Detecting Partially Fallen-out Magnetic Slot Wedges in AC Machines Based on Electrical Quantities only

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Abstract- **The winding system of high voltage machines is usually composed of pre-formed coils. To facilitate the winding fitting process stator slots are usually wide opened. These wide opened slots are known to cause disturbances of the magnetic field distribution. Thus losses are increased and machine's efficiency is reduced. A common way to counteract this drawback is given by placing magnetic slot wedges in the slots. During operation the wedges are exposed to high magnetic and mechanical forces. As a consequence wedges can get loose and finally fall out into the air-gap. State-of-the-art missing slot wedge detection techniques deal with the drawback that the machine must be disassembled, what is usually very time consuming. In this paper a method is investigated which provides the possibility of detecting missing magnetic slot wedges based only on measurement of electrical quantities and without machine disassembling. The method is based on exploitation of machine reaction on transient voltage excitation. The resulting current response contains information on machine's magnetic state. This information is composed of several machine asymmetries including the fault (missing wedge) induced asymmetry. A specific signal processing chain provides a distinct separation of all asymmetry components and delivers a high sensitive fault indicator. Measurements for several fault cases are presented and discussed. A sensitivity analysis shows the high accuracy of the method and the ability to detect even partially missing slot wedges.**

I. Introduction

The stator winding coils in medium and high voltage machines are usually manufactured outside the machine. To facilitate the assembling process, stator slots are thus wide open. But during operation these open slots cause disturbances of the magnetic air-gap field and higher harmonic components are induced. This leads to the increase of pulsations between stator and rotor state variables, like torque pulsations, uneven flux density and higher noise levels. All in all, the power factor as well as the machine's efficiency is reduced. Partially closing of the open slots by magnetic slot wedges seems to counteract these drawbacks [1]. Magnetic wedges are used to simulate semi-closed stator slots. The wedges act as paths for the leakage flux and reduce the effective slot opening.

The properties of the wedge material strongly influence the starting behavior of the machine [2]. Investigations have shown that the material must be of low conductivity and high permeability [3]. As an example, a material with this characteristic can be composited of 70% iron powder, 20% glass mat and 10% epoxy resin. Due to the relative high percentage of iron powder in the material the wedges are relatively brittle.

During operation slot wedges are exposed to high magnetic and mechanical forces [2]. The acting forces are caused by the fundamental-wave as well as the load profile. For example, a high number of motor starts or reciprocating load profile put additional stresses on the wedges [4]. Furthermore the life limiter for the wedges is the epoxy resin. Especially when the temperature is rising due to overload or high flux concentration the aging process of epoxy is accelerated. Thus also the bonding between stator teeth and wedges is affected and the wedges are free to move [5]. As a result the wedges can vibrate and start getting loose, up to finally falling out into the air gap. The consequences are debris of glass mat, resin and iron powder in the air-gap, the winding system and end windings area. Especially the iron powder can cause an increased discharge activity in high voltage machines. Further drawbacks are higher machine temperature, higher inrush currents at starting and higher vibrations and noise.

Up to now the most effective detection technique is the visual inspection of the air gap area of the machine [5]. Another evidence for missing slot wedges is the existence of dust and glass matting debris in the machine's air cooling circuit. However, a literature review has shown that all published methods deal with the handicap of machine disassembling [4]. So, one or more fallen out slot wedges can only be identified if parts of the machine are demounted. This procedure can be extremely time consuming and coupled with high costs due to machine size, location, and application.

A timely detected missing slot wedges can inform about the reduced machine's performance. Thus machines stress can be reduced, efficiency can be increased, and a spreading out of the fault can be avoided.

This paper investigates a new method for detection of missing slot wedges. The only inputs needed by the method are electrical terminal quantities, thus disassembling of the machine can be avoided. This advantage is based on the identification of machines transient reactance identified by current reaction to short voltage pulse excitation. The transient current reaction is mainly dominated by the transient leakage inductance. A considerable part of the leakage flux is the stator slot leakage. Assuming a symmetrical machine the leakage flux passes thru the slot wedges independent of the

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spatial direction of the excitation pulse. Missing slot wedges change the slot leakage paths distinctively and thus induce an asymmetry which can be detected. A special voltage pulse pattern and specific signal processing of the current signal provide a high sensitive fault indicator which was already introduced in [6]. The focus of this paper is placed on a sensitivity analysis and means to increase applicability of the method in field.

The investigations were realized on an 11kW induction machine with a squirrel cage. As voltage pulse generator serves a voltage source inverter which is controlled by a measurement/control system. The current measurements are performed by the inverter-built-in current sensors. According to the test machine's design with semi closed stator slots the slot wedges were specially adapted. The slot wedges are made of the same industry standard material also used for wedges in high power field applications.

II. Asymmetry detection by exploiting The Transient Reaction

In the following the excitation and signal processing steps for determination of a fault indicator will be described.

Parameter identification of a dynamical system is commonly done by observing the step response. In case of an electrical machine the excitation is realized by applying a voltage step to the machine terminals. The reactance will thus be a current slope, which can be measured and evaluated. An easy but effective way to realize these voltage steps is given by inverter switching. If the inverter state is changed from inactive to any active state a voltage step is applied. The step magnitude is equal the dc link voltage and the resulting current measurement can be done by the built-in current sensors of the inverter. Machine's voltage step reaction can be described by the well known stator equation (1) in the space phasor representation.

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

Basically, the current derivative $d\underline{i}_S/d\tau$ is influenced by different parameters, namely the voltage step $\underline{v}_S$ (with the magnitude of the dc link voltage), the stator resistance r_S, the rotor flux $\underline{\lambda}_R$ and the leakage inductance l_l. Considering, now only the first some ten µs of the current reaction the dominating voltage drop is the current derivative itself multiplied by the transient leakage inductance, denoted as $l_{l,t}$. In addition, also time derivative of the rotor flux (back-emf) as well as the stator resistance voltage drop influence the current slope. These disturbances have to be eliminated to achieve a distinct identification of $l_{l,t}$.

The disturbance elimination is possible by exploiting a special voltage pattern. The main idea is given by applying two short voltage pulses (some ten µs) with different inverter output states. As the pulses are subsequent, the fundamental-wave point of operation can be considered as constant within this duration. The back-emf as well as fundamental-wave stator current $\underline{i}_S$ will not change significantly. Each voltage pulse can then be described using (1). Subtraction of both equations leads to a simplified coherence presented in (2). Thereby currents and voltages of the first and second voltage pulse are denoted by the indexes *I* and *II*.

$$\begin{aligned} \underline{v}_{S,I} - \underline{v}_{S,II} &= \overbrace{r_S \cdot \underline{i}_{S,I} - r_S \cdot \underline{i}_{S,II}}^{\approx 0} + \\ & l_{l,t} \cdot \frac{d\underline{i}_{S,I}}{d\tau} - l_{l,t} \cdot \frac{d\underline{i}_{S,II}}{d\tau} + \underbrace{\frac{d\underline{\lambda}_{R,I}}{d\tau} - \frac{d\underline{\lambda}_{R,II}}{d\tau}}_{\approx 0} \\ \underline{v}_{S,I} - \underline{v}_{S,II} &= l_{l,t} \cdot \left[\frac{d\underline{i}_{S,I}}{d\tau} - \frac{d\underline{i}_{S,II}}{d\tau} \right] \end{aligned} \tag{2}$$

As stated, the fundamental-wave will not change significantly within the pulse duration. The stator current as well as the back-emf can thus be assumed constant within this time period. Due to the subtraction, these parts are eliminated. The voltage pulses and their spatial direction are known from the inverter switching states. On the other side the current slope is obtained from measuring the current signal within the pulse duration. Therewith the transient leakage inductance can be calculated by a simple division.

Until now the transient leakage inductance was considered as a scalar. Thus the resulting current slope will always be parallel to the excitation voltage pulse. Now, considering a real machine, the transient leakage inductance has to be extended from a scalar to a spatial complex value $\underline{l}_{l,t}$. Thus the inductance is getting dependent on the voltage pulse angular position. As a consequence the voltage pulse and current slope phasor will no longer have the same direction.

The so introduced non-scalar transient leakage inductance allows considering these angular differences. It can be divided into two parts. First one is representing the symmetrical machine and will be denoted '*Offset*' (l_{Offset}) in the following. The second portion is of complex nature and correlated to the machines asymmetries. In further description this part will be denoted as the modulated part or '*Mod*' (l_{Mod}). The composition of the complex transient leakage induction is given in (3).

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

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. In Fig 1 these coherences are depicted as an example for one missing slot wedge. The stator is assumed to have 18 slots within one pole pair and the missing slot wedges is located at $\gamma=60°$ (denoted *'missing wedge'*). The transient leakage inductance is represented as red solid line. The asymmetry caused by a missing slot wedges leads to a sinusoidal spatial modulation of the inductance. The *Offset* value is assigned to be the inductance mean value and *Mod* as a superposed modulation with period of 2γ. On the other side, the same modulation is obtained when a wedge is missing at angular position $\gamma+\pi=240°$. The *Mod* portion can thus provide information on machine's asymmetry and is the base for a fault indicator. In case of no missing slot wedges the modulated part is not present and the inductance is only determined by the *Offset* part.

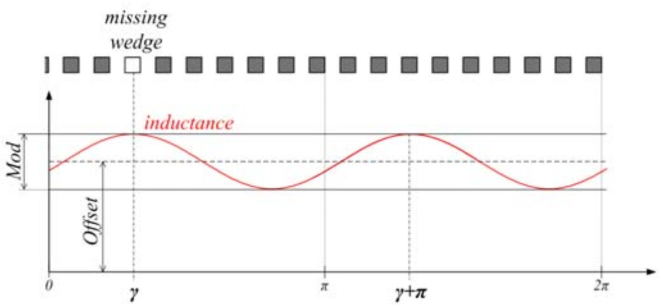

Fig 1: Spatial distribution of the transient leakage inductance within one pole pair. Missing slot wedge assumed at $\gamma=60°$.

According to the estimation of the transient leakage inductance in (2), also the current slope difference ($d\underline{i}_{S,I}/d\tau$-$d\underline{i}_{S,II}/d\tau$) can be separated into two parts. When (3) is inserted into (2) and the received equation is inverted, (4) is obtained. For shorter notation the current slope difference ($d\underline{i}_{S,I}/d\tau$-$d\underline{i}_{S,II}/d\tau$) is denoted as $d\underline{i}_\Delta$ and voltage difference as $\underline{v}_\Delta$. The symmetrical portion is determined by the value y_{Offset} and modulated by $\underline{y}_{Mod}$. These values are obtained from the inversion as shown in (5).

$$d\underline{i}_{\Delta,Offset} + d\underline{i}_{\Delta,Mod} = y_{Offset}\cdot\underline{v}_\Delta + \underline{y}_{Mod}\cdot\underline{v}_\Delta^* \tag{4}$$

$$\begin{aligned} y_{Offset} &= \frac{l_{Offset}}{l_{Offset}^2 + l_{Mod}^2} \\ \underline{y}_{Mod} &= -\frac{l_{Offset}}{l_{Offset}^2 + l_{Mod}^2}\cdot e^{j(2\gamma-\arg(\underline{v}_\Delta))} \end{aligned} \tag{5}$$

Thus it is sufficient to monitor only the resulting current slope. The symmetrical portion is pointing in the direction of the voltage difference phasor. The modulated part is depending on the angular position of the maximum inductance and on its magnitude. Therewith the modulated part of the current slope difference provides information on machine asymmetry. But before this information can be used as a fault indicator some further signal processing steps are needed as will be the described in the next chapter.

III. Fault Indicator Signal processing

As was shown, the current response to a special test voltage pattern can be used to obtain information on machine asymmetries. Voltage pulses as shown in Fig 2 are applied to the machines terminals. This excitation signal consists of two shorter and two longer pulses each with the positive or negative magnitude of the dc link voltage U_{DC}. The two main pulses are denoted as *pulse I* and *II*. The current slope measurement is realized within these pulses. The derivative is obtained from the difference of two sample points within each pulse, in the figure indicated as 'current sample points' with dashed gray lines. The reason for the two shorter pulses is thus to symmetrize the resulting current slope to the initial current value when the sequence is started. Measurements as well as the signal processing are executed on a digital signal processor. Due to the discrete nature of signal processing the current derivative $d\underline{i}_S/d\tau$ is replaced by $\Delta\underline{i}_S/\Delta\tau$. Now the current slope difference can be calculated by $d\underline{i}_\Delta = \Delta\underline{i}_{S,I}/\Delta\tau$-$\Delta\underline{i}_{S,II}/\Delta\tau$.

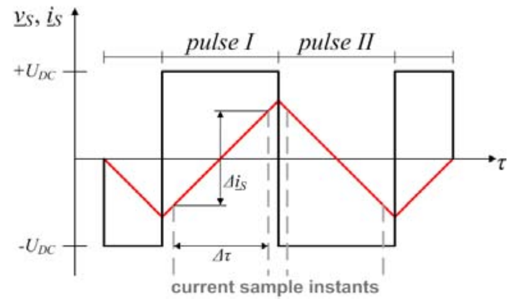

Fig 2: Voltage signal applied to one main phase direction (black) and current response (red).

The symmetrical portion of $d\underline{i}_\Delta$ is a disturbance when examining a fault indicator and must be eliminated. In (4) it was shown that the symmetrical portion is parallel to the excitation direction of the voltage difference phasor $\underline{v}_\Delta$. When applying the voltage signal given in Fig 2 subsequent to the three main phase directions also three current slope difference phasors $d\underline{i}_\Delta$ are obtained. The symmetrical portion of each phasor thus also points in one main phase direction. Combining the three phasors by adding them together leads to only one current difference phasor. Therewith the shares of the symmetrical portions leads to a zero sequence value that is eliminated. Now only one phasor is remaining that provides the information on machine's asymmetry. This phasor is denoted asymmetry phasor.

In a real machine asymmetries may not only be fault induced. There are also some inherent asymmetries, all present in the asymmetry phasor. Thus for fault detection these asymmetries must be separated. Elimination of inherent asymmetries is still possible due to their distinct behavior. Due to the focus of this paper on the induction machine with squirrel cage the following explanation is based on this machine type. Nevertheless this can be adapted also to other machine types. Main inherent asymmetries are caused by spatial saturation and the slotting of the stator/rotor lamination.

The saturation saliency arises from the different levels of the saturation along the flux paths of the fundamental wave. Modulation period is equal twice the electrical angle and corresponds to the machine's number of poles. The slotting saliency has its source in the opening of the lamination. The period is dependent on the angular position of the rotor with respect to the stator. Within one revolution of the rotor this asymmetry will have a period equal the number of rotor bars. In case of an unskewed rotor with open rotor slots this asymmetry is usually dominant. In case of skewed rotor bars this asymmetry will decrease. Closed rotor slots will reduce this modulation down to the case that it can be neglected.

A. Elimination of inherent asymmetries

In order to extract a high sensitive fault indicator the inherent asymmetries have to be eliminated. Therefore a specific signal processing chain has to be executed which will be described in the following.

As a starting point, voltage pulses (as shown in Fig 2) are applied to the machines terminals by inverter switching. Within the pulse duration current measurement provide the current derivative difference phasor $d\underline{i}_{\Delta}$. The excitation direction sequentially changes its direction in the main phase directions. Therewith one asymmetry phasor can be obtained from three current slope differences with its offset portion eliminated. Subsequently the asymmetry phasor is saved to a data storage arranged as an array. In the next step the rotor position is changed and the asymmetry phasor estimation is repeated. Each element of the storage array thus corresponds to one angular position of the rotor. The whole procedure is repeated until the rotor has moved at least one slotting period. The so obtained asymmetry phasor set is now available for spectral analysis like Fast Fourier Transform (FFT). The window size is chosen to one or a multiple of the rotor slotting period. Thus this modulation can be clearly identified.

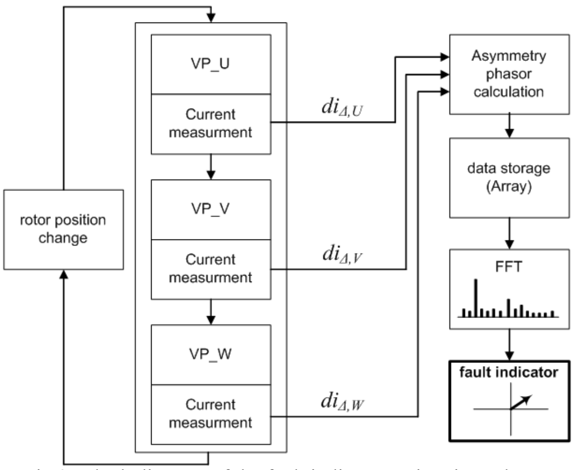

Fig 3: Block diagram of the fault indicator estimation scheme

A missing slot wedge causes a fault induced saliency which is considered to be fixed with the stator. In other words: the asymmetry arising from a missing wedge does not change its geometrical position with respect to the stator. The pulse excitation as well as the current measurements is also stator fixed. This indicates that the asymmetry can be detected in a spectral analysis as the offset of the spectrum. Thus the offset of the FFT directly serves as the fault indicator. As the asymmetry phasor is a complex value it is possible to detect the fault level by the magnitude and the fault position by the angle value.

The whole fault indicator estimation procedure is presented as a block diagram in Fig 3.

IV. Experimental Setup and Measurements

A. Experimental setup

The machine under test is an 11kW induction motor with an unskewed rotor. The number of rotor slots is 44 and of stator slots 36, respectively. The stator has 4 poles and a full pitched winding system. A voltage source inverter serves as excitation source. The measurements are controlled by computer system programmable under Matlab/Simulink.

Stator slot wedges are made of standard wedge material also used in industrial applications. The composition consists of about 75% iron powder, 18% epoxy resin and 7% glass mat. With the utilization of industrial standard wedge material the characteristics and behavior of applications in the field are well simulated. Geometry was specially adapted to fit in the slot openings of the machine. In Fig 4 a part of a standard slot wedge and an adapted slot wedge for the test machine are shown. Fig 5 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.

Fig 4: Industrial standard magnetic slot wedge material and adapted slot wedges.

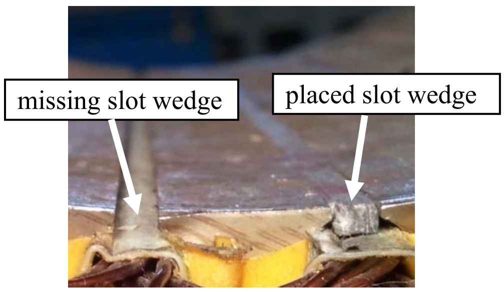

Fig 5: Close view of stator slots with specially adapted slot wedges. (one missing slot wedge on left side)

B. Measurement constraints

The measurements were carried out with the focus of field applicability. Basically magnetic slot wedges are applied in high voltage machines with high power rating. The method is based on voltage excitation by an inverter. Full size inverter in such power and voltage regions are coupled with high costs and equipment demands. Therefore the method is investigated with the constraint that the inverter power rating is only a fraction of the machine's. All measurements were carried out on a non magnetized machine with zero flux and no load. Current reactance measurement was realized by the inverter built-in current sensors. These sensors are standard industrial current sensors and have no specific demands on very high resolution or cut-off frequency.

In order to get a clear impression of the slot wedges positions with respect to the excitation directions Fig 6 shows a schematic representation of a cut-out of the stator lamination with the winding scheme. The cut-out represents 120° of the stator lamination. The winding system is double layer type and coils of each phase are marked in different colors. Red represents coils of phase U, green of V and blue of W, respectively. The excitation direction is assumed to be in direction U, indicated by the red solid phasor denoted $\underline{v}_{\Delta}$. In following investigations wedges in different slots are removed to simulate missing slot wedges. Starting with one whole missing wedge the fault level is decreased by removing only parts of wedges in a slot. Missing wedges are removed at the marked locations *'mw-U'*, *'mw-V'* and *'mw-W'*.

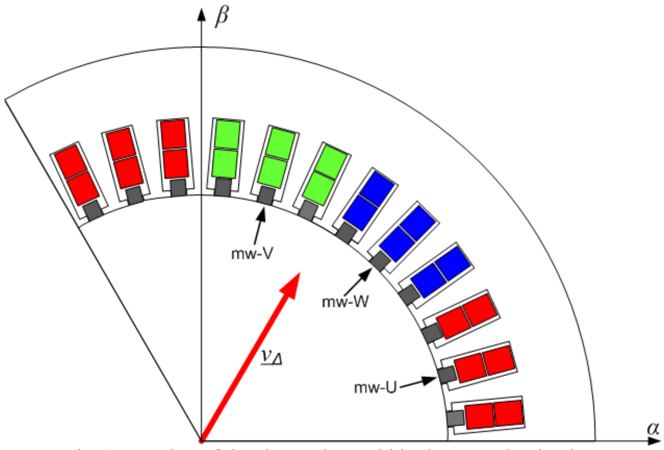

Fig 6: Location of the slot wedges within the stator lamination.

C. *Sensitivity analysis*

In a first step the machine was identified in the faultless case. All wedges were placed in the slots. The so obtained value of the fault indicator serves as a reference. Basically the fault indicator can still have an offset value although no fault is present. Considering a real system there are always some inherent asymmetries present. So, also the fault indicator in the symmetrical machine case shows a deviation from the origin. This offset value can be caused by asymmetries in the measurement system like different sensor transfer functions in the three phases and evaluation electronics. However, these disturbances can be eliminated in advance by offset elimination. For simulation of a fault case with a single missing slot wedge one wedge was removed in phase U and all other wedges left in the slots (in Fig 6 indicated as *'mw-U'*). After the measurement was finished, the missing slot wedge was placed back and another wedge removed in phase V (*'mw-V'*). Subsequently the same was done for phase W (*'mw-W'*). The fault indicator results are depicted in Fig 7.

Fault indicator values are presented as dot plots in the stator fixed frame. The units are given as arbitrary unit (a.u.) of the DSP inner representation. The reference value for the fault indicator is denoted *'faultless'*. The measurement result for a full missing wedge in phase U is denoted with '1 MW Ph U'. The fault indicator moves along the real axis which is equal the phase direction U. Thus one whole missing wedge can be clearly identified together with its direction. The next cases were realized by removing one wedge in phase V and phase W, respectively. It has to be stressed than there is always only one single slot wedge removed while all others are still in place. The locations of each missing wedge are shown in Fig 6 The fault indicator shows in each case the expected behavior. Thus a missing slot wedge can be clearly identified in each phase. All measurements were repeated 72 times to prove the method's accuracy. Hence, fault indicator appears as big "dots" due to the plot representation.

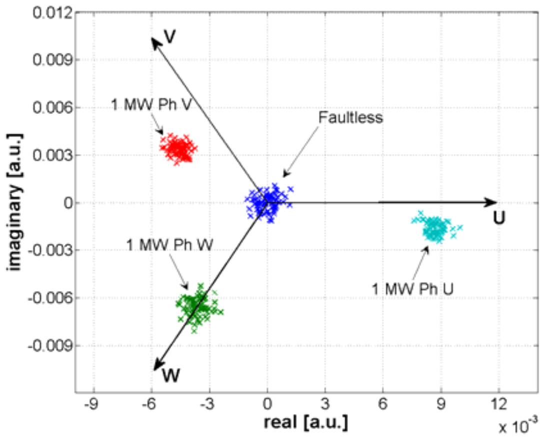

Fig 7: Measurement results for one missing slot wedge in each phase.

Field examinations have shown that usually not a whole wedge is falling out or missing but only parts of it [7]. A reliable method should provide the possibility to detect also partially missing slot wedges. To prove the applicability of the method for such fault cases further measurements were done. Thereby one wedge was cut into four parts. Fig 4 shows examples of split wedges.

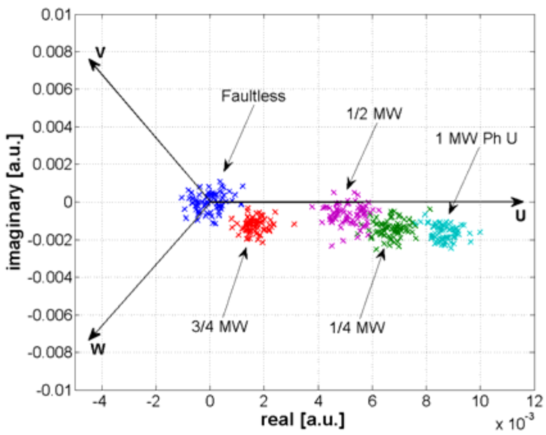

Fig 8: Measurement results for partially missing slot wedge in phase direction U.

At first all four wedge parts were placed in the slot and then one by one part was removed and a measurement executed. The faulty position was chosen in phase direction U at position *'mw-U'*. The Fig 8 shows the fault indicator values of this measurement series. The fault cases are denoted with '1/4 MW' till '1 MW Ph U' for 1/4 missing wedges up to one full missing wedge, respectively. The method shows still a good accuracy even if only a small part of 1/4 wedge is missing.

D. Reduction of excitation voltage

Up to now all measurements were done by a full size inverter. The dc link voltage was adjusted to its nominal value of 440V. As already mentioned before, magnetic slot wedges are usually applied in high voltage machines. Realizing a measurement device based on this method would require an inverter with very high dc link voltage and currents. But this is basically linked also with high costs of the inverter. To counteract this drawback the method was also tested with reduced excitation voltage magnitudes and clearly reduced currents with respect to rated.

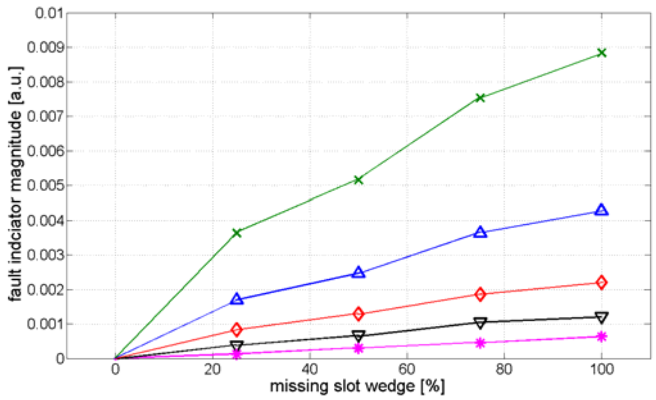

Fig 9: Fault indicator magnitude at different excitation voltages.
X…440V, ▲…220V, ◊…110V, ▼…60V, *…30V.

When the dc link voltage is reduced, so is also the magnitude of the voltage pulse. Thus the current slope will also decrease and with it also the fault indicator magnitude. However, detection of missing slot wedges is still possible due to the high reliability and accuracy of the proposed method. In Fig 9 results of measurements at different dc link voltage values are depictured. Cases under investigation were the same as in the previous subsection with only parts of a single wedge missing. The results are presented as fault indicator magnitude versus the percentage of a missing wedge. Voltage steps are shown in different colors starting with 440V (green) corresponding rated dc link voltage down to 30V (magenta) corresponding to ~7% rated.

Assuming rated dc link voltage, the current change during the pulse excitation is in the range of 5% to 10% rated. This value is reduced down to 3,5‰ to 7‰ rated when lowering the dc link voltage to 7% rated. Thus a machine with a power rating of 1MW can be tested using a test inverter with only a fraction of the power (less than 1 kW). Measurements on a some hundred kW machine have shown that the behavior of inherent saliencies (saturation/rotor slotting) is the same as on the test machine. Hence, it can be expected that the fault detection properties can be applied to machine of other sizes.

V. CONCLUSION

A method to detect missing magnetic slot wedges was investigated in this paper. An outstanding advantage of the method is given by the possibility to identify slot wedge faults without the usual disassembling the machine. Hence, high downtime periods and therewith coupled high financial losses can be reduced.

The method is based on the exploitation of the machine response on transient voltage pulse excitation. Measurement of the current slope provides information on the transient leakages inductance. This information can be utilized to obtain a fault indicator with high sensitivity. A specific signal processing is applied to eliminate any inherent asymmetry and thus to further increase detection accuracy.

Measurements on a small machine were performed to verify the applicability and accuracy of the method. It was proven that even a removal of only 25% of a single slot wedge can be accurately detected. In addition it is also possible to identify the position of the missing wedge. A further advantage of the method is that the inverter necessary for the excitation can be down-sized to only a fraction of the machines power rating.

VI. ACKNOWLEDGMENT

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