Inter Turn Short Circuit Detection at Higher Modulation Indexes Including Six Step Operation

G. Stojčić, G. Joksimović, M. Vašak, N. Perić, T. M. Wolbank

Abstract – **Inverter fed induction machine drives have become one of the most important part in industrial applications. The devices are usually operated near or at the rated vales. Additionally high dynamic operations, overload cycles and the fast switching inverter are putting additional stress to all machines components. The stator winding system is one of the most critical components. Faults in the winding system of a machine can cause a dramatic damage due to their fast developing behavior. An early detection of winding faults can reduce these consequences. In this paper a method is presented to achieve reliable fault detection on stator winding faults focused on application at higher speed levels where immediate detection is imperative. Higher inverter modulation indexes provide the possibility to estimate the transient leakage inductance in each PWM modulation cycle. This parameter contains the information on machine asymmetries. Specific signal processing steps provide a high sensitive fault indicator.**

Index Terms--**fault detection, stator winding fault, induction machine , inverter fed,**

I. Introduction

IN the past decades the inverter fed induction machine has grown to one of the most important application for adjustable speed drives. This is affiliated to their robustness and the possibility of high dynamic operation, especially in field oriented control frame. As any type of device the motor drive is also subject to various faults. Unscheduled outages of these components may lead to a reduction of production and increase of maintenance costs.

When operated in a controlled mode and with repeated and high dynamic load cycles all components of the machine are exposed to high stress. Many studies have been carried out to determine motor reliability [1], [2], [3] and [4]. These investigations have shown that the stator winding is one of the most critical component and winding faults are responsible for about 35% of all machine breakdowns. However not only the fault rate, but also the fault development of stator faults is a critical mechanism.

The fault in the isolation system is basically caused by several mechanisms. Electrical, thermal, mechanical as well as environmental stresses are the main reasons for the degradation process of the isolation. But also the isolation class and the field of application influence the insulations aging process.

Especially machines utilized in adjustable speed drives are known to suffer more likely from insulation failures caused breakdowns than mains fed machines. This fact can be lead back to faster isolation degradation due to the steep voltage rises generated by the voltage source inverter for machines operation.

The development of stator winding faults usually starts with a turn-to-turn fault. High current in the shorted turn lead to overheating of the damaged position and a further spreading of the failure. The faulty turns can so cause damages of coils and iron core and end up into a totally destroyed machine. The time constant of fault spreading to adjacent components is machine power-rating dependent and can reach from some minutes down to even fragments of seconds.

Basically the testing and monitoring methods published can be divided into online and offline methods.

Due to the fact that offline methods can only be applied at specific time instants (maintenance work) they cannot serve as a continuous and preventive fault detection method. Therefore methods have to be implemented which can deal with the regular operation of the machine - what means online. Many of the proposed methods require additional hardware components and are limited to line-fed operation [5],[6],[7]. The measurement of the motor's hf impedance for insulation condition monitoring is proposed in [8]. To avoid such additional measurement hardware sensorless and nonintrusive methods have been developed recently. Compared to other methods only electrical values e.g. current and voltage are handled. Therewith the monitoring system can reside in motor control devices. In [9] the fault detection is based on the motor current signature analysis (MCSA). The impact of closed-loop operation on the accuracy of such methods is investigated in [10]. Another method is given in [11] where the fault detection is realized by stator current reconstruction. Evaluation of inverter switching statistics is the base of the method given in [12]. The fault indicator is then calculated from the mean value deviation of all switching states within on electrical period.

However, most of the online methods are usually limited to steady state operation and fail in high dynamic inverter fed operation. On the other hand additional sensors or measurement equipment is needed.

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Furthermore most detection methods are able to detect faults in the primary insulation system e.g., phase-to-phase and phase-to-ground. The winding faults frequently start with turn-to-turn faults and rise then to greater damages. Hence, a safety system should be able to detect turn-to-turn faults in an early stage to provide an adequate fault handling.

II. Turn Fault Detection Based on Transient Leakage Inductance Estimation

The method presented in this article is an advancement of the procedure given in [14]. The previous work is based on the estimation of the machines transient leakage inductance. Machines response to transient voltage pulses is a current derivative which can be handled to provide information on machine symmetry state. A specific signal processing path calculates a fault indicator with high accuracy. The excitation of the machine is realized by voltage pulses generated by inverter switching. Thereby a special voltage step pattern is applied to the machine terminals. This method is well applicable in standard drive applications because it utilizes only the sensors and electronics already available in today's applications. However, investigations of the method have shown that there exist limitations when executed in practice. The main drawback is given by the fact that the application of the special voltage pulse pattern gets more and more difficult when the modulation index is increased and finally over-modulation is reached at high speed operation. A detailed description of how this limitation is avoided is given in the following sections.

A common way to identify the parameters of a dynamic system is to observe the step response. In electrical systems this can be realized by applying voltage or current steps to the terminals and measurement of the electrical quantities.

In case of electrical drives, especially inverter fed machines; an easy way is given by applying a voltage step with the dc link voltage to the machine terminals by inverter switching. Changing an inverter output state from inactive to any active state such voltage pulse is generated and the machines response will be a current slope. This current reaction is dominated by different machine parameters as can be described with the well known stator voltage equation in space vector formulation (1).

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

The parameters influencing the current slope are stator resistance r_S, leakage inductance l_l and the time derivative of the rotor flux $\underline{\lambda}_R$ (back emf). After applying a voltage step to the machines terminals the very first reaction of the machines current will be predominant influenced by the transient leakage inductance and the back emf. Especially when machine is operated at higher speed, back emf with its magnitude and direction will act as disturbance when identifying transient leakage inductance. But this drawback can be avoided if a special voltage pulse pattern and signal processing is realized. This pulse scheme is given in Fig. 1.

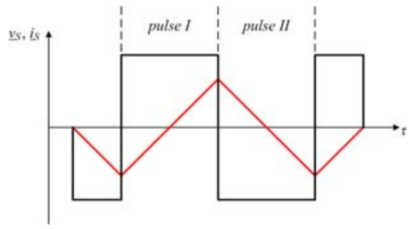

Fig. 1: Special voltage pulse pattern for transient leakage inductance identification. Voltage (black) and current reaction (red).

If two subsequent pulses (pulse I and pulse II) with opposite direction are applied, the fundamental-wave point of operation is almost unchanged due to the symmetrical nature of the pulse sequence. As the pulse duration is within some ten µs also the dc link voltage as well as the back emf can be considered constant. As a result, the elimination of the disturbing back emf and stator resistance can then be simply performed by subtracting the equations of both pulses. This leads to (2) where only the known parameters voltage and current derivative including the transient leakage inductance are remaining. The values are denoted with index I and II for the first and second pulse. The leakage inductance l_l is additionally denoted with the index t what introduces the transient leakage inductance that usually differs from the fundamental wave one. In (1) the fundamental wave voltage equation was given with l_l as fundamental wave leakage inductance. The current signal can easily be measured within the pulse duration at two different sample points. This is preferably done with the inverter built-in current sensors what results in no need of further hardware.

$$\begin{aligned} \underline{v}_{S,I} - \underline{v}_{S,II} &= l_{l,t} \cdot \left[\frac{d\underline{i}_{S,I}}{d\tau} - \frac{d\underline{i}_{S,II}}{d\tau} \right] \\ \underline{v}_{S,I-II} &= l_{l,t} \cdot \frac{d\underline{i}_{S,I-II}}{d\tau} \end{aligned} \tag{2}$$

Now the identification of the transient leakage inductance can be realized by a simple division. The obtained information can then be used to calculate a fault indicator. A detailed description of the measurement procedure is given in [13].

A. *Current limitations of the method*

The behavior of an induction machine is well described by stator equation (1). The back emf is speed dependent due to the time derivative of the rotor flux. The method described above deals with the identification of the transient leakage inductance after elimination of the back emf using special voltage pattern. As stated before, the back emf is considered constant during the pulse period. But this is only ensured at lower speed levels. When speed is rising, also the back emf will increase caused by the faster change of the rotor flux within one time period. This also leads to an increasing change of back emf value during the pulse sequence shown in Fig. 1. In addition, the additional excitation of the machine using the voltage pulse sequence gets more and more challenging when the modulation index is increased and finally six step operation is reached.

The consequence of this fact is that the initial method is well suitable for lower speed levels but has a reduced accuracy and applicability at higher speed levels. In Fig. 2 measurements were carried out to point out the deviation of the fundamental wave point of operation due to the pulse sequence with increasing speed levels.

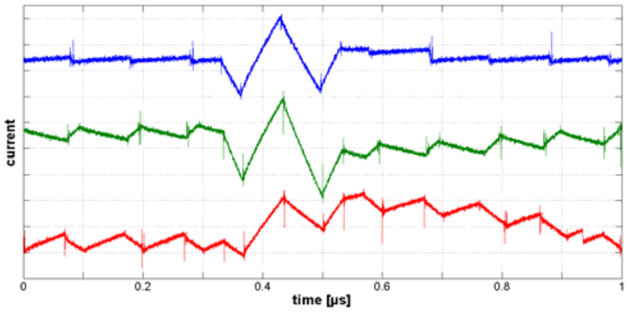

Fig. 2: Current signal for voltage pattern at three different speed levels. Blue (upper): 0.1 (p.u.), green (middle): 0.3 (p.u.), red (lower): 0.7 (p.u.).

At low speed (upper,blue curve, speed level 10% rated speed) the changing rotor flux position has almost no influence on the current signal due to the short pulse duration. The current reaction signal is symmetrical with respect to the pulse signal. Increasing the speed level leads to a higher back emf within the time period considered. This can be observed in the middle,green curve (speed level 30% rated speed). The current signal is no more symmetrical but can still be utilized for fault detection with high accuracy. Furthermore the current level before and after the voltage pulse sequence is not more the same. So the fundamental wave point of operation has changed considerably and the current controller has to trace back the current deviation.

If the speed level is further increased to high speed levels near rated value (red trace, speed level 80%), the influence of the back emf and the resulting change of the operating point is no more negligible. The deviation of the current from the reference value is very high and causes an additional control activity.

III. Proposed Approach for Transient Leakage Inductance Estimation at Higher Speed Levels

The previous section has shown that in regimes of high speed levels the transient leakage induction estimation by a special voltage pulse pattern has some drawbacks. These drawbacks can be avoided by applying a new approach to realize precise inductance estimation without special voltage pattern. This is achieved by measuring the current slope of a single active voltage pulse only and to eliminate the influence of the back emf using the flux obtained from a fundamental wave model of the machine as described in the next section. Thus the necessary pulse sequence can be reduced to a single pulse and integrated into the inverter modulation scheme.

Usually the output voltage of an inverter for machine control is generated by space vector pulse width modulation (SVPWM). The inverter state (voltage sector) and modulation index determine the direction and magnitude of the applied voltage phasor. As within each PWM cycle a set of voltage pulses is applied by switching of the inverter, the machine's response will be a set of current slopes within this period. It is assumed that at least one of the voltage pulses has a minimum duration of some 10µs to enable an accurate measurement of the current slope after the switching transients have settled in the current sensor signal. This assumption is met at higher modulation indexes and then the measured current slope can directly be used to realize transient leakage induction estimation.

If (1) is transformed into (3) the transient leakage inductance $l_{l,t}$ can be directly calculated (index t represents the transient inductance which differs from the fundamental-wave leakage inductance).

$$\underline{l}_{l,t} = \frac{\underline{v}_S - r_S \cdot \underline{i}_S - {d\underline{\lambda}_R}/{d\tau}}{{d\underline{i}_S}/{d\tau}} \tag{3}$$

Stator voltage $\underline{v}_S$ is obtained from the PWM, and time derivative of the flux $d\underline{\lambda}_R/d\tau$ from the same machine model used by the control algorithm. The ohmic portion $r_S \cdot \underline{i}_S$ can usually be neglected in medium and large machines, due to the small r_S value.

Assuming now an ideal symmetrical machine the transient leakage inductance can be considered as a scalar and thus independent of the inverter output voltage sector. However in a real machine even faultless or not this definition must be modified. The transient leakage inductance is then becoming a complex value introduced by the complex value $\underline{l}_{l,t}$, [15]. This is caused by inherent as well as by fault induced asymmetries which are presented in a real machine. As a consequence the direction of the obtained current slope and voltage pulse minus back emf are no more the same. This complex inductance can now be described as a summation of a scalar and a complex value as shown in (4).

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

The offset value l_{offset} represents the symmetrical faultless machine while the complex value (index 'modulated') $\underline{l}_{\text{mod}}$ introduces the fault induced asymmetry with its magnitude l_{mod} and direction 2γ. The modulated value points in the direction of the maximum inductance within one pole pair.

Considering (3) for the leakage inductance calculation one important issue is the measurement of the current time derivative. In the inverter it is preferably determined replacing the time derivative $di_S/d\tau$ by the difference $\Delta i_S/\Delta\tau$ and using two subsequent current samples within one voltage pulse.

Usually the current samples for machines control are taken at the beginning/end of each PWM cycle. If the current slope is calculated from these instants at lower modulation indexes, the mean current slope value of all voltage pulses applied during that cycle is obtained.

For the application of (3) it is however, necessary that the current slope of a single pulse is taken. Otherwise inverter interlock dead time considerably affects the result.

Thus additional sample instants have to be placed inside the PWM cycle. In Fig. 3 a PWM cycle with the stator voltage (blue line), stator current (red line) and current sample instants (black dots, marked CS) is depicted. The instants of the standard samples are denoted with 'CS' and the additionally placed with 'Additional CS'. Now the current difference resulting from the transient excitation can be calculated from the difference of the additional CS. Another possibility would be given by applying current derivative sensors. Thereby only one sample instant during the active voltage pulse would be necessary.

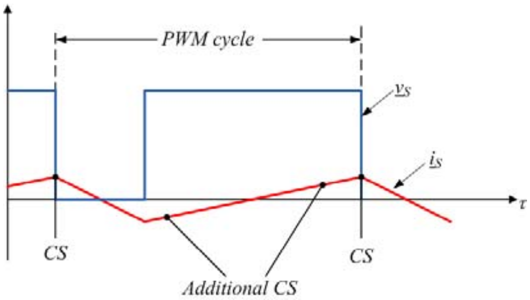

Fig. 3: Current sample scheme within one PWM cycle.

At low speed (low modulation indexes) the active voltage pulse duration in SVPWM is very short. This time duration is usually not sufficient to get an accurate current slope measurement. When speed is increased the voltage phasor's magnitude also increases. Then the time duration of an active inverter state is also becoming longer till it reaches the cycle time of the SVPWM signal at six step operation.

During six step operation the instants of the additional current samples are the same as the instants of the samples used for the current controller. Within this operating range the integration of the method into an existing system is thus most simple.

High rotational speed and six step operation is also most critical with respect to propagation of the fault from a single turn-to-turn short into phase to ground and/or phase to phase short. Thus this operation is considered in the following when describing the application of the method.

IV. Signal Processing for Fault Indicator Estimation

The ratio between the offset and modulated part of the transient leakage inductance is about 90% to 10% even in a faulty machine. For a high sensitive fault indicator these two parts must thus be separated. Special care has to be taken due to the offset parts dependence on the machines operating point. Basically there are two possibilities to eliminate the offset part. One is to identify its value in advance on the symmetrical, faultless machine. The parameters which have to be observed for the identification are the flux as well as the load level of the machine. Another possibility is given by a specific signal processing chain which is described in the following.

For the estimation process of the transient leakage inductance current slope $d\underline{i}_S/dt$ and the time derivative of the flux $d\underline{\lambda}_R/d\tau$ are measured and calculated, respectively. The time derivative of the flux will be replaced by the time difference denoted $\Delta\underline{\lambda}$, (similar to the current slope $\Delta\underline{i}_S$) in the following figures. Caused by the movement of the flux fundamental wave, $\Delta\underline{\lambda}$ will change its direction in each PWM cycle. Now, due to the coherences also $\Delta\underline{i}_S$ will point in different directions in subsequent cycles.

As stated in (4), the calculated transient leakage inductance is composed from a scalar (l_{offset}) and a complex part ($\underline{l}_{\text{mod}}$).

The overall value of $\underline{l}_{l,t}$ is determined by the mean leakage inductance as well as the fault induced asymmetries of the phase values plus inherent asymmetries like that caused by slotting or spatial saturation.

At first the separation of the fault induced component from the inherent ones is considered. Basically this can be done using measurement results form a commissioning test. This commissioning can be avoided if a set of inductance values with different angular positions of the inherent asymmetries is calculated.

For a clearer depiction of this subsequent collection of inductance values a schematically phasor diagram is depicted in Fig. 4.

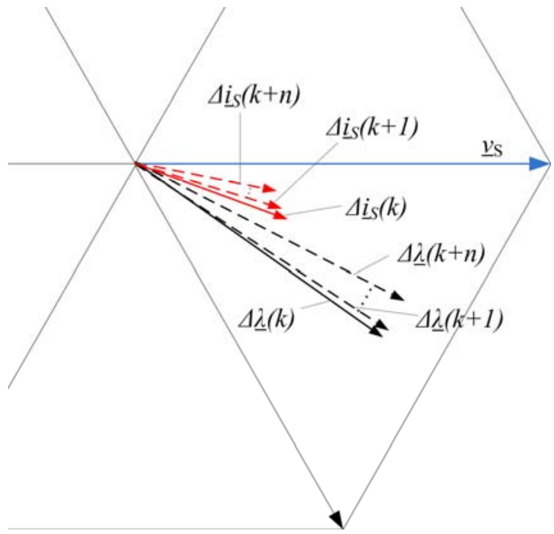

Fig. 4: Coherences of all parameters.

In the figure the active voltage phasor is assumed pointing in phase direction +U. This is indicated by the blue phasor denoted with $\underline{v}_S$. The corresponding flux time derivative is represented by the black solid phasor $\Delta\underline{\lambda}(k)$ and the current slope phasor by the solid red phasor $\Delta\underline{i}_S(k)$. As six step operation is assumed, the voltage phasor will remain unchanged in the following PWM cycles but $\Delta\underline{\lambda}$ and $\Delta\underline{i}_S$ will both change their directions. Furthermore, the magnitude of the current slope phasor will also change. These subsequent samples are indicated by the index *k+1* and marked as dashed phasors in the figure. The last samples are indicated by the index *(k+n)*. According to the six step operation, active voltage phasors are then switched from one active state to the other when the fundamental wave has passed a sector of 60°.

As a result, the obtained set of inductance phasors corresponds to this sector of the fundamental wave. After the voltage has changed in the next phase direction (e.g. in -W) the data acquisition is executed again.

As already shown in equation (4) the modulated part of the inductance has an angular dependence of γ. Therewith the modulated part of the inductance phasor will perform one revolution with respect to the movement of the saliency by the angle γ.

Depending on the demanded accuracy it is thus sufficient to measure only few points along the closed trace of the modulation in order to determine the midpoint of the modulation. This leads to a reduced number of samples that have to be taken and further processed.

Now the separation of the mean leakage inductance that represents the symmetrical machine is considered. When combining the inductance values obtained for the three main phase directions (after eliminating the inherent asymmetries) to one resulting phasor the share of the offset portion then leads to a zero sequence component that is eliminated.

The remaining part now only contains information on stator fixed asymmetries and thus serves as isolation fault indicator with high accuracy.

The separation of the inherent asymmetries was only roughly described above. The corresponding signal processing chain is described in the next chapter.

V. Measurement Setup and Results

The fault detection method deals only with state variables and sensor signals already measured and calculated in the control algorithm. As only PWM excitation is used the fault detection process has no influence on the system or control performance. The implementation of the method can thus be realized on an existing system without the need of additional hardware.

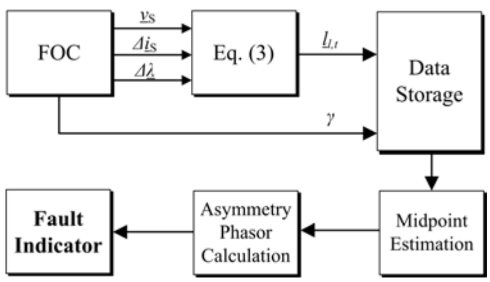

Fig. 5: Block diagram of Data acquisition and signal processing.

In Fig. 5 the whole data acquisition and signal processing is presented. The state variables $\underline{v}_S$, $\Delta\underline{i}_S$ and $\Delta\underline{\lambda}$ are obtained from the field oriented control algorithm (FOC) and current controller. Calculation of (3) provides the transient leakage inductance correlated to one PWM cycle, the corresponding fundamental wave point of operation, as well as the positions of the inherent asymmetries. A set of these values is clustered in the data storage with the corresponding angular positions (it has to me mentioned again that six step operation is assumed). After a predefined number of values are stored, all resulting from the same excitation voltage (inverter switching state) the midpoint estimation of the corresponding trace is done and thus the influence of the inherent asymmetries eliminated. The number of samples selected for this midpoint calculation can be reduced to some ten without significantly reducing detection accuracy. The resulting midpoint represents the phase mean value and is stored together with the correlated inverter switching state. This procedure is repeated till all three main phase directions are covered.

In the next block the three phase mean values are combined to one resulting space phasor. Thus the symmetrical portion of the phase mean values lead to zero sequence component and is eliminated. Only the asymmetrical part of the three phase values adds up in the resulting phasor that now servers as fault indicator.

This structure was realized on a test stand and verified by measurements. The test stand is composed of a special test machine, a voltage source inverter and a control and measurement system programmable under MATLAB/Simulink. Both, inverter and test machine are specially designed for laboratory use. The test machine is a 5.5 kW induction machine with a squirrel cage 28 slot rotor. The machine has 36 stator slots and a 4-pole winding system. The stator winding is specially designed to achieve a non destructive implementation of stator isolation faults. This is realized by taps which are connected to several positions at different coils. Therewith several fault cases can be realized by connecting the taps with resistances or wires. As described in the introduction, winding faults usually start with a single turn-to-turn fault. Therefore the measurements and sensitivity analysis are limited to this fault case. Furthermore the measurements have been carried out at different speed levels.

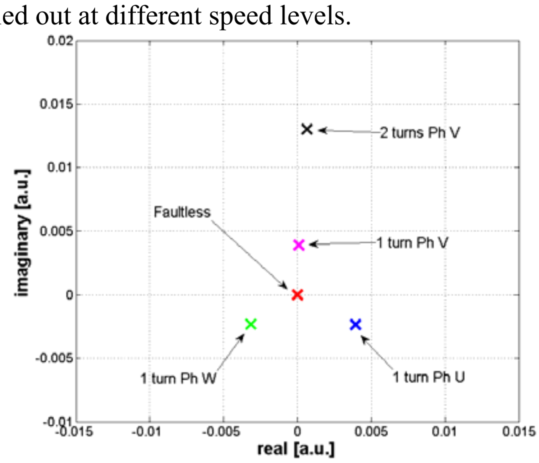

Fig. 6: Measurement results for different fault cases. Asymmetry phasor values presented as crosses. Speed level 0.5 rated value. Units are given in internal representation of the DSP.

Measurement results are presented in Fig. 6. In a first step the faultless symmetrical machine was identified. This value serves as a reference. As fault cases two different fault levels were investigated.

Therefore one and two turns were short circuited in one phase. Furthermore a single turn-to-turn fault was simulated sequentially in each phase to prove the ability of fault position detection. In the picture, one short circuited turn in phase U is denoted as '1 turn Ph U', in phase V with '…Ph V' and in phase W '…Ph W'. The two turns fault case was simulated in phase W, denoted '2 turn Ph W'. The results show a good accuracy in already detecting single turn-to-turn fault as well as determining fault severity. In a further step one short circuited turn in phase U was analyzed at different speed levels. In Fig. 7 this measurements are presented as fault indicator magnitude versus speed level. The results show that the fault indicator has almost no dependence on machines speed level.

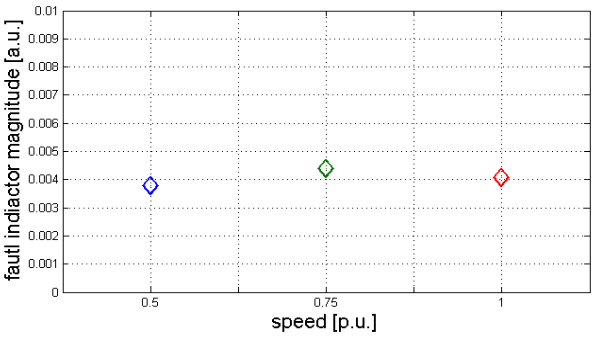

Fig. 7: Fault indicator magnitude at different speed levels. Fault indicator magnitude unit is given as internal representative of the DSP.

VI. Conclusion

A method has been proposed to detect inter turn short circuits in inverter fed machines at high modulation indexes including six step operation. The method is based on the transient leakage inductance estimation performed with voltage pulse excitation within the pulse sequence of a PWM cycle. Therefore the current slope is measured and transient inductance is calculated from different parameters provided by the control system. A subsequent specific signal processing scheme is proposed to obtain a fault indicator with high accuracy.

The procedure can be implemented in already existing systems with no additional hardware. The method has no influence on system's control loops or performance except a slightly higher computation load. The ability of increasing the drive reliability by detecting a fault in an early stage was proven.

Measurement results were done on a special test machine. The results have shown a high sensitivity. Furthermore the obtained fault indicator is independent on flux and speed.

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VIII. Biographies

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