Detection of Partially Fallen-Out Magnetic Slot Wedges in Inverter Fed AC Machines Under Various Load Conditions

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Abstract - **Electrical machines in the high voltage class are usually designed with open stator slots. This wide open slots cause an increase of higher order harmonics, vibrations, noise and temperature, thus the machines efficiency is decreased. To counteract this disadvantage magnetic slot wedges are applied. Due to the impact of high magnetic and mechanical forces these wedges can fall out and may cause further serious damages. Up to now reliable detection methods for single missing slot wedges are coupled with a disassembling of parts of the machine. In this paper an method is investigated which provides the possibility of detection, based on the measurement of electrical terminal quantities only.**

I. Introduction

In high power and high voltage machines the stator slots are usually wide open. This design scheme is a consequence of the assembling process of the fully formed winding coils. The open-slot structure, does however, carry a number of disadvantages compared to the semi-closed slots of machines with lower power and voltage rating. The main disadvantages are higher harmonic components in the air gap field, uneven flux distribution, vibration between stator and rotor, increased magnetising current and higher noise levels. As a consequence losses are increased and the power factor and efficiency are decreased [1]-[2]. To reduce these drawbacks magnetic stator slot wedges are applied to the stator slots. Therewith the flux density is becoming smoother and the magnetising current is lower due to the reduced effective air gap field [3]. Another benefit is the reduction of the inrush and starting current and increase of the starting torque when magnetic wedges are applied [4].

The machine's lamination, stator windings as well as the magnetic wedges are exposed to high magnetic and mechanical forces. These forces may lead to vibrations between wedges and stator notches and cause a loosening of the wedges. Especially, a high number of motor starts, operation above rated load and pulsating load profiles affect an increase of these forces. The so caused loosened wedges may fall out into the air gap and are either directly grinded down to powder or eventually lead to further damages. To achieve a high reliability and high efficiency of the machine, all machine components have thus to be monitored. Due to the properties of the slot wedges a monitoring system for these components is extremely challenging. Nowadays standard methods suffer from the drawback that identification of loosen or missing slot wedges is coupled with partial disassembling of the machine [5]. This can cause higher financial burden as well as higher down times of drives and systems.

In this paper a method for the detection of missing stator slot wedges without the need of machine dissembling is investigated [6]. The method is based on the examination of the machine's transient reactance. By applying short voltage pulses to the machine terminals using an inverter, the transient excitation is achieved. Measurement of the current response and a subsequent signal processing of the obtained values provide a fault indicator to detect missing slot wedges based only on machine electrical quantities. The main focus of this paper is placed on the verification of the detection sensitivity as well as on the method's applicability while the machine is in operation.

II. Machine Transient Reactance

When applying transient pulse voltage signals to the terminals the response will be a current slope which is dominated by the machine parameters. In the first transient reaction the dominating parameter is the transient leakage inductance. An essential part of the leakage flux is the stator slot leakage and the zigzag leakage flux. The leakage flux paths are basically predefined by the slot wedges. Assuming one or more missing wedges a significant change of the leakage flux path is given with respect to the faultless, symmetrical case and thus the transient leakage inductance will change. This variation can be detected by the obtained current slope and additional signal processing steps.

A simple and effective way to establish the transient excitation is realized by applying short voltage pulses generated by a standard industrial inverter. Changing from inactive to any active inverter state provides a voltage step with the magnitude of the dc link voltage. Due to the fact that only a short time trace of the current response is needed the voltage excitation can be realized as very short pulses of some ten µs duration only. Therefore the inverter is switched from inactive to active and back again. The current slope measurement can then be easily realized within the pulse duration by the inverter build-in current sensors. Thus no special measurement hardware is needed and costs can be kept low. Furthermore the measurements are done off-line at zero flux and no load; hence the power rating of the inverter can be reduced to a fraction of the machine's rated power.

The machines electrical behaviour is described with the well known stator equation in space phasor representation (1).

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

The three voltage drops which influence the current reaction within the voltage excitation $\underline{v}_S$ are determined by the parameters stator resistance r_S, leakage inductance l_l and the back emf ($d\lambda_R/d\tau$). Identification of the leakage inductance is challenging due to the disturbances of the back emf and stator resistance. An accurate identification of the leakage inductance is thus only possible after elimination of both disturbing voltage drops. This elimination can be realized by evaluating the stator equation for voltage pulse excitations with different inverter output states (e.g. opposite spatial direction). If the pulses are generated subsequently, the measurement can also be done on-line. Due to the short duration of the voltage pulses, the fundamental-wave operating point doesn't change significantly. Thus the magnitude and direction of back emf as well as the dc link voltage and the fundamental wave current can be considered constant. Elimination is then realized by subtraction of both stator equations; with index I and II what leads to (2).

$$\underline{v}_{S,I} - \underline{v}_{S,II} = \underline{v}_{S,I-II} = l_l \cdot \left[\frac{d\underline{i}_{S,I}}{d\tau} - \frac{d\underline{i}_{S,II}}{d\tau}\right] = l_l \cdot \frac{d\underline{i}_{S,I-II}}{d\tau} \tag{2}$$

Up to now a symmetrical machine has been assumed with leakage inductance equal the transient inductance. Due to the fact that the transient inductance differs from the fundament-wave leakage inductance the notation will be changed to $\underline{l}_{l,t}$ in the following. Furthermore the inductance was assumed to be scalar value. This assumption only holds if the current slope and the excitation voltages have the same direction. Considering now a real machine, faulty or not, the two directions will no longer be exactly the same. Thus in (2) the transient inductance will no longer be a scalar but a complex value. This results from the phase values of the transient inductance being no longer equal. As a result the direction of the voltage difference phasor $\underline{v}_{S,I-II}$ and current derivative difference phasor $d\underline{i}_{S,I-II}/d\tau$ will no more be the same. The so introduced complex transient inductance $\underline{l}_{l,t}$ is composed of a scalar portion l_{offset} and a complex portion $\underline{l}_{mod}$. The 'offset' part is representing the symmetrical portion of the asymmetrical machine and the 'mod' part the modulation due to asymmetry Magnitude and angle of $\underline{l}_{mod}$ contain the information about the asymmetry. The angle γ represents the spatial position of inductance's maximum within one pole pair. In case of a missing stator slot wedge the maximum inductance will point in this direction. The magnitude of $\underline{l}_{mod}$ will also increase in that case. So observation of $\underline{l}_{mod}$ will provide information about missing stator slot wedges.

$$\begin{aligned} \underline{l}_{l,t} &= l_{offset} + \underline{l}_{\mathrm{mod}} \\ \underline{l}_{\mathrm{mod}} &= l_{\mathrm{mod}} \cdot e^{j2\gamma} \end{aligned} \tag{3}$$

As shown in (2) it is sufficient to monitor the resulting current slope to calculate the angular position of the maximum inductance. This can be achieved if (3) is inserted in (2) with $\underline{l}_{l,t}$ replacing l_l and subsequent inversion, what leads to (4) with $\underline{y}_{l,t}=1/\underline{l}_{l,t}$. Therewith the number of mathematical calculations is reduced and the measurement/control system has not to carry out divisions.

$$\frac{d\underline{i}_{S,I-II}}{d\tau} = \underline{y}_{l,t} \cdot \underline{v}_{S,I-II} = \left[y_{offset} + \underline{y}_{\mathrm{mod}}\right] \cdot \underline{v}_{S,I-II} \tag{4}$$

In Fig.1 the coherences of all parameters are shown for an excitation with a voltage difference phasor $\underline{v}_{S,I-II}$ in phase direction U (blue phasor) in the stator fixed frame (α,β). This excitation is obtained by two subsequent pulses one pointing in positive and the other in negative direction of phase U. The position of the missing slot wedge was assumed with an angle of γ=100° with respect to the phase direction U. As shown, the resulting current change phasor $di_{S,I-II}/d\tau$ (red phasor) is composed of an 'offset' part and a 'mod' part. Both portions are shown as black, dashed phasors and denoted with $\underline{v}_{S,I-II} \cdot y_{offset}$ and $\underline{v}_{S,I-II} \cdot \underline{y}_{mod}$, respectively. The offset portion points in the excitation direction, the modulated portion has an angular direction of twice the angle γ. The obtained current slope after the measurement and signal processing is thus the summation of the symmetrical and the fault induced portion.

If the direction of the asymmetry is the same as the direction of the resulting excitation voltage $\underline{v}_{S,I-II}$ ($\gamma=0°$, $\gamma=180°$), the resulting current slope obtained has the same direction as the applied resulting voltage as if the machine was symmetrical. However, compared to the symmetrical portion its magnitude is smaller. With an angular asymmetry difference of $\gamma=90°$ again the same 'symmetrical' direction is obtained but with higher magnitude. Obviously the tip of the fault induced phasor ($\underline{v}_{S,I-II} \cdot \underline{y}_{mod}$) moves along the dotted circle twice when the position of the missing slot wedge is changed over one electrical period. However, before the obtained current slope can be used to detect missing slot wedges some further specific signal processing steps have to be executed to achieve a fault indicator with necessary high accuracy.

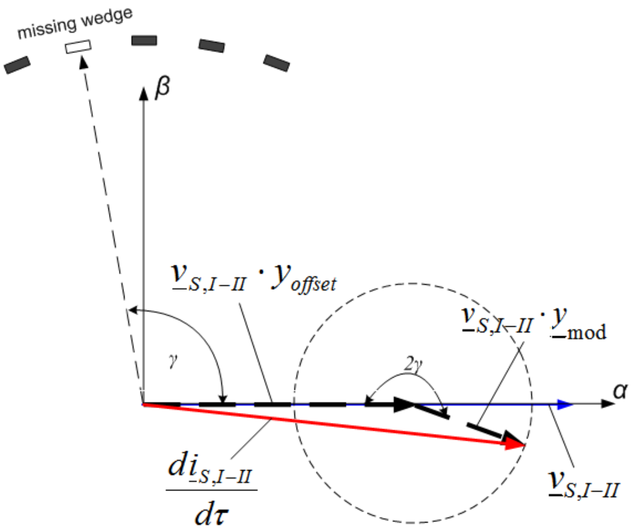

Fig 1: Pulse excitation and resulting current chance in presence of missing slot wedge.

III. Signal Processing for Fault Indicator Calculation

A. Elimination of the Symmetrical Portion

In the previous section it was shown that the modulated part of the complex transient leakage inductance corresponds with missing slot wedges. The current slope resulting from voltage pulse excitation is thus a well suited measurement signal for the determination of such faults. Before exploiting this information to develop a fault indicator, some disturbing signal components have to be eliminated. In every machine, faultless or not, the symmetrical part in the current response signal is predominant. Usually this part is responsible for about 90% of the overall resulting current change phasor. Thus it is clear that the symmetrical portion has to be eliminated to obtain a high sensitive fault indicator. The elimination can be done using a voltage excitation sequence that sequentially changes its resulting direction ($\underline{v}_{S,I-II}$) in the main three phase axes. Thus three different current change phasors are obtained, each with the symmetrical portion pointing in one main phase direction. Combining the current change phasors of each phase to one resulting phasor, the share of the symmetrical machine leads to a zero sequence and is eliminated. The remaining phasor after carrying out this step now only contains information on machine asymmetries and will be denoted asymmetry phasor in the following.

B. Fault Indicator Calculation

The asymmetry phasor serves as base for the fault indicator. However, the asymmetry phasor consists not only of fault induced modulations, but also contains some inherent asymmetries. These inherent parts superpose and thus clearly reduce the indicator’s accuracy. However, separation is still possible due to the deterministic behaviour of each inherent asymmetry. The main inherent asymmetries are caused by spatial saturation and rotor slotting. Saturation saliency arises from different levels of saturation of the lamination material along the circumference caused by the fundamental-wave. The period of this asymmetry corresponds to the number of poles and is twice that of the fundamental-wave. Another inherent asymmetry is the slotting saliency which is caused by the openings of the slots in the lamination. It’s period is linked to the mechanical rotor angle and equals the number of rotor slots. Basically this description of inherent saliencies is limited to a squirrel cage induction machine because this investigation focuses on that machine type. Nevertheless, it can be adapted also to other types of ac machines like permanent magnet synchronous machines.

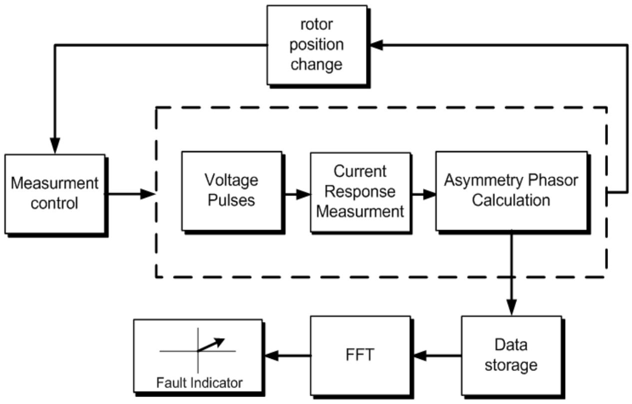

Fig 2: Block diagram of data acquisition and fault indicator calculation process

For separation of the mentioned asymmetries some specific signal processing steps have to be carried out. To get a clearer presentation of the separation process Fig 2 shows the data acquisition and fault indicator estimation as a block diagram. Different steps are executed as described in the following. The measurement control unit decides when a measurement process starts and triggers the asymmetry phasor estimation. In the figure this part is marked with the dashed box. The machine is excited by voltage pulses applied and the current response within the pulse duration is measurement. Subsequently the asymmetry phasor is calculation as described above. The voltage pulses are applied subsequent to the main three phase directions and so three current change phasors ($d\underline{i}_{S,I-II}/d\tau$) are obtained. By adding them into one resulting phasor the symmetrical portion $\underline{v}_{S,I-II}\cdot\underline{y}_{offset}$ is eliminated. Subsequently the obtained asymmetry phasor is forwarded to the data storage block. This storage is realized as a vector-array which elements correspond to specific rotor positions. The respective rotor positions can be obtained from the control algorithm or by a manual evaluation. The asymmetry phasor is stored in the corresponding element. Meanwhile the rotor position is changed. This can be done manually, by load, or using the inverter. After that, the procedure is repeated and a new asymmetry phasor is obtained and stored. The whole process is repeated for at least one rotor slotting period. To achieve a higher resolution a set of asymmetry phasors are collected for one mechanical revolution of the rotor. Thus a multiple of periods of all rotor fixed saliencies is obtained. Fig 3 presents the asymmetry phasor signal for one mechanical rotor revolution.

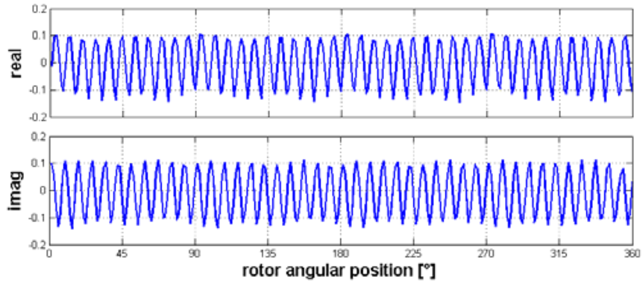

Fig 3: Asymmetry phasor signal for on rotor revolution.

The set of asymmetry phasors is then forwarded from the data storage to the FFT block where separation of all asymmetries is realized. Due to the window length being a multiple of the rotor fixed saliency periods a clear identification and elimination of these modulations is realized. If the spectral filtering is used to eliminate also the saturation saliency (when present in a magnetized induction machine or a permanent magnet machine), then the FFT has to be repeated with window length chosen to a multiple of the saturation saliency period.

Considering the origin of the saliency induced from a missing slot wedge it is obvious that the geometrical position of the asymmetry with respect to the stator does not change. Neither with the rotor angle nor with the fundamental wave flux angle. As the pulse excitation and current measurement is stator fixed too, the offset component of the FFT thus corresponds to the slot wedge asymmetry and serves as fault indicator. Due to the complex nature of the FFT the fault indicator (offset component) has a magnitude and direction. Both parameters are used to characterize a fault. Basically this complex value denoted as the fault indicator in the following.

IV. MEASUREMENT SETUP AND RESULTS

The measurement setup to verify the detection method consists of an 11kW squirrel cage induction machine, a voltage source inverter and a measurement and control unit programmable under Matlab/Simulink. The current samples are measured by standard industrial current sensors. The test machine is a 4 pole type with unskewed rotor bars and the stator has 36 stator slots and full pitched windings. The wedges are made from standard industrial magnetic slot wedge material. Due to the fact that the stator of the test machine has semi-closed slots, the slot wedges are specially adapted to fit in these slots. Fig 4 presents two close views of the stator, one with all wedges placed and another with one removed wedge. But not only whole missing wedges can be realized; also partially falling out wedges can be simulated by applying only parts of a wedge in the slots. Field experiences have shown that usually at first not the whole but only one part of a wedge is missing [5]. This is caused by the fault development of missing slot wedges. In a first step the slot wedge is getting loose on one end or in the centre of the stator length. Due to the loosening of the wedge and impact of high magnetic and mechanical forces the wedge starts vibrating and is pulled towards the air gap. Gradually the vibration magnitude is getting higher. As consequence the wedge breaks and one part falls out into the air gap while the other is still remaining in the slot.

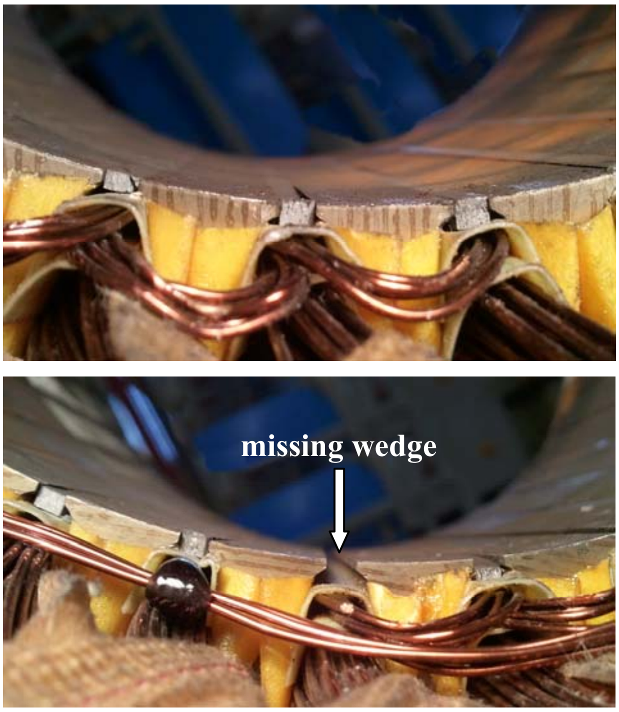

Fig 4: Placed and removed slot wedge in the test machine for simulation of missing wedge faults.

A. *Sensitivity analysis*

To test the sensitivity of the proposed method, a first set of measurements was done on a non magnetized machine with zero flux and no load. The measurement results are shown in . Results presented in the following show the method's accuracy as an offline procedure. The method is not only applicable for inverter fed machines. It can also be adapted to main fed machines while maintenance work e.g. Due to the complex nature of the asymmetry phasor and fault indicator, respectively, the results are given in the complex frame format. This is also a well suited illustration to get a clear impression on faults magnitude and direction at once.

At the first set of measurements the machine was tested for the symmetrical case. Thereby all slot wedges were placed in the slot openings and the fault indicator value here serves as reference (denoted 'symmetrical') but differs already from the origin. This can be explained by stator fixed asymmetries like lamination anisotropy, current sensors and distribution of the windings which cause an offset value. However, this value can be obtained in advanced and used for later elimination. A deviation of the fault indicator from the ‘new’ origin now indicates a faulty slot wedge.

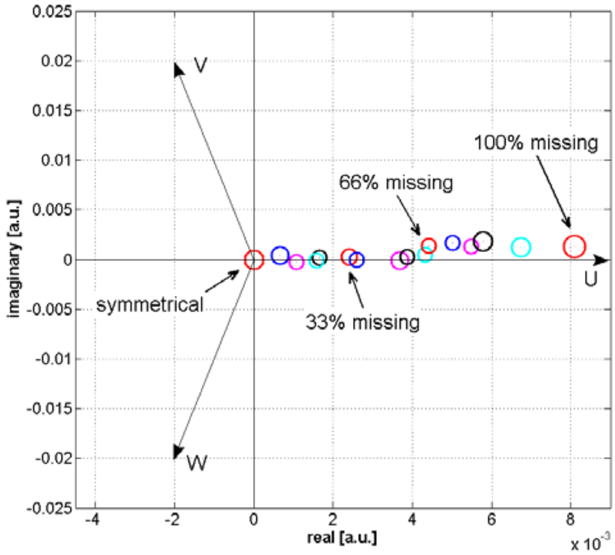

Fig 5: Measurement results of sensitivity analysis for partially missing slot wedge in phase U.

In the following steps only fractional parts of one wedge were removed from the stator lamination. The steps were portioned into 1/15 of stator length. In each step the fault indicator estimation was repeated 250 times to prove the fault indicator statistical distribution. All measurement results are shown as circles for each step. Circle’s midpoint represents the mean value of all fault indicators and the radius the maximum deviation. The axes values of the diagrams are given in arbitrary units [a.u.] corresponding to the internal representation of the digital signal processor. In the fault indicator’s magnitude and angle are plotted against the percentage of one missing stator slot wedge. The results show a clear coherence of fault indicator magnitude and fault severity. On the other side also the fault direction is clearly detectable.

B. *Online measurments*

The investigation results and description in the following are limited to online inverter fed operation. The machine is fed by a full-size inverter and operated by field oriented control scheme. The inverter control scheme is a standard pulse with modulation (PWM). The test machine was coupled to a load machine.

Due to the relative short time duration of the excitation voltage pulses (some 10µs) estimation procedure can be realized within one PWM cycle. During this estimation process the current control is interrupted, and a special voltage pattern is applied which is shown in . The figure shows a symmetrical time trace of the voltage signal $\underline{v}_S$ in one phase direction. It consist of positive and negative switching states (+, -, +, -) in phase direction U. The resulting voltage during this period is thus zero.

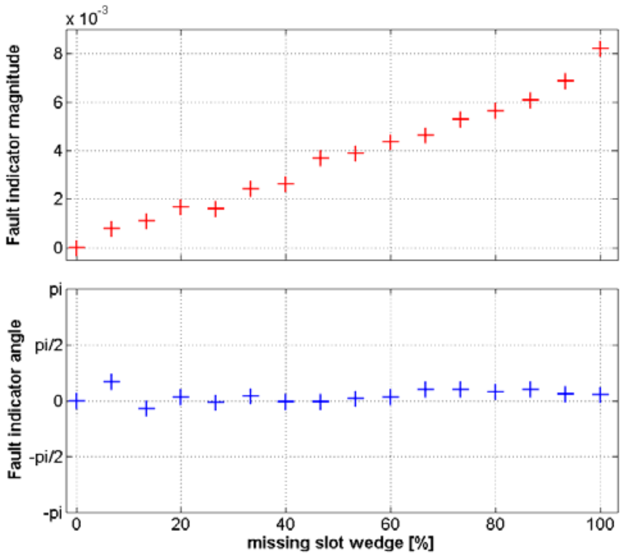

Fig 6: Measurement results and accuracy of fault indicator versus the percentage of one missing slot wedge in phase direction U.

Further, also the current trace (red line) is shown. The fundamental-wave point of operation is indicated by the horizontal time axis. Due to the symmetrical nature of the excitation signal the fundamental-wave point before and after the excitation period is almost unchanged (current value almost the same). The voltage pulse magnitude is equal the dc link voltage.

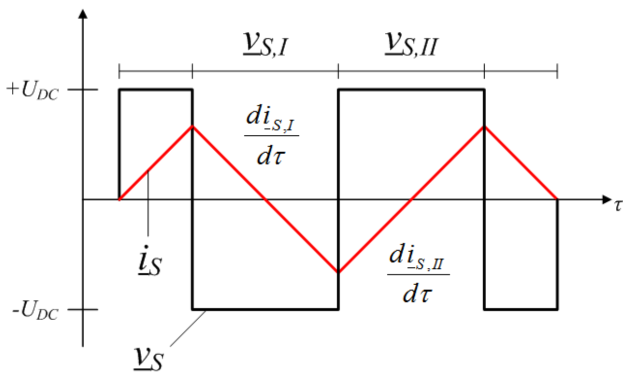

Fig 7: Voltage pulse excitation signal during online detection.

Basically the investigated fault cases in the section online measurements are done with fully removed slot wedges in phase direction U. Starting with only one removed wedge the fault severity was increased by removing a second and finally a third slot wedge. To identify the fault indicator load dependency the detection procedure was repeated at different load levels. Beginning with zero load the load level was increased up to 60% rated load. All fault indicator results are given in Fig 8. The fault indicator magnitude is plotted against the load level for different fault cases. It can be seen that the fault indicator is almost independent on machines load. A detection of missing slot wedges is thus also possible online during normal operation of the drive.

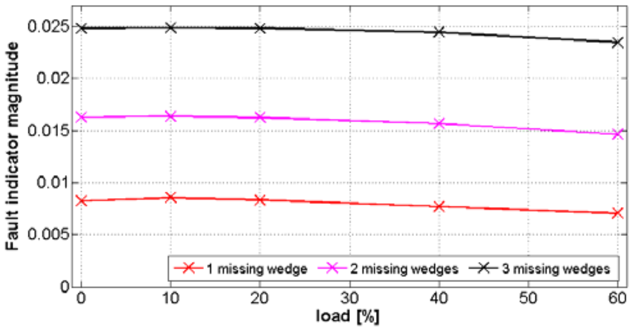

Fig 8: Fault indicator dependency on machines load. Symmetrical case represented by the x-axis.

V. Conclusion

A method has been investigated to detect missing and partially missing magnetic slot wedges in ac machines. The method provides the advantage that detection is possible without disassembling of the machine. It can be applied offline at standstill as well as online during operation of the drive. The detection is based on the spatial properties of the transient leakage flux. These properties can be identified by a transient excitation of the machine with short voltage pulses. Measuring and subsequent signal processing of the resulting current response delivers a fault indicator with high accuracy both of fault severity as well as direction. The accuracy was proven for partially as well as whole missing slot wedges. Furthermore applicability was verified offline on a non-magnetized as well as online on a machine operated by an inverter with different load levels. The results have shown a high accuracy of the fault indicator even if only 1/15 of one wedge is missing.

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VII. References

[1] H. Mikami, K. Ide, K. Arai, M. Takahashi, and K. Kajiwara, “Dynamic harmonic field analysis of a cage type induction motor when magnetic slot wedges are applied”, *IEEE Trans. Energy Convers.*, vol. 12, no. 4, pp. 337–343, Apr. 1997.

[2] Curiac, R.; Li, H.; , "Improvements in energy efficiency of induction motors by the use of magnetic wedges," *Petroleum and Chemical Industry Conference (PCIC), 2011 Record of Conference Papers Industry Applications Society 58th Annual IEEE* , vol., no., pp.1-6, 19-21 Sept. 2011

[3] Shuping Wang; Zhengming Zhao; Liqiang Yuan; Buyao Wang; , "Investigation and analysis of the influence of magnetic wedges on high voltage motors performance" ,*Vehicle Power and Propulsion Conference*, 2008. VPPC '08. IEEE, vol., no., pp.1-6, 3-5 Sept. 2008.

[4] Kappatou, J.; Gyftakis, C.; Safacas, A.; , "A study of the effects of the stator slots wedges material on the behavior of an induction machine," *Electrical Machines, 2008. ICEM 2008. 18th International Conference on* , vol., no., pp.1-6, 6-9 Sept. 2008

[5] Hanna, R.A.; Hiscock, W.; Klinowski, P.; "Failure Analysis of Three Slow-Speed Induction Motors for Reciprocating Load Application”, *IEEE Trans. on Industry Applications*, vol.43, no.2, pp.429-435, March-April 2007.

[6] Stojicic G., Samonig M., Nussbaumer P., Joksimovic G., Vasak M., Peric N., Wolbank T., "A method to detect missing magnetic slot wedges in AC machines without disassembling", *37th Annual Conference of the IEEE Industrial Electronics Society*, IECON 2011, vol., no., pp.1698-1703, 7-10 Nov. 2011