Evaluation of Stator and Rotor Interturn Stress with Electrical Signature Analysis in Variable Frequency Drive and Wind Generator Applications

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***Abstract*— Electrical Signature Analysis is the application and analysis of Voltage and Current data collected on electrical machinery systems. The measurements are converted to amplitude modulated Fast Fourier Transforms that can be evaluated for power, machine and powertrain conditions. Electrical and mechanical conditions are determined through their effects on the airgap magnetic field. One of these effects includes the detection of winding shorts. It has been found in variable frequency drive and wind generation applications that stator and rotor interturn stresses can be detected prior to insulation breakdown. The application of the technology in determining these conditions allows for mitigation of the conditions surrounding the winding stress and potential breakdown.**

Keywords—MCSA, ESA, Wind Generation, Stator, Rotor, Winding Stress, Winding Shorts, Rotor Fault, Stator Fault

I. Introduction

The purpose of this paper is to identify a method for evaluating the successful tuning of PWM Variable Frequency Drive (VFD) and motor applications and condition of wind generation rotors and stators. The study resulted from a discovery while performing the research associated with the Evaluation of Offline Partial Discharge in Vacuum Environments [1]. Continued research also identified the methodology applied in wind Doubly Fed Inverter Generators (DFIG) stators and the development of a new method for the identification of developing defects in DFIG rotors.

These discoveries provide the ability to verify VFD installation and set-up as part of commissioning and the DFIG processes for the early detection of winding failure through either continuous monitoring or data collection. In the case of VFDs, this improves the electrical and mechanical reliability of the electric motor decreasing the life-cycle cost of the system. In the case of wind generation, the early detection of DFIG winding failures reduces the associated repair cost and unplanned outage through planning advantages with cranes, spares and coordination with repair facilities. In many cases, it was found that the method identified that winding stress was occurring in DFIG as the result of problems in either the rotor or stator control circuits that can be corrected prior to winding failure.

II. Electrical Signature Analysis

The study was performed utilizing a Framatome EMPATH instrument which has a resolution to 0.0005 Hz to 0.001 Hz across the Fast Fourier Transform (FFT) spectra to greater than 5kHz required to distinguish between peaks. Electrical Signature Analysis (ESA) involves the collection of three phases of voltage and current which is then presented in the form of power quality, voltage and current spectra, RMS values, and the data can be transformed to other types of analysis including air gap torque spectra and power spectra. The amplitude modulated frequencies are evaluated in either linear or decibels. In the dB scale, the detection of faults is normally from the peak voltage or current down to the associated peaks with the terms -dB or ‘dB down.’ The peak voltage and current are referred to as ‘0 dB.’ This provides relative ‘force’ associated with the frequencies being evaluated.

The use of the technology was first introduced by Haynes and Essenberg [2] in the mid-1980s for nuclear power motor operated valve electrical and related mechanical components. ESA application within the industrial and VFD environments is well documented with the mechanical applications further identified by Penrose [3] and successfully applied to wind generation by Penrose [4,5] for generator and powertrain analysis.

The capabilities of ESA have been well documented [6,7] with the original concepts around the detection of winding shorts and limitation in time before failure in across the line operation. For the stator, the prevailing theory is related to the effect of current at a point that impacts the machine airgap. While performing testing on special assembled motor-generator assemblies in vacuum [1] with determined PD inception (PDIV) and extinction (PDEV) voltages, the signatures were identified when incorrectly sized filters were applied and the VFDs were not tuned. In these cases, the windings had a high rate of failure. When correct filters were applied the expected signatures were not present and the windings were not failing.

III. ESA Detection of Interturn Stress in VFDs

A review of previous VFD commissioning data was performed in relation to pre- and post-tuning. It was found in all reviewed cases that improperly tuned VFDs, as well as improperly filtered applications, showed the ‘winding short’ signature even though the windings were not shorted. Testing with an Electrom iTIG II D surge tester with offline PD

Figure 1: Commissioning of VFDs and Pumps 1800 RPM (30 Hz) synchronous speed

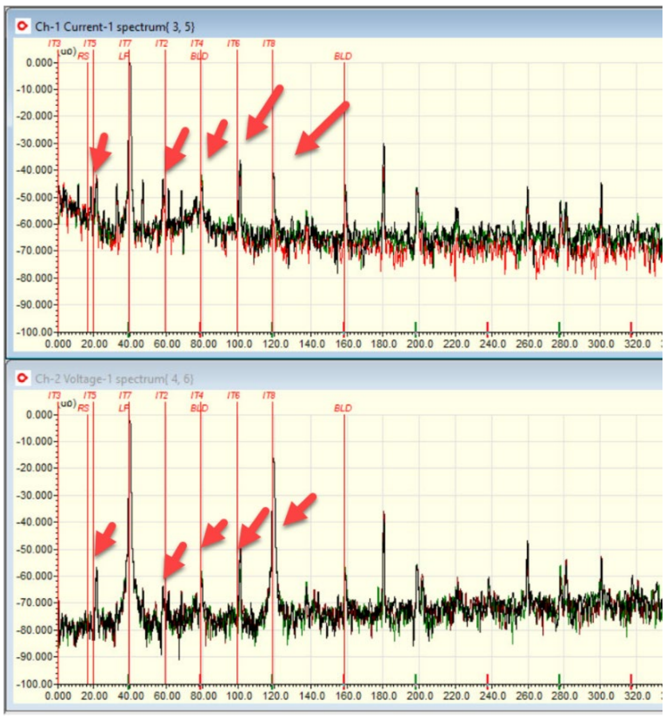

Figure 2: Voltage and Current Spectra before Autotune

identified the PDIV was close or above the expected applied voltage from the associated VFDs in two of the applications. However, the windings did not show fault signatures and the VFDs did not trip. This would indicate that the winding short indication may also indicate interturn stresses and may be associated with some value of PD in both random wound and form wound stators. Further testing during commissioning and evaluation pre- and post- VFD tuning through 2019 on nine applications have produced similar results with two showing existing winding stress signatures after tuning, but at a lower value.

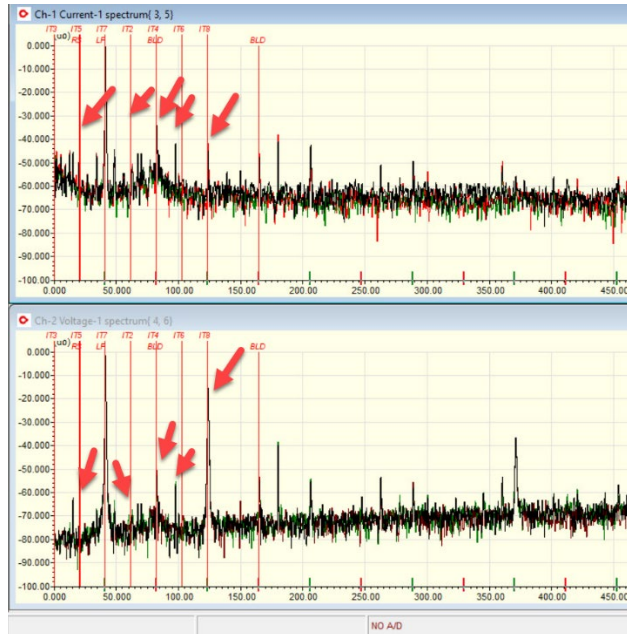

Figure 3: Voltage and Current Spectra after autotune

$$f_{st} = f_1 \left\{ \frac{n}{p}(1-s) \pm k \right\} \qquad (1)$$

$$f_{st} = frequency\ peaks\ representing\ shorted\ turns$$

$$f_1 = supply\ frequency, n = 1,2,3\ldots, k = 1,2,3\ldots$$

$$p = pole\ pairs, s = slip$$

The formula for interturn shorts (1) is represented in this paper as also representing winding stress for stators.

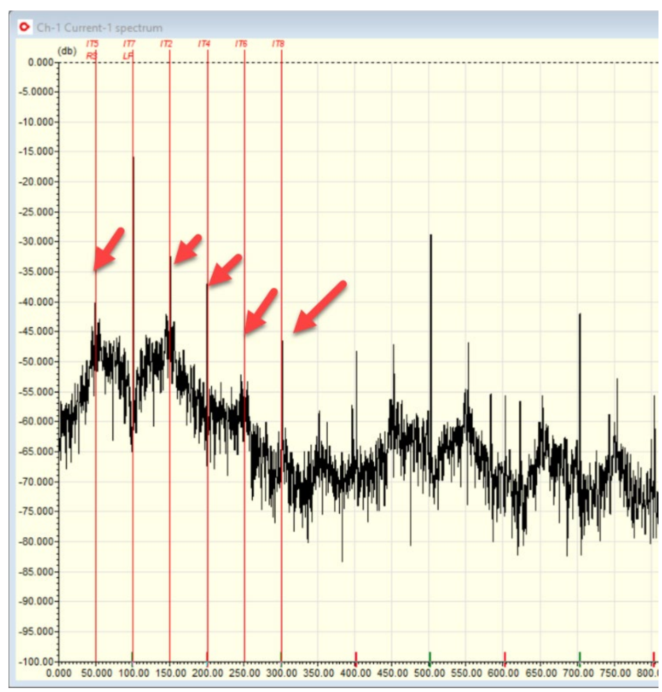

Figure 4: 4-Pole Machine at 100 Hz with poor drive output filter

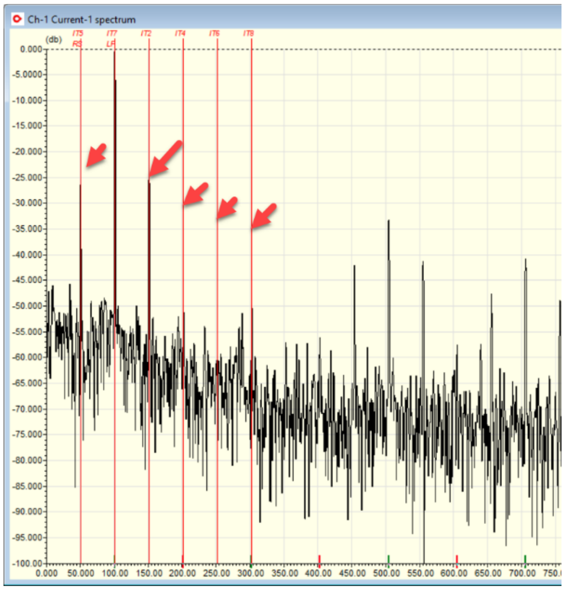

Figure 5: 4-Pole Machine at 100 Hz after installation of sine wave filter

IV. Winding Stress in DFIG Wind Generator Stators

An evaluation of 352 DFIG generators of one manufacture across four sites in different environments and load conditions were performed and evaluated for winding stress signatures. Twenty-two of the stators showed winding stress indicators. Another two DFIG stators of a different generator manufacturer were evaluated as part of troubleshooting and both had winding stress detected. Surge comparison testing of the two stators indicated weak insulation. Following these findings and while awaiting test results from the 352 DFIG stators, an additional twenty DFIG of a third design were evaluated with two showing stator stress without operating fault indications. Subsequent surge comparison testing indicated weakness in the turn insulation of the stators. The signatures primarily show in the voltage spectra.

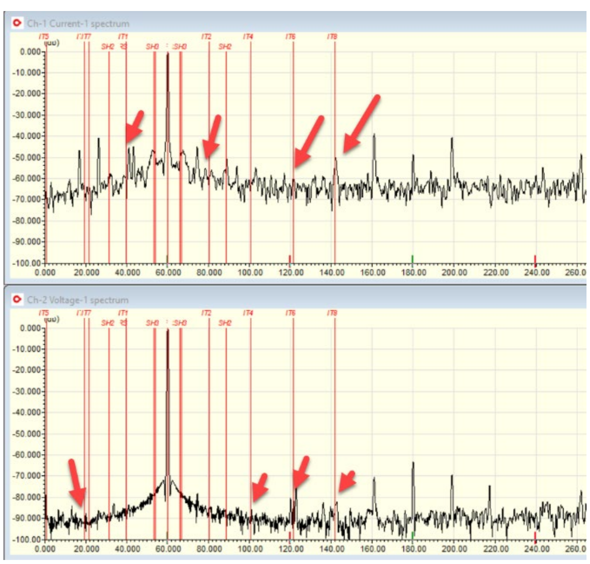

Figure 6: Stator Winding Stress 6-pole 1.5MW wind generator

V. Rotor Winding Stress in DFIG Wind Generators

During evaluation of the 374 DFIG generators for stator stress signatures, it was noted that several had unusual rotor signatures. A method for determining wye ring fractures in DFIG generators had been developed using ESA by Penrose [8] with other rotor electromagnetic defects showing in specific patterns that include dynamic eccentricity. A significant number of rotors had slip speed and pole pass frequency sidebands around dynamic eccentricity signatures. Two of the generator rotors were tested and found to have interturn insulation breakdown with one having tripped due to a rotor circuit fault and the second had not yet tripped.

$$PPF = p(N_s - N_r) \qquad (2)$$

$$PPF = pole\ pass\ frequency, p = poles$$
$$N_s = synchronous\ speed\ (Hz)$$
$$N_r = running\ speed\ (Hz)$$

$$ECC_d = (N_r * RS) \pm (f_l \pm N_r) \qquad (3)$$

$$ECC_d = dynamic\ eccentricity, RS = Rotor\ Slots$$
$$f_l = line\ frequency$$

Figure 7: Developing rotor winding short PPF and 2x PPF sidebands around low level dynamic eccentricity peaks in current and voltage

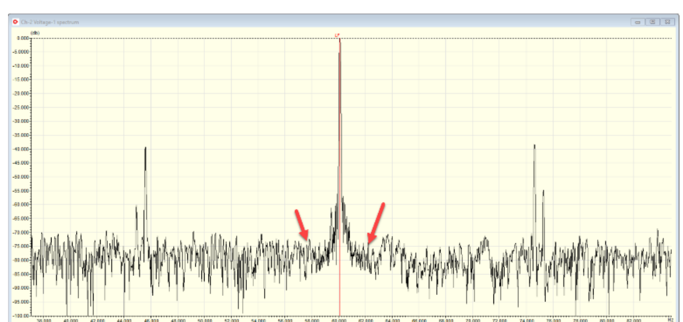

Figure 8: Low level PPF sidebands around line frequency associated with Figure 7 in voltage

VI. DISCUSSION OF STATOR INTERTURN STRESS

According to Thompson [6] the effect of shorted turns in an induction motor stator is identified through the inter-turn stator short equation (1) referencing Joksimovic and Penman [7] equations related to the detection of inter-turn short circuits in operating induction motors. Testing theory assumed dead faults in the stators between conductors versus the normal discharge and arcing that will occur between conductors prior to failure [9].

The interturn stresses on the winding of an induction motor in a PWM inverter prior to autotune or proper sizing of drive output filters are significant on both random wound and form wound stators [10, 11]. The impact of these stresses in the air gap magnetic field appear to replicate the type of impact that would occur if there were an interturn short in the stator. As the stress is reduced as the PWM inverter is autotuned to the motor, or appropriate filtering is selected, the impact of the interturn stresses decreases or becomes imperceptible in the stator current signature.

For DFIG stators the signature will appear as a voltage signature [3] as opposed to current signature in an induction motor. As the stator is supplying direct 50 or 60 Hz to the distribution system the detection of these faults will appear as a weakness, or developing short, with surge comparison testing. Theoretically the application of the converter control of the rotor will reduce the stress on the stator due to variations in wind and gusts with a longer potential before stator winding failure.

VII. DISCUSSION OF DFIG ROTOR INTERTURN STRESS

In an induction motor a defect in the rotor circuit will appear as a Pole Pass Frequency (PPF) (2) sideband around the line frequency of the motor [12]. In some cases, where the defect is severe enough, the field around the rotor becomes unbalanced enough that it will also show as a dynamic eccentricity.

With a DFIG rotor, a developing winding short or interturn stress will have a PPF signature in current and a dynamic eccentricity. In some cases, when the defect is not severe enough, such as prior to insulation breakdown, the effect from the rotor converter control will cause stresses that show up as dynamic eccentricity with PPF sidebands around at least two peaks. This would be calculated as (3) and may also show a weakness or defect if the rotor is tested with a surge comparison tester.

The rotor fault detection identified within this paper were identified well in advance of any corrective action being required, with the exception of one DFIG that was only able to operate under part load for less than five minutes.

VIII. CONCLUSION

The use of ESA technology extends beyond just fault detection of components and can be utilized for commissioning of motors and PWM VFDs. The capability also extends into wind for the detection of a number of generator and powertrain faults. In the case of this paper we are focused on the early detection of stator and rotor faults of DFIG generators for purposes of failure planning or fault mitigation.

The ability to detect interturn stresses in in these applications in advance of failure allows ESA data collection or continuous monitoring in order to plan for repair, replace or mitigation. In the case of VFD application commissioning tuning or proper sizing of filters can be identified.

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