



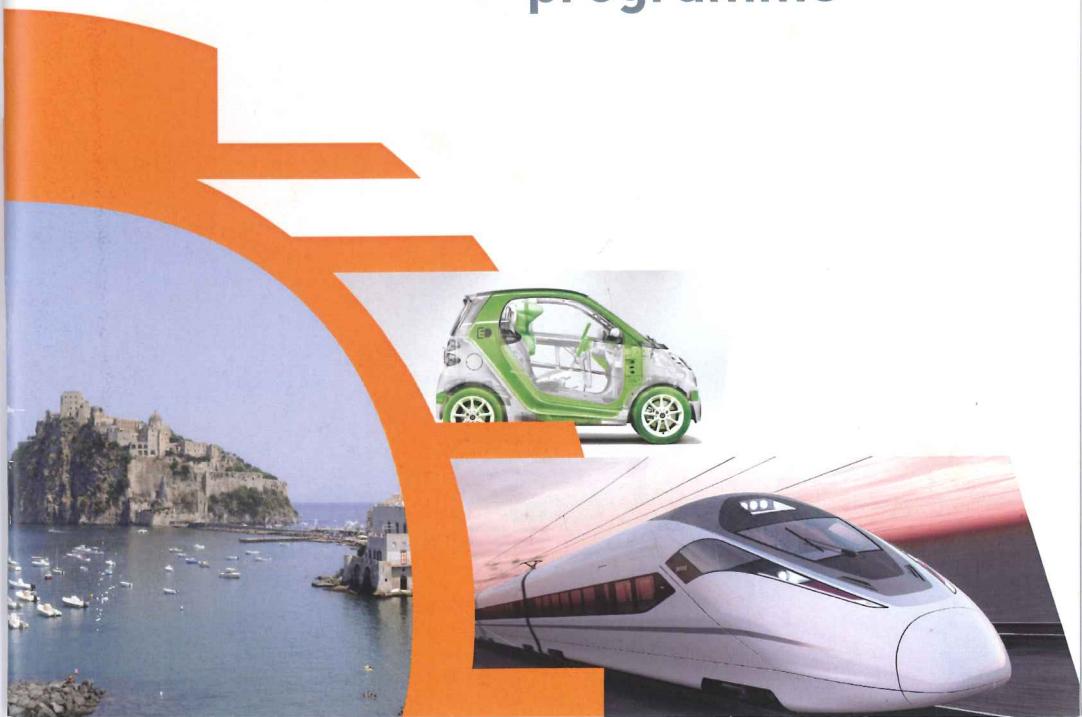
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# Detecting Insulation Condition Changes of Inverter Fed AC Machines Based on Two Current Sensors and Indirect Phase Step Excitation

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**Abstract**—A high number of breakdowns of adjustable speed drives (ASD) is caused by a fault of the machine, especially stator related insulation faults frequently occur. The evaluation of the insulation condition is possible with the current sensor signals only. The analyses of the transient part of the current response give evidence if a change in the insulation system occurred. The degradation of the insulation state is noticeable through a capacitive change, which influences the high frequency behavior of the machine and as a consequence the transient part of the current signal.

The proposed method is capable to detect insulation degradation through analyzing the transient current response of the sensors already used for the control of the machine. Additionally, the profitable capital expenditure demands the design with minimal number of components. To reduce the costs only two current sensors are available. The non-measured transient phase current response can be reconstructed by a special excitation sequence and signal processing without significant deterioration of sensitivity.

**Keywords**—Variable speed drives, Fault detection, Induction motors, Insulation degradation, Condition monitoring, Power system transients

## I. INTRODUCTION

Through demand for a high dynamic behavior, adjustable speed drives getting more and more important. With focus laid at economic design all components are operated at their rated values with no reserves. To ensure the requirements of a reliable and safe operation over a long period without maintenance, fault diagnosis with monitoring systems have been an active area of research. In literature detailed investigations specify stator related faults with 35% as the second most common faults, causing a machine outage, see [1] and [2]. Furthermore about 70% of these stator faults are based on a failure of the insulation system. Thus, monitoring systems analyzing the stator insulation condition seem to be a good approach to prevent a breakdown. The process of insulation degradation is proceeding very slowly, sometimes even over decades. Different stresses like electrical, thermal, thermo-mechanical, mechanical and environmental are stated as responsible causes for a reduced insulation lifetime [3]. In [4] the effect of thermal-electrical aging for high operation time and a high number of thermal-mechanical aging cycles

on the stator bars are analyzed. The results of experiments on simple epoxy resin specimens show that the capacitance of the specimen has changed over time and with the number of aging cycles. According to [5] a change in the winding turn capacitance after stress through thermal cycles is detectable and in [6] the results approve the trend of a changed capacitance of a coil aging setup through a high number of aging cycles. The capacitance is in all cases usually considered as the dominant parameter for insulation health state evaluation. Degraded insulation at first lead to a turn to turn fault and finally to severe ground faults as described in [7]. With inverter-fed machines the insulation suffers from the high voltage step rates and the degradation process will be aggravated.

Most monitoring methods have in common that special equipment or knowledge of appliance and analysis are needed. With the proposed method in [8] insulation condition monitoring only based on the current sensors signals is shown. The technique is based on analysis of the transient part of the current sensor signals after voltage step excitation. The same sensors are also needed for the control of the machine. Resulting to a voltage step excitation of the phases, changes in transient signal ringing occur, depending on the actual insulation health state. Every phase is analyzed with the corresponding current sensor.

With regard to the economic view a reduction of system components is preferred and thus usually only two sensors are available. This puts additional challenges to the insulation monitoring method. An accurate reconstruction of the missing phase from the assumption that the sum of all phase currents is zero is only possible in the low frequency range. Thus in the following a technique is presented enabling insulation state monitoring even in the non measured phase. This technique (using only two current sensors) can be seen as one extension and practical realization of patent (AT511807 B1), applied to the practical restrictions in traction drives.

## II. GENERAL ASPECTS, MEASUREMENT PROCEDURE AND SIGNAL PROCESSING

The insulation health state monitoring method is based on analysis of the transient current reaction to a voltage step excitation of all phases. With the inverter, every phase can be excited separately, e.g. with a switching transition from an

inactive to an active inverter output state. The fast rising voltage steps in combination with the improper terminated transmission lines from the inverter to the machine cause transient overvoltage on the end of the line, which can reach 2-4 times of the DC-link voltage, investigated in [9] and [10] for instance. This ringing with exponential decaying behavior is also observable in the current sensors response to a voltage step excitation. In Fig. 1 the first 20 $\mu$ s of the current response to a step excitation from lower short circuit to a positive switching state in the corresponding phase is shown. The data is recorded with a standard industrial current sensor with a specified bandwidth of DC-150 kHz and a maximum di/dt of 50A/ $\mu$ s.

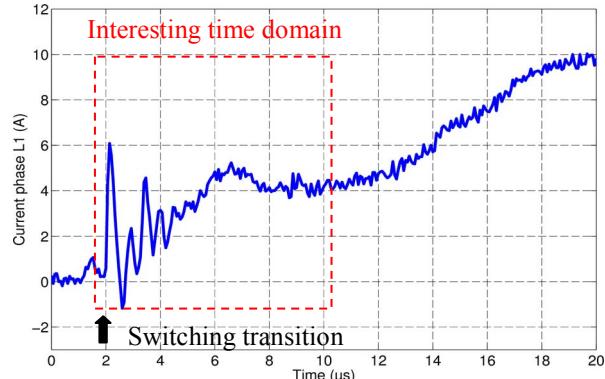


Fig. 1 Resulting phase current signal to voltage step excitation in corresponding phase

The transient part is visible within the first 20 $\mu$ s. Thus, a high sampling rate of at least 10-20 MS/s is recommended to reach acceptable accuracy. A sampling rate of 15MS/s is used for the analyses in this report. The length of the interested time window delineated in Fig. 1 depends on different factors, e.g. the inverter switching time, supply voltage level, cabling between inverter and machine and the machine itself. The components inverter, cabling and machine form a complex network of resistances, inductances and capacitances. In Fig. 2, a schematic diagram of this complex network is depicted.

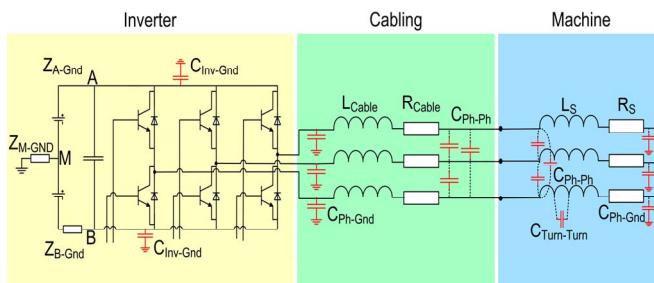


Fig. 2 Schematic view of the complex system inverter, cabling and machine with parasitic capacities

On the left side, the inverter with capacitive coupling  $C_{Inv-Gnd}$  to ground is visible. In the mid section the cabling with the resistances  $R_{Cable}$ , inductances  $L_{Cable}$  per unit length and the capacitances phase to ground  $C_{Ph-Gnd}$  and phase to phase  $C_{Ph-Ph}$  are indicated. On the right part of Fig. 2 the machine with the main parameter stator resistance  $R_S$  and  $L_S$  is shown. Aside from these parameters there are existing again additional parasitic capacitances, e.g.  $C_{Ph-Gnd}$ ,  $C_{Ph-Ph}$ ,  $C_{Turn-Turn}$  etc., which

influence the high frequency behavior of the machine at step excitation and thus the transient current response. In literature the insulation condition, respectively its possible degradation is always linked with a change of the machine's parasitic capacitances, see section I. Therefore the capacitance is considered as the dominant parameter for insulation health state evaluation. Before the measured current signal of Fig. 1 is subsequently analyzed, further signal preprocessing steps are necessary. To avoid deviation of the switching transition through jitter of the inverter system, a trigger detection algorithm is used to determine the accurate instant of the rising edge of the current. Furthermore, the mean signal slope is calculated to prevent influences of inherent machine asymmetries. Finally the mean of the signal is subtracted to remove the DC-component in the spectra. The measurements are conducted at a demagnetized and current less machine. Hence, no influences on the current response through the operating point of the machine and possible effects of inherent asymmetries like saturation or anisotropy have to be considered. The measurements are conducted on a test stand with a special type 1.4 MW induction machine with tappings leading through a terminal area. With this machine, insulation degradation is emulated with capacitors placed parallel the winding, forcing a change of the impedance characteristic of the machine. A high number of tabs in phase L1 and L2 are available to facilitate the investigations of different insulation degradation characteristics. The change in the impedance characteristic affects the current response after a step excitation is applied. This deviation is compared with a measurement of the same machine in a new (healthy) machine state. In Fig. 3, a comparison of the current response in case of the new and healthy machine (blue) and the same machine with emulated insulation degradation with a capacitor of 15nF parallel the whole phase L1 is shown.

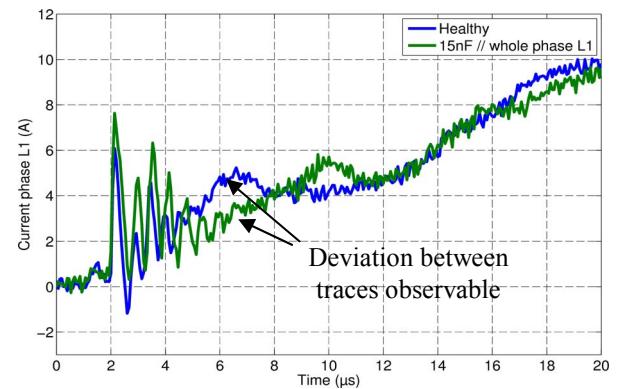


Fig. 3 Phase current signal, healthy machine state (blue, denoted Healthy) and emulated insulation degradation (green, denoted 15nF // whole phase L1)

The deviation between both traces is clearly observable. The oversampled current responses of a phase after step excitation with different machine conditions, regarding the insulation state, show characteristic deviations suitable for an insulation state evaluation. After the signal processing steps mentioned above (trigger detection, mean slope and mean value subtraction), the signals are analyzed in the frequency domain using the Fast Fourier Transformation FFT. To enable

statistical analyses a sequence of measurements are carried out to analyze one machine state. The mean of the resulting spectra for the healthy machine condition (blue trace), the emulated insulation degradation with 15nF placed in parallel to the whole phase L1 (green trace) and the square deviation of both traces (dashed red, scaled because of clarity) are shown in Fig. 4.

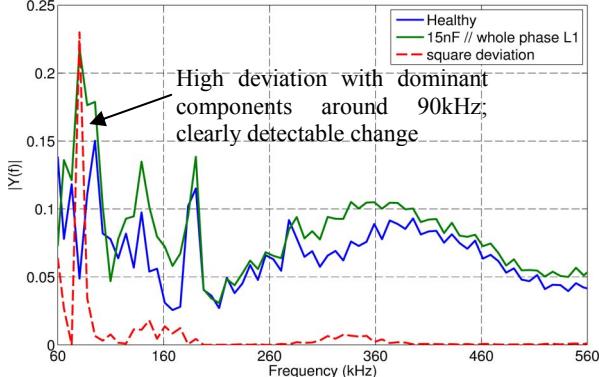


Fig. 4 Comparison of the spectra of the current response for a step excitation in phase L1 measured with sensor phase L1; solid blue: healthy machine, solid green: emulated insulation degradation with 15nF parallel whole phase L1, dashed red: square deviation of both spectra (scaled because of clarity)

The blue trace serves as a reference and represents the first measurement after initial operation of the drive system. A change of the green trace (representing measurements taken during operation of the drive) with respect to the reference can be interpreted as insulation degradation. The observed frequency range is selected from 60 kHz to 560 kHz. Below 60 kHz the magnitude values of the analyzed spectra are occasionally subjected to higher fluctuations and inaccurateness in the mean derivative estimation that affect this low frequency range. The most noticeable change of the frequency spectrum due to the additional capacitor in Fig. 4 occurs in a very narrow range around 90kHz. The main deviation depends on the size and position of the capacitor, therefore the whole frequency range mentioned before is analyzed with the integration of all deviations. An indicator was introduced to assess the severity of the insulation degradation, denoted Insulation State Indicator ISI. The Root Mean Square Deviation (RMSD) calculated with the spectra of reference measurements and further measurements has been found to be a good choice to determine changes in the winding capacitance. The calculation of the indicator is based on the two following equations (1) and (2).

$$ISI_p = RMSD_p(x_1, x_2) = \sqrt{\frac{\sum_{i=1}^n (Y_{ref-sum,p}(i) - |Y_{con,p}(i)|)^2}{n}} \quad (1)$$

$$Y_{ref-sum,p} = \frac{\sum_{i=1}^l \left( \sum_{k=1}^m \frac{Y_{ref,p,k}}{m} \right)_i}{l}; Y_{con,p} = \frac{\sum_{k=1}^m Y_{con,p,k}}{m}; \quad (2)$$

The index  $p$  identifies the investigated phase. The variables  $Y_{ref-sum,p}$  and  $Y_{con,p}$  represent the mean of the amplitude

spectrum of at least one reference and of a later condition measurement respectively. To increase the accuracy, quantity of measurements for the mean is set to at least 33 measurements (Index  $m$ ). The principle in detecting changes in the current response through repetitive measure procedures demands same conditions in every measurement. The reference signals are confirmed through several test measurements at a healthy machine state. Only after the reference signal can be verified the examination of changes can be done. It is recommended to improve the signal processing method with a high number ( $l$ ) of reference measurements taken at different time instants and to use the mean as base value  $Y_{ref-sum,p}$  (Index  $l$ ) for the comparison. With the correctly obtained reference and further measurements the comparison and observation of changes in the current response is possible. The variable  $n$  depends on the frequency resolution and time window length. The described signal processing method delivers accurate results as already evaluated in [8]. However, each phase current needs to be measured by an individual current sensor.

Omitting one phase current sensor thus leads to a lack of information. The transient current reaction in the non-excited phases is very small and hardly influenced by a change of the phase capacitance, as depicted in Fig. 5. The excitation of phase L1 with 15nF parallel the whole phase L1 shows hardly visible deviations between the healthy machine (blue) and the degraded insulation machine state (green). Despite the phase with degraded insulation (L1) is directly excited, the current reaction deviation compared to the healthy machine state is hardly observable in the non-excited current reaction (L2).

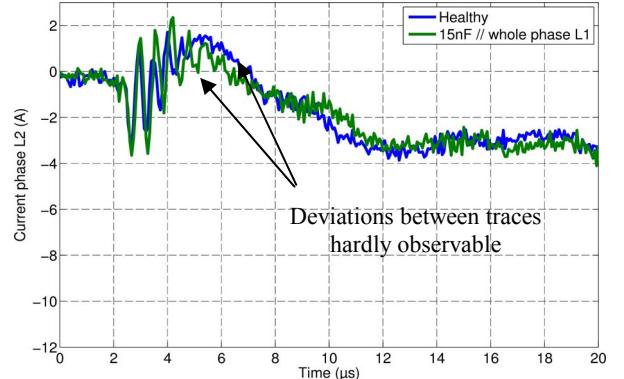


Fig. 5 Current response of phase L2 for step excitation in phase L1. Blue: healthy machine; green: emulated insulation degradation with 15nF parallel phase L1

This indicates that deviations in the spectra, as characterized in Fig. 4, are hardly detectable if the corresponding current sensor is omitted although a capacitor of 15nF is used for the insulation degradation emulation corresponding to a clear and severe deterioration. As a consequence, the omission of one sensor implicates that the information about the insulation state in the corresponding phase is almost lost.

A simple substitution of the missing transient current reaction by using the sum of the two other currents is not helpful as equation (3) is only valid for low frequencies.

$$i_{L1} + i_{L2} + i_{L3} = 0 \quad (3)$$

The sum of the transient current signal part is different from zero through e.g. the appearance of displacement currents. Using the composite signal of (3) does not deliver satisfactory results. Furthermore, the sensibility to detect a change on the base of excitation in the sensor-less phase while measuring the response in another phase is not sufficient for smaller deviations.

Therefore, a new excitation and signal processing method has been developed and the resulting insulation state indicator is denoted with ISI\_2S (2S: two sensors). Fig. 6 depicts the scheme of the ISI\_2S procedure.

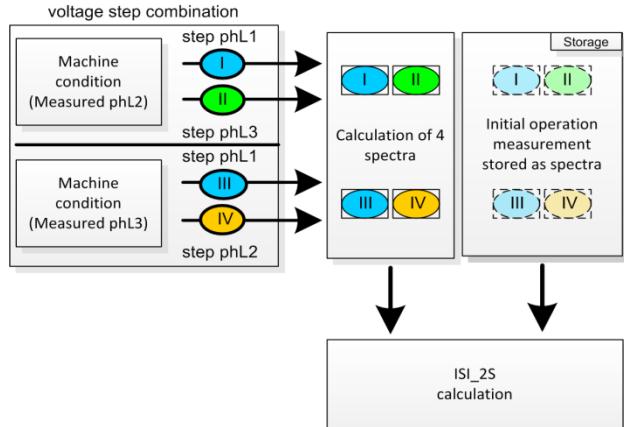


Fig. 6 Scheme of the ISI\_2S calculation process

The new indicator is based on comparison of different step excitations and current reactions of the non-excited phases. It uses the principle of the symmetric machine at a healthy machine condition. The new indicator ISI\_2S serves as an enhancement of the ISI to facilitate the omission of one current sensor and to observe the insulation condition of the non-measured phase. The new method uses four voltage steps (denoted I,II, and III, IV in Fig. 6) each analyzed with one of the two current sensors if the non measured phases are excited alternately. For the following explanation it is assumed, that no sensor in phase L1 is available. First the measurements are done only with sensor phase L2 if two equivalent steps, e.g. one in phase L1 and one in phase L3 are carried out (I,II upper left block in Fig. 6). Comparing the two measurements (I,II) gives an evidence for a possible asymmetry of phases L1 and L3. The procedure described above is repeated for excitation in phase L1,L2 and measurement in phase L3 (III,IV lower left block in Fig. 6). Thus, the measurement of the current reaction is always taken in the non-excited phase and the resulting spectra are used for the evaluation.

The comparison of the two steps of one sequence is done with the simple difference of the spectra. This means that the difference of spectra step I and II respectively step III and IV are calculated. In Fig. 7 a) and b) these differences are shown for the initial operation measurement (reference, healthy insulation state) from the storage and a measurement after unspecified operation time of the drive system with the assumption of existing insulation degradation. In subfigure a) the blue trace represents the difference of I and II for the healthy machine condition at initial operation. The green trace

gives the results in case of emulated insulation degradation with 15nF parallel phase L1. The dotted red shaded area should emphasize the deviation between the two machine conditions. With equation (1) the RMSD between these two traces is calculated and serves as the ISI\_2S indicator only based on measurements of phase L2. In subfigure b) the difference of the spectra III and IV for the healthy machine condition at initial operation (blue trace) and in case of emulated insulation degradation with 15nF parallel phase L1 (green trace) are shown. Again the deviation between the traces is emphasized and is used for the RMSD calculation. This result in a second ISI\_2S indicator calculated only based on measurements in phase L3. The results of the two ISI\_2S indicators can then be compared to each other.

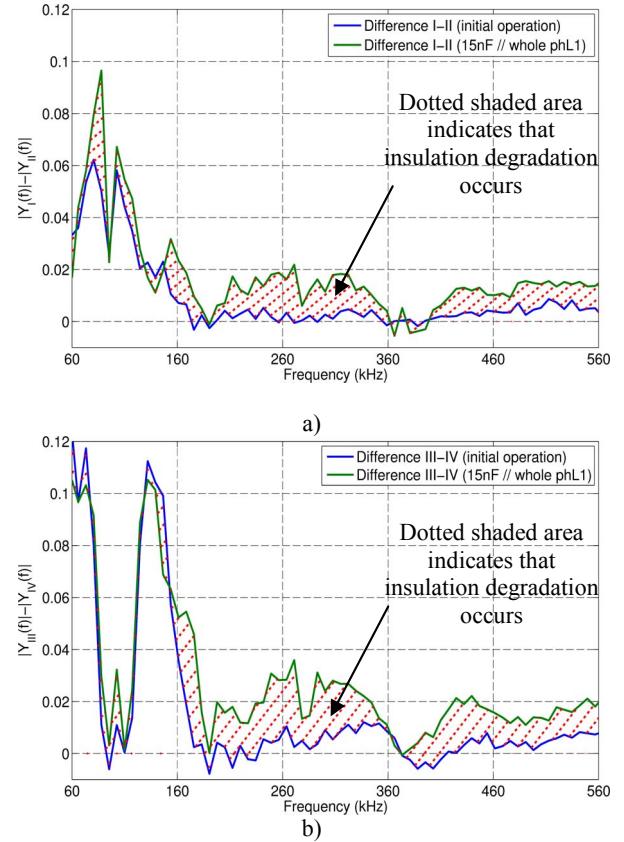


Fig. 7 a) Resulting trace for difference I-II of the initial operation measurement (blue trace) and for the difference I-II in case of degraded insulation (green trace) measured with sensor phase L2. b) Resulting trace for difference III-IV of the initial operation measurement (blue trace) and for the difference III-IV in case of degraded insulation (green trace) measured with sensor phase L3

The deviation between the traces in every subfigure is clearly visible and thus the indication of a change in the insulation state is possible.

### III. EXPERIMENTAL RESULTS

The experimental results illustrate the possibility to detect a deterioration of the insulation state, by detecting a change of the machine's impedance system. Additionally, the

investigated cases are separated according to different severity. The proposed method was investigated on an industrial 4-pole, 1.4MW squirrel cage induction machine. The machine has a three phase stator winding with various tappings. Thus, a high number of possible positions to place capacitors in parallel to different numbers of turns or coils is possible. The machine size implies that form-wound windings are used. The measured winding-to-ground capacitance of the winding system is determined with 63nF, resulting in 21nF per phase. The DC resistance of one phase is about 30mΩ. The measurements are carried out with different capacitors with a size of 15nF, 6.8nF and 3nF placed parallel the first coil of phase L1 and the whole phase L1 between terminal connection and neutral point. Remembering that phase L1 is the strand without a current sensor; these are the interesting cases regarding the proposed method. In Fig. 8 the measurements are statistically analyzed with the box-plot representation. It shows the distribution of the resulting ISI\_2S values. The box plots show the median of the 33 consecutive measurements (red line) and the lower and upper limit of the blue box indicates the 25<sup>th</sup> respectively 75<sup>th</sup> percentile. Additionally, with no overlapping notches it can be concluded that with 95% confidence the medians differ between the analyzed machine conditions. Therefore, all machine conditions are clearly separable from the healthy machine state.

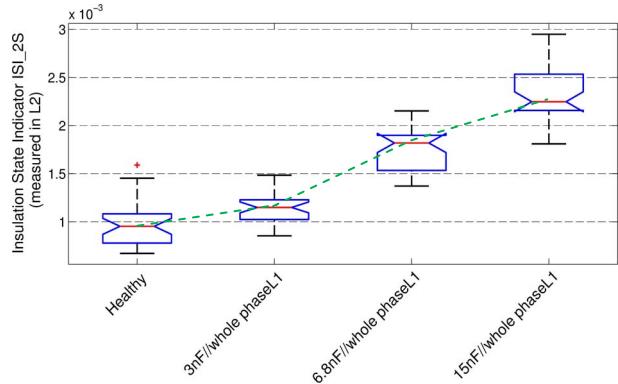


Fig. 8 Box plots of the Insulation State Indicator for different machine conditions compared with reference measurement (healthy condition)

The green dashed line marks the possible evolution of the insulation state respectively the ISI\_2S value over a continuous deterioration of the insulation health state.

The following Table 1 gives an overview of the calculated ISI\_2S values for all tested fault conditions.

Table 1 ISI\_2S values for emulated insulation degradation with a capacitor parallel the whole phase L1 and parallel 1<sup>st</sup> coil phase L1

Fault condition	ISI_2S (I and II)	ISI_2S (III and IV)
Healthy	$9.64 \times 10^{-4}$	$1.25 \times 10^{-3}$
3nF//1 <sup>st</sup> coil phL1	$1.06 \times 10^{-3}$	$1.51 \times 10^{-3}$
6.8nF//1 <sup>st</sup> coil phL1	$1.28 \times 10^{-3}$	$1.74 \times 10^{-3}$
15nF//1 <sup>st</sup> coil phL1	$1.53 \times 10^{-3}$	$2.14 \times 10^{-3}$
3nF//whole phL1	$1.14 \times 10^{-2}$	$1.90 \times 10^{-3}$
6.8nF//whole phL1	$1.74 \times 10^{-3}$	$2.02 \times 10^{-3}$
15nF//whole phL1	$2.33 \times 10^{-3}$	$2.28 \times 10^{-3}$

According to the signal processing procedure described in Fig. 6, it can be seen that two ISI\_2S values can be calculated. It is visible that both values of the insulation state indicator ISI\_2S clearly change with placement of a capacitance parallel to the winding or a single coil. The results of Table 1 also show that the calculated indicator values depend on the size and position of the capacitor. A lower capacitance value placed over a few turns results in a very low indicator value. The measurement taken at initial drive operation acts as reference. If this measurement is repeated on the healthy insulation, measurement noise leads to deviations in the spectra that add up to a non-zero value of the indicator value. These results are given in the first row of Table 1 denoted 'healthy'. A small impedance change is stimulated by a small capacitance of 3nF that is placed parallel to the first single coil of the winding. This corresponds to a slight deterioration of the insulation condition and leads to a clear detectable increase of the fault indicator value (from  $9.64 \times 10^{-4}$  to  $1.06 \times 10^{-3}$ ). To enable an easy interpretation of the insulation state indicator values, they can be scaled to the initial measurements taken at the initial operation of the machine set. In the following, always the average of both ISI\_2S values (left and right column in Table 1) is used. The scaling on the average of the indicators denoted 'healthy' is used in Fig. 9.

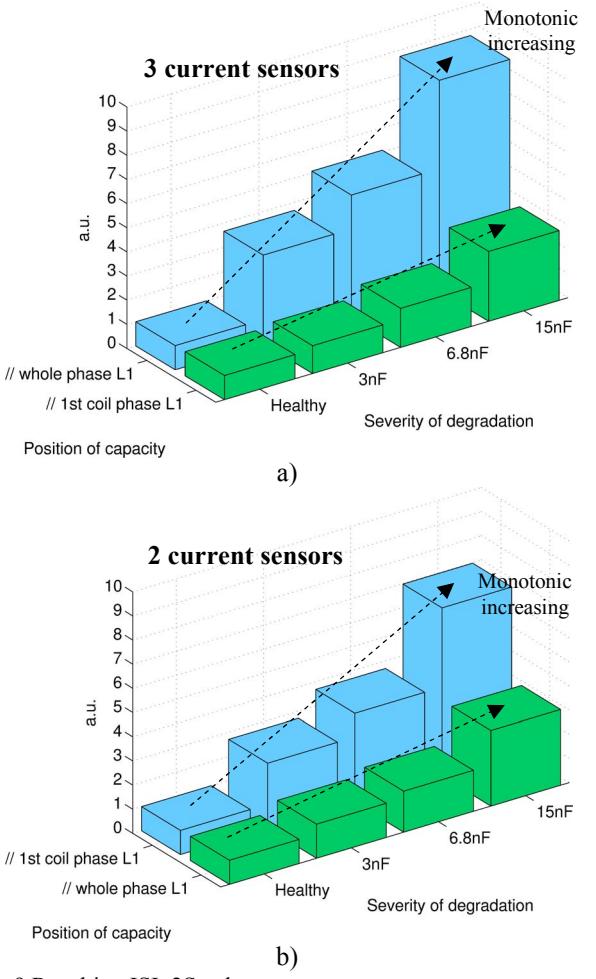


Fig. 9 Resulting ISI\_2S values

On the vertical axis in Fig. 9 a) and b) the averaged and scaled ISI\_2S value is given. The figure also depicts the comparison of the indicator values obtained when using the data of the current sensor in phase L1 (subfigure (a) denoted ‘3 current sensors’) and if the indicator is calculated with the data of the remaining phase current sensors L2,L3 (subfigure (b)). Both subfigures indicate a monotonic increasing tendency for increasing capacitor values placed parallel a single coil or the whole phase winding. Comparing the results of Fig. 9 a) and b) it can be seen that even when omitting a phase sensor, the insulation state indicator can be calculated based on the remaining sensors and the procedure proposed. The resulting insulation state indicator values show nearly the same behavior and no significant deterioration of accuracy or sensitivity. It has to be stressed that the presented two-sensor-method is an extension to a method already published ([8],AT511807 B1).

#### IV. CONCLUSION

A method to detect insulation degradation based only on the information of two current sensors has been presented. The proposed technique is based on evaluating the transients of the current sensors. These transients are mainly influenced by the drive’s parasitic capacitive components and insulation degradation is always linked with a change of this capacitance that is considered as the dominant parameter for insulation health state evaluation. A new fault indicator was derived and its sensitivity to capacitive changes verified. A combination of different step excitations and measurement sequences enables the monitoring with only two current sensors. The time signals of the current responses are transferred into frequency domain and based on the calculation of a root mean square deviation, between reference measurement at initial operation of the drive and later in-service measurements, information about the insulation condition is obtained. Measurements performed on a 1.4MW induction machine with different machine conditions verify the applicability of the proposed method. The emulated insulation degradation cases tested are detectable and show a monotonic increasing tendency for increasing windings capacitance values. There is no significant deterioration of sensitivity if one single phase current sensor is omitted.

#### ACKNOWLEDGMENT

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#### REFERENCES

- [1] IEEE Committee Report; “Report of large motor reliability survey of industrial and commercial installation, Part I,” *IEEE Transactions on Industry Applications*, vol.21, no.4, pp.853–864, 1985
- [2] IEEE Committee Report; “Report of large motor reliability survey of industrial and commercial installation, Part II,” *IEEE Transactions on Industry Applications*, vol.21, no.4, pp.865–872, 1985
- [3] G. C. Stone, E. E. Boulter, I. Culbert, and H. Dhirani, “Electrical Insulation for Rotating Machines”. *IEEE Press*, 2004
- [4] Farahani, M.; Borsi, H.; Gockenbach, E.; “Study of capacitance and dissipation factor tip-up to evaluate the condition of insulating systems for high voltage rotating machines,” *Electrical Engineering*, vol.89, no.4, pp.263-270, 2007
- [5] Perisse, F.; Werynski, P.; Roger, D., “A New Method for AC Machine Turn Insulation Diagnostic Based on High Frequency Resonances,” *Dielectrics and Electrical Insulation, IEEE Transactions on* , vol.14, no.5, pp.1308,1315, October 2007
- [6] Farahani, M.; Gockenbach, E.; Borsi, H.; Schafer, K.; Kaufhold, M.; “Behavior of machine insulation systems subjected to accelerated thermal aging test,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol.17, no.5, pp.1364-1372, 2010
- [7] Kim, H.D.; Yang, J.; Cho, J.; Lee, S.B.; Yoo, J.-Y.; “An Advanced Stator Winding Insulation Quality Assessment Technique for Inverter-Fed Machines,” *IEEE Trans. on Ind. Appl.*, vol.44, no.2, pp.555-564, Mar./Apr. 2008
- [8] Nussbaumer, P.; Santin, C.; Wolbank, T.M.; “Analysis of current reaction on inverter-switching to detect changes in electrical machine’s high-frequency behavior,” *38th Annual Conference on IEEE Industrial Electronics Society, IECON*, pp.1678-1683, 2012
- [9] Peroutka, Z., “Requirements for insulation system of motors fed by modern voltage source converters,” *Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual* , vol.6, no., pp.4383,4389 Vol.6, 20-25 June 2004
- [10] Persson, E., “Transient effects in application of PWM inverters to induction motors,” *Industry Applications, IEEE Transactions on* , vol.28, no.5, pp.1095,1101, Sep/Oct 1992