounding configurations (grounding wire disconnected on both sides ('disconnected'), on the machine side ('inverter only') and on the inverter side ('machine only')). The blue star illustrates the tip of the spatial insulation state indicator for healthy machine condition and disconnected grounding wire and shielding. It can be seen that it is shifted from origin. However, it is still clearly separable from the scenario 'U 1nF full'.





A summary of the SISI for both investigated scenarios and all three different grounding configurations can be found in Table II.

TABLE II. SPATIAL INSULATION STATE INDICATORS SISI OBTAINED FOR DIFFERENT MACHINE CONDITIONS AND GROUNDING CONFIGURATION.

Crounding	SISI (·10 <sup>-2</sup> )		
Fault condition	Inverter only	Machine only	Dis- connected
Healthy	0.07	0.006	0.22
U 200pF partial	0.28·e <sup>j·3.50°</sup>	0.25·e <sup>j·1.23°</sup>	0.71·e <sup>-j·1.38°</sup>
U 200pF full	0.36·e <sup>-j·0.28°</sup>	0.29·e <sup>-j·3.25°</sup>	0.30·e <sup>-j·2.80°</sup>
U 500pF partial	0.48·e <sup>j·2.68°</sup>	0.40·e <sup>-j·1.19°</sup>	0.94·e <sup>-j·3.88°</sup>
U 500pF full	0.67·e <sup>j·0.93°</sup>	0.56·e <sup>-j·1.21°</sup>	0.90·e <sup>-j·2.57°</sup>
U 1nF partial	0.96·e <sup>j·3.78°</sup>	0.90·e <sup>j·4.93°</sup>	1.57·e <sup>-j·2.92°</sup>
U 1nF full	$1.42 \cdot e^{-j \cdot 0.98^{\circ}}$	$1.33 \cdot e^{-j \cdot 1.61^{\circ}}$	$1.62 \cdot e^{j \cdot 1.54^{\circ}}$

The results should be compared to the first column in Table I also. For the grounding configurations with only one side disconnected the SISIs are similar to the standard drive configuration. Thus no disturbance of the fault indicator can be detected. For both wires disconnected, the accuracy of the SISI is reduced. However, the introduced changes of the machine's high frequency behavior are still clearly separable from healthy machine condition.

#### VII. CONCLUSIONS

A novel method for insulation condition monitoring based on the detection of changes in the machine's hf-behavior by evaluating the transient current reaction on inverter switching has been presented. Different components and effects like cabling or the drives grounding configuration influence the hfbehavior as well and have to be separated to ensure accurate assessment of the insulation condition. This separation is possible by appropriate signal processing.

Experimental results show that even replacing the cable with a completely different type does not influence the insulation state indicator. Changes in the grounding configuration and cable shielding may lead to alterations in the same frequency range as insulation degradation in the worst case. However, a deterioration of the machine's insulation system can still be detected if the insulation state indicator is observed over time.

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