A Method to Detect Missing Magnetic Slot Wedges in AC Machines without Disassembling

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Abstract – **In high voltage induction machines the stator slots usually are wide opened to facilitate the assembling of the stator winding coils. Thus the magnetically effective air gap and higher order harmonics are rising, the power factor is decreasing. To compensate this negative effect magnetic stator slot wedges are frequently applied. During operation these slot wedges can get loose and eventually fall out totally. Currently a detection of fallen out slot wedges is only possible by time consuming partially disassembling the machine and optical inspection. Simple and reliable testing methods can thus increase the reliability and reduce costs due to unnecessary disassembling of the machine. For such testing methods high frequency or transient electrical properties of an electrical machine suit very well as the base. When high frequency or transient voltage signals are applied to the terminals of the machine the resulting current response contains information about the machine's magnetic state. Therein superposed are the magnetic material properties, several inherent asymmetries such as spatial saturation or slotting, as well as fault induced asymmetries. This paper introduces a new signal processing chain to detect and isolate the fault induced asymmetries caused by fallen out stator slot wedges. The chain consists of data capturing by collecting current response values due to voltage pulses and following Fast Fourier transformations. Measurements for several slot wedge fault cases are presented. The measured and calculated results show the high sensitivity and reliability of the proposed method.**

Index Terms-- **condition monitoring, fault diagnosis, induction machines, stator slot wedges, transient excitation.**

I. Introduction

Electrical machines whose stator windings are constructed for higher voltages are usually constructed with open stator slots. The reason for that is the facilitation of the assembling process of the stator winding coils. However, these wide opened stator slots lead to higher harmonic components in the air gap field, increasing pulsations between stator and rotor, uneven distributed flux density, higher noise and vibration. All together the losses are increased and the performance of the machine is reduced [1]. To counteract this fact, in some cases magnetic stator slot wedges are placed into stator notches. Thus stator slot harmonics are reduced and the air gap field density is much smoother. Hence losses can be decreased what strongly influences machine performance [2].

During operation stator windings and slot wedges are exposed to magnetic and mechanic forces. This leads to wedges getting loose and finally falling out into the air gap. Another reason for loosening of wedges is found in a wrong fitting process [3]. Detection of fallen out slot wedges in such fault cases without disassembling the whole machine is challenging nowadays but can increase the reliability of the machine also. Normally the detection of loose or fallen out slot wedges is done during routine maintenance work of the machine. A fallen out slot wedge can thus be detected not until before at least parts of the machine are separated. It can manifest itself as debris from magnetic wedge material inside the stator when one or more wedges were fallen out. A timely detection of one fallen out slot wedge can inform the operator about the reduced performance and thus reduce the impact of such a defect. Further a determination of the number of missing wedges can facilitate the decision if a disassembling of the machine is yet needed or not. A review of the literature has shown that currently hardly anymeasuring techniques for detection of such fault cases without disassembling the machine are known [3].

This paper introduces a new method to detect such fault cases by measuring electrical terminal quantities only. The base of the method is provided by an identification of the machines transient reactance. Therefore short voltage pulses are applied to the machines terminals and current response is measured. Time trace of this current signal is dominated by the transient leakage inductance. A considerable part of the leakage flux is the stator slot leakage and the zigzag leakage flux. In a symmetrical configuration the stator slot leakage passes throught the stator slot wedges independent of the spatial angle of the high frequency or transient excitation. With one or more missing slot wedges, there is a significant change in the transient leakage flux paths when changing the excitation angle. These changes lead to an asymmetry which can be detected by the measuring process. The proposed method is applied at standstill with zero load and zero flux, what suits very well to any downtime or during maintenance works.

The measurements performed for this investigation where done on an 11kW laboratory induction machine fed by an inverter. The voltage pulses for the excitation where thus applied by the switching of different inverter stages. The current response was measured by the built-in current sensors of the inverter. The stator slot wedges were specially adapted to fit the laboratory machine using composite iron powder, glass mat and epoxy. The whole measurement setup is controlled by a computer system.

II. Estimation of the Transient Leakage Inductance

The proposed method is based on the identification of the asymmetries in the machine's transient reactance. In this investigation an excitation with voltage pulses is applied. However, instead of this transient excitation also a high frequency harmonic excitation using rotating or pulsating signals can be used. A more detailed description on the pulse excitation is given in [4]. As already described the measurements are done on an inverter fed induction machine. Thus the following description is based on this machine type. However, the method can easily be adapted to other machine types like permanent magnet synchronous machines.

The most common way to identify the parameters of a dynamic system is the analysis of the step response. With a three phase electrical machine this can be achieved by applying voltage pulses to the machine terminals and measuring the three phase current responses. A simple way to achieve transient excitation in case of inverter fed machines is to use the six different active inverter output voltage states. Changing from inactive to active output states generates a voltage step with the magnitude equal to the dc link voltage of the inverter. The current measurement can be done by the built-in current sensors. Due to the fact that the measurements are done at zero flux and no load, the power rating of the inverter can be a fraction of the machine's.

Assuming a symmetrical machine the well known stator voltage equtation in space phasor representation (1) describes the machine's behavior.

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

The voltage phasor $\underline{v}_S$ generated by the inverter switching state leads to a current change $d\underline{i}_S/d\tau$. This current time derivative is influenced by the inverter switching state, the dc link voltage, the leakage inductance l_l, the stator resistance r_S and the back-emf $d\underline{\lambda}_R/d\tau$. After realization of the voltage step (some ten µs long) the transient reaction of the machine is dominated by the voltage drop of the transient leakage inductance $l_{l,t}$. An additional influence exists from the back-emf if the machine is not operated at standstill. Then an identification of the transient leakage inductance is only possible after elimination of this back-emf disturbance.

The elimination of the back emf as well as stator resistance voltage drop can be realized by evaluating the step responses of two voltage steps with different inverter output states. If these two output states are subsequent the fundamental-wave point of operation and especially the direction and magnitude of the back-emf will not change significantly.

Both output states can be described by the stator voltage equation. The voltage pulses and the sampled current reaction of the two inverter output states are denoted with the indexes I and II (2). The elimination of disturbing parts can now be done by a simple subtraction of the two stator equations. Further, the transient inductance of the machine differs from the fundamental-wave leakage and is denoted as $l_{l,t}$ in the following what leads to (2).

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

The fundamental-wave point of operation of the stator current $\underline{i}_S$ as well as the time derivative can be directly measured. Even if the machine is not operated at standstill the back-emf does not change significantly between the two subsequent pulse excitations. Thus the back-emf is eliminated by the subtraction of the two stator voltage equations. The same applies for the influence of the stator resistance. When the voltage phasors of the subsequent pulses point in opposite spatial directions, then the fundamental-wave operating points in both cases are almost equal due to this symmetrical pulse pattern.

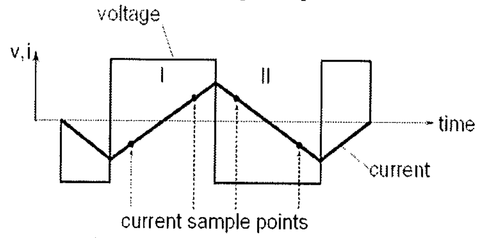

Fig. 1 Pulse excitation, current response and current sample instants.

Fig. 1 depicts the excitation and measurement procedure. The pulse sequence consists of positive and negative voltage pulses (thin line). Further, the current response (thick line) and time periods of the two pulse sequences for back-emf elimination are shown. The detection of the two time derivatives of the current response is done with four sample points as depicted. Thereby the actual current values are measured short time after beginning and before ending of each pulse period. Out of it time derivatives of the current can be approximated. The whole measurement is done in some ten µs.

Assuming an ideal symmetrical machine (operated at zero main flux and zero speed), the transient leakage inductance $l_{l,t}$ can be considered a scalar, and thus the direction of the resulting current slope is parallel to the excitation pulse voltage. However, in a real machine even faultless there are always some inherent spatial asymmetries, which also lead to an angle dependence of the transient leakage. Consequently the directions of the voltage pulses and the resulting current slopes are not the same. Therefore in (3) a complex transient leakage inductance $\underline{l}_{l,t}$ is introduced. Thereby the asymmetries of the three phases are combined in one parameter. This complex transient leakage inductance is composed of a scalar offset value l_{offset} and a complex value $\underline{l}_{mod}$ as described in (3). The offset value is representing the symmetrical machine while the complex value represents the fault induced asymmetry with its magnitude and spatial direction. It is assumed that no other asymmetry is present.

$$\underline{l}_{l,t} = l_{offset} + \underline{l}_{\text{mod}}, \quad \underline{l}_{\text{mod}} = l_{\text{mod}} \cdot e^{j2\gamma} \qquad (3)$$

The angle γ of the asymmetry portion gives the spatial position of the maximum inductance within one pole pair. The asymmetry has thus a period of two with respect to one electrical revolution and a fixed position with respect to the stator.

When applying a voltage pulse sequence and evaluating the current reaction the overall time derivative of the machine current can thus also be separated into a 'symmetrical' portion determined by l_{offset} that corresponds to the scalar value $l_{l,t}$ and an 'asymmetrical' portion that is influenced by $\underline{l}_{\text{mod}}$, leading to an angle-dependent cross-coupling.

Magnitude and angle of $\underline{l}_{\text{mod}}$ contain the information about the asymmetry. In case of a missing stator slot wedge its spatial position corresponds with the direction of $\underline{l}_{\text{mod}}$ with respect to the stator windings.

For the evaluation algorithm it is sufficient to monitor the resulting current slope of two switching states after elimination of stator resistance and eventually back-emf according to (2). For calculation of the angle γ of the asymmetry an exact knowledge of l_{offset} and $\underline{l}_{\text{mod}}$ is needed. Therefore (3) is insert in (2) and the received equation is inverted. This leads to (4) where the complex conjugate is marked with '*' and finally to (5). Therewith reduction of mathematical operations is realized. The measurement and control system then only has to calculate equation (5). According to the discrete processing nature of a digital system the time derivative is replaced by the difference denoted $\Delta\underline{i}_s/\Delta\tau$, in the following and $\Delta\underline{i}_{s,I}/\Delta\tau$ - $\Delta\underline{i}_{s,II}/\Delta\tau$ are composed to $\Delta\underline{i}_{s,I-II}/\Delta\tau$. Same index change is done to the voltage phasors.

$$\frac{\Delta\underline{i}_{S,I}}{\Delta\tau} - \frac{\Delta\underline{i}_{S,II}}{\Delta\tau} = y_{offset} \cdot \left(\underline{v}_{S,I} - \underline{v}_{S,II}\right) + \underline{y}_{mod} \cdot \left(\underline{v}^*_{S,I} - \underline{v}^*_{S,II}\right) \qquad (4)$$

$$\frac{\Delta\underline{i}_{S,I-II}}{\Delta\tau} = \underline{y} \cdot \underline{v}_{S,I-II} \qquad (5)$$

The measured current slope of the excitation sequence is thus directly influenced by the magnitude and position of $\underline{l}_{\text{mod}}$ according to (4), with the values of y_{offset} and $\underline{y}_{mod}$ obtained from inversion as depicted in (6).

$$y_{offset} = \frac{l_{offset}}{l_{offset}^2 - l_{mod}^2}$$
$$\underline{y}_{mod} = -\frac{l_{\text{mod}}}{l_{offset}^2 - l_{mod}^2} \cdot e^{j(2\gamma - 2\arg(\underline{v}_{S,I-II}))} \qquad (6)$$

The main direction of the resulting current change is determined by the two inverter switching states as can be seen from the previous equations. In symmetrical machines the value of y_{offset} is always clearly dominant with the magnitude of $\underline{y}_{\text{mod}}$ even for a faulted machine being only up to 10% of the symmetrical y_{offset}.

In Fig. 2 the above described coherences are depicted for an asymmetry caused by a missing slot wedge in the stator at angular position γ=50°. The resulting asymmetry is assumed to lead to an ideal sinusoidal modulation of the leakage inductance.

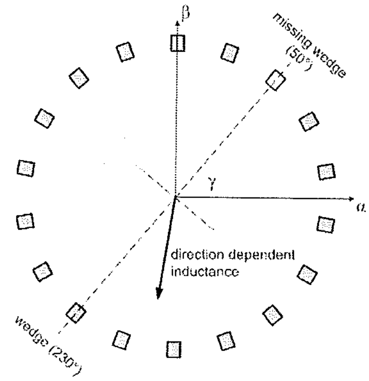

Fig. 2 Direction dependent inductance for one missing slot wedge. Assumed asymmetry position 0=50°.

The corresponding direction dependence of the leakage inductance is indicated as ellipse with the minimum inductance in the direction of the magnetic axis corresponding to a magnetomotive force located in the slot with the missing wedge. The same ellipse is obviously obtained with a wedge missing at γ=230° as already considered in (3),(6).

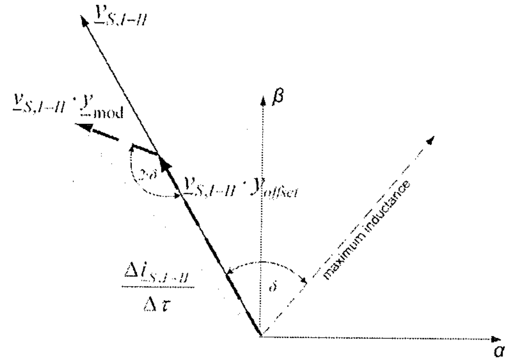

Fig. 3 Influence of y_{offset} and $\underline{y}_{\text{mod}}$ on the transient current change for a given pulse sequence in phase V. (asymmetry position according to Fig. 2)

The corresponding signals are depicted in Fig. 3 for a difference voltage phasor $\underline{v}_{S,I-II}$ pointing in direction of phase V ($\underline{v}_{S,I}$=+V and $\underline{v}_{S,II}$=-V). The resulting current change phasor $\Delta\underline{i}_{s,I-II}/\Delta\tau$ is composed of two parts already described, depicted as black-dashed arrows denoted $\underline{v}_{S,I-II}\cdot\underline{y}_{\text{mod}}$ and $\underline{v}_{S,I-II}\cdot y_{\text{offset}}$ according to (4) and (5). The position of the asymmetry is chosen according to Fig. 2 with the main axis of the ellipse denoted "maximum inductance". The angle δ defines the difference of the direction of the maximum transient inductance (slot wedge) with respect to the direction of the difference voltage vector ($\underline{v}_{S,I-II}$) of the pulse excitation.

As depicted, the fault induced asymmetry leads to a resulting current slope (gray arrow) composed of $\underline{v}_{S,I-II}\cdot y_{\text{offset}}$ parallel to the direction of the excitation (phase V) and $\underline{v}_{S,I-II}\cdot\underline{y}_{\text{mod}}$ with a direction corresponding twice the angle δ.

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 $\underline{v}_{S,I-II}$ ($\delta=0°$), 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 machine its magnitude is smaller. With an angular difference ($\delta=90°$) again the same 'symmetrical' direction is obtained but with bigger magnitude. Obviously the tip of the resulting phasor (gray arrow) moves along the dotted circle twice when the position of the missing slot wedge is changed over one electrical period.

III. ANALYSIS OF TRANSIENT FLUX DISTRIBUTION BY SIMULATION

In order to analyze the described influence of missing slot wedges on the current change and to support the explanations, a finite element (FE) simulation was done. Thus the change in the transient field path can be identified.

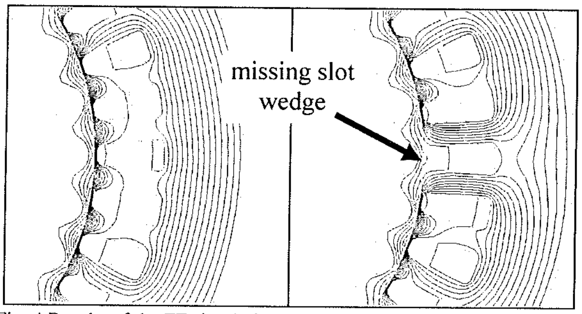

Fig. 4 Results of the FE simulation. Left: all stator slot wedges existing. Right: one missing slot wedge.

The results of the FE simulations are depicted in Fig. 4. On the left side the healthy machine with all slot wedges placed, and on the right side a faulted case with one removed slot wedge are shown. The machine was operated without fundamental wave excitation. Only voltage pulses were applied in direction of phase axis U. The wedge was removed in a slot of phase winding U also (electrically orthogonal to the phase axis). As can be seen in the figure the path of the transient flux is changed from the symmetrical case (left) when removing the slot wedge (right). This change is directly related to the change in the transient current slope sampled in the measurements. It finally leads to the stator fixed asymmetry detectable in the asymmetry phasor.

IV. MEASUREMENT SETUP AND SIGNAL PROCESSING

The previous sections have described asymmetry dependent modulation of the resulting current slope due to voltage pulse excitation. Magnitude and orientation of this modulation contain the information about the asymmetry. To develop a precise fault indicator out of this information it is necessary to follow some specific steps in the signal processing.

In the control and measurement setup a processor takes care of the voltage pulses for excitation and the trigger signals for measurement. The voltage pulse sequence is generated from stored values. Thus the voltage phasor ($\underline{v}_{S,I-II}$) can be calculated in advance. The current difference phasor ($\Delta\underline{i}_{S,I-II}/\Delta\tau$) is resulting from current samples taken at specific instances, like shown in Fig. 1. As this current difference phasor is composed of a symmetrical part as well as an asymmetrical portion, it is necessary to clearly separate these two shares in the measured signal. This can be done as follows. As depicted in Fig. 3 the y_{offset} influenced part of the current difference phasor points in the direction of the excitation pulses. The voltage pulse sequences are applied to the three main phase directions subsequently. Combining the three resulting current difference phasors by adding them together leads to only one current difference phasor. In this phasor calculation the symmetrical shares are eliminated as zero sequence value. This phasor now contains only information on the machine's asymmetries. In the following this overall current difference phasor is thus denoted as asymmetry phasor.

For the final detection of fallen out stator slot wedges some further signal processing steps are necessary. The obtained asymmetry phasor contains not only fault induced asymmetry but also some inherent asymmetries. The main inherent asymmetries are caused by spatial saturation, slotting and rotor anisotropy. They exist in every machine, faultless or not. All these asymmetries are superposed on the asymmetry phasor, but identification and separation can be done due to their deterministic behavior. To ensure a high sensitivity, the detected asymmetry phasor has thus to be split up into these components.

A. Inherent machine asymmetries

As described in the previous section the asymmetry phasor consists of several components caused by inherent and fault induced asymmetries. The following description of inherent asymmetries is based on squirrel cage induction machines but can be adapted also to other types of machines.

The main inherent asymmetry in induction machines is the saturation saliency. It is arising from the different levels of saturation caused by the fundamental-wave along the circumference. The modulation period is twice that of the electrical fundamental-wave corresponding to the number of poles. The identification and separation of the saturation saliency induced asymmetry can be done feed forward after a commissioning phase.

A further asymmetry is caused by the openings of the slots in the lamination. The period of this asymmetry is linked to the rotor angle and its period equals the number of rotor slots per mechanical revolution. In unskewed open slot machines the magnitude of this asymmetry is dominant. Skewing clearly reduces this asymmetry and for machines with closed slots its modulation is very small and can usually be neglected in the signal processing chain.

B. Inherent asymmetry separation by signal processing

For the identification and separation of the non-fault induced asymmetries some specific signal processing steps have to be performed as depicted in Fig. 5.

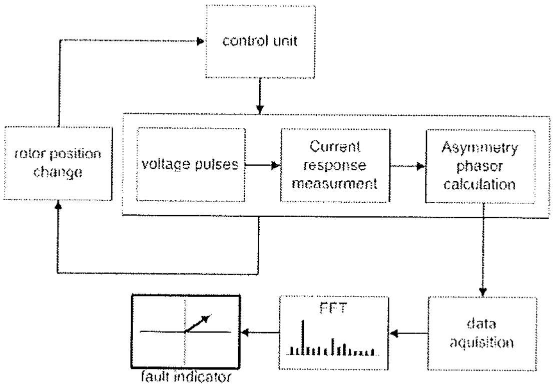

Fig. 5 Block diagram of signal processing to eliminate inherent saliencies.

In a first step a voltage pulse sequence is generated by the switching of the inverter. During these pulses current samples are taken (as shown in Fig. 1) and the current difference $\Delta \underline{i}_s/\Delta\tau$ according to (5) is calculated and stored. The trigger signal generation for inverter switching and measurement is done by a control system based on a real-time processor. The same type of pulse sequence is then applied to all three phase directions subsequently. Combining the calculated phasors of all three directions the symmetrical part is eliminated and the asymmetry phasor obtained.

In the next step the rotor position is changed and the signal generation, measurements and calculations are repeated. This procedure is repeated for at least one rotor slotting period or till the rotor has done one mechanical revolution. The asymmetry phasors obtained are available for a spectral analysis like Fast Fourier Transformation (FFT). The window is chosen a multiple of the rotor slotting angular period thus the slotting modulation can be clearly identified and eliminated. If a saturation saliency is present (for example due to the magnets in a permanent magnet machine) it can also be eliminated by spectral filtering.

Considering the origin of the fault induced saliency of a missing slot wedge it is obvious that the geometrical position of the asymmetry with respect to the stator does not change. 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 asymmetry phasor being a complex value as the input to the FFT the offset value contains both magnitude and direction. Thus it is possible to detect both single and multiple missing slot wedges together with their positions as shown in the next section.

V. MEASUREMENT RESULTS AND SENSITIVITY OF DETECTION

The experimental setup consists of a test machine, a voltage source inverter and a measurement and control unit realized by a real-time processor system. The chosen test machine is a 4pole 11kW induction machine with a squirrel cage rotor with 44 unskewed rotor bars. The stator has 36 slots and full pitched windings. The stator slot wedges are made of composite iron powder (75%), glass mat (7%) and epoxy resin (18%). Their geometry was specially adapted to fit the slot openings of this machine.

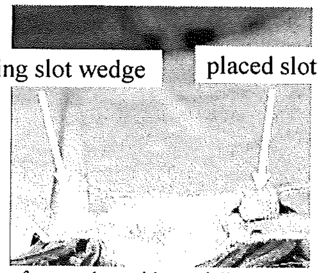

Fig. 6 Close view of stator slots with specially adapted slot wedges. (one missing slot wedge on left side)

Fig. 6 shows a close view of the stator slots with the adapted slot wedges placed in the stator slot openings. On the left side a slot wedge is missing.

All measurements were carried out using a programmable control unit (Matlab/Simulink). The excitation and data acquisition sequence was done as described in the previous section. To implement a fault induced asymmetry one or more stator slot wedges at various positions had been removed.

A. *Measurement results*

All measurements presented were taken at zero load and flux on a non magnetized machine. In a first set of measurements the symmetrical machine having all slot wedges placed in the slot openings was investigated in order to obtain reference values of the fault indicator.

To test the performance of the method further measurements were done with various different configurations of the slot wedges. For a better understanding Fig. 7 depicts the position of the slots within the stator. In order to show the actual spatial angles in electrical degrees the picture shows a 2 pole representation with 18 slots for a clearer depiction (instead of 4 pole and 36 slots as the test machine). The gray and black squares symbolize the stator slot wedges. The excitation direction is assumed in the axis of phase U along the horizontal axis. The corresponding active coils are marked gray. As was also shown by the FE simulations the removal of a slot wedge at ±90° will lead to a change of the fault indicator in direction of phase axis U.

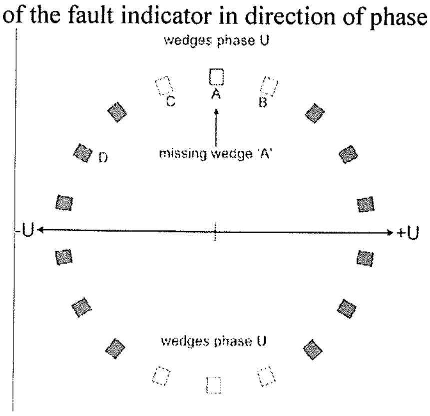

Fig. 7 Location of slot wedges within the stator. (2 pole representation with 18 slots)

Though only ±90° exactly leads to phase direction U the removal of a wedge at ±70°,90°,110° will nevertheless be denoted 'missing wedge in phase U' in the following.

The following Fig. 8 depicts the measurement results for missing slot wedges in phase U and W in the complex plane.

The measurement of each specific fault condition was repeated 72 times in order to allow also a determination of the statistical signal properties.

At first the symmetrical machine was measured with all slot wedges placed. This result is used as the reference and is denoted 'faultless' (yellow) in the figure. Thus possible offset values in the sensor and evaluation electronics can be eliminated. Then a first slot wedge was removed at the winding of phase U (+90°). The spatial location is depicted in Fig. 7 as 'A'. As can be seen in Fig. 8 the fault indicator changes from the fault less position approximately towards direction of phase axis of U (denoted 'wedge A', green) as was expected. To show the influence of a 'bigger' asymmetry a second and third wedge was removed from the same phase winding lying aside the first wedge (wedge 'B' and 'C' in Fig. 7). The dominant effect of this increased asymmetry is the rise of the fault indicator magnitude as can be seen in Fig. 8 ('wedge A+B', red and 'wedge A+B+C', blue). A distinction between the different fault conditions is clearly possible. The slight change in direction can be explained by the different spatial positions of the three wedges with respect to the phase axis. It has to be stressed that intentionally only the wedges on one side of the winding were removed. Finally, the combination of missing wedges in different phases was investigated. Wedges A, B, C and D were removed with wedge D located at phase winding W.

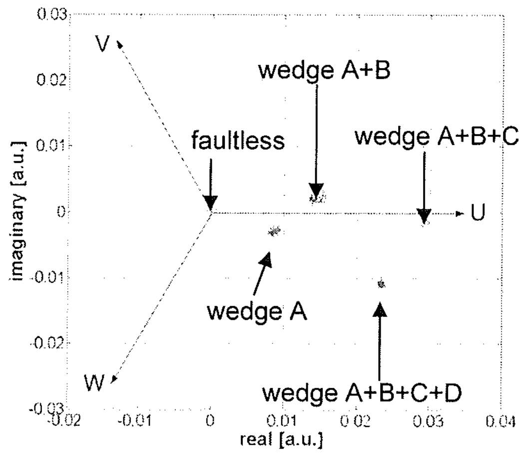

Fig. 8 Measurement results of fault indicator for faultless machine and different fault induced asymmetries.

The corresponding fault indicator is depicted by the black results marked 'wedge A+B+C+D' in Fig. 8. Comparing the different measurement results it can be seen that each missing wedge is correlated to a phasor of the fault indicator. The combination of several wedges is obtained by a summation of the individual phasors. Thus it is not only possible to detect missing slots but also to distinguish between a single and multiple wedges and to determine their spatial position within one pole.

VI. Discussion

The results obtained so far show that it is clearly possible to detect and locate missing slot wedges in open slot machines using the proposed approach. The necessary excitation of the machine is not limited to voltage pulses. As the leakage flux paths are identified it is also possible to establish a high frequency (some hundred Hertz) harmonic excitation instead.

It is important to stress that the proposed method is not yet ready for field measurements. Current results are based on special machine setup and measurements under symmetrical (healthy) as well as asymmetrical (faulty) conditions to clearly determine the symmetrical condition. If the method is integrated in the drive control software the healthy condition could be identified during commissioning of the drive. However to apply the method for machines already in service such reference measurement data are not available. Ongoing research is focused on eliminating this issue.

VII. Conclusions

A new method to detect missing magnetic slot wedges in electric machines was proposed. It is based on a high frequency or transient excitation of the machine using an inverter and measurement of the machine current reaction. As the measurement can be done without fundamental wave the rating of the inverter needs to be only a fraction of the machine rating. The signal processing removes any inherent asymmetries to finally deliver a fault indicator that allows a precise detection and location of single as well as multiple missing wedges. FE simulation as well as measurements on a small machine verified the applicability and accuracy of the method. It is non invasive and allows a detection without disassembling of parts of the machine.

VIII. Acknowledgment

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IX. 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] 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.

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

[4] Wolbank, T.M.; Nussbaumer, P.; Hao Chen; Macheiner, P.E., "Non-invasive detection of rotor cage faults in inverter fed induction machines at no load and low speed," *IEEE International Symposium on Diagnostics for Electric Machines, Power Electronics and Drives,* 2009., pp.1-7, 2009.