Evaluation of DFIG Wind Turbine Generator and Transformer Conditions with Electrical Signature Analysis

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***Abstract*—During field studies of Doubly-Fed Induction Generators (DFIG) and Singly-Fed Induction Generators (SFIG) transformer and generator failures several unusual conditions were detected. A combination of sub-synchronous control interaction, sub-synchronous torsional interaction, and starting resonances were detected with electrical signature analysis in specific operating conditions of the machines. A review of historical operating conditions, wind, thermal and power distribution system design indicate that low-level sub-synchronous resonances are present that result in unusual transformer heating/aging, generator rotor component electrical and mechanical fatigue, and gearbox wear after years of service. The severity of the condition results from a combination of average loading and distance from customer loads and wind farm configuration. In this paper we will discuss the discovery and progress in the research with potential in-service solutions to be presented.**

Keywords—Windpower, Wind Generator, Transformer, Electrical Signature Analysis, Power Distribution, DFIG, SFIG, Winding Failure

I. Introduction

Three major windpower generation faults are documented in Doubly-Fed Induction Generators (DFIG) and Singly-Fed Induction Generators (SFIG) including the generator rotor wye ring connection, gearbox, and transformer.[1, 2] These conditions are often presented as separate reliability investigations while overlooking the impact of system-wide conditions such as Sub-Synchronous Resonance (SSR)[3]. Since multiple SSR events starting in 2009 related to wind farms globally[4] studies have been performed related to the potential of damage to specific generator components.

This study involves the applied research associated with SSR effects on DFIG and SFIG individual wind turbines including transformer degradation and gassing, generator rotor wye ring fractures, stator insulation degradation, and gearbox wear and bearing fractures. Similar in fashion to the study performed by Dong, Dong and Xu[5] practical field data was collected using an EMPATH™ Electrical Signature Analyzer (ESA) across several wind farms, wind speeds, and wind turbine manufacturers. Additional data gathered included historical wind speeds, temperatures, humidity, and location and age of the towers. Where possible, major component repair histories of the tested towers and sites were made available including approximate dates.

II. DFIG and SFIG

Two of the more popular wind turbine designs are the DFIG and SFIG turbines. DFIG involves the use of a parallel inverter to the stator providing control the rotor circuit in specific operating conditions while drawing additional power from the rotor. SFIG involves the use of a rotor control for adding and removing impedance from the rotor without drawing additional power. Both operating schemes provide correct frequency output from the stator circuit regardless of rotor speed and VAR correction at lower windspeeds and resulting sub-synchronous rotor speeds.

The rotor controls for both designs generate a rotating field synchronous speed with a resulting line frequency output for either 50Hz or 60Hz. At low wind speeds that result in a sub-synchronous operating speed the control operates in such a way that the rotor magnetic field turns at synchronous speed. At higher wind speeds the rotor mechanically turns at a super-synchronous speed and the control operates in such a way that the rotor magnetic field turns at synchronous speed. In the case of sub-synchronous mechanical speed, there is an additive rotating field and in the case of super-synchronous there is a negative rotating field in the rotor.[6]

$$S_1 = \frac{f_n - f_m}{f_n} \tag{1}$$

$$S_2 = \frac{f_n + f_m}{f_n} \tag{2}$$

As noted in (2) which represents the slip (S_2) at super-synchronous speed, f_n are the positive and negative components of the electrical frequency, and f_m is the electrical frequency of the rotating speed of the rotor, the slip is always a positive value and stable. In (1) the rotating speed is sub-synchronous, and the slip is always negative and potentially unstable. The conditions surrounding (1) are the result of low wind speed as determined by the power curve of the turbine design. The stability is directly impacted by the turbine electrical circuit to the transformer, the wind farm impedances based upon the associated turbines on-site, and the impedances associated with the transmission lines.

III. Turbine Circuit

The turbine circuit of interest includes the transformer, which may be located either at the base or in the nacelle, the rotor circuit and controls, and the stator. The remainder of the mechanical system includes the generator to gearbox coupling, three stages of gearbox and planetary gear, main bearings and shaft, and turbine blades (Figure 1). Not included in this paper are the yaw gearbox motors which turn the nacelle, the pitch motors which turn the blades, and other accessory motors.

In the case of DFIG systems, the VAR correction is accomplished through the rotor drive to independently control active and reactive power. The purpose is to provide power factor correction at lower wind speeds and resulting lower points on the power curve (Figure 2). A combination of VAR correction and wind ride-through are required at the PCC between the windpower site and grid connection. SFIG systems utilize a combination of capacitors and rotor switching and changes to impedance in order to provide similar control. Standards development for interconnection and interoperability address the quality of power delivered from the windfarm to the grid.

The primary impacts on turbine stability range from grid events to wind farm site events to wind gusts.[7] In the case of the tower in this study the commissioning of the site was in 2011 and testing of the site was in 2021. Wind speeds across the site history are included as Figure 3 with a majority of wind speed falling to an average of 5.5 m/sec. This is relatively low on the wind speed curve (Figure 2) with production in the range of 200 kW at 690 Volts in the tower between the generator and primary of the step-up transformer.

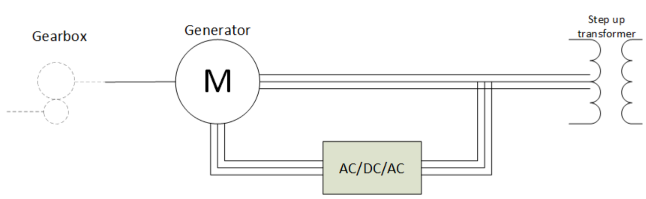

Figure 1: General representation of DFIG circuit

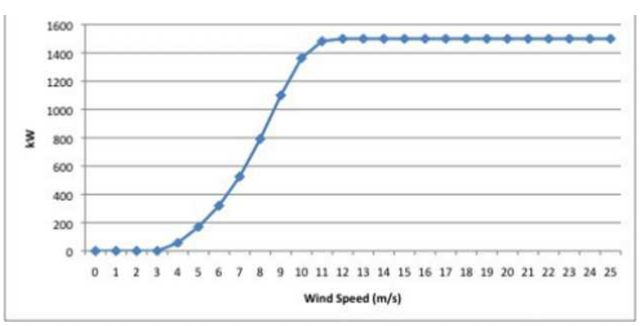

Figure 2: 1.5 MW DFIG wind speed to power curve in m/s

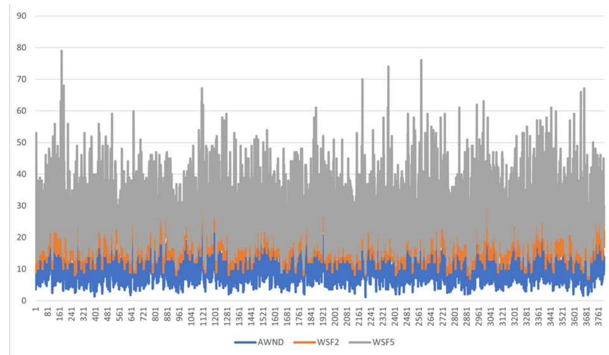

Figure 3: Average and peak windspeed gusts in mph from 2011 (NOAA database)

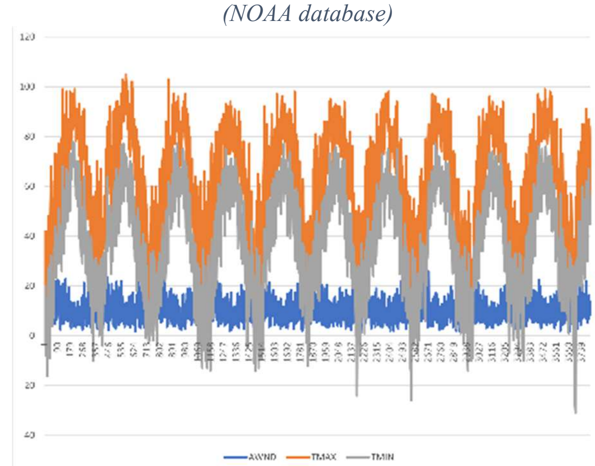

Figure 4: One year sample of NOAA database wind speeds and gusts in mph

IV. Defects

The study involves three types of defects in the wind turbine system: transformer gassing; rotor wye ring and other rotor connections; and gearbox gear and bearing failures.

Figure 5: gearbox planetary gear fracture

Figure 6: gearbox ring gear damage and smearing.

Common defects in wind turbine gearboxes occur either at the high-speed bearings (39.6%) or planetary gear set (22.5%) damage such as shown in Figures 5 and 6.[8] The primary defects found in both bearings and gears are fractures that have been under investigation since 2010. The types of faults may be a combination of cyclical loading or manufacturing defects.

Wye ring and connection failures in the generator rotors (Figure 7) are observed through damage to the insulation material encasing the conductor. Splits and fractures are indicators and other technologies, such as ESA, are used to detect early changes in rotor circuit conditions as an indirect method of detection.[9] Inspection of wye ring materials identify that the fractures are the result of fatigue (Figure 8).

Wind turbine pad mount transformers have had a historically high rate of failure as well as high gassing conditions that are normally attributed to high temperatures and Ferroresonance.[10, 11] These conditions are a combination of thermal cycling, cyclical loading, and light loading application.

Figure 7: advanced wye ring connection failure

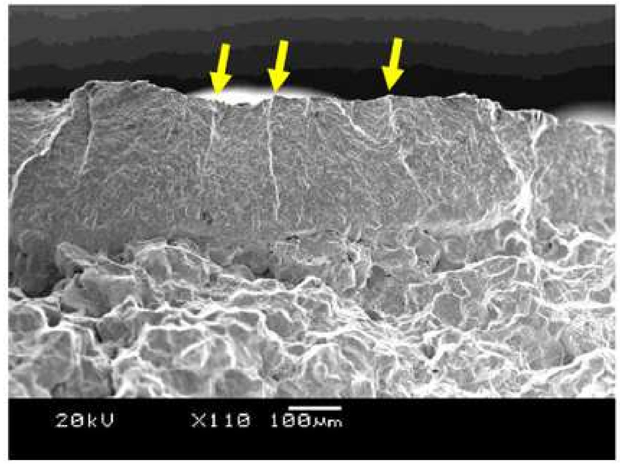

Figure 8: fatigue cracking on wye ring prior to failure.

One common root cause for each fault described is fatigue from cycling. In wind conditions where towers are operating close to cut-in and cut-out wind speeds (under 4 m/s) for extended periods, a turbine may stop and re-start every 5-10 minutes. As noted in Figures 3 and 4, these conditions vary by time of day and season by location. These starting conditions also include high VAR correction resulting in potential electrical and mechanical resonance and sub-synchronous resonance. Linear and parallel VAR correction in long distance transmission lines also add to an individual wind turbine tank circuit between the generator and transformer.[12]

V. Site Testing

The selected test site had been in operation for ten years with a relatively high rate of failure. For purposes of the study, data was collected from the generator in the nacelle on a 1.5 MW turbine. Connections were made on one cable in each phase of the generator connection box.

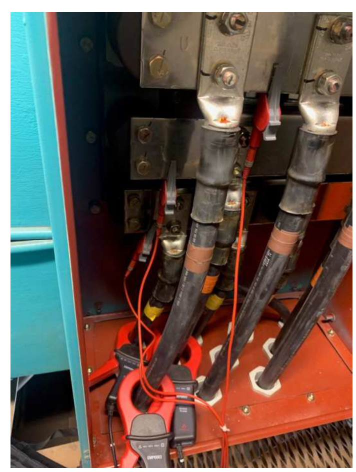

Figure 9: nacelle connections made in the 1.5 MW turbine generator connections.

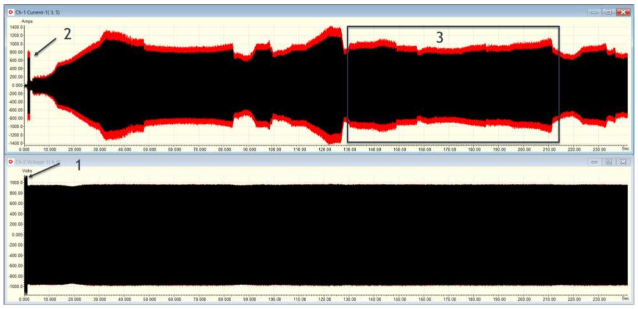

Figure 10: ESA inrush data 240 seconds. Top is current and bottom is voltage.

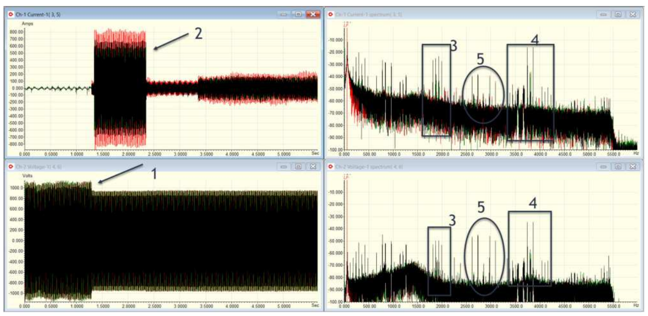

Figure 11: FFT analysis of current (top) and voltage (bottom).

Voltage and current ESA data was set to trigger on current one second prior to starting for a period of 240 seconds at a wind speed of 5.8 m/sec with gusts to 8 m/sec at an ambient temperature of 13C. Figure 10 point 1 is the voltage drop as the turbine is connected to the grid. Point 2 is an initial ~2 second resonance and inrush specific to this turbine design before the controls implement a soft-start. In Figure 10 point 3, this represents a stead-state while conditions on either side are the result of wind variations and gusts. The wind turbine has already yawed towards the best wind direction prior to point 2.

Figure 11 point 3 is the firing frequency of the rotor drive as read through the stator and point 4 is the second harmonic of the firing frequency. As ESA is an amplitude modulated technology, there are multiple sidebands around the carrier frequency. Point 5 is a resonance between the stator and transformer with a center frequency of 2854.0 Hz. This frequency is 190X the SSR frequency present at 15.02 Hz, which is an identified wind turbine SSR.[13]

Figure 12 points 1 and 2 are the firing frequency of the drive and its harmonic. Point 3 has shifted position from 2854.0 Hz to 2852.9 Hz which is a shift in the SSR frequency to 15.016 Hz. The output from the turbine is 161.75 kW and the losses at the SSR frequency are 1.6 kW, or 1% of the total load. An existing wye ring fracture is showing a loss of 5 kW, or 3% of the total load.

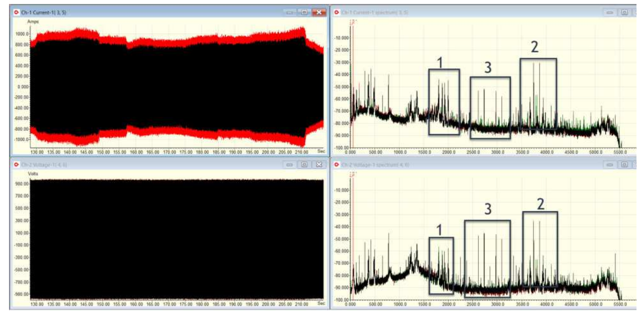

Figure 12: data from Figure 10 point 3.

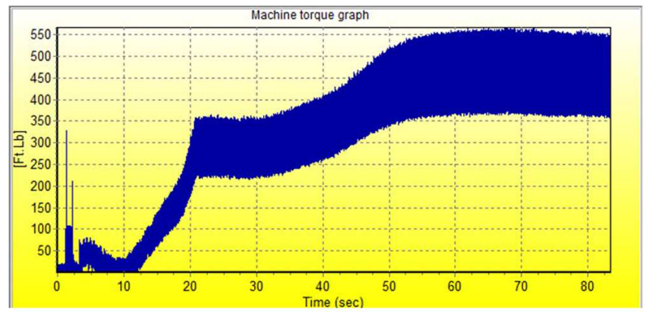

Figure 13: air gap torque across 85 seconds

A review of the torsional data (Figure 13) identifies that the initial start (Figure 10 point 2) has several impulses at the start and end of the closing of the breaker to the grid. As the turbine comes up to speed the airgap torque oscillation increases with loading. The mechanical RPM of the turbine remains constant.

VI. Discussion

The example in this paper is a sample from over 3,000 datasets from multiple wind turbine OEMs in different operating environments through North America. A smaller dataset includes 50 Hz applications from Asia. In all cases, similar conditions and frequencies exist and are consistent with related SSR literature. Within the SSR we are including Sub-Synchronous Torsional Interaction (SSTI) and Sub-Synchronous Control Interaction (SSCI) as defined in [3]. SSTI is the torsional SSR result from site and grid VAR correction. SSCI is the torsional SSR result from the turbine control and within the circuit between the transformer and generator stator and rotor. Practical data analysis using ESA concurs with the simulation data presented in the literature cited in this paper and the practical study presented in [5].

Based on the work presented in this paper, there is a combination of conditions that lead to the system effects between the transformer, generator, and gearbox. These include the SSR effect as well as the number of starts and load cycling.

In all operating conditions the turbine is brought to speed by the blades with the entire powertrain reaching the appropriate mechanical speed. Once the tower is at speed and the yaw control has directed the nacelle in the correct direction for a designed period of time, the breaker connecting the turbine to the grid is closed. This places a direct full load on the powertrain generating a shock through all components with an emphasis on the planetary gear system, high speed gear system, gearbox to generator coupling, generator rotor, and an oscillation between the generator and transformer. This effect will occur for more than one second regardless of manufacturer. Other operating conditions include:

- Equipment ambient and operating temperature. There is rarely cooling or heating present in the powertrain to control temperature. On the first, and depending on time between starts, subsequent starts the components may be at thermal extremes.
- Humidity in windings and other components including transformer and gearbox oils.
- Wind gusts and related extremes, including rapid changes to wind direction.

Load cycling will vary in addition to the loading. In the case of the transformer, turbine average loading capacity is 35% with the result of low transformer loading. Some transformer strategies include undersizing the transformer with occassional overloading when the turbine is operating at optimal wind speeds, which are normally above 12 m/s to 25 m/s, depending on size and blade design.

Through observation of the sites and failure histories of each site, the average time before an increase in the described failure modes is 12-15 years. In the example used in this paper, the site experienced rapid failures of main powertrain components and rotor wye rings at ten years.

Observations related to life improvements in such components as the rotor wye rings include the wye ring design, local operating conditions, control soft start design, and stiffness of the rotor windings. The starting shocks associated with machine operation include flexion of the rotor winding resulting in wye ring fatigue, operating torsional variations (Figure 13) which relate to long-term fatigue, and location of faults occur at the transition points of connection braising.

VII. Corrective Actions

There are multiple corrective actions to be considered to extend the operating life of wind turbines. These require a review of the transmission and distribution system as well as turbine control strategies. Following are recommendations to be considered:

- Existing short-term reliability improvements include stiffening systems such as thicker wye rings and modifications to gearbox design. For transformers, acceptance of higher gassing standards.
- Modifications to long-distance transmission and distribution strategies for VAR correction. Observations have shown that series and parallel VAR strategies have the same impact on wind farm reliability.
- De-tune SSR frequencies by turbine. Each turbine, depending on it's location in the wind site system, and operating environment, is effected differently. The use of active or passive filtering strategies at different operating points can eliminate the driving forces or improve turbine reliability.
- Changes to control strategies including soft-start and starting/loading characteristics. Modification to the rotor control firing frequencies can also provide improvement.
- A clutch between the generator and gearbox to reduce impact on the gearbox and shocks to the generator.

VIII. Conclusion

Wind turbine reliability related to key powertrain and circuit components is directly affected by the starting and control strategies, SSTI and SSCI (SSR), number of starts, and environmental conditions. The greatest stress related to SSR occurs at low wind speeds where power factor correction strategies initiate air gap torsional oscillations. These generate long-term rotor fatigue, gearbox component fatigue, and transformer gassing and aging.

Solutions for correcting and improving the reliability of the wind turbine requires a combined change in transmission and distribution strategies and turbine control and filtering strategies. Future control strategies should include a soft start ability that initiates concurrently with the closing of the main breaker connecting the turbine to the grid.

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