Increasing Sensitivity of Stator Winding Short Circuit Fault Indicator in Inverter Fed Induction Machines

G. Stojčić[1], J. Stanković[1], G. Joksimović[2], M. Vašak[3], N. Perić[3], T.M. Wolbank[1];

[1]Department of Electrical Drives and Machines, Vienna University of Technology, Austria
[2]Faculty of Electrical Engineering, University of Montenegro Podgorica, Montenegro
[3]Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia

***Abstract* — The inverter fed induction machine is becoming one of the most important drive application due to speed variability, dynamics, and robustness. These advantages are possible by the development of high-power transistors. On the other side these fast switching components lead to steep voltage rises and high stress on the winding insulation of the machine. Faults in the winding system of a machine can cause a dramatic damage due to their fast developing behaviour. An early detection of winding faults can reduce the consequences. In this paper a method is investigated to detect stator winding faults in their early stage. The method is based on voltage pulse excitation done by inverter switching. Current response measurements and subsequent signal processing lead to a fault indicator with high precision and low dependence on the machine point of operation. Measurements on a specially designed machine are carried out to determine the sensitivity of the fault indicator to early stage faults.**

***Keywords* — condition monitoring, fault diagnosis, ac machines, stator fault, winding fault, transient excitation.**

I. Introduction

Inverter fed induction machines are the first choice when it comes to speed variable and/or rough operating conditions. This is possible due to the robust design (especially squirrel cage machines) and the development of high-power semiconductor switches. Hence, the motor drive has grown to one of the most important components in industrial as well as commercial applications. Unexpected outages of these components may lead to high economical losses or even dramatic consequences in safety critical areas as x-by-wire systems.

The stator winding insulation is one of the most critical components of these systems. In the past years several investigations have been carried out to determine the motor reliability [1-4]. As a result it was shown that the reason of a drive breakdown can be found by about 50% in bearing faults, 35% in stator winding faults and about 10% in rotor faults. But not only the fault rate, also the fault development have to be taken into account. A not detected fault in the insulation system may burn the whole machine down within few minutes to even fragments of seconds [5] affecting also the core and adjacent components. Depending on the machines size, the fault induces possible high fault currents. These currents cause overheating and can lead to further damage.

Insulation system faults are caused by several different mechanisms and forces. Thermal, electrical, mechanical and environmental stresses are the main reasons. Furthermore the isolation class and the machine's industrial field of application influence the ageing of the isolation. Especially inverter fed machines are subjected to a fast degradation of the inter-turn winding due to the steep voltage rises.

Basically all published methods for isolation fault detection of controlled inverter fed drives can be divided into three groups: spectral analysis/fundamental wave behavior, model based methods and symmetry of measured quantities [5].

Spectral analysis and fundamental wave behavior methods are usually designed for line-fed operation. Hence their applicability to inverter-fed drives is limited. These methods often use signals from additional sensors [6] or sensors already used in the control loop [7-8].

The model based methods use measured voltage, current and rotor position to calculate the machine's state variables. One or more state variables serve as fault indicator. In [9] a state variable is compared with a measured reference quantity. Another method is given in [10] where the fault detection is realized by stator current reconstruction.

The third group of detection methods is limited to inverter-fed drives. Usually they are totally independent of mathematical machine models. In [11] inverter switching statistics are evaluated. The fault indicator is calculated from the mean value deviation of all switching states counted for one electrical period. In steady state condition it shows good accuracy and calculation effort is low but in dynamic operation efforts rise strongly.

Most of the published methods are limited to steady state operation or require additional sensors or measurement equipment. Furthermore the majority of investigated methods are able to detect faults in the primary insulation system (phase-to-phase and phase-to-ground).

Insulation failures frequently start with a turn-to-turn fault and develop into more severe faults [12]. Hence detection of turn-to-turn faults in an early stage is necessary to avoid greater disaster. Especially when down time is intolerable the detection should be online and performable while machine is operating to enable a possible emergency operation.

The method introduced in this paper is based on the detection methods published in [13]. Basically the machine's behavior on transient excitation is investigated and hence a fault indicator calculated. The transient excitation is realized by voltage steps generated by the switching of the inverter. The current response is measured by the same built-in sensors of the inverter that are used for the control system. The method thus utilizes only the sensors and electronics already available in today's industrial drives.

II. Estimation of the Transient Leakage Inductance

In the following the method and signal processing for a fault indicator are described.

The proposed method is based on the injection of voltage pulses and measurement of the current response. In the case of inverter fed machines the voltage pulses can be easily realized by inverter switching. Switching from inactive to any active state of the inverter a voltage step is applied to the machines terminals with a magnitude equal the dc link voltage. The resulting current response will be dominated by the transient leakage inductance. The leakage inductance contains information about the machine's asymmetries which can be used to calculate a fault indicator.

An ideal symmetrical induction machine can be described by the well known stator equation in the space phasor representation (1).

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

The machine's transient reaction to a voltage step is dominated by the leakage inductance l_l times the current time-derivative and the time-derivative of the rotor flux $\underline{\lambda}_R$ (back emf). The stator current is measured at two different time instances and its time-derivative approximated by the difference as shown below. The disturbing influence of the back emf has to be eliminated to enable an accurate identification of the leakage inductance. This elimination is realized by applying two different and subsequent voltage pulses. The duration of each pulse is some ten µs. As the duration of the pulse excitation is only short, the fundamental wave point of operation, the back emf and the dc link voltage can be considered constant. In Fig. 1 the voltage pulses as well as the current response in one main phase direction is depicted. As can be seen a special voltage pulse pattern is applied to the machines terminals. Therewith the fundamental wave point of operation remains unchanged. As shown in the figure the first pulse sequence is denoted with index *I* and the second with *II*. Further the time derivative of the current is approximated by $\Delta\underline{i}_S/\Delta d\tau$ due to the time discrete behavior of the measuring system.

For each voltage pulse the stator equation can be calculated. Subtraction (considering $d\underline{\lambda}_{R,I}/d\tau \approx d\underline{\lambda}_{R,II}/d\tau$ and $\underline{i}_{S,I} \approx \underline{i}_{S,II}$) of the two step responses leads to (2). In (3) the equation is represented in a shorter notation where $v_{S,I-II} = v_{S,I} - v_{S,II}$ and $d\underline{i}_{S,I-II}/d\tau = d\underline{i}_{S,I}/d\tau - d\underline{i}_{S,II}/d\tau$.

$$\underline{v}_{S,I} - \underline{v}_{S,II} = \underline{l}_{l,t}\left(\frac{d\underline{i}_{S,I}}{d\tau} - \frac{d\underline{i}_{S,II}}{d\tau}\right) \qquad (2)$$

$$\underline{v}_{S,I-II} = \underline{l}_{l,t}\left(\frac{d\underline{i}_{S,I-II}}{d\tau}\right) \qquad (3)$$

Considering now a non symmetrical machine the leakage inductance l_l will no longer be scalar, it's a complex value $\underline{l}_{l,t}$ denoted underlined as phasor and additional with index t for transient excitation (2)-(3).

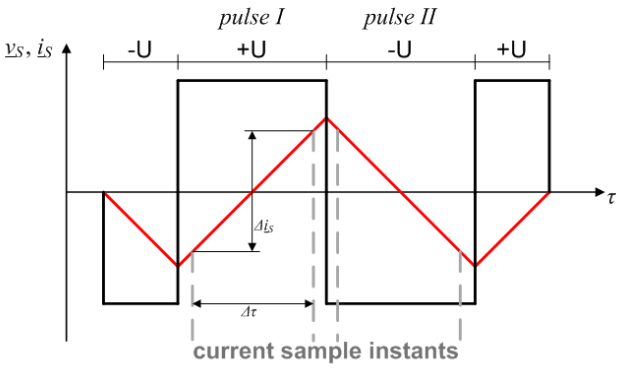

Fig. 1: Voltage steps (black) and current response (red) in one phase direction.

Such an unbalance may be induced by faults (isolation fault, eccentricity, rotor faults, missing slot wedges, ...) or/and by inherent asymmetries like anisotropy, not symmetrical voltage system and manufacturing imperfectness.

The so introduced complex transient leakage inductance consists of a symmetrical part l_{offset} and a complex part $\underline{l}_{mod}$, with its magnitude l_{mod} and direction θ. The symmetrical part represents the symmetrical machine, the complex portion the fault induced asymmetries, respectively. This complex portion points in the direction of maximum inductance within each pole in the presence of a winding fault.

$$\begin{aligned} \underline{l}_{l,t} &= l_{offset} + \underline{l}_{\text{mod}} \\ \underline{l}_{\text{mod}} &= l_{\text{mod}} \cdot e^{j2\theta} \end{aligned} \qquad (4)$$

Inserting (4) into (3) and inverting the equation to reduce the number of mathematical operations leads to (5) and (6), respectively. There the conjugated complex value is marked with * and the leakage inductance is transformed to the inverse transient inductance $\underline{y}_{I-II}$.

$$\frac{d\underline{i}_{S,I-II}}{d\tau} = y_{offset} \cdot \underline{v}_{S,I-II} + \underline{y}_{mod} \cdot \underline{v}^*_{S,I-II} \qquad (5)$$

$$\frac{d\underline{i}_{S,I-II}}{d\tau} = \underline{y}_{I-II} \cdot \underline{v}_{S,I-II} \qquad (6)$$

These coherences are illustrated in Fig. 2 in the stator fixed frame to give a clear geometrical impression. Thereby the excitation direction ($v_{S,I-II}$) and the resulting current response vector *($\Delta\underline{i}_S/\Delta d\tau$)* together with the direction of maximum inductance are shown. The voltage pattern is applied in phase direction U ($v_{S,I}$ = +U and $v_{S,II}$ = -U). The transient inductance is assumed to have an ideal sinusoidal disturbance along the circumference. As shown in the picture this disturbance is assumed to have the maximum value at θ=40° with respect to the excitation direction. This leads to a current slope ($v_{S,I-II} \cdot \underline{y}_{mod}$) which differs from the symmetrical portion ($v_{S,I-II} \cdot \underline{y}_{offset}$). As mentioned before the modulated part represents the imperfectness of the machine (fault induced or not). Assuming now a faulty machine the magnitude of this part is rising with the fault severity. However, the symmetrical part is always clearly dominant. The part of $\underline{y}_{mod}$ is being only a fraction of the offset part even in a faulty machine. In order to exploit this information for fault detection with high precision some further signal processing steps have to be carried out.

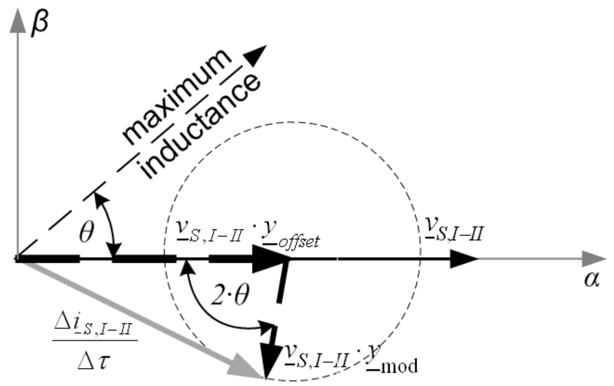

Fig. 2: Current slope vector (gray) for applied voltage pulses in phase direction U. The direction of maximum inductance is assumed θ=40°.

III. Asymmetries in the Transient Leakage Inductance of AC Machines

In the previous section it was shown that a current response resulting from a special voltage pulse excitation contains information about the machine state and its asymmetries. The obtained current slope and thus the inverse transient leakage shows a distinct behavior in presence of faults and can thus be used to exploit a high precision fault indicator for monitoring purpose. But before a fault indicator is generated out of the current signal, some specific signal processing steps have to be executed to separate the asymmetry portion from the symmetrical one.

A very simple but effective way to carry out the excitation is to apply the voltage pulse sequence by inverter switching. The sequence is realized by two active inverter output states whose voltage phasors point in opposite directions. From the measured current slopes the asymmetry phasor is obtaind with (2) – (6). As only the modulated portion of the phasor contains information about the fault, the symmetrical part acts as disturbance and must be eliminated. Basically there are two options to carry out this task.

One is to determine the magnitude of the symmetrical component in advance on a faultless machine. Therefore the flux and the load level of the machine have to be observed. Elimination is then realized by subtraction of the obtained asymmetry phasor (in fault case) and the identified faultless phasor.

A second option for eliminating the symmetrical portion is given by voltage excitation in the three main phase directions. Thus three current response vectors are obtained and one resulting phasor can be calculated. The share of the symmetrical part then leads to a zero sequence component that is eliminated. This resulting phasor now only contains information on machine asymmetries. In the following the phasor will be denoted asymmetry phasor.

Basically this phasor can now be used as fault indicator but due to the superposition of inherent and fault induced asymmetries; high sensitive fault detection can be very challenging.

A. *Inherent Asymmetries of Faultless Machines*

In every machine even when faultless there are always some inherent asymmetries. The reasons for these asymmetries are spatial saturation, slotting and anisotropy. Their presence affects the asymmetry phasor what results in the need for a separation of these asymmetries to achieve a high precision fault indicator.

However, an identification and separation of these asymmetries can be reached without previous identification due to their deterministic behavior.

Concerning induction machines the main asymmetry when faultless is the saturation saliency. It arises from the spatial distribution of the fundamental wave saturation level along the circumferences of the stator. The period of this modulation is twice that of the fundamental wave. Flux and load determine this modulation's magnitude and deviation from the direction of the machine's current phasor. It will be shown in the following that identification and separation can be done without pre-commissioning by specific measurements.

Another asymmetry also present in the asymmetry phasor is the slotting saliency. It is influenced by the slot openings in the lamination of the rotor. The period of this portion corresponds to the number of rotor slots of the machine. The flux, load or speed levels have almost no influence in this modulation.

Additional there is a further asymmetry detectable in the asymmetry phasor. This component arises when saturation and slotting are present and results from intermodulation. The magnitude and direction also depends on the operating point of the machine.

IV. Fault Indicator Estimation

In the previous section it was shown that the current response phasor to voltage pulses deliver information about the machines state and asymmetries. The resulting phasor can so be utilized for stator winding fault detection. Nevertheless, before this asymmetry phasor serves as fault indicator some specific signal processing step must be executed.

The duration of the voltage pulse excitation is within a short time period of some 10µs. This excitation can for example be realized within one cycle of a pulse width modulation period. The current value at the beginning and ending of the voltage pulse sequence is almost the same (Fig. 1). Therewith consequences on the control loop and operating point of the machine are almost negligible.

The so detected asymmetry phasor represents the machine asymmetry for a specific state of the machine (i.e. rotor and flux position). Fig.3 depicts the data acquisition process.

The field oriented control (FOC) provides the state variables γ_{el} and γ_{mech} to the measurement control unit. This unit decides when a voltage excitation has to be done and interrupts the FOC control loop and the PWM (pulse width modulation). Then the voltage pulses from Fig. 1 are applied to the machine and the current response is measured. With the so obtained current slope phasor the asymmetry phasor is calculated and forwarded to the data storage block. This storage is realized as a matrix. Each element corresponds to a specific rotor and flux position. The related flux and rotor position (γ_{el} and γ_{mech}) are obtained from the measurement control.

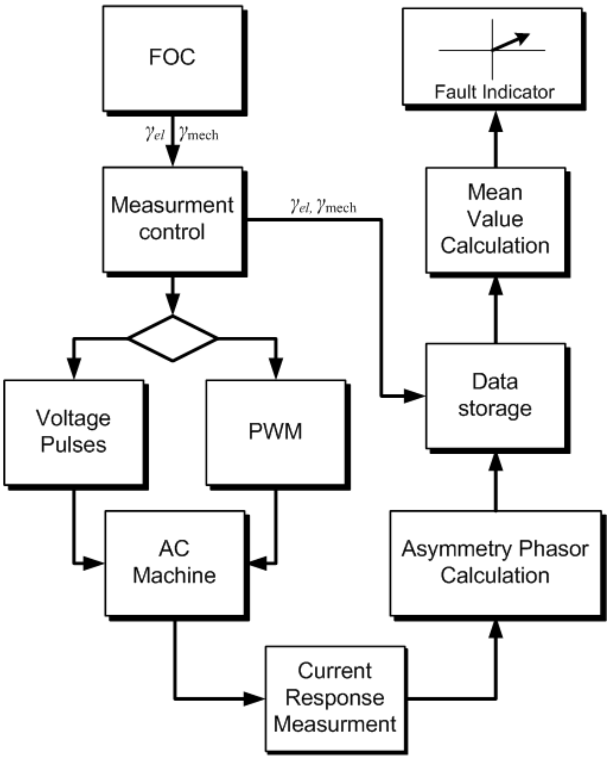

Fig. 3: Block diagram of the data acquisition / signal processing

The location within the matrix where the phasor value has to be stored is determined from γ_{el} and γ_{mech}. Columns represent asymmetry phasors at one rotor position and one revolution of the flux. On the other side the rows are used for storing one flux position and one revolution of the rotor. The procedure is repeated until a complete set of asymmetry phasors is collected with respect to one mechanical and electrical revolution of the rotor/flux. The matrix is subsequent forwarded to a mean value calculation block. This block realizes the separation of all asymmetries contained in the asymmetry phasor. The separation is done by mean value calculation (MVC) of rows and columns. In the first step the mean values of each row (corresponding one mechanical revolution) are determined. Thus the slotting modulation is eliminated. This MVC leads to a set of phasors each representing the remaining asymmetries for one flux position. Each phasor is thus composed only of saturation saliency and fault induced asymmetry.

In the second step the MVC is done again. Now the set of phasors is combined to only one resulting phasor. Due to the MVC with respect to one flux revolution the saturation modulated portion is also eliminated. This phasor now only contains information about asymmetries that are fixed with the stator and can be used as stator isolation fault indicator. In a symmetrical machine this indicator leads to a zero phasor; in the case of fault the magnitude of this phasor will rise and its angular position will point into the fault direction.

The influence of the different inherent saliencies on the asymmetry phasor and the separation method are also shown in Fig 4. The locus of the asymmetry phasor is depicted as a function of the rotor and flux position.

The left diagram of the figure depicts the trace of the asymmetry phasor for zero flux and no load. The trajectory thus consists only of the slotting modulation. For the middle diagram the machine was operated with rated flux and no load. Now the saturation saliency has a dominating portion with the slotting superposed. The right diagram shows a set of trajectories for a load level of 70%. The clear increase of the saturation induced modulation is visible while the slotting modulation remains almost unchanged.

V. MEASURMENTS AND RESULTS

The experimental setup consists of a load machine, a test machine, a voltage source inverter and a measurement and control unit. The test machine is a specially designed 5.5 KW induction machine with a squirrel cage rotor. The parameters of the machine are given in Table 1. The stator windings are specially designed to enable a non destructive simulation of stator winding faults. For this purpose the winding coils have taps on several positions. Different fault levels can thus be investigated by connecting some of these taps by different resistances. Disconnection of these joints leads to a healthy, not destructed symmetrical machine again.

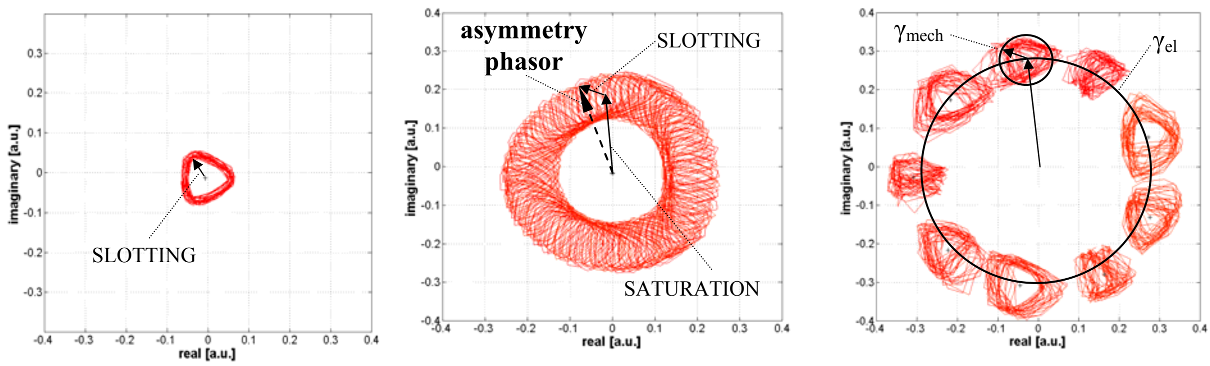

Fig 4: Asymmetry phasor trajectory for different machine operating states of a symmetrical machine. Left: zero flux / no load. Middle: rated flux / no load. Right: rated flux / 70% load

TABLE 1:
PARAMETERS OF TEST MACHINE

NUMBER OF POLES:	P = 4
NOMINAL VOLTAGE:	U_N = 187V
NOMINAL CURRENT :	I_N = 14.3A
NOMINAL EL. FREQUENCY:	F_N = 50HZ
NUMBER OF STATOR SLOTS:	N_S = 36
NUMBER OF ROTOR SLOTS:	N_R = 28
NUMBER OF TURNS PER PHASE	W_S = 130

The measurements were carried out using a programmable (MATLAB/Simulink) control and measurement unit. The excitation and data acquisition sequences were done as described in the previous sections. The machine was controlled by the field oriented control scheme. The inverter control mode is a standard pulse width modulation (PWM) with 5kHz carrier. As described above the fault detection procedure is based on voltage pulse excitation. Due to the short pulse duration this can be realized with one PWM cycle.

The sensitivity of the method is verified by several measurements. As described in the first section, winding faults usually start with turn-to-turn faults. Therefore only these types of faults were investigated.

The fault levels are examined in different stages. First, a turn-to-turn fault was realized by a copper wire between two coil taps. Thus a damaged insulation and a low resistance connection of two coil turns was simulated. In further consequence the copper wire was exchanged by resistors with rising values. So the method was tested for already existing and developing turn-to-turn faults. Furthermore the fault indicator sensitivity was investigated at different load levels.

A. *Fault indiactor and fault direction*

Fig. 5 shows measurement results for different fault levels and fault positions. The measurements were done at rated flux and a load level of 30%. The faultless case serves as reference of the symmetrical machine (brown X). The first stage was a turn-to-turn connection realized by a copper wire. In the figure, measurement results for theses three cases are marked by * denoted Cu U, Cu V, and Cu W. Further, in in all three pahses the copper wire was changed by an resistor marked with + (Res1).Additional in phase U a second resistor was applied denoted with Res2. Res2 has a greater value than Res1. The currents in the shorted turn were measured to 5.1A for copper wire, 0.29A for Res1 and 0.13A for Res2 (rated current of the machine was 14.3A). The taps in each phase are placed on the two very first turns of each phase.

The measurement results of Fig. 5 show that the connection of two taps (turn-to-turn fault) closed by a high conducting connection like a copper wire and even connected by a resistor can be clearly detected. Furthermore also the fault's direction is detectable.

B. *Sensitivity analysis*

In the next step the focus of investigation was the fault indicator dependency on different resistor values in the shorted turn. With what also the sensitivity of starting turn-to-turn faults can be examined. Starting from a shorted turn by a copper wire the connection between these two taps was closed by resistor with increasing values. The limit of detection is reached when fault direction is not more determinable. All measurements were done at three different machine operating states. Fig. 6 presents the measurement results. Firstly the machine was operated with zero flux and no load. Fault detection procedure was done for different resistance values. As can be clearly seen the fault indicator magnitude is increasing with declining resistor value and increasing current in the shorted path. The current in the shorted path was measured to 35% of machines rated current when connected by a copper wire. The limit of detection is given at 1% rated current in the shorted path (resistor of 2Ω). After that the measurements were repeated with rated flux / no load and finally with 30% nominal load. The presented method shows negligible variations of fault indicator if flux or even load is present in the machine. This circumstance can be ascribed to the separation of inherent asymmetries by the signal processing. The indicator magnitude axis is scaled logarithmically for an improved readability.

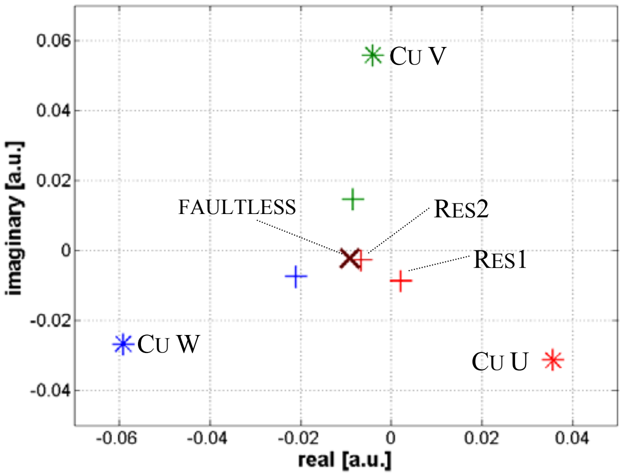

Fig. 5: Measurement results of the fault indicator at load level on 30%.

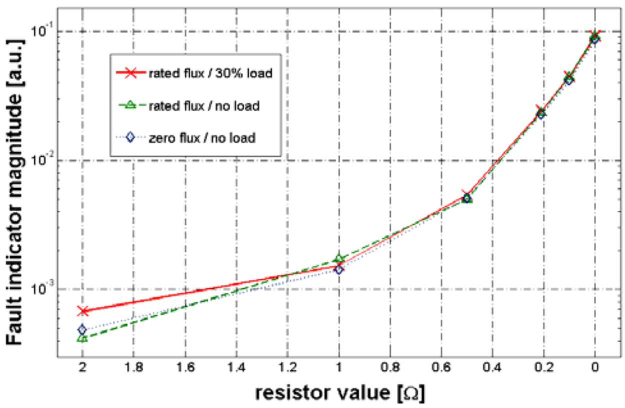

Fig. 6: Fault indicator magnitude versus resistance values of short circuit for three different points of operation.

C. *Load dependancy*

The operating state of inverter fed drives has mainly dynamically changing. This is coupled with high load changes. Therewith a fault indicator in such cases should be ideally load independent. In Fig 4 it was shown that the flux and load impact induce changes of inherent asymmetries (saturation saliency). However, the load dependence of the fault indicator investigated in this paper is eliminated by the signal processing. In Fig. 7 measurement results for several fault cases at different load levels are presented. The fault indicator magnitude is plotted against the load. The load is given in percent values of machine's rated torque. The fault indicator magnitude is the difference between reference and fault case. The indicator magnitude axis is scaled again logarithmically for a clearer presentation. Starting again with a copper wire (blue, 35% rated current in shorted path) the resistor value between two taps (turn-to-turn) in phase direction U was increased. Thus the current in the shorted path is reduced (pink: 1% of rated value). In each fault case the load level was increased from zero load to 80% rated load in 6 steps. As can be seen the measurement results show that the load dependency of the fault indicator is almost negligible.

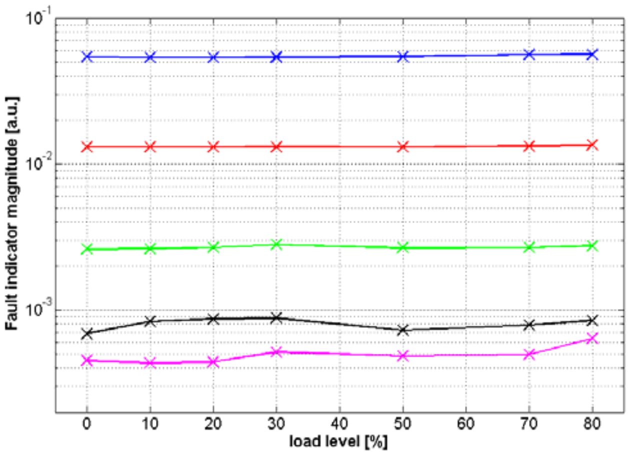

Fig. 7: Fault indicator load dependency. Blue: 35% and pink: 1% rated current in shorted path.

VI. Conclusion

A method has been proposed to detect developing turn-to-turn faults in inverter fed induction machine windings. The method is based on voltage pulses generated by inverter switching and current response measurement. A subsequent signal processing scheme leads to a high precision fault indicator without the need of pre commissioning. This fault indicator was investigated by measurements on an induction machine fed by an inverter. The measurement results have shown a high sensitivity of the fault indicator. Existing as well as already developing turn-to-turn faults are still detectable. Furthermore the fault indicator shows negligible load dependency.

Acknowledgement

The work to this paper was supported by the European Union in the SEE-ERA.NET PLUS framework.

References

[1] MOTOR RELIABILITY WORKING GROUP, "Report of large motor reliability survey of industrial and commercial installations, Part I," *IEEE Trans. Ind. Appl.*, vol. IA-21, no. 4, pp. 853–864, Jul. 1985

[2] MOTOR RELIABILITY WORKING GROUP, "Report of large motor reliability survey of industrial and commercial installations, Part II,"*IEEE Trans. Ind. Appl.*, vol. IA-21, no. 4, pp. 865–872, Jul. 1985

[3] Thorsen O. V. , Dalva M., "A survey of faults on induction motors in offshore oil industry, petrochemical industry, gas terminals, and oil refineries," *IEEE Trans. Ind. Appl.*, vol. 31, no. 5, pp. 1186–1196,Sep./Oct. 1995.

[4] Joksimovic G., Penman J., "The Detection of Interturn Short Circuits in the Stator Windings of Operting Motors", *IEEE IECON Conference Record*, pp. 1974-1979, 1998.

[5] Wolbank, T.M.; , "On-line detection of stator winding faults in controlled induction machine drives," Diagnostics for Electric Machines, Power Electronics and Drives, *SDEMPED, 5th IEEE International Symposium on* , vol., no., pp.1-6, 7-9 Sept. 2005.

[6] Henao, H.; Capolino, G.A.; Martis, C.; , "On the stray flux analysis for the detection of the three-phase induction machine faults," Industry Applications Conference, *38th IAS Annual Meeting. Conference Record of the* , vol.2, no., pp. 1368- 1373, 12-16 Oct 2003.

[7] El Hachemi Benbouzid, M.; , "A review of induction motors signature analysis as a medium for faults detection," *Industrial Electronics, IEEE Transactions on* , vol.47, no.5, pp.984-993, Oct 2000.

[8] Nandi, S.; Toliyat, H.A.; , "Novel frequency domain based technique to detect incipient stator inter-turn faults in induction machines," *Industry Applications Conference, 2000. Conference Record of the 2000 IEEE* , vol.1, no., pp.367-374 vol.1, 2000.

[9] Haylock J.A., Mecrow B.C., Jack a.G., Atkinson D.J., "Online Detection of Winding short-circuits in inverter fed drives. *IEEE 9th International Conference on Electrical Machines and Drives*, 1999.

[10] Wolbank, T.M.; Wohrnschimmel, R.; , "On-line stator winding faults detection in inverter fed induction motors by stator current reconstruction," *Electrical Machines and Drives, 1999. Ninth International Conference on (Conf. Publ. No. 468)* , vol., no., pp.253-257, 1999.

[11] Wolbank, T.M.; Loparo, K.A.; Wohrnschimmel, R.; , "Inverter statistics for online detection of stator asymmetries in inverter-fed induction motors," *Industry Applications, IEEE Transactions on*, vol.39, no.4, pp.1102-1108, July-Aug.2002.

[12] 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," *Industrial Electronics, IEEE Transactions on* , vol.55, no.12, pp.4127-4136, Dec. 2008.

[13] Wolbank, T.M.; Nussbaumer, P.; Hao Chen; Macheiner, P.E.; , "Monitoring of Rotor-Bar Defects in Inverter-Fed Induction Machines at Zero Load and Speed," *Industrial Electronics, IEEE Transactions on* , vol.58, no.5, pp.1468-1478, May 2011