Evaluation of Asynchronous Wind Generator Stator Magnetic Slot Wedge and Coil Movement Using Electrical Signature Analysis

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***Abstract*— Two significant issues in wind power asynchronous generators are magnetic wedge loss and coil movement resulting in winding faults. Most of the time the failures occur unexpectedly or require borescope or visual inspections of the generator stators. In this paper we will identify how both conditions can be detected during operation through Electrical Signature Analysis. The application of the technology provides an opportunity to correct issues prior to insulation failure or to schedule generator replacement.**

Keywords—Wind Power, ESA, MCSA, Stator Wedge, Coil Movement, Asynchronous Machines

I. INTRODUCTION

A sampling of 3,165 wind power asynchronous generators between 660kW and 3MW repaired at one facility from 2005 to 2015 identified bearings at 35% of the cause of failure and stator wedges at 20% with rotor failures at 17% [1]. A second study sampled 430 wind power asynchronous generators from 1.5MW to 3MW tested with ESA of which 4% of total generator and powertrain confirmed defects, identified in place, were missing stator wedges [2]. Wind power generators normally use magnetic wedges which may become dislodged and pulverized between the stator and rotor resulting in ferrous materials spreading through the stator winding. This initiates a failure to ground as the ferrous materials penetrate the stator insulation [3].

The ability to provide early detection of missing wedges in place allows mitigation prior to winding failure, scheduling generator replacement and other cost and availability planning. Present methods of borescope and visual inspections require significant outage time of 4-8 hours, technician tower climbs, and partial disassembly or opening of the generator. Electrical Signature Analysis (ESA) techniques are performed between the tower transformer and generator stator which allows for data collection at the base for most configurations and convenient single-point locations for continuous monitoring systems [4].

Most fault detection theory in electrical machinery related to ESA and Motor Current Signature Analysis (MCSA) are established. Through a review of literature, it was discovered that data associated with stator coil looseness and missing wedges is stated in instrument manufacturer data and some vibration analysis academic papers, but not expressly identified, and sometimes identified in a manner that is not repeatable based on experience.

II. THEORY OF STATOR SLOT DEFECTS

It is understood that ESA data is analyzed by an amplitude modulated signal from both Voltage and Current which results in line frequency sidebands associated with defects when above twice the line frequency spectra and defect signature sidebands around line frequency in all other cases. This is established in literature [5] with a focus on the rotating components of the electric machine and not the stationary, except for stator winding shorts as noted in (1).

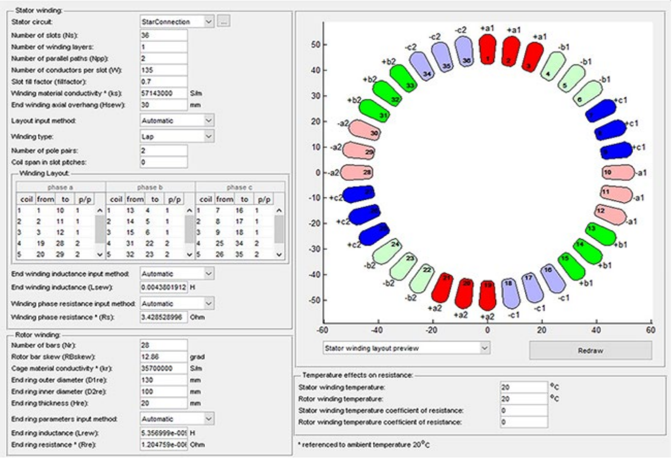
$$f_{ss} = f\left[\frac{n}{p}(1-s) \mp k\right] \tag{1}$$

Where f_{ss} are the stator short frequencies, n and k are integers (1, 2, 3, …), f is the line frequency; p is the number of pole pairs and s is rotor slip.

Stator unbalances have some relation to static eccentricity in an electric machine and could theoretically appear in severe cases of missing wedges and other stator defects. These defects are established in relation to Unbalanced Magnetic Pull (UMP) [6] primarily in relation to vibration analysis and ESA [7] using the static eccentricity calculation (2).

$$f_{rs} = R\left[\left(\frac{f}{p}\right) * (1-s)\right] \mp f \mp 2f \ldots \tag{2}$$

Where f_{rs} are the static eccentricity frequencies and R is the number of rotor slots/bars



Stator winding:

Stator circuit: StarConnection
Number of slots (Ns): 36
Number of winding layers: 1
Number of parallel paths (Npp): 2
Number of conductors per slot (W): 135
Slot fill factor (fillfactor): 0.7
Winding material conductivity * (ks): 57143000 S/m
End winding axial overhang (Hsew): 30 mm
Layout input method: Automatic
Winding type: Lap
Number of pole pairs: 2
Coil span in slot pitches: 0

Winding Layout:

phase a				phase b				phase c			
coil	from	to	p/p	coil	from	to	p/p	coil	from	to	p/p
1	1	10	1	1	13	4	1	1	7	16	1
2	2	11	1	2	14	5	1	2	8	17	1
3	3	12	1	3	15	6	1	3	9	18	1
4	19	28	2	4	31	22	2	4	25	34	2
5	20	29	2	5	32	23	2	5	26	35	2

End winding inductance input method: Automatic
End winding inductance (Lsew): 0.0043801912 H
Winding phase resistance input method: Automatic
Winding phase resistance * (Rs): 3.428528996 Ohm

Rotor winding:

Number of bars (Nr): 28
Rotor bar skew (RBskew): 12.86 grad
Cage material conductivity * (kr): 35700000 S/m
End ring outer diameter (D1re): 130 mm
End ring inner diameter (D2re): 100 mm
End ring thickness (Hre): 20 mm
End ring parameters input method: Automatic
End ring inductance (Lrew): 5.356999e-00 H
End ring resistance * (Rre): 1.204759e-00 Ohm

Temperature effects on resistance:

Stator winding temperature: 20 °C
Rotor winding temperature: 20 °C
Stator winding temperature coefficient of resistance: 0
Rotor winding temperature coefficient of resistance: 0

* referenced to ambient temperature 20°C

Fig. 1. Finite Element Analysis Model Setup with MotorAnalysis

The work related to UMP is primarily the evaluation of the potential that a rotor will come in contact with the stator core through vibration and MCSA [8]. The approach requires specific measurements related to the airgap and airgap length of the electric machine and is usually calculated in millimeters. Depending on the size of the machine being evaluated with ESA, the measured movement of stator coils may be found in much smaller increments. The values associated with magnetic wedge loss are also relatively small except for many missing wedges. With the rotor, the air gap magnetic field interacts with the number of rotor bars/slots as identified in (2) and the stator with a theoretical value related to the number of stator slots as identified in (3).

$$f_{ss} = S_s\left[\left(\frac{f}{p}\right) * (1-s)\right] \mp f \ldots \tag{3}$$

Where f_{ss} are the stator slot frequencies, S_s is the number of stator slots.

This would translate into a general vibration analysis industry rule-of-thumb for induction machines presented as the running speed times the number of stator slots which would appear as plus and minus line frequency sidebands in ESA.

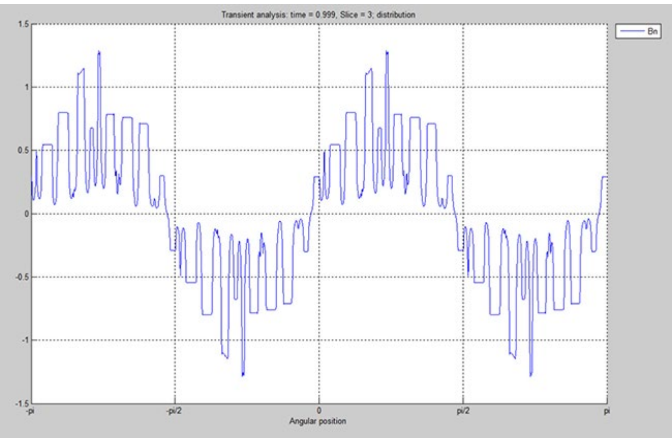


Fig. 2. Simulation with all slot wedges in-place

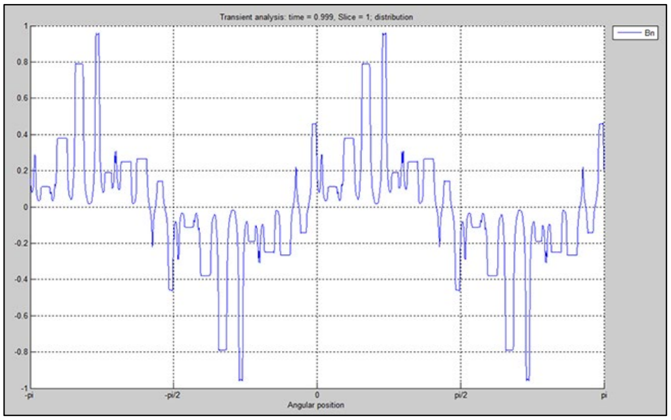


Fig. 3. Simulation with one full missing wedge

III. Evaluation of Beat Frequency

A Finite Element Analysis (FEA) was performed using a combination of MatLab® and MotorAnalysis® software. The system was selected to analyze both stator windings and rotor construction including materials. It was noted that the system did allow for rotor analysis but was not designed to identify stator related phenomena, requiring some modification to allow for the identification of generic slot defects. This was accomplished by adding and subtracting the number of turns in a single coil to identify how it would affect the machine air gap (Fig. 1).

The low-resolution air-gap flux density ripples (Bn in Tesla) with all wedges in place (Fig. 2) versus one missing full slot wedge (Fig. 3) identify a change in the magnetic field above the effected slot for both a missing wedge or potential moving coil. This was determined enough to be affected by the rotor field in the machine airgap to be identified by a slot beat frequency, but not enough to cause significant UMP [9]. This identifies that a small number of missing wedges would not have a measurable impact on the rotor static eccentricity.

IV. Field Application of an induction electric motor

Prior to the winding failure of an 800-hp, 1785 RPM (29.75 Hz), 4160 Vac motor with 72 stator slots and an ESA-measured running speed of 29.877 Hz (1792.6 RPM) was measured with ESA. The frequencies to be evaluated for stator coil movement

Fig. 4. Wedge signature in an 800 hp induction motor

Fig. 5. 800 hp induction motor stator with no missing wedges

or missing wedges based upon (3) would be 2091.14 Hz and 2211.14 Hz which were identified as shown in Fig. 4.

The electric motor subsequently failed shortly after data collection and was disassembled to identify fractures in the stator insulation where the coils exited the slots, which is also where one coil failed to ground. There were also general findings of end-coil movement and the stator wedges appeared to be intact (Fig. 5). Testing of seven identical electric machines in the same application were performed with similar ESA findings related to the stator slot frequencies. Further investigation discovered that the surge rings were not laced to the stator bracing and each stator was repaired following a second identical failure.

V. FIELD APPLICATION OF AN ASYNCHRONOUS WIND GENERATOR

Prior to removal of a 3MW, 4-pole, Doubly-Fed Inverter Generator (DFIG) operating at 30.224 Hz (1813.44 RPM) an ESA was performed to evaluate detection of known missing magnetic wedges. The signature was found as Fig. 6 with the stator slot signatures at 1572.1 Hz and 1692.1 Hz. Additionally, a winding short signature was found which, as noted in literature, can relate to other conditions such as stator slot sparking. The winding failed to ground prior to removal and was disassembled as shown in Fig. 7.

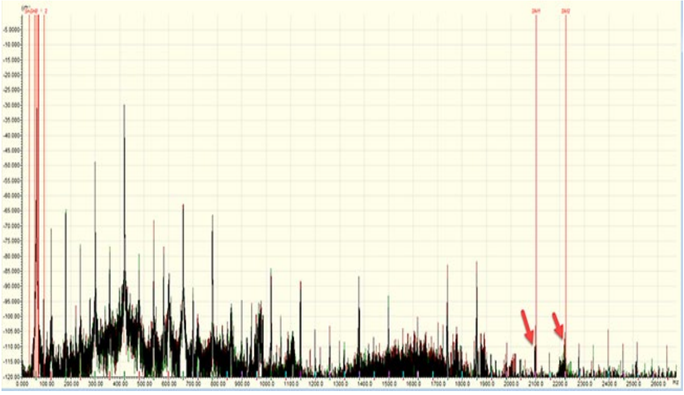


Fig. 6. Wedge signature in DFIG generator with scale in -dB

Fig. 7. Stator of DFIG missing wedges and failure point

A second wind generator of the same design was found and removed from service prior to failure. The wedges were replaced, and side packing added to the sides of coils that had signs of movement. ESA was performed before and after identifying that the fault could be mitigated.

VI. ADDITIONAL FIELD NOTES

It has been identified that some wind power generator repairs are performed by replacing missing magnetic wedges with non-magnetic wedges. This has resulted in some false positives when field testing which were resolved once repair information was provided. Other field modifications to wind power generators are normally considered when performing ESA analysis of wind power generators and related powertrain.

A review of missing wedge signatures and UMP identified that the resulting static eccentricity would be a function of both load and number of missing magnetic wedges. As noted by Thompson and Culbert [10], the general force equation for UMP (4) is influenced by the peak flux density. The detection of a volume of missing magnetic wedges, signficant coil movement, and progression of these conditions would require machine loads close to full load. This condition also allows monitoring of increased movement or wedge loss as an increase in static eccentricity resulting from UMP. Beat frequency increases based upon the number of wedges and coil movement based upon (3) is load independent and can be used to provide a variable load identifier with UMP as a measurement of severity.

$$F_{UMP} = \left(\pi D L B_p^2 e_c\right)/4\mu_O \tag{4}$$

Where D is the rotor diameter in mm, L is the rotor length in mm, B_p is peak flux density in Tesla, e_c is the absolute airgap eccentricity level in mm, and μ_o is $4\pi * 10^{-7}$ H/m. This does provide the ability to evaluate the amount of UMP and equivalent rotor mixed eccentricity and relative loss of clearance between the stator and rotor as noted by Kim, Nerg, Choudhury, and Sopanen [11]. The scope of the degree of UMP, equivalent coil movement, volume of missing slot magnetic wedges, and potential loss of airgap clearance in DFIG wind generators is being investigated as part of a separate research project.

VII. CONCLUSION

Field experience and literature had identified stator slot related signatures in relation to beat frequencies and potential UMP in electric machines. With the second largest number of faults detected through repair in wind generators being missing magnetic wedges in several common generator manufacturers, the ability to detect such faults in advance has a significant economic and availability impact. While the signature has been generally known in industry, a review of the reason for the signature has not been found in literature. A relating formula for the detection of static eccentricity involving UMP of the rotor was evaluated and found to be accurate in measurements of Voltage and Current in induction motors and asynchronous generators. The use of UMP measurements under specific load conditions to evaluate the relative coil movement, volume of missing slot magnetic wedges, and potential loss of airgap clearance in DFIG wind generators is part of a continuing research project for continuous monitoring and risk assessment.

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