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Detecting Changes of the Insulation State of Variable Speed Drive Systems Based on Inverter-built-in Current Sensors

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***Abstract*-- Modern electrical drive systems basically consist of three components determining its complex impedance system – the inverter, the cabling and the machine itself. For high efficiency and good return on investment these components are operated at or near their rated values. Furthermore stress is added due to high dynamic operation, transient overload and the very fast switching of modern power electronics like IGBT. At the same time more reliability and fail-safety is required by many applications like x-by-wire. This leads to the necessity of continuous drive monitoring that allows the detection of a developing fault in an early stage. The proposed method aims on the detection of an alteration in a component of the drive's complex impedance system by evaluating the transient reaction of the current on an applied voltage pulse. Such an alteration is e.g. the change of the machine winding's turn-to-turn or phase-to-ground capacitance due to degradation of the insulation.**

***Index Terms*--Fault diagnosis, Induction machines, Insulation testing, Monitoring, Pulse width modulated inverters, Squirrel cage motors, Switching transients**

I. Introduction

Inverter-fed drives are becoming the preferred system in various applications. Especially in safety critical devices such as the ones in the so-called more electric aircraft or in production lines with a high amount of drives installed (e.g. steel or paper manufacturing) high reliability is a necessity as breakdown would lead to high economic losses. To meet this requirement preventive maintenance, fault tolerant operation and continuous condition monitoring is needed.

Basically three different causes that lead to machine breakdown can be found in literature: bearing related faults with ~50%, stator related faults with ~35% and rotor related faults with ~10% as summarized in [1] and [2]. About 70% of the stator related faults are due to a failure in the machine's insulation system.

The breakdown of the insulation system is slowly developing, starting with a degradation of the insulation, leading to a turn-to-turn fault and finally resulting in a severe ground fault as reported in [3]. According to [4] this is primarily caused by thermal stresses. However, electrical, mechanical and environmental strains may enhance the degradation process. If it comes to inverter-fed drives the high rise-times of the applied voltage pulses lead to additional stress of the insulation system. This is analyzed for example in [3].

Many different techniques to detect insulation faults have been proposed in literature so far. All of these can be categorized into online or offline procedures. Most industrially accepted techniques are offline and can only be applied during general maintenance every three to six years [5] as disassembling of the drive is required often. One of the most promising offline techniques is the surge test as described in [6].

Further offline insulation detection techniques are the DC conductivity test [7], the insulation resistance (IR) test [8], DC/AC HiPot test [9] and polarization index (PI) test [9]. An industrially accepted online insulation monitoring method is the partial discharge (PD) test. This test is described in [10] for example. However, it is only applicable for medium to high voltage machines and additional measurement hardware and high sophisticated evaluation software is needed.

Due to the obvious disadvantages of offline insulation monitoring techniques many other online procedures have been developed and presented in literature. Only a short compendium of these procedures will be shown here.

Current signature analysis (CSA) can be applied to investigate the insulation condition as presented in [11] and [12]. A further development of the surge test for online application is described in [13]. The leakage current from conductor to ground can be measured and evaluated to assess the machine's phase to ground insulation as discussed in [3]. This test is also applicable for inverter-fed machines. The current's reaction to voltage pulses applied by a voltage source inverter (VSI) can be used to calculate the transient leakage induction that is influenced in case of a winding-fault as presented in [14].

The aim of the novel machine condition monitoring technique presented is to overcome the drawbacks of the already investigated methods. It should be applicable online, that is to say no disassembling of the drive should be necessary. Furthermore the technique is designed for voltage source inverter (VSI)-fed machines, no additional sensors should be necessary and even a developing insulation fault (degradation of the insulation) before a short circuit should be detectable. The application of insulation monitoring to inverter-fed drives is of special

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interest as the short rise-times of the voltage pulses applied by the VSI and the mismatch of the surge and machine impedances lead to transient overvoltage of twice to four times (for sequential fast change of the switching state) the dc-link voltage as investigated in [15] and [16]. Despite of thermal strains this overvoltage results in increased stress for the windings and an insulation breakdown is even more likely.

Advancements in signal processing and insulation state indicator calculation to ensure a more accurate detection of insulation state alteration will be investigated in the present paper. The capability to detect minor changes in the machine's complex impedance system that may correspond to a degradation of the machine's insulation will be proved by experimental results.

II. General Aspects of the Proposed Machine Condition Monitoring Approach

Basically an inverter-fed drive system consists of three components:

- Inverter (e.g. VSI)
- Machine cables
- Machine (e.g. induction machine)

All these components form a complex impedance system consisting of a network of resistances, inductances and capacitances. Primarily this impedance system is determined by the characteristic parameters of the involved components like stator resistance r_s, stator inductance l_s, cable inductance and resistance per unit length, etc.. However, it consists of many parasitic elements like capacitances phase-to-ground (cabling), winding-to-ground (machine), winding-to-winding (machine), turn-to-turn (machine) and the inverter's capacitive coupling to ground. Many of these parasitic elements result from and are influenced by the insulation and its condition and determine the machine's high-frequency behavior.

According to the signal and system theory the values of these elements generally lead to a mismatch of surge impedance and the machine impedance and therefore to reflections of the applied voltage pulse at the machine terminals. Furthermore these reflections result in an oscillating transient overvoltage with decaying magnitude and frequencies in the range of tens kHz to tens MHz according to [16]. This high-frequent oscillation can be detected in the machine current as well. To perform the measurement it is advantageous to use the sensors already available in the drive system like current or current derivative (CDI) sensors. For that reason the proposed method is based on measurement of the current reaction on a voltage pulse applied by the VSI with focus on the high-frequency oscillation visible in the current or current derivative signal.

The characteristic of this high-frequency oscillation is determined by the drive's complex impedance system. A developing fault like a degradation of the machine's insulation system may lead to an alteration of this complex impedance system. Therefore this change will be detectable in the high-frequency oscillation.

The proposed condition monitoring technique is based on the analysis of the current or current derivative signal immediately after the switching instant with sufficient resolution in time to detect the mentioned changes in the high-frequency oscillation.

III. Measurement and Signal Processing

The measurement and signal processing procedure of the proposed condition monitoring technique is relatively simple to realize. A voltage step (e.g. PWM-excitation) is applied and the current's reaction is measured with sufficient resolution in time. Then either characteristic signal parameters of the high-frequency oscillation described in [17] or a comparative value between measurement and reference measurement (healthy condition) will be calculated and represent an insulation state indicator.

To get a better understanding of the signals that are analyzed Fig. 1 shows the trace of the measured current derivative after a switching instant from inactive (000) to active (001) in phase U. The figure clearly depicts the high-frequency oscillation decaying after about 10µs caused by reflections at the machine terminals. This signal component is analyzed in the proposed machine monitoring technique to detect an alteration e.g. due to a degradation of the insulation system.

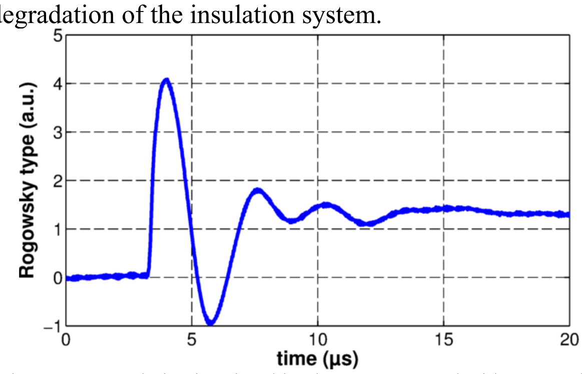

Fig. 1. Current derivative signal in phase U measured with Rogowsky type sensors (CDI) during switching of the VSI sampled with 40MS/s.

The reaction on the same switching instant measured with standard industrial current sensors can be seen in Fig. 2.

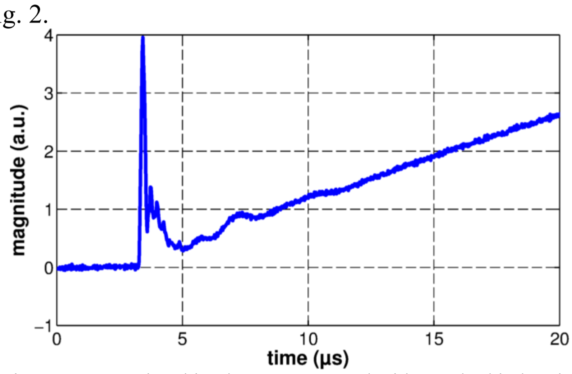

Fig. 2. Current signal in phase U measured with standard industrial current sensors during switching of the VSI sampled with 40MS/s.

Signals as shown in Fig. 1 and Fig. 2 are recorded and stored for a healthy machine (reference measurement) and then compared to later measurements (condition monitoring measurement). Different comparative values can be calculated to serve as indicators for condition monitoring measurements.

The signals can be examined in the time or frequency domain. To eliminate dependencies e.g. of the rotor position which would influence the steady state of the current derivative, the steady state value in case of the CDI-measurement or the mean signal slope in case of the standard industrial current sensors is subtracted from the signals after detection of the exact switching instant. Furthermore the signal's mean value is subtracted to eliminate a possible DC-component in the frequency spectrum. The measured current reaction of Fig. 2 after these signal processing steps is depicted in Fig. 3.

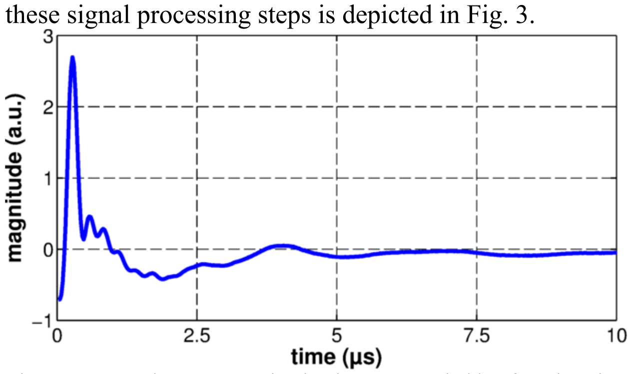

Fig. 3. Measured current reaction in phase U to switching from inactive to active (+U) after signal processing $y_k(t)$.

The signal in Fig. 3 represents the reference measurement that is compared to a later condition monitoring measurement if analyzed in the time domain. This signal can be transformed into the frequency domain by Fast Fourier Transform (FFT). The magnitude spectrum of the signal in Fig. 3 is shown in Fig. 4.

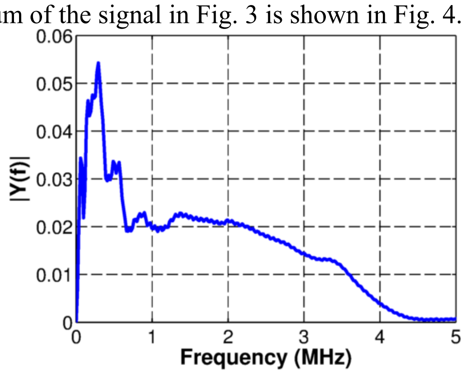

Fig. 4. Magnitude spectrum of measured current in phase U resulting from switching (inactive to active +U) after signal processing $Y_k(f)$.

After the identification of the signals for the healthy machine the machine insulation condition can be estimated by performing the following steps:

1) Measurement of machine's step response to voltage steps (PWM)
2) Calculation of comparative value of this signal to the reference signal in the time or frequency domain; the calculated comparative value represents the insulation state indicator (ISI)
3) If threshold value is exceeded => maintenance is necessary

If the steps 1) and 2) are performed several times in a row and the statistical properties are calculated, the accuracy can be increased. As the necessary pulses are only in the range of some µs the measurements can be even integrated into PWM and repeated without increasing the measurement duration to a distracting amount.

For the present investigation each condition estimation consists of a set of 140 measurements. The mean signal in time or frequency domain of this set for the healthy machine serves as the reference and is used to be compared to the measurements with altered machine condition.

IV. Calculation of Insulation State Indicator

The correct choice and accurate calculation of the comparative value is a crucial task of the proposed condition monitoring technique.

For the present investigation the Root Mean Square Deviation (RMSD) was chosen as the comparative value. This value is defined as follows

$$RMSD_k(x_1, x_2) = \frac{\sqrt{\sum_{i=1}^{n}(x_1(i) - x_{2,k}(i))^2}}{n} \quad . \tag{1}$$

The reference signal is calculated by evaluating the set of 140 measurements at healthy machine condition. For investigation in the time domain after signal processing each of these measurements results in a trace similar to the one in Fig. 3 in case of standard industrial current sensors. The signal $y_{ref}(t)$ is the mean signal of the set of 140 measurements. Each single measurement is represented by $y_k(t)$. The number of measurements is m.

$$y_{ref}(t) = \frac{\sum_{k=1}^{m} y_k(t)}{m} \tag{2}$$

In case of the investigation in the frequency domain the Fast Fourier Transform is calculated for each measurement $y_k(t)$ at healthy machine condition resulting in $Y_k(f)$. The reference signal in this case is calculated as follows

$$Y_{ref}(f) = \frac{\sum_{k=1}^{m} |Y_k(f)|}{m} \quad . \tag{3}$$

In this investigation the variable x_1 in (1) represents the healthy machine (reference condition). In the time and frequency domain this reference condition is characterized by y_{ref} and Y_{ref}, respectively.

$$x_1 = y_{ref}(t) \quad or \quad x_1 = Y_{ref}(f) \tag{4}$$

For the variable x_2 in (1) one single condition monitoring measurement in the time $y_{con,k}(t)$ (similar to Fig. 3) or frequency domain $Y_{con,k}(f)$ (similar to Fig. 4) is used.

$$x_{2,k} = y_{con,k}(t) \quad or \quad x_{2,k} = |Y_{con,k}(f)| \tag{5}$$

This results in a set of 140 RMSD-values, which can be statistically analyzed to improve accuracy. The number n depends on the time or frequency resolution and the chosen window length. In this investigation the analysis in the frequency domain n results in 1024 and in the time domain to 400 (10µs). The length of the time signal transformed to the frequency domain depends on the duration of the transient signal ringing. An algorithm detects this end. If the length of data points does not equal to a power of two the time signal is padded with trailing zeros to fit the next power of two (1024 for all measurements). This signal is then transformed to the frequency domain by FFT.

A comparison in performance showed that the results gained in the frequency domain are more accurate than the ones in the time domain. Therefore the domain of choice is the frequency domain in the following.

The insulation state indicator *ISI* is determined as

$$ISI_k = RMSD_k(Y_{ref}(f), |Y_{con,k}(f)|) = \frac{\sqrt{\sum_{i=1}^{n}(Y_{ref}(f) - |Y_{con,k}(f)|)^2}}{n} \qquad (6)$$

V. Experimental Setup and Fault Condition Realization

For proof of the proposed condition monitoring method a 5.5kW, 2-pole squirrel cage induction machine with tapped windings and an un-skewed rotor is investigated. The taps of the different windings in all three phases lead to the possibility to shorten a certain amount of windings by connecting the taps with each other or the machine terminal connection. In this way a turn-to-turn short circuit can be realized without destructing the machine. If instead of a short circuit a capacitance – further denoted as fault capacitance C_{fault} – is inserted between the taps and the machine terminal connections an alteration of the machine's impedance system and therefore the machine's high-frequency behavior can be realized. This can be e.g. the result of a degradation of the machine's insulation system. A schematic overview of the machine windings and its parasitic capacitances as well as a fault capacitance inserted between terminal connection of phase U and tap of the first turn is depicted in Fig. 5.

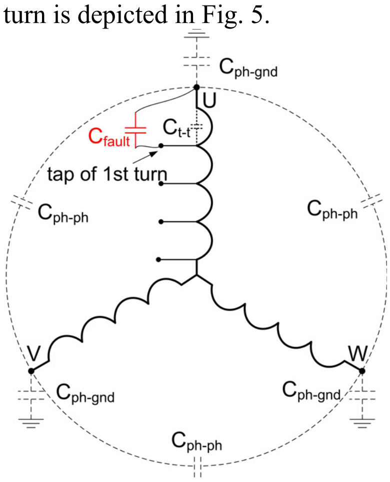

Fig. 5. Additional Capacitor C_{fault} inserted between machine terminal of phase U and tap of a turn in phase U.

The phase-to-ground $C_{ph\text{-}gnd}$ and phase-to-phase capacitance $C_{ph\text{-}ph}$ are determined to 1.71nF and 742pF, respectively. As can be seen in Fig. 5 the fault capacitance is inserted in parallel to the turn-to-turn capacitance which results in an increase. This increase of the insulation capacitance is in correlation with investigation of degraded turn-to-turn insulations in [18].

The measurements as well as the machine control are realized by a combination of a real-time system programmable under MATLAB/Simulink (dSPACE 1103) for control and a FPGA for the PWM generation (5kHz) and data preprocessing. The signal sampling is done with 40MHz 16bit ADCs that communicate with the FPGA via data buffers.

To investigate the performance of the proposed condition monitoring technique measurements are done for different fault condition. That is to say capacitances of different value and at different connections are inserted.

VI. Experimental Results

The experimental results shown in the following proof the possibility to detect an alteration in the machine's complex impedance system and separate it according to severity. Measurements with different capacitances C_{fault} (200pF, 333pF, 500pF and 1nF) inserted between terminal connection and star-point (in parallel to 'full' phase winding) as well as terminal connection and a tap at ~50% of the phase winding (in parallel to 'partial' (50%) phase winding). All capacitances have been added in phase U. The pulse is applied to the altered phase and the current and current derivative signal is measured in this phase. As mentioned before the measurements are repeated 140 times to increase accuracy and eliminate outliers. This leads to 140 insulation state indicators for each measurement set. These insulation state indicators are then statistically analyzed. Fig. 6 shows a comparison of the calculated insulation state indicator for different machine conditions as a box plot. For the calculation of the insulation state indicator the current signals where processed and analyzed in the frequency domain. The box plots show the median (central mark; red lines) for the different measurements. The upper and lower limit of the box represents the 75th and 25th percentile, respectively. The red crosses mark outliers. If the notches of the different box plots don't overlap, one can conclude with 95% confidence that the true medians differ. As can be seen in Fig. 6 this is true for all observed measurement sets. Therefore all investigated machine conditions are clearly separable from the healthy machine state (reference condition).

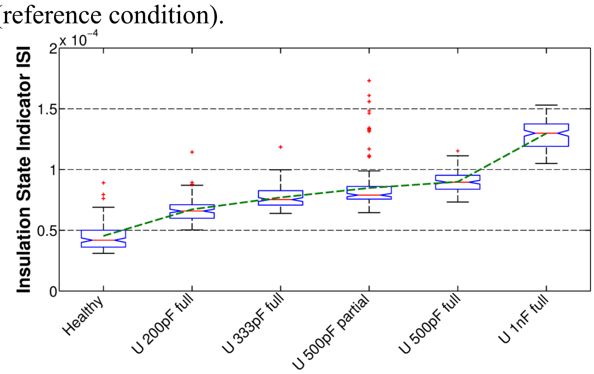

Fig. 6. Box plots for different machine conditions compared with reference measurement (healthy condition); Sensors: standard industrial current sensors; Insulation state indicator calculated in frequency domain.

The green dashed line in Fig. 6 marks the trace of the mean values of the ISI for the different conditions analyzed.

The naming convention for the denotation of the different realized conditions (e.g. ‘U 1nF full’) in tables and figures is as follows: location of insertion (e.g. U for insertion in phase U) and severity of applied change (value of inserted capacitor (e.g. 1nF), insertion in parallel to ‘full’ or ‘partial’ (~50%) phase winding).

TABLE I. MEDIANS AND MEAN VALUES OF INSULATION STATE INDICATORS GAINED FROM THE ANALYZED CURRENT SIGNAL IN THE FREQUENCY DOMAIN AT DIFFERENT MACHINE CONDITIONS

Statistical property / Fault condition	Median	Mean value
Healthy	$4.182\cdot10^{-5}$	$4.538\cdot10^{-5}$
U 200pF full	$6.586\cdot10^{-5}$	$6.718\cdot10^{-5}$
U 333pF full	$7.526\cdot10^{-5}$	$7.705\cdot10^{-5}$
U 500pF partial	$7.894\cdot10^{-5}$	$8.480\cdot10^{-5}$
U 500pF full	$8.955\cdot10^{-5}$	$8.990\cdot10^{-5}$
U 1nF full	$12.985\cdot10^{-5}$	$12.973\cdot10^{-5}$

The measurement set labeled with ‘Healthy’ in Fig. 6 is a second measurement of the healthy machine compared to the actual reference measurement. This measurement can be used to determine the limits to detect an alteration of a parasitic capacitance in the machine’s impedance system. In this case an insulation state indicator (mean value) below e.g. $5\cdot10^{-5}$ cannot be separated from the reference measurement. An alteration of the machine’s complex impedance system by inserting a 200pF capacitance in parallel to the full phase winding is the lower detection limit of the proposed signal processing technique in the present stage. As different environmental or other influences like temperature,… may cause a temporary alteration of the machine’s high frequency response although not related to a fault an elimination of such influences would be preferable. As impacts like temperature,… will influence all three phases symmetrically whereas a fault would only affect one phase it would be advantageous to develop a fault indicator based on an analysis of this asymmetry. However, this task needs further investigations and analysis of environmental influences. This issue is currently on going and will be presented in a future publication.

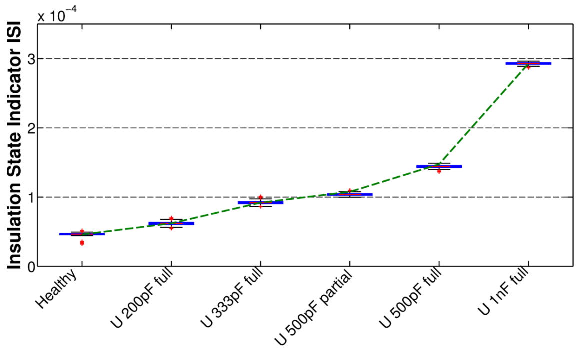

Fig. 7. Box plots for different machine conditions compared with reference measurement (healthy condition); Sensors: Rogowsky type current derivative sensors; Insulation state indicator calculated in frequency domain.

A summary and comparison of the insulation state indicator’s statistical properties (median and mean value) for different machine conditions after analysis of the current signal in the frequency domain can be found in Table I.

The same evaluation has been carried out for the application of current derivative (CDI) sensors of Rogowsky-type. The results are shown in Fig. 7. The green dashed line again shows the mean values of the ISI evaluated for signals gained from current derivative sensors.

In comparison to the results gained by evaluating the current signal the relative difference of the ISI’s median is higher for smaller alteration of the capacitance (below 1nF) and the variance is much lower. The different investigated scenarios can be clearly separated. However, the application of standard industrial current sensors is preferable as these sensors are usually already available in the drive system.

A summary of the statistical properties of the insulation state indicator for measurements performed with current derivative sensors of Rogowsky-type can be found in Table II.

TABLE II. MEDIANS AND MEAN VALUES OF INSULATION STATE INDICATORS GAINED FROM THE ANALYZED CURRENT DERIVATIVE SIGNAL IN THE FREQUENCY DOMAIN AT DIFFERENT MACHINE CONDITIONS

Statistical property / Fault condition	Median	Mean value
Healthy	$4.649\cdot10^{-5}$	$4.599\cdot10^{-5}$
U 200pF full	$6.210\cdot10^{-5}$	$6.217\cdot10^{-5}$
U 333pF full	$9.193\cdot10^{-5}$	$9.204\cdot10^{-5}$
U 500pF partial	$10.386\cdot10^{-5}$	$10.762\cdot10^{-5}$
U 500pF full	$14.415\cdot10^{-5}$	$14.748\cdot10^{-5}$
U 1nF full	$29.290\cdot10^{-5}$	$29.283\cdot10^{-5}$

As described in section III. the steady state value or the mean slope are subtracted from the current derivative or current signal, respectively. This is done to eliminate influences like the rotor position.

TABLE III. MEDIANS AND MEAN VALUES OF INSULATION STATE INDICATORS GAINED FROM THE ANALYZED CURRENT DERIVATIVE SIGNAL IN THE FREQUENCY DOMAIN FOR DIFFERENT ROTOR POSITIONS

Statistical property / Relative position	Median	Mean value
Healthy (0°)	$4.649\cdot10^{-5}$	$4.599\cdot10^{-5}$
Healthy (3.27°)	$5.366\cdot10^{-5}$	5.37910^{-5}
Healthy (6.42°)	$5.409\cdot10^{-5}$	$5.3778\cdot10^{-5}$
Healthy (9.68°)	$4.084\cdot10^{-5}$	$4.0669\cdot10^{-5}$
Healthy (12.83°)	$3.071\cdot10^{-5}$	$3.104\cdot10^{-5}$

To proof the independency of the proposed condition monitoring method of the rotor position measurements have been carried out for healthy conditions but different rotor positions. For induction machines the rotor slotting is influencing the transient current derivative. For machines with un-skewed open rotor slots – like the investigated test machine – this effect is relatively big and therefore influencing the current derivative depending on the rotor position. Therefore the angle steps between the different measurements of the healthy machine for different rotor positions have been chosen according to the slot pitch. As the investigated test machine has 28 rotor slots the angular difference between the slots results in 12.86°. The measurements have been performed for four different rotor positions within one slot pitch and compared to the reference measurement. This results in an angular difference between the investigated positions of approximately 3.21°. With the investigated positions it can be ensured that different conditions like slot opening directly above direction of voltage pulse injection and the perpendicular situation. The measurements and evaluation of the ISI have been performed for the current derivative sensors. Table III summarizes the results. As can be seen the mean values of the measurements for different rotor positions are clearly separable from the measurements with a small capacitor inserted (e.g. 'U 200pF full'). The reason for the relative difference of the measurements shown in Table III can be found in the above described possible influence due to environmental conditions like temperature,… The accuracy can be increased by measuring all three phases and evaluating a possible asymmetry due to an alteration of the high-frequency behavior in one phase only. As already mentioned this needs further investigation and is currently on-going.

VII. Conclusions

A novel method to detect changes in the machine's parasitic capacitances e.g. resulting from degradation in the winding insulation was presented. The proposed technique is based on evaluating the transients in the current or current derivative signal after switching of the VSI (e.g. PWM-excitation) and is therefore suitable for inverter-fed drives. Due to high-frequency sampling the transients in the evaluated signals can be analyzed. These transients are strongly influenced by the drive's parasitic components due to the mismatch of machine and surge impedance. The experimental results show that an alteration of the machine's parasitic capacitances can be detected by comparing measurements during healthy and altered machine condition. An insulation state indicator is developed based on the calculation of the root mean square deviation of the Fourier-transformed transient current or current derivative signal between reference and condition measurement. Different machine conditions have been analyzed and a proof of the possibility to separate each condition has been given.

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