Online Detection of Insulation Degradation in Inverter Fed Drive Systems Based on High Frequency Current Sampling

P. Nussbaumer, A. Mitteregger, Th.M. Wolbank
Department of Electrical Drives and Machines
Vienna University of Technology, Austria
thomas.wolbank@tuwien.ac.at

Abstract- **The electrical part of modern drive systems usually consists of different components like power electronics, cabling, windings. Each of these components is usually operated at or near its rated values. In addition, high dynamic operation, overload cycles, as well as the fast switching of the power devices puts additional stress on all drive components. As a consequence overall reliability is reduced. Especially in security critical applications a continuous monitoring of the different components is thus necessary. In order to detect possible defects in an early stage or to enable prediction of a developing fault very sensitive measurement and evaluation methods are essential. In this paper a new method is proposed to monitor the state of different drive components like windings insulation, cabling and power electronics very accurately. The method is based on the current sensors available in the inverter in combination with a high frequency sampling. Each change in the switching state of the inverter leads to a transient voltage excitation of the electrical system consisting of power electronics, cabling, machine windings, leading to a step response of the machine current. Assuming a sufficient high sampling rate of the current, the characteristic features of the step response like eigenfrequency, damping rate and steady state value can be calculated and compared. Each of these characteristic values is influenced by the inductances, capacitances and resistances of the system. If for example the inter-turn insulation deteriorates the capacitance changes before the actual breakdown leading to a change in the mentioned characteristic values. Measurement results are presented to verify the applicability to detect changes in the phase winding capacity.**

I. Introduction

The application of inverter-fed machines is constantly increasing in various fields. The implementation of such drive systems ranges from standard industrial application and traction drives to safety critical devices like x-by-wire systems what results in a growing demand on reliability. This can only be met with preventive maintenance and continuous condition monitoring.

One major cause for drive breakdown can be found in insulation failures in the stator windings. According to [1] and [2] 30%-40% of all drive failures that result in drive shut-down are stator related, around 70% of these are caused by turn and ground insulation failures.

The insulation of the stator windings is exposed to increased stress when operated at an inverter. The different failure causes resulting from thermal, electrical, mechanical and environmental stress are summarized in [3]. This strain causes a degradation of the winding-insulation over time and may lead to severe machine failure and outage of the whole drive system as reported in [4].

In literature, different detection procedures for insulation faults have been proposed in the last years. The various techniques can be separated basically into two groups – online and offline methods. A summary and evaluation of the different procedures can be found in [3]. Up to now only offline-testing of insulation condition is accepted in industrial application. The main drawback of these insulation-fault detection techniques is that the drive has to be taken out of service for fault inspection. Depending on the application, this can only be done once in a while – often only every three to six years during general maintenance [5].

According to [3] the most promising offline-test is the surge test. It is the only offline test that can detect a deterioration of turn-to-turn insulation, the common trigger of severe machine breakdown due to electrical failures in the stator. This approach is evaluated for example in [6].

Other offline insulation testing methods include the DC conductivity test [7], insulation resistance test (IR) as described in [8], DC/AC HiPot test and polarization index (PI) test. All these tests can be applied to low voltage machines. A very common and industrially accepted insulation test for medium to high voltage machines is the partial discharge (PD) test as described in [9]. However, it is not applicable for low voltage machines.

Due to the relatively long time span between each test, offline testing cannot employ preventive condition monitoring. Therefore various online monitoring procedures have been developed and presented in literature. Many of the online-testing procedures require additional hardware installed in the drive system. The measurement of the motor's hf impedance for insulation condition monitoring is proposed in [10]. The application of current signature analysis (CSA) for insulation fault detection is shown in [11] and [12]. The influence of closed-loop operation on this type of fault detection procedures is discussed in [13]. An online-testing technique based on the surge test is developed in [14].

As in case of a winding-fault an asymmetric voltage distribution has to be applied to guarantee symmetrical stator currents the switching behavior of the current controller can be evaluated for fault detection [15]. The change in the machine's transient behaviour due to a winding-fault by evaluating the current response on the voltage pulses applied

978-1-61284-971-3/11/$26.00 ©2011 IEEE

by a voltage source inverter (VSI) is analyzed in [16]. The separation capability of eccentricity and inter-turn short circuit faults with the before stated monitoring procedure based on transient voltage injection is discussed in [17]. In [18] the difference of the measured stator currents to the currents reconstructed from the stator voltage equation and voltage measurements is used as a fault indicator.

The evaluation of the leakage current from conductor to ground is used for online insulation fault detection in inverter fed drives in [4]. Another online turn-to-turn fault detection technique evaluates the negative sequence voltage in closed-loop multiple-motor drives and allows separation of fault location [19]. The evaluation of the current's Park's vector for winding fault detection in mains fed induction machines is presented in [20]. Another insulation fault detection technique for mains fed machines analyzing the odd multiples of third harmonic in motor terminal voltage immediately after switch-off is proposed in [21]. Detection of winding faults by superposition of hf carrier-signal (voltage) on the fundamental excitation is discussed in [22].

So far, no reliable method that is capable to detect a deterioration of the insulation system in inverter fed drives online, has been proposed. A novel online approach to detect a degradation of the turn-to-turn insulation is discussed in the present article. It is based on the evaluation of the current's transient reaction on voltage pulses applied by the inverter. To investigate the current's transient phenomenon after a change of the inverter's switching state, high frequency sampling of the current or current derivative signal is employed. The paper presents a first investigation of experimental results gained on a laboratory test stand.

II. Insulation Failures under Consideration of VSI-Fed Operation of Adjustable Speed Drives

Adjustable speed drives fed by voltage source inverters are even more likely to suffer from machine-breakdown due to insulation failures than mains-fed ac machines. According to [4], [23] and [24] the very short rise times (around 50ns and even below) of modern switching devices like IGBT lead to transient overvoltage and therefore to additional stress of the winding-insulation. In [24] the cause of this overvoltage is analyzed. The mismatch of surge impedance of the machine cables and the machine impedance itself leads to reflections of the applied voltage at the machine terminals. The magnitude of these voltage oscillations can reach up to twice or even four times the dc-link-voltage and frequencies in the range of tens kHz to tens MHz. The transient overvoltage strongly depends on the length of the cables from the inverter to the machine, dc-link-voltage and the rise time of the inverter output voltage as studied in [23] and [24].

III. Novel Online Detection of Insulation Deterioration

A. General Aspects

The configuration of a drive system including an inverter and an induction machine represents a complex network of resistances, inductances and capacitances. On the one hand this network consists of the different machine parameters – like stator inductance and stator resistance, cable resistance, etc.. On the other hand each single component of the drive adds parasitic inductances and capacitances to the system. The cables connecting the inverter output with the machine terminals have certain resistance and inductance per unit length and, depending on the insulation material and configuration, a capacitance to ground. The topology and construction of the installed inverter affects its parasitic capacitive coupling to ground. The machine's insulation system influences the parasitic capacitances including phase-to-ground, phase-to-phase and turn-to-turn capacitance of course.

As mentioned before, the different values of these elements lead to a mismatch of the machine cable's surge impedance and the machine impedance itself. The very small rise-times of the voltage pulses applied by the switching of the inverter lead to reflections and therefore to high-frequency oscillations of the applied voltage thus evoking a similar oscillation in the current as well. If an element in the aforementioned complex network is altered for example due to a degraded turn-to-turn insulation the whole system is detuned leading to a change in the high-frequent voltage and current oscillation. As in most drive systems current or current derivative sensors are already available for machine control, it is advantageous to use these sensors for condition monitoring as well.

B. Description of the novel detection technique

The proposed novel insulation-fault detection technique exploits the changes in the current step response like eigenfrequency, damping rate and steady state value due to a fault-induced alteration in an element of the aforementioned complex system for insulation monitoring. The step response to the switching of the inverter is measured by current sensors or current derivative sensors.

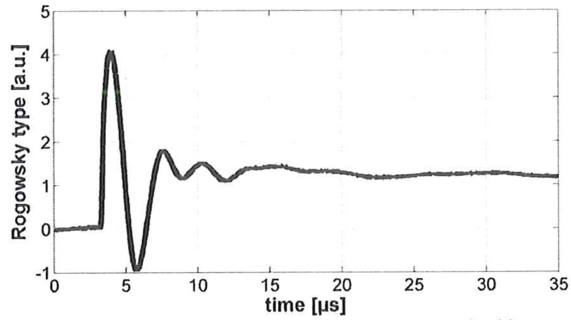

Fig. 1. Current derivative signal in phase W measured with Rogowsky type sensors (CDI) during switching of the VSI sampled with 40MS/s.

By applying different inverter switching states and measuring the system reaction on these steep voltage changes with relatively high sampling rates of several MS/s, changes in the parameters of the high-frequency current oscillation can be detected. In this first investigation of the proposed novel approach, Rogowsky type current-derivative (CDI) sensors are used. The following Fig. 1 shows the reaction of the current-derivative signal in phase W sampled with

40MS/s on a change of the switching state from zero voltage vector (000) to an active voltage vector in phase W (001) for healthy machine winding insulation. Using this high frequency sampling it is obvious that the characteristic parameters of the step response like eigenfrequency, damping rate and steady state value can be seen accurately calculated.

The measurement itself can be carried out at machine standstill whenever the machine is shut down for a short period of time. Therefore it is perfectly suited as a start-up test. As the rotor has not to be turned during the measurement an attached load is not an issue for the proposed technique. Possible dependencies on the operating state and a suitable compensation technique have to be analyzed in a latter state of the investigation of the proposed novel fault-detection approach. The steady state value of the current time derivative strongly depends on the machine's transient leakage induction $l_{l,t}$. The well known stator equation of an induction machine illustrates this relationship:

$$\underline{v}_S = r_S \cdot \underline{i}_S + l_{l,t} \cdot \frac{d\underline{i}_S}{d\tau} + \frac{d\underline{\lambda}_R}{d\tau} \qquad (1)$$

The time derivative of the stator current space phasor $\underline{i}_S$ is further influenced by the applied stator voltage phasor $\underline{v}_S$ the voltage drop of the stator resistance r_S and the back EMF (electromotive force; time derivative of rotor flux $\underline{\lambda}_R$).

If the machine is considered ideal symmetrical the transient leakage induction is a scalar. However, even a faultless machine has some inherent asymmetries due to e.g. rotor slotting. This leads to the fact that the steady state value of the current time derivative may depend on the rotor position. However, these dependencies can be identified in advance and then eliminated feed-forward.

To realize the fault detection method different steps have to be performed. These are described in the following:

1) Application of voltage steps and measurement of machine's step response
2) Calculation of characteristic parameters like eigenfrequency, damping factor, overshot, etc. that serve as fault indicator
3) Comparison of parameters with previous measurements
4) Determination if fault indicator is above certain threshold value
5) If threshold value is exceeded => maintenance is necessary

C. *Calculation of Fault Indicators*

As already mentioned different signal characteristics of the transient trace in the current or current derivative signal can serve as fault indicators.

For increased accuracy it is possible to consider more than one measurement, calculate the fault characteristic signal properties and determine the average over these values. In Fig. 1 it can be observed that the transient effects in the time trace decay after a few µs to several 10µs. Therefore an application of the voltage step in the range of 20 to 40µs is sufficient for most applications. This leads to the fact that even if the measurement is repeated several hundred times to increase accuracy, the duration of the measurement procedure is still in the range of milliseconds.

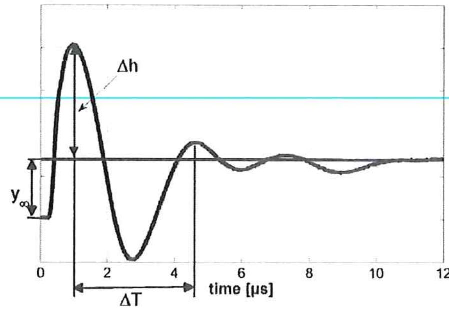

Fig. 2. Transient effect in current derivative signal; signal characteristics like steady state value y_∞, first positive overshot Δh and inverse of eigenfrequency ΔT are indicated.

The application of voltage steps in different phase directions offers the possibility to detect in which phase the fault or the deteriorated winding insulation is located. The most significant change in the fault indicator can then be detected in the current time trace of the faulted phase due to a voltage step vector applied in the direction of the same phase.

In Fig. 2 the transient effect in the current derivative signal is shown. Different signal characteristics that can serve as fault indicator are highlighted. The steady state value is marked as y_∞, Δh is indicating the first positive overshot and ΔT the inverse of the eigenfrequency f_0.

1. *Calculation of Eigenfrequency*

The eigenfrequency of the transient system response represented in the current or current derivative signal can be calculated employing different algorithms. One simple and very effective way especially with respect to real-time capability is the determination of the extrema in the transient effects visible in the measured signal. This can be done with a very fast and robust algorithm and leads to a direct calculation of the eigenfrequency.

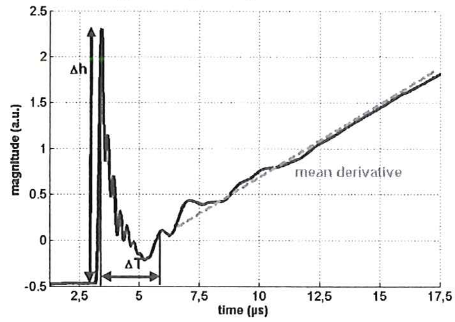

Fig. 3. Measured switching transient using absolute value current sensor; signal characteristics like mean time derivative, first positive overshot Δh and inverse of eigenfrequency ΔT are indicated (arbitrary units a.u.).

A maybe more elegant and exact algorithm is to calculate the inherent frequencies by application of Fast-Fourier-Transform (FFT) techniques. Accurate selection of parameters for the employed window function is of particular importance. The inverse of the eigenfrequency f_0 is marked as

ΔT for both sensors, Rogowsky type CDI (Fig. 2) and absolute value compensating current sensors (Fig. 3).

2. Calculation of Overshot

As mentioned in the discussion concerning the calculation of the eigenfrequency it is possible to determine the extrema of the transient trace in the current or current derivative signal with very fast and simple algorithms. The same procedures can be used for the calculation of the signal's overshot values. Considering the time trace measured by application of current derivative sensors the overshot value represents the difference between the extrema and the steady state value. In Fig. 2 the value of the first positive overshot is marked with Δh for application of CDI sensors. Concerning the application of standard absolute value current sensors the time course after the settling of the switching transients follows an almost linear trace. Therefore a steady state of the signal is not reached during the application of voltage steps in the considered time range of some μs. During an active switching state the current is continuously increasing in this time window, only the time derivative of the current is eventually reaching steady state. The maximum value during the switching transient in the current signal with respect to the last current value before the switching state is changed can be regarded as the first positive overshot (Fig. 3).

3. Calculation of Steady State Value

If the duration of the applied voltage step is long enough – that is to say long enough that the steady state of the current derivative is reached – the determination of this signal characteristic can be done in a simple way. With respect to the current derivative sensors the steady state value is the last measured value during the application of constant voltage step. This could be directly done without high-frequency A/D-converters however, signal accuracy can be increased if the steady-state value is determined by averaging over several of the last values.

If applying absolute value current sensors the interesting value is the steady state of the current slope. This can be calculated by taking at least two current samples. The difference in time between the two sampled values has to be high enough to ensure an accurate determination of the current time derivative. The benefit of high-sampling ADCs can be exploited to employ averaging techniques and therefore increase accuracy as well.

For a deteriorated insulation the steady state value will not change in comparison to the healthy machine. However, once an inter-turn short circuit happens, measurements show that the steady state value is changed significantly even if only one turn is shortened in a single phase. However, due to the modulation of the airgap resulting from slotting, etc. this steady state value is further dependent on the rotor position. This dependency has to be identified in advance and compensated in the fault indicator if this approach is applied to a machine at standstill. In [16] and [17] the steady state value of the current derivative is exploited to calculate a fault indicator.

IV. Experimental Setup and Results

A. *Experimental Setup and Realization of Deteriorated Insulation*

Measurements were carried out on a specially designed 5.5kW squirrel cage induction machine. It is a 2pole machine with an unskewed rotor. In all phases several windings are tapped. By connecting one of these taps with the corresponding machine terminal it is possible to shorten a variable number of turns resulting in a non-destructive implementation of a stator inter-turn insulation fault. If, instead of a direct connection, an additional capacitor is inserted between two taps a deteriorated turn-to-turn insulation is simulated. This is illustrated in Fig. 4 exemplarily for phase U and the tap of a turn of the winding.

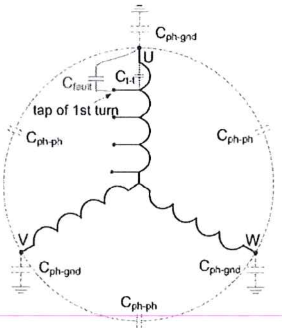

Fig. 4. Additional Capacitor C_{fault} inserted between machine terminal of phase U and tap of a turn of winding in phase U.

The additional capacitor is in parallel to the insulation capacitance $C_{t\text{-}t}$. Therefore the turn-to-turn insulation capacitance is increased. A similar increase can be investigated during a degradation of the insulation's dielectric properties as measured in [10]. To identify the properties of the insulation system the induction machine's phase-to-phase $C_{ph\text{-}ph}$ and the phase-to-ground capacitance $C_{ph\text{-}gnd}$ were determined to 742pF and 1,71nF, respectively.

The control and measurement setup consists of a real-time rapid prototyping system programmable under Matlab/Simulink (Dspace 1103) responsible for the control of the machine. The PWM generation and the data pre-processing is done in a FPGA. The high frequency sampling is done using 40MHz 16Bit ADCs. Communication to the FPGA is realized by data buffers.

To investigate advancing stages of insulation degradation capacitances of different values were inserted between the machine terminal and tapping of a winding.

B. *Experimental Results*

In a first set of measurements an additional capacitance was inserted between terminal of phase U and the first turn of this phase winding as indicated by C_{fault} in Fig. 4. When showing the sampled quantities on the vertical axis of the following figures, the values are scaled in the internal representation of the FPGA denoted arbitrary units (a.u.).

In Fig. 5 a comparison is shown of the transients caused by a change of the inverter switching state from inactive to active in phase U. The measurement was done using current derivative sensor (CDI). Only the first few μs are shown and the steady state value cannot yet be detected. The black solid trace gives the results obtained with the healthy insulation, the gray dashed trace represents the deteriorated inter turn insulation by inserting a capacitance C_{fault}=66nF as described above.

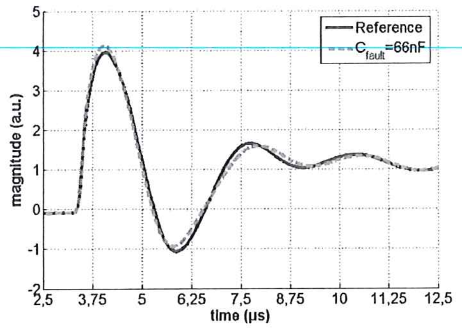

Fig. 5. Measured transients due to inverter switching from inactive to active; sensor: CDI, black solid: reference measurement; gray: 1 winding with C_{fault} = 66nF (a.u. arbitrary units).

As was expected, this change in winding capacitance can not be detected by the steady state values of the sensor as both signal traces deliver the same results. But there is a clear difference detectable in the overshot and eigenfrequency. This change is only visible when the voltage phasor of the active switching state points in the phase axis of the 'deteriorated' phase. It has to be stressed, that the switching transients depicted have very low statistical variations as shown later. Each trace is the mean value determined from 240 measurements.

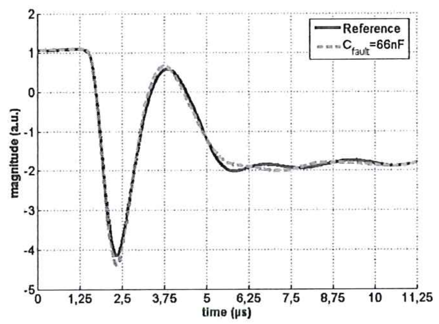

Fig. 6. Measured transients due to inverter switching from active to active; sensor: CDI, black solid: reference measurement; gray dashed: 1 winding with C_{fault} = 66nF (a.u. arbitrary units).

The same arrangement but with a change from one active to another active inverter switching state is depicted in Fig. 6. Again the difference in the signal properties overshot, and eigenfrequency are obvious.

Another set of measurements was done to investigate the influence of deteriorated coil-coil insulation of one phase. The capacitance C_{fault} was inserted between the machine terminals and different taps of one winding including also the star point.

As can be seen in Fig. 7 even if a capacitance of only 1nF is introduced at different taps the signal quantities change significantly and can be exploited to detect such a change in the distribution of the winding capacitance. What can also be seen from the figure is that the frequency during the first part of the transient starting from the switching instant at ~3,4µs till the first maximum and minimum stays almost the same when introducing the capacitance. This part is obviously dominated by the arrangement of the inverter and cabling responsible for the reflection of the steep voltage wave. After this first 'reflection' however, the influence of the winding capacitance on the frequency (shown also in Fig. 8, lower) is increased what can be clearly seen by comparing the different results shown.

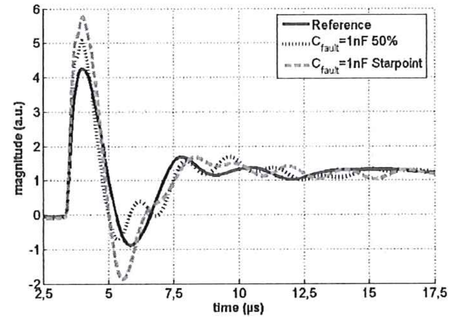

Fig. 7. Measured transients due to inverter switching from inactive to active; sensor: CDI, black solid: reference measurement; black dashed: C_{fault} = 1nF to star point; gray: C_{fault} = 1nF to 50% phase winding.

The black trace in Fig. 7 shows the results of the healthy winding insulation ('reference', black). The light gray, dotted and the dark gray, dashed traces are obtained when shorting 50%, or 100% ('starpoint') of the winding using the 1nF capacitance. As can be seen from the corresponding traces it is possible to detect these changes by comparing the eigenfrequency approximately after the first period of the switching transient.

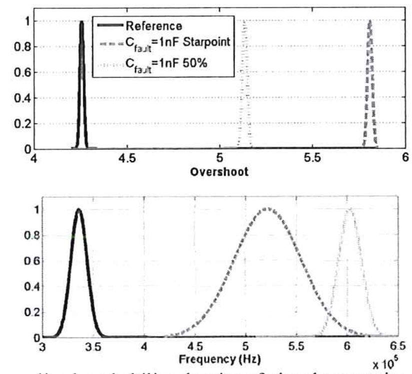

Fig. 8. Normalized probability density of signal properties obtained from switching transients (upper: overshoot value, lower: frequency).

To investigate also the reliability of the measured switching transients the statistical properties of the sensor signal were tested. A set of 240 measurements were taken from each arrangement of the machine/winding and the results and signal parameters were compared.

The overshot is determined by a simple peak detection algorithm, searching for the maximum in the signal trace. As mentioned before the frequency of the first half-wave in the signal remains more or less unchanged, therefore only the following half-waves in the oscillations superimposed to the current derivative signal are considered. The frequency of the

3 following half-waves is calculated by detecting the extremas in the oscillation, calculating the time difference and inverting this value – again a very simple algorithm. The mean value of these three frequencies is regarded as the eigenfrequency. As can be seen from Fig. 8 the estimated signal parameters have a low variance what enables the detection of even small changes in the winding capacitance.

A summary of the signal properties (Overshot and frequency) averaged over 240 measurements for different fault conditions can be found in TABLE I.

TABLE I. SUMMARY OF MEASUREMENT RESULTS

Fault condition \ Signal property	Frequency	Overshot
Healthy (Reference; Phase U)	336 kHz	4.25 a.u.
50% (1nF; Phase U)	603 kHz	5.13 a.u.
Starpoint (1nF; Phase U)	522 kHz	5.81 a.u.

In order to monitor the state of a winding insulation online using the proposed method it is however, necessary to identify the transient signal properties of the healthy arrangement during a commissioning phase. As cables with different length or materials (insulation,...) lead to an altered value of resistance, inductivity and/or capacitance per unit length, changing the machine cables may result in a different characteristic impedance thus changes in the transient signal parameters. Any changes from the identified signal parameters can then be assigned to changes in the arrangement like winding capacitance that are also correlated to degradation of insulation.

V. CONCLUSIONS

A new method to detect changes in the winding capacitance during operation of inverter fed machines was presented. Similar capacitance changes are reported to be connected with a deterioration of winding insulation. The method is based on a high frequency sampling of current sensor signals to measure the transients associated with a change in the inverter output switching state. It was verified by measurements that it is possible to detect changes in the winding capacitance by calculating signal properties of the switching transients like overshoot and eigenfrequency. Measuring the switching transients and calculating characteristic signal parameters during normal operation of the drive it is possible to detect changes in the inverter, cabling, machine arrangement associated to developing faults in the insulation like winding short circuits.

ACKNOWLEDGMENT

The work to this investigation was supported by the Austrian Science Fund (FWF) under grant number P23496-N24.

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] Grubic, S.; Aller, J.M.; Bin Lu; Habetler, T.G.; "A Survey on Testing and Monitoring Methods for Stator Insulation Systems of Low-Voltage Induction Machines Focusing on Turn Insulation Problems," *IEEE Trans. on Industrial Electronics*, vol.55, no.12, pp.4127-4136, (2008)

[4] 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, (2008)

[5] Younsi, K.; Neti, P.; Shah, M.; Zhou, J.Y.; Krahn, J.; Weeber, K.; Whitefield, C.D.; "On-line capacitance and dissipation factor monitoring of AC stator insulation," *IEEE Trans. on Diel. and El. Ins.*, vol.17, no.5, pp.1441-1452, (2010)

[6] Wiedenbrug, E.; Frey, G.; Wilson, J.; "Impulse testing and turn insulation deterioration in electric motors," *Annual Pulp and Paper Industry Technical Conference*, pp. 50- 55, (2003)

[7] Schump, D.E.; "Testing to assure reliable operation of electric motors," *Industry Applications Society 37th Annual Petroleum and Chemical Industry Conference*, pp.179-184, (1990)

[8] Stone, G.C.; "Recent important changes in IEEE motor and generator winding insulation diagnostic testing standards," *IEEE Transactions on Industry Applications*, vol.41, no.1, pp. 91- 100, (2005)

[9] Stone, G.C.; Sedding, H.G.; Costello, M.J.; "Application of partial discharge testing to motor and generator stator winding maintenance," *IEEE Trans. on Industry Applications*, vol.32, no.2, pp.459-464, (1996)

[10] Perisse, F.; Werynski, P.; Roger, D.; "A New Method for AC Machine Turn Insulation Diagnostic Based on High Frequency Resonances," *IEEE Trans. on Diel. and El. Ins.*, vol.14, no.5, pp.1308-1315, (2007)

[11] Joksimovic, G.M.; Penman, J.; "The detection of inter-turn short circuits in the stator windings of operating motors," *IEEE Transactions on Industrial Electronics*, vol.47, no.5, pp.1078-1084, (2000)

[12] Nandi, S.; Toliyat, H.A.; "Novel frequency-domain-based technique to detect stator interturn faults in induction machines using stator-induced voltages after switch-off," *IEEE Trans. on Ind. Appl.*, vol.38, no.1, pp.101-109, (2002)

[13] Bellini, A.; Filippetti, F.; Franceschini, G.; Tassoni, C.; "Closed-loop control impact on the diagnosis of induction motors faults," *IEEE Trans. on Industry Applications*, vol.36, no.5, pp.1318-1329, (2000)

[14] Grubic, S.; Habetler, T.G.; Restrepo, J.; "A new concept for online surge testing for the detection of winding insulation deterioration," *Energy Conversion Congress and Exposition (ECCE)*, pp.2747-2754, (2010)

[15] Wolbank, T.M.; Loparo, K.A.; Wohrnschimmel, R.; , "Inverter statistics for online detection of stator asymmetries in inverter-fed induction motors," *IEEE Trans.on Ind. Appl.*, vol.39, no.4, pp. 1102- 1108, (2003)

[16] Wolbank, T.M.; Wohrnschimmel, R.; "Transient electrical current response evaluation in order to detect stator winding interturn faults of inverter fed ac drives," *Symposium on Diagnostics for Electric Machines, Power Electronics and Drives (SDEMPED)*, pp.1-6, (2001)

[17] Wolbank, T.M.; Macheiner, P.E.; "Detection of air gap eccentricity in the presence of stator inter-turn fault of inverter fed induction machines," *Power El. Specialists Conference*, pp.2633-2638, (2008)

[18] Wolbank, T.M.; Wohrnschimmel, R.; "On-line stator winding faults detection in inverter fed induction motors by stator current reconstruction," *El. Machines and Drives Conf. (EMD)*, pp.253-257, (1999)

Cheng, S.; Zhang, P.; Habetler, T.G.; "An Impedance Identification Approach to Sensitive Detection and Location of Stator Turn-to-Turn Faults in a Closed-Loop Multiple-Motor Drive," *IEEE Transactions on Industrial Electronics*, vol.58, no.5, pp.1545-1554, (2011)

[20] Marques Cardoso, A.J.; Cruz, S.M.A.; Fonseca, D.S.B.; "Inter-turn stator winding fault diagnosis in three-phase induction motors, by Park's vector approach," *IEEE Trans. on En. Conv.*, vol.14, no.3, pp.595-598, (1999)

[21] Nandi, S.; "Detection of Stator Faults in Induction Machines Using Residual Saturation Harmonics," *IEEE Transactions on Industry Applications*, vol.42, no.5, pp.1201-1208, (2006)

[22] Briz, F.; Degner, M.W.; Garcia, P.; Diez, A.B.; "High-Frequency Carrier-Signal Voltage Selection for Stator Winding Fault Diagnosis in Inverter-Fed AC Machines," *IEEE Transactions on Industrial Electronics*, vol.55, no.12, pp.4181-4190, (2008)

[23] Persson, E.; "Transient effects in application of PWM inverters to induction motors," *IEEE Transactions on Industry Applications*, vol.28, no.5, pp.1095-1101, (1992)

[24] Peroutka, Z.; "Requirements for insulation system of motors fed by modern voltage source converters," *IEEE 35th Annual Power Electronics Specialists Conference, PESC*, vol.6, pp. 4383- 4389, (2004)