Using Smart Converter to Obtain Traction-Machine Insulation Health State Information

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Abstract

In traction applications, inverter-fed machines are widely used, where they operate near and even above their rated values leading to high strains on the machine. Especially the winding insulation of the machine suffers from increased stress caused by high inverter switching frequencies and fast voltage rise times (high dv/dt rates) through the continuous development of new semiconductor technologies (silicon carbide SiC or gallium nitride GaN). A smart converter, which is a power inverter with integrated control, monitoring and protection functions, enables a safe and reliable operation of a drive. With an integrated smart online monitoring method by evaluating the current response after voltage step excitation, the detection of incipient insulation degradation is possible and enables that further maintenance tasks can be defined if necessary. With the usage of the integrated current sensors of the inverter and a low ADC sampling rate due to economic reasons, a special signal acquisition strategy is implemented to improve the performance of the method despite the limited hardware and software resources imposed by product constraints.

1. Introduction

In traction applications medium voltage drives operate with voltage source inverters (VSI) at voltage levels of approximately 3 kV covering power ratings of few megawatt (MW). The inverter generally converts the DC voltage to a three-phase AC voltage with adjustable magnitude and frequency. Induction motors are being extensively used in modern traction drives where fast and accurate control of speed is needed using vector control technology. Basically, the design of the induction machine is very simple, with windings in the stator which forms electrical poles, carrying the supply current to induce a magnetic field that penetrates the rotor, wherein the rotor is designed as a squirrel cage with closed bars. Especially in public and cargo transportation systems a reliable and safe operation of the drive is demanded over decades to prevent high costs. With focus on the machine side after bearing faults, stator related faults are the second most common faults, causing an outage of the drive system [1, 2]. A high fraction of these stator faults are based on a failure of the insulation system. The modern voltage source inverters with fast switching transients fed the induction machine on the stator side. Literature clearly states, that the magnitude of the applied voltage and the temperature are most influencing the insulation status life-time [3]. Additionally, modern voltage source inverters with fast switching transients in today's traction drive applications lead to transient overvoltage, stressing the machine's insulation system. Additionally new emerging semiconductor technologies with high switching frequencies and high dv/dt rates increase the stress for the motor winding insulation. This leads to insulation deterioration and a loss of the electrical strength of the system, which finally results in an insulation breakdown. The insulation degradation is usually a slowly proceeding process, usually affecting at first turn-to-turn insulation, followed by a complete phase-phase and

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finally phase-to-ground short circuit. In addition to the aforementioned stress factor several further stresses can be stated, e.g. thermal, mechanical or environmental stress, that all lead to aging of the insulation system. These main causes responsible for a machine breakdown have been analyzed in [3]-[7]. To increase the reliability of the drive system different strategies like fault tolerant design, electrical filters etc. can be implemented. However, filters are bulky, cause space requirements and lead to additional costs.
An integrated smart online monitoring method by evaluating the transient current response after voltage step excitation enables the detection of incipient insulation degradation. With the proposed method the converter is able to analyze the insulation state of the machine using the integrated current sensors, also used for the control of the machine. This is one of the key requirements and targets of the proposed online insulation monitoring technique. The current sensors are of standard industrial type transducers based on the Hall-effect based closed loop measurement principle, with low bandwidth specification of about f_{3dB}~150 kHz and the di/dt with 50A/µs. With the opportunity of the observation of the insulation state during the operation or at least at startup or shutdown of the drive without additional signal injection and sensor equipment and without disassembling of the drive unexpected down times can be avoided and maintenance on demand scheduled. The analysis of the transient current response requires sufficient resolution in time during the sampling process. The additional hardware limitation of a low sampling ADC unit (sampling rate max. 1MS/s) requires a sophisticated sampling strategy to improve the performance of the method and reach the necessary resolution which is multiple times greater than 1MS/s.

2. Online Insulation Monitoring with Smart Converter Topology

In Fig. 1 (a) the scheme of the smart converter as part of the main components of a drive system inverter, cabling and machine is depicted. The inverter consists of three half bridges, at which every power switch is controlled by its own gate drive unit (GDU). The built in current sensors are standard industrial current transformers (hall-effect based closed loop) with a bandwidth of 150 kHz and a di/dt of 50 A/µs and are normally used for the control of the machine only. The current signals are sampled with an ADC unit with a maximum sampling rate of 1MS/s. The machine can be represented by the equivalent circuit diagram (Fig.1 b), consisting of resistances, inductances and capacitances. The test machine is a 1.4MW induction machine designed for railway applications equipped with taps for further investigations of a winding insulation change. In this work the degradation of the insulation system is emulated with a capacitor placed parallel to the winding system or parts of it. Due to the impedance mismatch of the cables and machine and high dv/dt-rates of modern semiconductor switching devices, transient overvoltages appear at the machine terminals after inverter switching. These oscillations with decaying amplitude are also visible in the current signal. The occurring frequency components of the transients are defined by the electrical components of the machine-cabling system and are unique for every setup. Thus the frequency response can be considered as the fingerprint of the system. According to [3] and [7] different studies show that the parasitic capacitances of the machine's winding system change after a high number of thermal- or mechanical aging cycles have been applied. Thus, in this work the degradation of the insulation system can be emulated with a capacitor placed parallel to the winding system or parts of it using a special machine equipped with taps (depicted in Fig.1 b with "*Cfault*"). The capacitance value of the complete winding system of the test machine (1.4 MW) measured to ground is given with 63nF. In Fig. 2 (a) – upper subfigure, the time signals of the current response of the machine, measured on phase L1, as a reaction of a voltage step applied with the inverter from lower short circuit to high DC-link voltage is depicted for two machine insulation states. The healthy machine condition (blue trace) and the machine with a capacitor placed parallel to the first coil of phase L1 (red trace) representing the machine condition with insulation degradation are shown. After detection of the accurate switching time instant by the trigger detection unit (Fig.1 a) and the elimination of the current slope to prevent influences through e.g. slotting, the time domain data is transformed into the frequency domain, depicted in Fig. 2 (a) – lower subfigure.

If insulation degradation occurs, also the current step response changes and can be compared to the initial measurements stored in the storage device of the smart converter. Based on the history data of the machine, the system is able to check the insulation condition before each startup of the drive. This is done by alternatively applying a voltage step in every phase and evaluation of the transient current response of the machine and their frequency components. By calculation of an indicator to assess the severity of the insulation recommendations for maintenance actions can be advised.

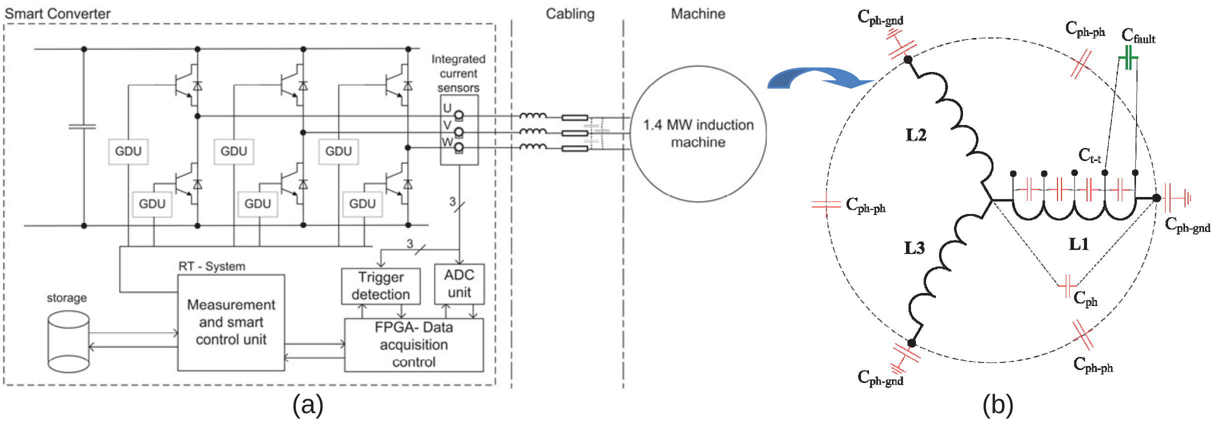

Fig. 1 a) Smart converter topology, b) machine electrical parameter and parasitic components.

The used converter system is a three phase IGBT-inverter. With the measurement and smart control unit as depicted in Fig 1 (a) the inverter starts an insulation test at the startup of the drive, with all three phases connected to low side of the dc potential and then initiate a transition of the corresponding inverter lag by turning off the low side transistor and turn on the high side one of the corresponding phase. The process is repeated several times for every phase to enable a statistical representation of the measurement. Due to the fact that the capacitance change of the winding system is the dominant parameter to indicate the insulation health state the position and the value of the capacitor “C_{fault}” is varied from 3nF to 15nF, cf. Fig. 2 (a) and (b), to emulate a trend in the severity of the insulation degradation. Regarding the nominal voltage levels of the test machine, the presented measurements in this work are made with lower DC link voltage of about 440 V.

In the target application the nominal power of 1.4MW is reached with a DC link voltage of around 2.8 kV, which imply that the current levels in this work are quite small and the currents will be about 6.4 times higher. However with the low DC-link voltage of 440V the sensitivity of the current transducer responses is still high enough to analyze the insulation health state.

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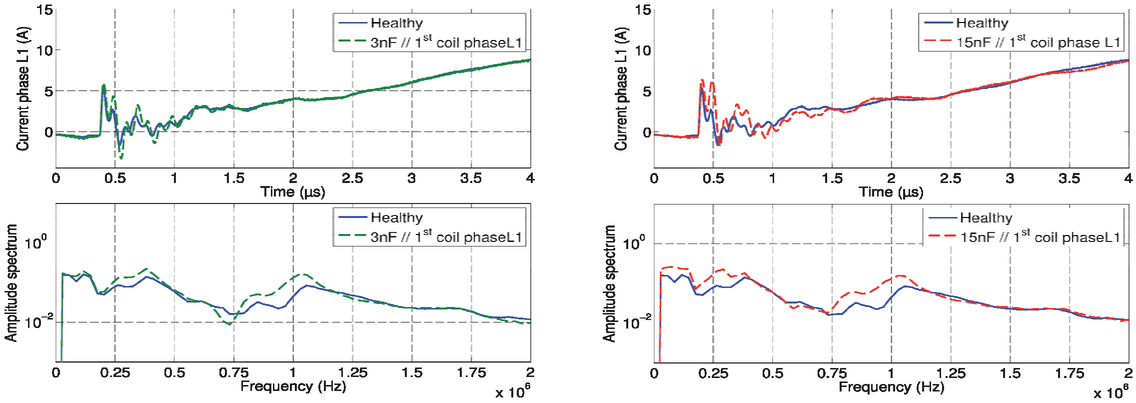


(a) (b)

Fig. 2 Transient current response after voltage step excitation by the inverter, with emulated insulation degradation (a) 3nF parallel to phase L1 and (b) 15nF parallel to phase L1.

3. Introduction of an Indicator to Assess Winding Insulation State

First it is important to perform measurements on a healthy machine to determine the initial insulation state. This is done at the first startup of the drive system. This measurement is repeated several times for statistical analysis and serves as a reference which represents the healthy machine state. This measurement is compared to later measurements in operation to assess the machine's actual insulation condition respectively possible deterioration. With the introduction of the Insulation State Indicator (ISI) the assessment of the insulation condition for each phase is possible. In a comparison process each equidistant value of the amplitude spectrum of the investigated current machine state is compared with the reference (healthy machine condition) based on the Root Mean Square Deviation (RMSD), see equation (1). With equation (2) the mean value of the repeated measurements is obtained. The Fourier components Y_{ref} represent the reference obtained at the healthy machine at the initial operation. The further Fourier components Y_{con} represent the condition assessment after several operation of the drive.

$$ISI_{p,k} = RMSD_{p,k}(x_1, x_2) = \sqrt{1/(n_{high} - n_{low}) \sum_{g=n_{low}}^{n_{high}} \left(Y_{ref,p}(f) - Y_{con,p,k}(f)\right)^2} \tag{1}$$

$$ISI_p = \frac{\sum_{k=1}^{m} ISI_{p,k}}{m} \tag{2}$$

The difference of the variable "n_{high}-n_{low}" represents the analysis frequency range defined by sampling frequency and FFT-window length (50-500kHz). The index p defines the investigation phase (L1, L2, L3) and m indices the number of measurement repetitions.

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

In order to assign the insulation degradation to a spatial location the linear combination of the previous calculated phase ISI values is introduced with equation (3). In the further course of this work it is denoted with Spatial Insulation State Indicator (SISI). With this indicator changes of the high-frequency behavior due to temperature variation are eliminated as these would lead to zero-sequence components.

$$SISI = ISI_{L1} + ISI_{L2} \cdot e^{j\frac{2\pi}{3}} + ISI_{L3} \cdot e^{j\frac{4\pi}{3}} \tag{3}$$

In Fig. 3 (a) different machine scenarios with the 1.4MW test machine with emulated insulation degradation are analyzed based on the calculated indicators. An increase in the indicator by use of different increasing capacitance values (3nF, 6.8nF and 15nF) can be equated with an increasingly deteriorated insulation, and this is equivalent to a change in the capacitance of the winding. The capacitors are placed separately parallel to phase L1. Thus an increase mainly of the indicator ISI_L1 is expected and observable. In Fig. 3 (b) the spatial indicator for the analyzed machine states are represented. It can be seen that the values points in the direction of phase L1 as the change of the machine's high frequency has been carried out there

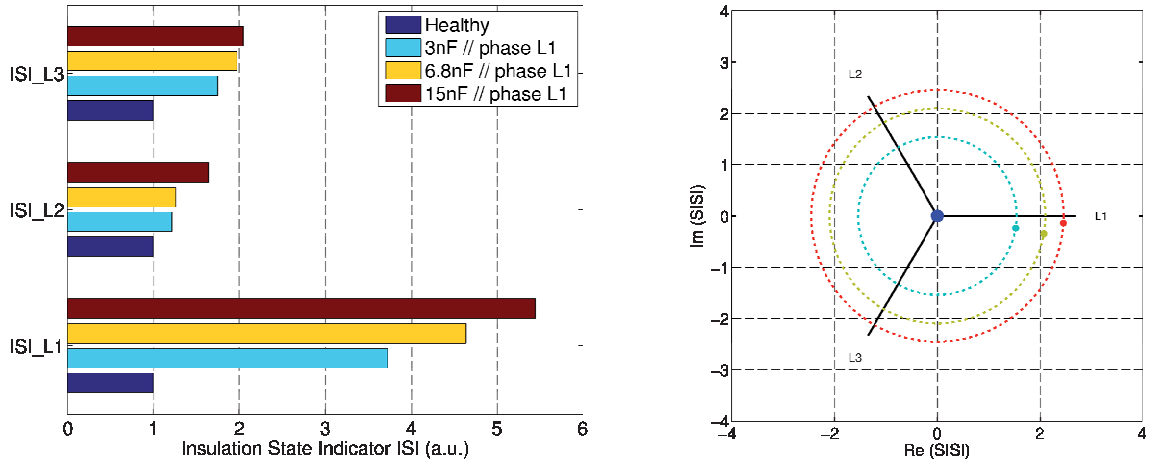
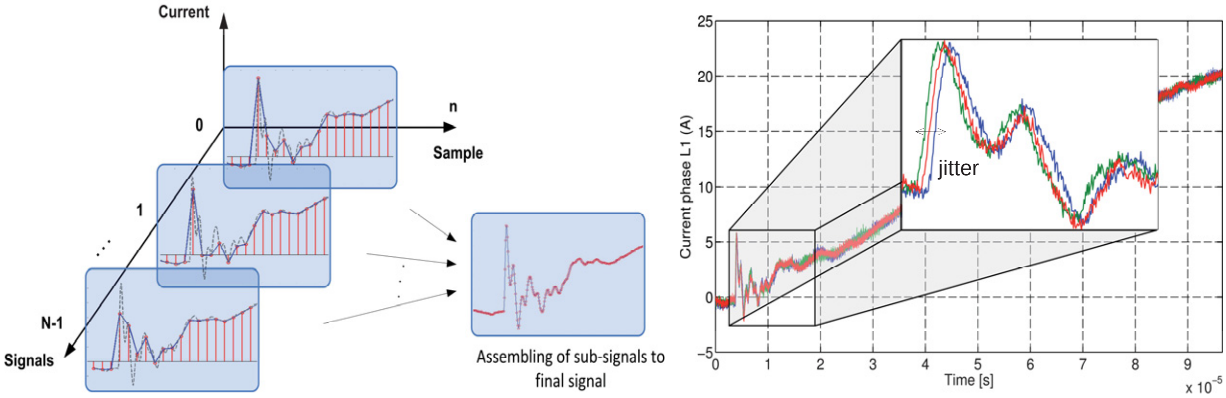


Figure 3 (a) Insulation State Indicator (ISI) for different investigated machine scenarios. (b) Spatial Insulation State Indicator (SISI).

4. Influences due to Hardware Restrictions

Due to the fact that the interesting frequency components of the step response are typically in the range of some tens kHz to MHz, depending on different factors e.g. machine type, cabling etc., a strategy to enable the monitoring using built-in ADC-unit (1MS/s) is proposed. The time resolution for the test machine in this work (1.4MW induction machine) is aimed 15MS/s. For the extension of the frequency range a smart sampling technique based on equivalent time-sampling, in the following referred to as repetitive sampling, was implemented on an FPGA to enhance the frequency resolution. Instead of gathering all samples for a waveform with one trigger event the system acquires the data with several trigger events over multiple (15) measurements each shifted by 66.6 ns (1/(15 MS/s)), as depicted in Fig. 4 (a). The sub-signals are assembled to the final current response.

Furthermore, time jitter is an unwanted behavior that the system posses which is unavoidable. With the usage of repetitive sampling to increase measurement bandwidth, jitter is an important issue that has to be taken into account. A timing error between the actual switching transition and the trigger of the ADC unit can have different reasons, for instance, jitter of the gate drive units GDU's. It was analyzed that the target system in which the monitoring method has to be implemented has a time jitter of up to 50ns, which seems to be realistic compared to other systems. Fig. 4 (b) shows the shifted current responses occurring after consecutive voltage step excitation by the inverter. Simulations of the influence of up to 50ns jitter are conducted and compared to the results of the measurement system.

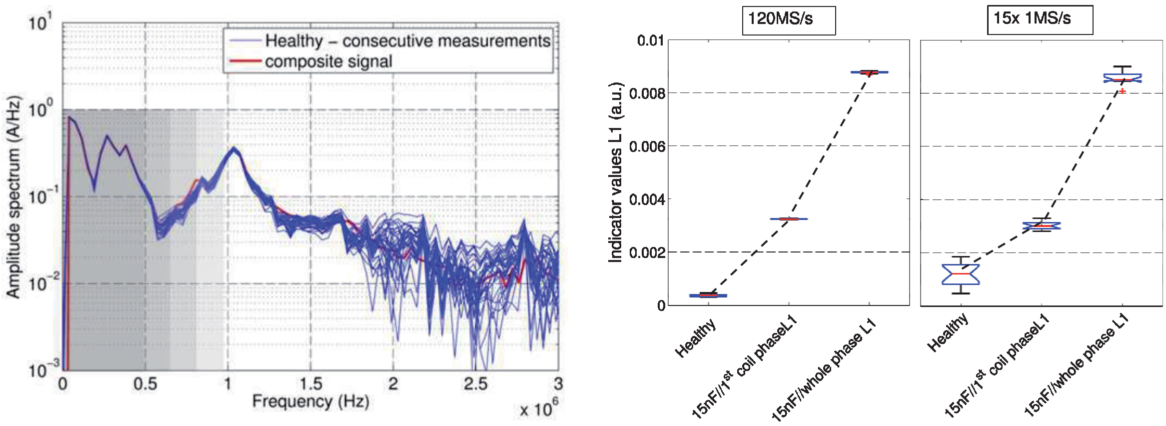


(a) (b)

Figure 4 (a) Scheme of the repetitive sampling process (b) effect of time jitter on the current response.

4.1. Experimental Results with Sampling approach

In this section the influence of the jitter on the results of the indicators are analyzed. For this purpose one complete measured signal recorded with a very high sampling rate of 120MS/s (sample points every 8.3ns) is taken as the basic signal. A maximum jitter of 50 ns has been added randomly to the equidistant sample points of the basic signal. In Fig 5 (a) the blue traces represent fifteen spectra calculated out of measurements with jitter of this healthy machine state. With jitter added in the simulation a widespread trend is observable above 1.5MHz. The red curve depicts the reference signal where all the step responses are combined into one 120 MHz signal.



(a) (b)

Figure 5 (a) Spectra of 15 signals with randomly added jitter (blue traces) and combined signal out of the 15 signals (b) box-plot representation of different machine states with emulated insulation degradation in phase L1 based on signals with hgih sampling rate (120MS/s) and signals with low sampling rate (1MS/s) and repetitive sampling

It is difficult to determine what is acceptable regarding the frequency variation. Therefore, no statements will be made regarding how much time jitter is manageable. The the highest frequency current component of interest focused from the authors for this machine type is located at 0.5 MHz, but can be enhanced to 1MHz.

Within the interesting frequency range (up to 500 kHz) the deviations are negligible and the results show the applicability of the sampling method for systems with a jitter value up to 50ns.

In Fig. 5 (b) the measurements are statistically analyzed with the box-plot representation. In these two subfigures only the ISI values of phase L1 are analyzed. It shows the distribution of the resulting indicator values from the repeated measurement and shows the difference between the results of the high sampled data and the repetitive sampling results. It can be seen that the results analyzed with a resolution of 120 MS/s show a smaller variance than the data analyzed with repetitive sampling and a final resolution of 15 MS/s. However, all tested fault scenarios are still detectable.

5. Conclusion

A smart converter system with integrated online health state monitoring of the machine's insulation system has been presented. The detection of incipient insulation degradation by evaluating the current response after predefined voltage pulse excitations prevents unexpected outages and enables scheduling of further maintenance tasks. The method was enhanced and tested with a special sampling technique and tests are conducted on a 1.4 MW induction machine with different insulation degradation scenarios. The intention was to determine whether the standard industrial current sensors and standard ADC units (1 MS/s) can be used with the presented smart concept. It can thus be stated and concluded that the approach of the proposed online insulation condition monitoring method is well working and applicable to inverter fed AC machines.

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 Insuation for Rotating Machines". *IEEE Press*, 2004.

[4] Farahani, M.; Gockenbach, E.; Borsi, H.; Schaefer, K.; Kaufhold, M.; "Behavior of machine insulation systems subjected to accelerated thermal aging test," *IEEE Trans. on Dielectrics and Electrical Insulation*, vol.17, no.5, pp.1364-1372, 2010.

[5] Nussbaumer, P.; Vogelsberger, M.A.; Wolbank, T.M.; "Induction Machine Insulation Health State Monitoring Based on Online Switching Transient Exploitation," *IEEE Trans. on in Industrial Electronics,* vol.62, no.3, pp.1835-1845, 2015.

[6] D Yang, J; Cho, J.; Lee, S.B.; Yoo, J.-Y.; Kim, H.D.; "An Advanced Stator Winding Insulation Quality Assessment Technique for Inverter-Fed Machines," *IEEE Trans. on Industrial Appl*., vol.44, no.2, pp.555-564, 2008.

[7] Sumislawska, M.; Gyftakis, K.N.; Kavanagh, D.F.; McCulloch, M.; Burnham, K.J.; Howey, D.A.; "The Impcact of Themal Degradation on Electrical Machine Winding Insulation," *10th IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives (SDEMPED)*, 2015.

[8] Zoeller, C.; Vogelsberger, M.A.; Fasching, R.; Grubelnik, W.; Wolbank, Th.M., "Evaluation and current-response based identification of insulation degradation for high utilized electrical machines in railway application," *10th IEEE International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED)*, pp.266-272, 2015.