Stimulating and detecting changes in the insulation health state of inverter fed ac machines

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Keywords

«AC machines, Insulation, Breakdown, Voltage Source Inverters (VSI), Current sensors»

Abstract

In modern traction drive applications condition monitoring is getting more and more important. Insulation health state monitoring can be done by evaluating the high frequency current response to voltage step excitation by the signal analyses of the current sensors, which are also used for the control of the machine. This reduces the costs and number of necessary system components. A change in the current response is, amongst others, correlated to a change through insulation degradation. The dominant influencing parameters of the high frequency current response of the machine are parasitic winding capacitances as well as insulation resistances, which are slowly changing over time if the insulation is deteriorated through different stresses, e.g. thermal or electrical. These slow changes can be monitored over long time period and give evidence if additional maintenance steps are required. Thus an unforeseeable outage of the traction drive system caused by damage of the machine can be prevented. Before the insulation state can be evaluated certain signal processing steps are necessary to increase the sensitivity. In this work the method of stimulation as well as detection of changes in the dominant parameters is verified on a 1.4MW induction machine.

Introduction

In order to ensure a reliable and safe operation of inverter fed drives over a long period without maintenance, the knowledge of the machine's health condition is important. Monitoring systems in that sense seem to be a good approach. Stator related faults are with 35% the second most common faults, causing a machine outage, described in [1] and [2]. Furthermore, about 70% of these stator faults are based on a failure of the insulation system. The failure is caused by different stresses like electrical, thermal, thermo-mechanical, mechanical and environmental acting on the insulation system [3]. The insulation deterioration process usually progresses very slowly. The effect of thermal-electrical aging for high operation time on single stator bars are analyzed in [4]. The results of the investigated scenarios show, that the parasitic capacitance is decreasing with time and the number of aging cycles respectively. In [6] this tendency is approved through a high number of aging cycles tested on stator segment specimen. And according to [6] the results show that the turn-turn capacitance has changed after thermal stresses.
Modern drive systems basically consist of the components machine, machine cables, and the inverter. These components form a complex impedance system whose high frequency characteristic is defined

by the parasitic parameters like phase-ground capacitances, phase-phase capacitances, as well as insulation resistances. With changing health state of the insulation system of the machine, the parasitic elements and thus the high frequency behavior is changing as well. According to signals theory the impedance mismatch between cabling and machine in combination with fast inverter switching leads to a transient overvoltage decaying after few μs depending on the parameters mentioned above [7]. On the other side, the signal ringing of the current, resulting from a switching transition is also influenced by a change of the parasitic elements and can thus be exploited for insulation health state monitoring. With the method proposed, signal analysis is done with the current sensors already used for the control of the machine. A developing fault becomes apparent through insulation degradation and hence an alternation of the impedance system. The signal trace of the high frequency current response after inverter switching is recorded to detect changes in the transient part.

Measurement procedure and signal processing of the proposed method

Theoretical description of the insulation state evaluation

For the insulation condition monitoring method applied, the current responses of all three phases are acquired after a voltage step is applied with the inverter. The transition of the inverter can be from lower or upper short circuit to one of the three positive respectively negative active switching states and is carried out for the investigations in this work on the non-magnetized machine at standstill.
The interesting part of the current signal is the transient oscillation occurring at the beginning of the response and decaying within the first few μs. The duration of the ringing depends on different factors e.g. machine size, voltage excitation level or used sensor. Before an estimation of the insulation state can be done based on the current transient the measured signal is subsequently preprocessed. In a first step the exact switching time point is detected. Because a pre trigger is used to record the complete transient part of the current and through possible jitter in the inverter output waveform, the actual switching point is varying between different measurements. Furthermore, after the exact switching time point is known the mean signal slope is calculated. The current slope is determined by the machines transient leakage inductance that in turn is influenced by inherent machine asymmetries like slotting. These fundamental wave signal components do not contain information necessary for the insulation state estimation and thus the slope is removed from the recoded signal. Through elimination of the current slope, influences caused by slotting and saturation of the iron core are also prevented and the applicability of the method during operation of the drive system is also given. Finally the mean value is removed from the signal. After preprocessing the signal the current response obtained is analyzed in the frequency domain. To detect changes in the insulation system these steps are performed on a new (healthy) machine and repeated with the same machine during operation to monitor possible degradation of the insulation. In [8] first experimental results of the proposed condition monitoring technique are given. For this work the degradation of the insulation health state is emulated on the test stand with a resistance or capacitance parallel the winding or parts of it using taps, for instance with a capacitance parallel 1st coil of phase L1 depicted in Fig. 1. The emulation of insulation degradation is only possible in phase L1 and L2. This figure also illustrates the parasitic capacitances existing in a stator three phase winding. Every phase consists of a specified number of coils and every coil is formed out of a number of turns. The exemplary component $C_{ph\text{-}gnd}$ and $C_{m\text{-}gnd}$ represents parasitic capacitances between the winding system and ground potential. Between the individual phases a capacitive coupling also exists denoted with $C_{ph\text{-}ph}$. The whole phase consisting of a specific number of coils forms also a capacitive component C_{ph} and additionally the turn-turn

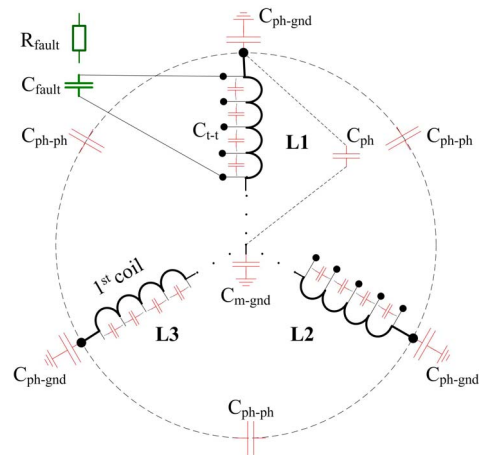


Fig. 1 Scheme of the parasitic fault capacitances and taps with emulated insulation degradation through capacitance or resistance parallel of the winding

capacitance is depicted with $C_{t\text{-}t}$. The phase to ground capacitance $C_{ph\text{-}gnd}$ for the tested machine with nominal power of 1.4MW is 21nF. The turn-turn capacitance $C_{t\text{-}t}$ is determined with the geometrical dimension and dielectric properties of the used materials using equation (1).

$$C_{t-t} = \varepsilon_0 \varepsilon_r \frac{l_w l_l}{2d} \tag{1}$$

With the permittivity of free space ε_0 and the relative permittivity ε_r of the insulation material between the turns, the length of the strand l_l respectively the width l_w and the thickness d of the insulation the equation results in a $C_{t\text{-}t}$ of about 1nF. The additional components C_{fault} respectively R_{fault} connected through taps with the winding depict the fault components forcing a change in the frequency response of the machine visible in the current response after step excitation. Due to the fact that aged insulation material would lead to a change of capacitance or resistance the approach of placing capacitive or resistive fault components is chosen to emulate the insulation deterioration. This change in capacitive/resistive decreasing/increasing is in accordance to the investigations in [4]-[6] as mentioned in the introduction. The severity of the insulation degradation is defined by the value of the fault component.

Analyses of the current response for insulation state evaluation

The monitoring method is based on analyses of the current response after voltage step excitation. With the inverter the phases are excited separately and the current response is recorded with a pre trigger to record the transient oscillation occurring at the beginning of the response. The current sensors used for these investigations are standard industrial hall-effect based closed loop sensors with a specified bandwidth of 150 kHz and a *di/dt* following of 50A/µs. In Fig. 2 current sensor signals after step excitation of phase L1 can be seen. The blue trace gives the results for a healthy machine, the green one with a capacity of 15nF placed in parallel to the whole phase L1. As mentioned above, a first set of measurements taken on a new machine serves as a reference. A change of the measured signal with respect to that reference can then be interpreted as insulation state change, as first analyses can be seen in [8]. The deviation is analyzed in frequency domain and to facilitate statistical evaluation of a possible insulation change several measurements are done to represent one insulation state. The Root Mean Square Deviation (RMSD) calculated with the spectra of the reference measurements was found to be a good compromise between calculation effort and signal accuracy. The calculation is based on the two following equations (2) and (3) and the value obtained is denoted insulation state indicator (ISI).

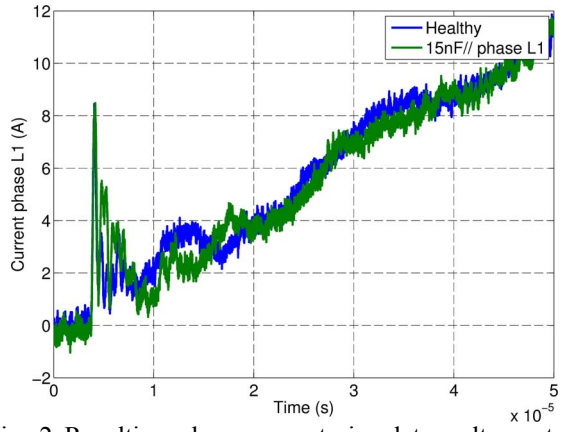


Fig. 2 Resulting phase current signal to voltage step excitation in corresponding phase. (blue: "healthy machine", green: emulated insulation degradation with 15nF parallel whole phase L1)

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

$$Y_{con,p} = \frac{\sum_{k=1}^{m} Y_{con,p,k}}{m}; \tag{3}$$

The index p identifies the investigated phase. The variables $Y_{ref,p}$ and $Y_{con,p}$ represent the mean of the amplitude spectrum of at least one reference and of one later set of condition measurement respectively. To increase the accuracy, quantity of measurements for the mean is set to at least 33 measurements (Index m). The variable n depends on the frequency resolution and time window length.

Finally, after calculation of the ISI values of all phases is done, the linear combination of these values form a spatial indicator (3) to reduce the influence of symmetrical changes and to identify the phase which is affected.

$$SISI = ISI_{L1} + ISI_{L2} * e^{\frac{j2\pi}{3}} + ISI_{L3} * e^{\frac{j4\pi}{3}} \tag{4}$$

The alteration between the reference spectrum and the faulty machine spectrum occurs in different frequency components. This change in the high frequency behavior of the machine due to the emulation of insulation degradation is visible in a frequency range of several kHz to few MHz. The range of important spectrum components suitable for insulation state evaluation can be limited from 50 kHz to 500 kHz. Below 50 kHz inaccuracy in the slope estimation are affecting especially this range. Although the range up to 500 kHz is above the specified frequency range of the current sensor the transfer function is still reproducible and is applicable for detecting changes in the transient ringing. At lower frequencies the sensor operates using the electronic components including the hall sensor. However, at higher frequencies the compensation winding with the flux concentrating core operates as a current transformer providing the output of the current sensor. In [9] fundamentals and separation of disturbing influences as well as investigation of the cabling influence are described. The identified range influenced by the cabling is around 2 MHz for an induction machine with nominal power of 5.5 kW. Investigations of measurements with the machine used in this paper (nominal power 1.4MW) showed a deviation around 1MHz caused by changes on the cabling. Based on the fact that a wide range is taken into account for the insulation state evaluation and even though a filter is applied to traction drive systems if the cable and the motor are not adequately shielded, this frequency range above 500 kHz can be excluded. Furthermore all three phases are affected symmetrically by a change of the cabling. Therefore, if evaluations for all three phases are performed and combined according equation (4) representing the spatial indicator representation, the effect of the cabling is eliminated by the signal processing.
The advantage of the monitoring system is the applicability as an online noninvasive insulation monitoring.

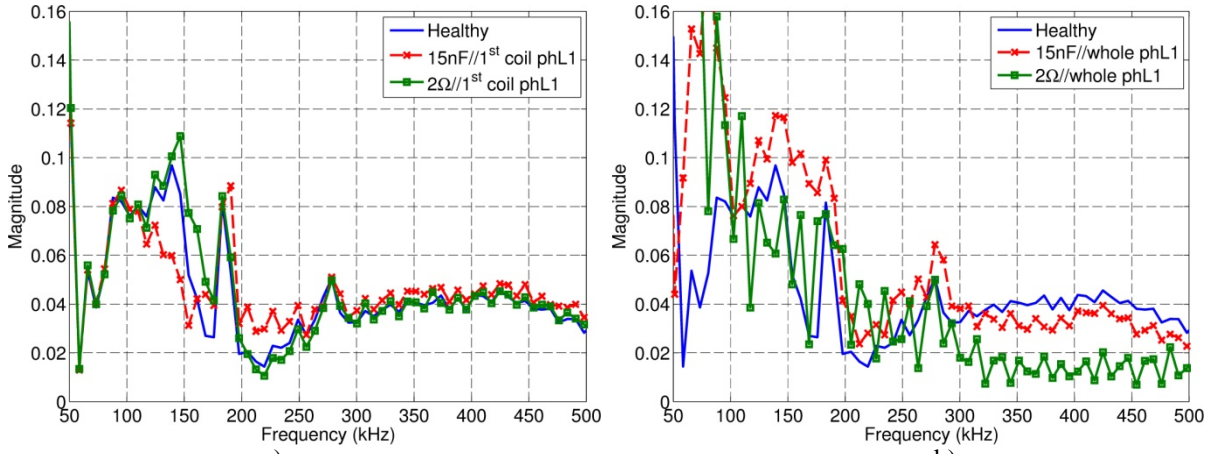
Alternative measurement with frequency response analyzer

Analyses of the insulation state based on the frequency response with a vector network analyzer has been presented as a simple technique for detecting faults of stator windings in rotating machines, for instance [10] and [11]. The evaluation of the impedance of the winding in the frequency domain is done with a sine wave at constant amplitude and logarithmic frequency sweep mode from 10Hz to 40MHz. With the transfer function of two input channels the impedance frequency response can be analyzed.

Experimental results

The method described was tested at the 1.4 MW squirrel cage induction machine. The machine is equipped with several tapping's of the three stator windings. Thus, a high number of positions to place resistances or capacitors in parallel to single or multiple turns or coils, is possible. In Fig. 3 a) and b) different fault scenarios emulated with capacitances and resistances parallel the winding are shown. Subfigure a) depicts the fault scenarios with lower severity by placing the fault component parallel to the 1st coil of phase L1. The spectra are calculated after step excitation of phase L1 and measurement of the current response in the same phase with the aforementioned signal processing steps are applied. The solid blue trace shows the result of the reference measurement, which represents the healthy machine without insulation degradation. The results for a placement of 15nF (dashed red) parallel to the 1st coil of phase L1 are depicted in the figure as well as that of the placement of 2Ω (solid green) parallel to the 1st coil in phase L1. The DC resistance of one phase is 28mΩ and the total winding capacitance is 63nF. It can be seen that though only one out of 12 coils is affected, a clear change in the calculated signal is detectable for all configurations. It is also observable that the capacitances affect the deviation in another way as the resistances. As can be seen through the signal traces the significant frequency range for changes in the insulation parameters of the machine considered is located between 50 kHz to 500 kHz. The main part of the deviation from the reference trace occurs

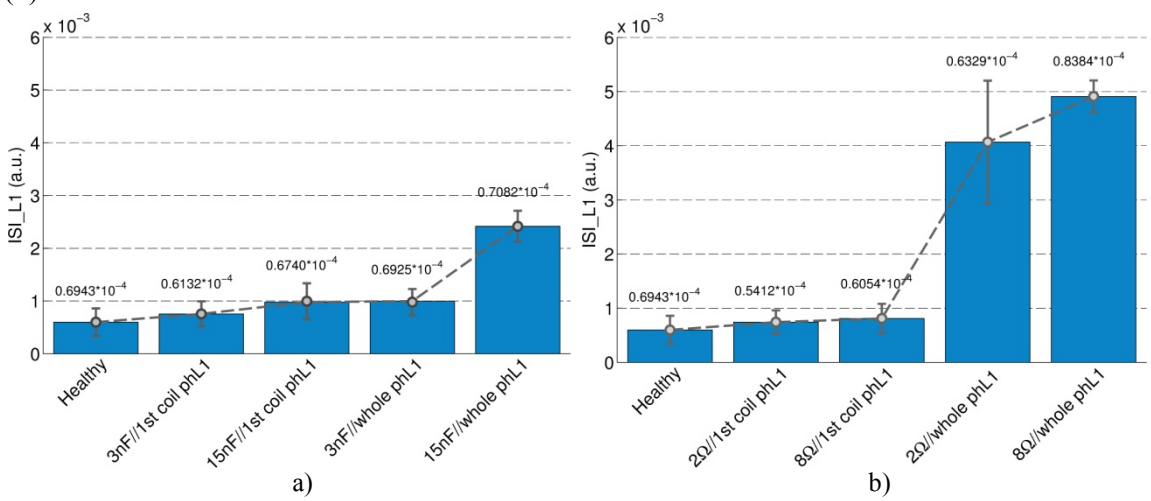
between 100 kHz to 300 kHz in all investigated cases. In subfigure b) the same measurements with the emulation of insulation degradation with a capacitance or resistance parallel the whole phase L1, representing a high severity of insulation degradation are shown. As expected the deviation occurs over the whole frequency range and the analysis is done over the whole range from 50 kHz to 500 kHz.



a) b)

Fig. 3 a) Magnitude spectra for healthy machine condition (solid blue), emulated insulation degradation with 15nF (dashed red) and 2Ω (solid green) parallel 1st coil L1; b) magnitude spectra of emulated insulation degradation with 15nF (dashed red) and 2Ω (solid green) parallel whole phase L1

Comparing the influence of parallel resistance and capacitance it can be seen that both changes significantly influence the magnitude spectrum, however with different directions. Due to the signal processing and equation (2) and (3) only the square deviation is considered and thus both changes lead to an increase of the ISI value. Furthermore, the value of the deviation increases with decreasing value of the parallel resistance. To give an evidence of the severity of the analyzed degradation respectively for the insulation state, an indicator was introduced based on the deviation between a reference spectrum trace and the spectrum trace through insulation degradation, as described with equation (2). In Fig. 4 a) and b) the mean value of 33 calculated indicators from the spectra of Fig. 3 with equation (2) are shown.



a) b)

Fig. 4 Mean value of 33 calculated indicators for different fault scenarios with standard deviation of the series of measurement and indication of outliers.

In both figures a monotonic increase of the indicator for increasing severity is observable. In subfigure a) the different fault capacitances are used and a value of 3nF parallel the 1st coil is still distinguishable from the healthy measurement. In subfigure b) the indicators if resistances are placed as a fault component are depicted. A value of 2Ω is distinguishable from the healthy machine state and defines the lower limit of resistive fault components. The value above a bar shows the standard deviation for the 33 measurements for this machine state and the vertical lines indicates the spread of

the resulting values. The values of the standard deviation are in the same range for all analyzed machine states. 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 1.

Table 1 Calculated ISI values for different fault scenarios

Machine state/ Fault scenario	Capacitance	ISI mean value	ISI median value	Resistance	ISI mean value	ISI median value
Healthy	-	$5.98*10^{-4}$	$5.77*10^{-4}$	-	$5.98*10^{-4}$	$5.77*10^{-4}$
//1st coil phase L1	3 nF	$7.56*10^{-4}$	$7.39*10^{-4}$	2 Ω	$7.95*10^{-4}$	$7.99*10^{-4}$
//1st coil phase L2		$7.60*10^{-4}$	$7.70*10^{-4}$		$6.87*10^{-4}$	$6.97*10^{-4}$
//whole phase L1		$9.96*10^{-4}$	$9.76*10^{-4}$		$4.93*10^{-3}$	$4.92*10^{-3}$
//whole phase L2		$7.20*10^{-4}$	$7.17*10^{-4}$		$6.92*10^{-4}$	$6.72*10^{-4}$
//1st coil phase L1	7.5 nF	$8.80*10^{-4}$	$8.60*10^{-4}$	3 Ω	$8.10*10^{-4}$	$7.93*10^{-4}$
//1st coil phase L2		$7.45*10^{-4}$	$7.38*10^{-4}$		$6.92*10^{-4}$	$6.72*10^{-4}$
//whole phase L1		$1.60*10^{-3}$	$1.63*10^{-3}$		$4.91*10^{-3}$	$4.91*10^{-3}$
//whole phase L2		$7.77*10^{-4}$	$7.89*10^{-4}$		$1.70*10^{-3}$	$1.70*10^{-3}$
//1st coil phase L1	15 nF	$9.79*10^{-4}$	$9.95*10^{-4}$	8 Ω	$7.42*10^{-4}$	$7.37*10^{-4}$
//1st coil phase L2		$6.98*10^{-4}$	$6.86*10^{-4}$		$7.10*10^{-4}$	$6.88*10^{-4}$
//whole phase L1		$2.4*10^{-3}$	$2.42*10^{-3}$		$4.07*10^{-3}$	$4.08*10^{-3}$
//whole phase L2		$7.26*10^{-4}$	$7.17*10^{-4}$		$1.71*10^{-3}$	$1.71*10^{-3}$

The result in the first row denoted 'Healthy' is a second measurement of the healthy machine compared to the reference measurement. With this value it can be stated that an insulation state indicator below $5.98*10^{-4}$ is not separable from the healthy machine. Hence, the values in the table show that the difference between mean and median are very low. Thus, it can be assumed that the measurements are normally distributed and the mean value serves as an indicator of the insulation degradation.

In Fig. 5 the values of the spatial insulation state indicator are shown for measurements and fault scenarios affecting phase L1 or phase L2. The magnitude of the SISI corresponds to the severity of the emulated insulation degradation and the angle with the location. The results show that if the fault affects only the 1st coil the difference between the capacitive (rectangle) or resistive (cross) fault is negligible. However, if the fault affects the whole phase, resistive faults result in higher indicator values, approximately twice as in case of the 15nF capacitance parallel the whole phase.

As mentioned above, the insulation state is analyzed additionally with a vector network analyzer. This technique is often used for offline evaluation of the insulation state. The machine is disconnected from the inverter to prevent any influences of the attached devices. The impedance characteristic is recorded over a wide range in a frequency sweep from 10 Hz to 40 MHz with a constant sinusoidal supply voltage. With the recorded frequency response of the healthy winding system the trace can be

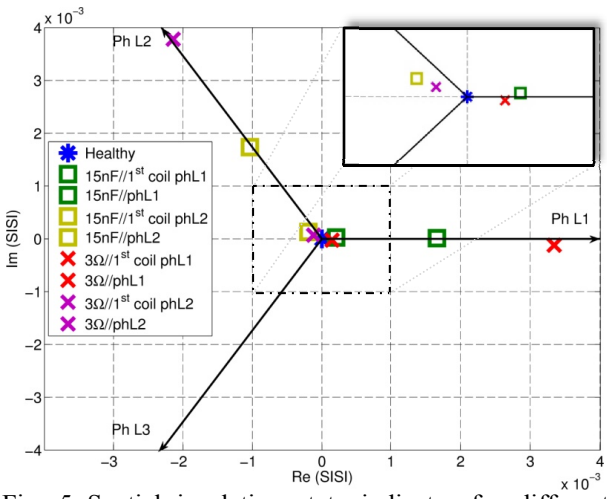


Fig. 5 Spatial insulation state indicator for different investigated machine conditions. Healthy machine state (blue *), emulated insulation degradation with a capacitor (green and amber □) and emulation with a resistance (red and magenta **x**)

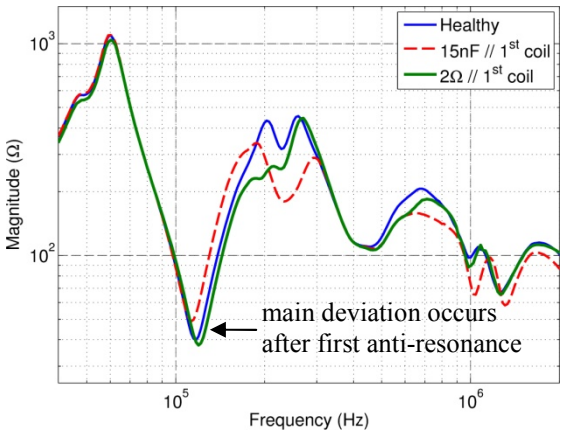
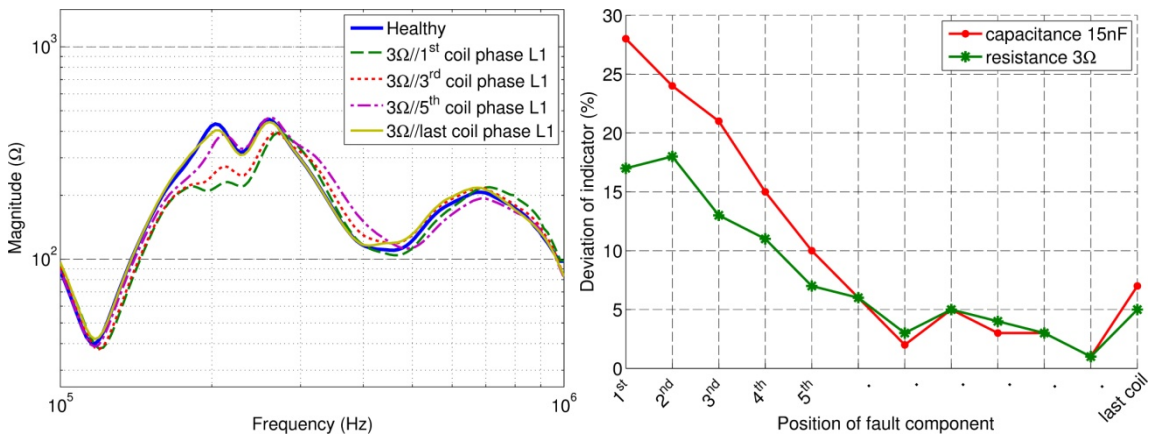


Fig. 6 a) Impedance frequency characteristic measured with LCR-meter for a healthy machine condition (solid blue), emulated insulation degradation with 15nF (dashed red) and 2Ω (solid cyan) parallel to the 1st coil of phase L1

used as a reference for further measurements after a long period of time in operation. With the assumption that the form wound coils can be modeled as an equivalent parallel resonance circuit consisting of a complex resistances, inductances and capacitances a change in the frequency response with respect to the reference measurement can be identified as a change of a single network component. In Fig. 6 the results of the RLC meter measurements are shown. The impedance frequency characteristic is measured from terminal phase L1 to star point. The traces show the same analyzed machine conditions as described in Fig. 3 a). The deviations of the emulated insulation degradation traces from the reference values occur after the first anti-resonance peak around 100 kHz and continue at the following resonance peaks. The amount of the deviation between reference and emulated insulation degradation conditions is again highest in the range from 100 kHz to 300 kHz. The difference between parallel capacitance and resistance is also clear visible. In literature the process of insulation degradation is always linked with a change of capacitance that is usually considered as the dominant parameter for insulation health state evaluation. However, at least when an actual breakdown of the insulation occurs, resistance also changes dramatically. In this sense the sensitivity of detecting also resistive changes of the insulation system leads to additional information that helps to detect a breakdown in a very initial state before a significant short circuit current is flowing and thus to protect the defect area as well as the whole winding from overheating. As was shown, emulated insulation degradation with resistances of around 2Ω parallel a single coil - with a resistance value of 2.4mΩ, cause a change in the impedance characteristics that is clearly detectable. Evaluating the change in sign of the deviation from the reference spectrum (Fig. 3 a) enables to clearly identify the critical resistance change.

Analyzing the position of the fault component it was observed that the highest deviation occur if the fault component is placed parallel the first coil at the terminal connection. The severity of the deviation is decreasing if the same capacitance or resistance value is placed parallel to a single coil in the middle of a phase or at the last coil at the star point. In literature the line-end coil suffers the most from stress through overvoltage [12]-[13] and thus insulation degradation is likewise at the first windings. This tendency can be seen in Fig. 7 a) measured with the vector network analyzer if a fault resistance is placed parallel one coil separately toward star point. The solid blue trace represents the healthy machine. The dashed green trace denoted with 3Ω//1st coil phase L1 shows the highest deviation between 100 kHz to 300kHz, whereas the deviation with 3Ω parallel 3rd coil phase L1 (dotted red, denoted with //3rd coil phase L1) and 3Ω parallel 5th coil phase L1 (dotted–dashed magenta, denoted with //5th coil phase L1) is decreasing. For instance the effect of a fault component parallel to the 11th coil of phase L1 show hardly deviations and is not detectable if considering the tolerance of measurement accuracy. The same tendency is given if the results of the insulation state indicators for different affected coils is analyzed, see subfigure b). The solid red trace shows the ISI values calculated out of the spectra if a capacitance of 15nF or resistance (solid green, 3Ω) is placed parallel one coil separately toward star point.



a) b)

Fig. 7 a) Impedance frequency characteristic measured with vector network analyzer with a resistance parallel one coil separately toward star point; b) decreasing ISI indicator if a capacitance of 15nF (solid red) or resistance with 3Ω (solid green) is separately placed parallel one coil toward star point

It has to be mentioned that a deviation below 10% is not distinguishable from the healthy measurement regarding the measurement tolerance. This limit may depend on the used voltage source level or sensor hardware equipment.

Conclusion

The basic idea of the applied method is to detect a change of the winding insulation system through analyzing the transient reaction of the machine current on inverter switching. This transient reaction is analyzed for a healthy machine state and emulated insulation degradation with a resistance or capacitance placed parallel to parts of the winding. The current signals are transformed to frequency domain and the deviation between reference spectrum and spectrum resulting through insulation degradation is calculated with the root mean square deviation. A change of the insulation state is always linked with a change of the parasitic capacitances or resistive components of a winding system. Thus the high frequency behavior of the machine and as a result the transient ringing of the current response is also changing. The proposed method is able to detect capacitive changes as well as resistive changes. The severity of the deviation is decreasing if investigations with different coils toward star point are affected by the fault component. The measurements are validated with a vector network analyzer and the same tendency for the investigated fault scenarios was observable. It has to be stressed that the presented method is a practical realization of patent (AT511807 B1), applied to the practical restrictions in traction drives.

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