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Trends in Monitoring and Diagnostics of Wind Generators

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SUMMARY

This paper reviews the state of the art of monitoring and diagnostics for the electric machines used in wind generation. Wind generators experience a very unusual operating environment with varying duty cycles and ambient conditions. Access can be difficult and maintenance is expensive. The paper surveys different options for monitoring and diagnostics for synchronous and asynchronous wind generators. Current and vibration monitoring as well as flux density measurements are considered in order to diagnose the machines and the drive-train to which they are connected. Gaps are identified and recommendations are made on preferred schemes.

KEYWORDS

Wind generation, monitoring, current monitoring, vibrations, machine failures.

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I. INTRODUCTION

This paper reviews the state of the art of monitoring and diagnostics for the electric machines used in wind generation. The electrical generator, a high speed gearbox, main bearings and shaft comprise the drive-train, and account for a significant amount of turbine downtime as described in the next section. In addition to these, there are other electrical machines in the turbine, which, while small, also have an impact on turbine availability. This includes the pitch and yaw motors, which can be of the order of 10's of kW. Since wind generators and motors are relatively inexpensive, the value of monitoring and diagnostics is not always clear to wind farm operators. Hence there is reluctance to making additional investment in monitoring equipment. Wind farm operators also have some level of redundancy available in the dozens, and sometimes hundreds of turbines, they operate. This drives the need for techniques that make use of available hardware and keep costs low. In this paper we survey the major techniques by which this can be done, including those that are used in the broader electric machines industry but have not found their way into wind applications. Some emerging technologies are also discussed. We will also assess the impact of the availability of electromechanical systems on the turbine and illustrate the value of Monitoring and Diagnostics for representative cases.

II. JUSTIFICATION FOR WIND MONITORING AND DIAGNOSTICS

Operation and maintenance and parts costs for wind turbines are estimated to be 10-15% of the total income for a wind farm. The OM cost for offshore wind turbines is estimated to be 20-25% of the total income. Repair and maintenance that require usage of cranes create extra cost due to lack of crane availability and needs for optimal weather conditions to operate. Maintenance optimization could be realized using condition monitoring and early fault diagnosis. 40% of induction generator failures are related to bearings, 38% to the stator, and 10% to the rotor. Condition monitoring technologies such as vibration and stress wave analysis could detect some of these faults. There is an increased interest in using generator current and power signals to detect generator faults as well as gearbox problems such as gear eccentricity. The remote nature of wind turbines either on-shore or off-shore have dictated certain technical design needs to increase turbine reliability and availability by:

- Designing high reliability machines to reduce the number of repairs
- Building high redundancy in the design to reduce the number of turbine visits required
- Using automated systems and condition monitoring for high maintainability and shorter job times
- Increasing remote functionality of the turbine control system to reduce frequency of human intervention at site.

Both synchronous and asynchronous generators are still the main technologies in operation with no clear differentiation between the two in terms of reliability and availability. Some studies show a positive effect of the use of variable speed wind turbine generators on the power system stability of a weak grid. The use of solid-state power conditioning equipment has introduced more failures and increased system complexity.

III. FAILURE RATE, MTTR, AND AVAILABILITY OF WIND GENERATORS

A study on the reliability of more than 6000 wind turbines in Denmark and Germany shows that the failure frequency of direct drives generators is generally higher than that of geared generators but do have better potential to improve their reliability with time (see Fig. 1). However, the Mean Time To Repair (MTTR) of electrical-related subassemblies is lower than the MTTR of gearboxes. This suggests that all electric, direct drive wind turbines may ultimately have higher availability than an indirect drive wind turbines.

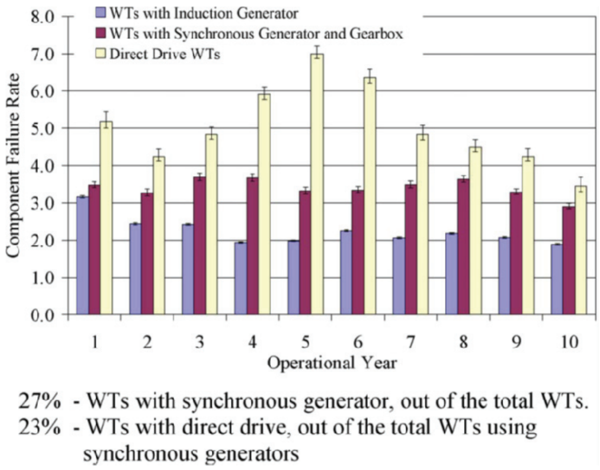

Fig 1. The failure frequency of the direct drive generator could be improved by replacing the field coils by permanent magnets

IV. Online Monitoring Techniques

Online monitoring of electric machines typically involves monitoring the mechanical and thermal quantities like shaft vibration and coil temperatures, terminal electrical quantities of the machine (e.g. current signature analysis), and near field and radiated electromagnetic quantities. The major electrical schemes are described below.

A. Current Monitoring

It has long been known that current monitoring can be used to detect certain irregularities in the electric machine. For example, broken bars and end rings of induction machines can be found by measuring the stator current waveform. After signal processing certain harmonics (notably 1-2s and sidebands) can be used to identify a broken bar.

Many rules of Current Analysis are somewhat similar to mechanical vibration analysis. For example, raised noise floor signature relate to issues such as looseness. Peak pairs that do not relate to running speed or line frequency are usually bearing related problems.

Comparing voltage signature to current signature could further help with identifying the root cause of the problem. For example, peaks that show in both current and voltage signature relate to electrical issues. On the other hand, peaks that only show in current signature relate to winding and mechanical faults [13].

Recent advances show that generator current signature analysis can also be used to pick-up torsional vibrations without any mechanical sensors [14]. Thus information about the mechanical condition of the gearbox in the drivetrain can be obtained directly from the electrical signals that are already being measured in wind turbines. Modern signal processing techniques can be used to obtain a diagnostic system that is robust to the influence of transmission error,, eccentricities and contact stiffness variations.

This technique also can be used to identify air gap eccentricity. Figure 2 shows a 4 pole induction machine which was modeled with broken bars, end rings and eccentricity. In Figure 3 we see the stator current over a number of cycles. An FFT of the stator current waveform shows the signal at 1-2s indicating the broken bar or other rotor anomaly.

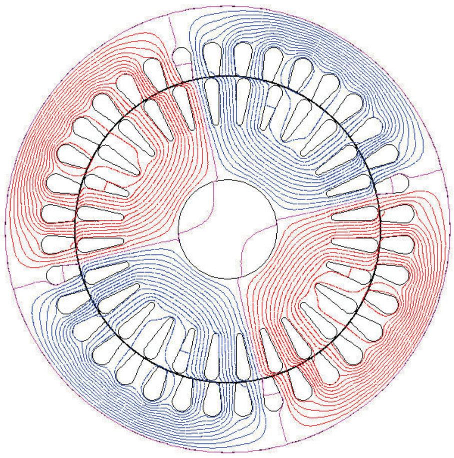

Fig 2. Commercial Induction Machine with Broken Bar

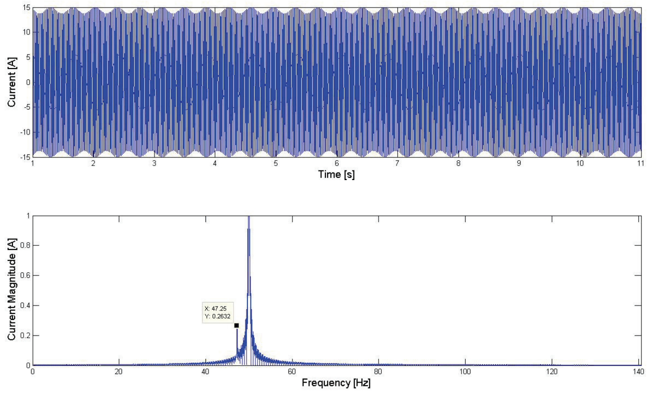

Fig 3. Stator current waveform and FFT with 1 broken rotor bar

Other techniques have been used for the processing of the stator current. For example wavelet transforms in addition to Fourier transforms may provide additional information [10]. In addition performing computation with the measured currents and voltages to computer instantaneous power, frequency, torque both in the 3 phase reference and the Parks (dq0) frame, all add additional value and information.[11][12]

B.   Air Gap Field Monitoring

Air gap flux monitoring can also be used to find faults in the machine. In Figure 4 we see a wound field synchronous generator. An air gap flux probe measures the flux density. It has been shown that by such measurements one can detect rotor short circuits and rotor ground faults. In Figure 5 we see the balanced signal (red) and the case of a ground in the field near the middle of the winding (blue).

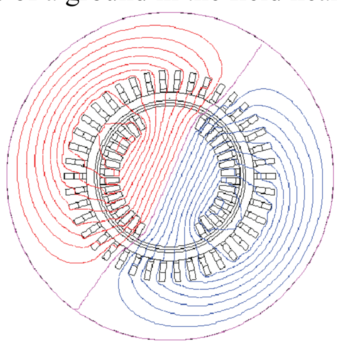

Fig 4. Flux Plot of Synchronous Machine.

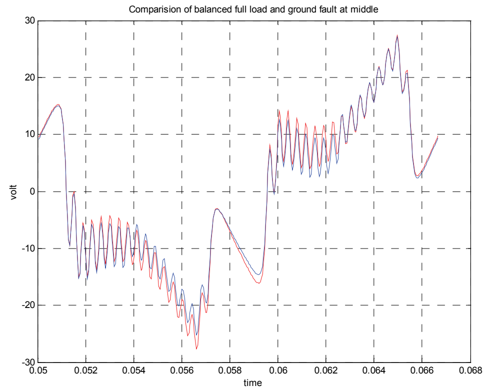

Fig 5. Balanced and Faulted Signal from Gap Flux

C. External Field Monitoring

Recently there have been advances in the measurement of external or leakage field of electric machines. This is due to accurate and inexpensive measuring devices and to the development of software to analyze the spatial distribution in multipole decompositions. By looking at certain multipole components we can diagnose faults or eccentricities in the machine. Figure 6 shows the field of a 6 pole synchronous machine at 1 meter with balanced poles while Figure 7 shows that same machine with a slight imbalance causing the dipole component to dominate.

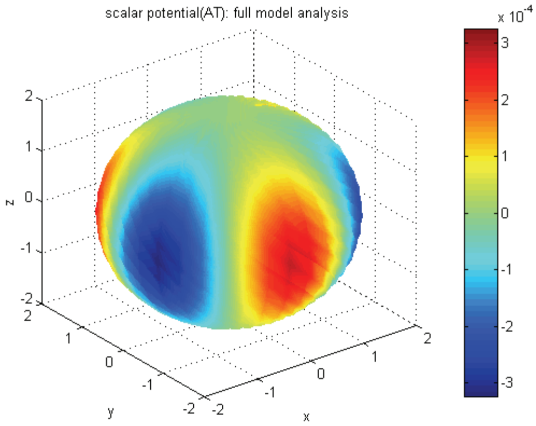

Fig 6. External Field of Balanced 6 Pole Machine

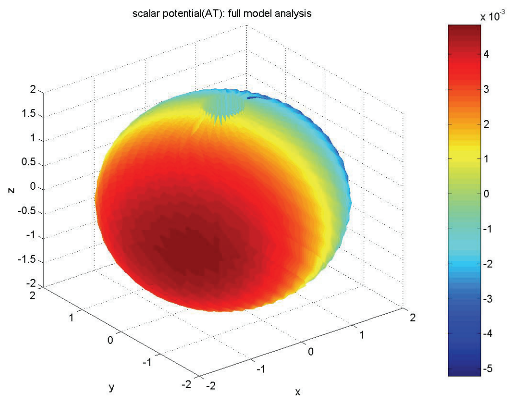

Fig 7. Same machine as Fig 6 but with small imbalance on the rotor

D. Mechanical Vibration Signature of Electrical Discharge Machining

One of the causes of premature bearing failure is known as Electrical Discharge Machining (EDM). EDM or fluting, as it is more commonly referred to, is the passage of electrical current through the bearing. This fault is also referred to as frosting, electrical pitting, and electric arc damage. The rate of failure can vary from a few months to a few years depending on the amount of shaft voltage present, the resistance of the bearing, the distance between the bearing ball and raceway, the type of lubrication, and the type of bearing.

There are three sources of shaft voltages and currents: electromagnetic, electrostatic, and external voltages supplied to rotor windings. Bearing damage resulting from fluting or shaft voltages and currents can be seen in a high frequency high-resolution vibration spectrum. This type of fault consists of high frequency modulated energy and appears as a mound of energy in the high frequency range between 2000 - 4000 Hz (see Fig 8). The location of the mound of energy due to EDM doesn't appear to be related to running speed or any other speed related variable. It has been suggested that the location may be related to the natural frequency of the bearing or encapsulating structure [5].

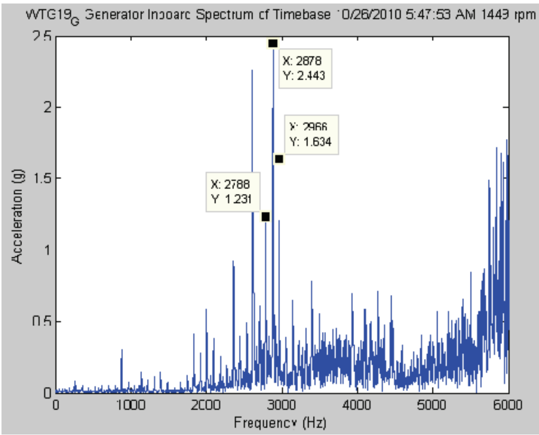

Fig 8. Vibration signature of EDM

The introduction of variable frequency drives in wind generation using Pulse Width Modulated (PWM) principles using the Insulated Gate Bipolar Transistors (IGBT) has introduced high frequency circulating currents, capacitive discharge currents coming from the high rate rise of voltage (dv/dt) and high switching frequencies coming from the common mode voltage indirectly. The combination of high frequency and capacitive discharge currents induce shaft voltage and bearing currents.

As the bearing lubricant film acts like a capacitor, every time this capacitor discharges, high frequency currents pass through the bearing generating magnetic fields. One way of detecting these electrical discharges causing premature bearing failure is by using an antenna to detect changes of the magnetic field that reflect the occurrence of discharges happening in the bearings.

V. Conclusions

Existing M&D techniques such as vibration analysis and Electrical Current Signature provide tools to detect bearing defects, unbalance, as well as rotor and stator defects. However, the economics of wind turbine generator requires a low cost M&D system. Wind turbine maintenance cost is going down as more reliable and more robust wind turbine generator designs are being introduced to the market. This puts more pressure on pushing the M&D system cost down to keep the payback cycle short. The trend is to offer a cost-effective integrated M&D system that monitors the health of the whole wind turbine drive train, which includes the gearbox, the generator, and the main bearing(s). Vibration accelerometers are the sensors used for a number of systems in the market. However, Electrical Current Signature is a promising technology as it offers a wide range of analysis for the whole drive train components using a minimum number of sensors, thus, reducing overall system cost. Moreover, the current signal could be obtained by tapping into existing current transformers, eliminating the cost of current sensors. Also, Electrical Current Signature technology could be used to detect defects of components such as auxiliary motors, if the fault signatures for these components are captured in the electrical current spectrum. Correlating current signature with other signals captured by the wind turbine SCADA system, such as bearing temperature, increases confidence level of failure detection and provides early warning of component defects.

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