Analysis of Wound Rotor Induction Generator Transient Vibration Signal under Stator Fault Conditions

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Abstract
This paper investigates wound rotor induction machine stator fault detection by vibration analysis under variable speed operation. The influence of stator electrical fault on machine operation is first examined using a time-stepped circuit model. The simulation results indicate that fault specific frequencies appear in the electromagnetic signal as a result of pulsating torques produced by stator asymmetric conditions. The fault specific frequencies are then translated into mechanical vibration at the machine frame that can be employed for fault detection purposes using conventional vibration analysis. Measurements taken in a series of laboratory tests on a commercial 30 kW machine under variable speed operation are used to investigate the spectral content of the generator vibration signal.

Keywords: Induction generator, condition monitoring, stator fault detection, vibration analysis, variable speed.

1 Introduction
During a wind turbine (WT) lifetime, a large proportion of wind power generation cost is related to WT operation and maintenance, with unscheduled maintenance accounting for about 75% of the overall maintenance cost [1]. This scenario becomes especially relevant in remote offshore installations, where emergency repairs may in many cases more than double the operator cost in comparison with onshore wind farm installations. Hence, in order to reduce overall generation cost associated to Wind Energy Conversion Systems (WECS), much effort has recently been put towards the development of practical condition based maintenance techniques.

Available WT subassembly fault surveys suggest that a considerable amount of WT downtime originates from generator failures [1]. Recent data indicate that for wind generators above 1 MW an important portion of failures/downtime is related to stator faults [1], [2]. With the current ongoing increase in WT generator size and the widespread use of wound rotor induction generators in modern WT drive systems the importance of achieving early and efficient detection of machine stator faults becomes apparent.

The most common approach for achieving non-invasive detection of stator winding faults in rotating AC machinery is based on spectral analysis of the machine electrical signals [3]. However, commercially available WT condition monitoring systems today typically employ the generator vibration signal analysis as a means of extracting information on generator electromechanical integrity [4], making no provisions for high fidelity current signal measurements. Vibration based monitoring systems today typically focus on double supply frequency generator vibration components for detecting stator electrical fault, however this approach can lead to ambiguous results in on-line applications as it is highly sensitive to excitation unbalance. In [5] it has been shown that, under steady state operation, the electrical faults in the stator of a wound rotor induction machine (WRIM) can result in torque oscillations at predictable frequencies. These torque pulsations are then transmitted as vibration onto the machine frame and can consequently be used to assist the conventional condition monitoring systems based on vibration analysis in achieving electrical fault detection and diagnosis. Variable speed operation is however the prevalent condition in a WT system and the manner in which the fault induced vibration frequencies are manifested during WRIM transient operation still remains to be evaluated.

This paper therefore investigates WRIM winding fault detection by vibration monitoring under variable speed operation. The presented analysis employs an advanced numerical model [6] to
predict and investigate the WRIG electromagnetic torque signal under transient operation for healthy and faulty operating conditions with a view to examining the possibility of detecting the fault induced torque pulsations in the machine frame vibration signal. Model predictions for transient electromagnetic torque are then compared with corresponding vibration signal measurements on a commercial 4 pole, 240 V, 30kW WRIM.

2 Modelling and experimental tools

The WRIG model used in this work is based on the principles of generalized harmonic analysis and enables detailed analysis of higher order fields effects in machine electrical quantities for a range of electrical faults [6-8]. In order to emulate the behaviour of the laboratory machine used for experimental research in this work, the machine design and operational data were used as model inputs.

The laboratory test rig comprises a four pole 30kW wound rotor induction machine coupled by a common shaft to a 40kW DC machine. The DC machine was configured to be used as a time-varying load for the WRIM by providing the field excitation that follows a prescribed time varying profile and recreates an operating speed transient representative of those found in WT generators. For the purpose of this research the WRIM rotor windings were short circuited and the stator windings were connected to the grid via a three-phase variable transformer. To enable the experimental emulation of winding faults, the IM stator was wounded with the individual coil connections taken out to an external terminal box where healthy and faulty winding configurations were achieved by appropriate connection of the coil terminals [6,7].

Effects of common open and short-circuit faults in stator phase windings with two parallel paths are investigated in this work. The healthy machine stator and rotor winding configuration corresponding to the manufacturer’s specifications, along with the investigated stator winding fault scenarios, are shown in Fig. 1. To avoid damage to the machine windings during the short-circuit test, the short-circuit current was limited using a variable resistor set at 0.3Ω, as illustrated in Fig. 1c). Power analyzers were used in IM stator and rotor circuits to monitor and record currents and voltages. The rotational speed was measured by 1024ppr incremental encoder. The vibration signal was recorded by installing an accelerometer on the top of the drive end bearing in the radial direction. The accelerometer output signal was conditioned using the Brüel&Kjær Pulse vibration analysis platform [9], thus enabling time-domain vibration signal acquisition. The recorded vibration signal was further processed using a short-time FFT algorithm for joint time-frequency analysis.

3 Vibration frequencies

Depending on the operating conditions of the machine, a series of specific frequencies are expected to appear in the electromagnetic torque signal spectra [5]. Neglecting the machine mechanical modes, these electromagnetic signal frequencies can be manifested at identical frequencies in the machine frame vibration signal. The induced vibration signal components have the potential to be used to obtain information on the existence of machine electrical fault or unbalance, as shown in [5, 10-13]. In [5], a series of slip dependant expressions that relate specific electromagnetic torque frequency components with the machine operating conditions were derived. These expressions are reproduced in Table I for completeness.

<table>
<thead>
<tr>
<th>Windings</th>
<th>Supply</th>
<th>Torque Frequencies</th>
</tr>
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<tbody>
<tr>
<td>Balanced</td>
<td>Unbalanced</td>
<td>[\frac{bk}{p} (1-s)] \omega</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[2 \pm \frac{bk}{p} (1-s)] \omega</td>
</tr>
<tr>
<td>Unbalanced</td>
<td>Unbalanced</td>
<td>[\frac{k}{p} (1-s)] \omega</td>
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<tr>
<td></td>
<td></td>
<td>[2 \pm \frac{k}{p} (1-s)] \omega</td>
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In Table I, \(k = 0,1,2,...\), \(s\) is the fractional slip, \(p\) is the number of pole pairs and \(\omega = 2\pi f\), with \(f\) being the system frequency. These expressions enable real-time tracking of fault specific components under variable speed operation, thus paving the way for achieving fault detection under transient operating conditions.

4 Simulation results

Fig. 2 shows the speed profile used in the numerical model for simulating WRIM variable speed operation. The presented speed profile is a filtered form of the WRIM speed signal recorded
during laboratory experiments and is used in the model simulations to ensure consistency in transient operating conditions between the experimental and the model results. The presented speed profile was simulated in the WRIM time-stepped numerical model, where a transition from healthy to faulty machine operation was induced in the calculations at $\approx 10s$ mark. Both open and short circuit fault scenarios were simulated in the laboratory experiments and model simulations.

Fig. 3 shows the spectrogram of the predicted electromagnetic torque signal for the open circuit case, demonstrating the appearance of additional time-varying pulsating torque components in the spectrum after the fault takes place. Monitoring these spectral changes would therefore enable the operator to achieve fault detection. For fault frequency tracking purposes, the expressions in Table I may be used to define frequency bands of interest as a function of rotational speed. This is illustrated in Fig. 4, where the spectrogram for machine operation using the speed profile in Fig. 2 is shown for a simulated short circuit fault, Fig. 1 c). The dotted lines in Fig. 4 represent the narrow spectral bands around fault specific frequencies that were obtained using the expressions for the unbalanced winding case from Table I. The fault frequency band width was set to 5 Hz in this example for graphical illustration purposes. It can be seen from the results that the occurrence of short-circuit fault at $\approx 10s$ results in presence of additional time-varying pulsating torques and that these are accurately predicted and contained by the identified narrowband spectral regions. The increase in magnitude of these components can therefore be monitored in real time for fault detection purposes.

The data in Fig. 3 and Fig. 4 demonstrate that identical frequencies appear in the torque signal as a result of different types of stator electrical fault. This is believed to be due to the nature of the fault induced air-gap field distortion which is identical for the considered open and short circuit faults. The expressions in Table I were derived for the general case of stator winding imbalance [5] and it is believed that any stator winding asymmetry, including the existing inherent manufacturing unbalance, will give rise to identical additional pulsating torques whose magnitude will then be determined by the type and the severity of the prevailing unbalance or fault condition. This is further illustrated in Fig. 5, where a moderate resistance unbalance ($\approx 10\%$) between the two groups forming a single phase winding, is applied at $t=10s$. The presented data illustrate that the applied phase unbalance results in the appearance of the same frequencies as those induced by stator winding faults. It is thus expected that, due to inherent asymmetries existent in any practical machine, low magnitude torque components at these frequencies can exist even under an assumed healthy operation. However, as can be inferred from the simulation results in Fig. 3 to Fig. 5, and as will be show later in this paper, the energy levels resulting from an actual failure in the tracked fault frequency are quite different from those present due to inherent machine asymmetry. This significant energy level difference allows for unambiguous fault detection.
5 Experimental results

In order to experimentally assess the viability of vibration analysis for stator electrical fault detection, the recorded vibration signals obtained from the laboratory test-rig under variable speed operation identical to that considered in section 4 were analyzed. Due to the physical constrains of the experimental set up, the present analysis is limited to sub-synchronous WRIM operation.

The results in Fig. 7 show the WRIM vibration spectrogram obtained from the test rig for the speed profile in Fig. 6 for an open circuit fault case. The dotted lines in Fig. 7 correspond to narrow bands around the first nine fault frequencies identified in the 1-1000Hz frequency range, as predicted by the expressions in [5]. As may be expected, and in contrast to the numerical simulation, the measured vibration signal is extremely noisy, illustrating the effects of the electro-mechanical interactions that are not considered in the numerical model. Consistently with the numerical simulation, high energy frequencies are seen to appear in the measured vibration signal after the fault takes place at \( \approx 10 \)s, indicating that by tracking such changes, fault detection should be feasible under practical conditions.

It should be noted that, on the contrary to the simulation results, some of the expected fault frequencies clearly appear before the fault takes place, the energy levels between the healthy and faulty conditions vary drastically and are solely electric fault dependant for the identified spectral components, so can therefore be used for fault detection purposes. For the machine under analysis it was found that the differences in energy levels between the healthy and faulty conditions were pronounced the most for the second and third fault frequencies, thus providing a practical fault detection mechanism. Hence, these two components were selected to illustrate the applicability of the proposed fault detection method. However, it should be noted that, fault detection is also possible using other frequency components.

The fault detection is performed in the time-frequency (TF) domain. To that end, the spectrogram of the vibration signal is calculated using a window function that ensures good TF resolution. Using relation (7) in [5], we can identify frequencies associated with faulty operating conditions, and based on these frequencies we can form TF bands that correspond to fault-specific non-stationary components. Tracking
energy changes within these TF bands provides a basis for detecting faulty conditions. More precisely, in healthy operating condition, the energy within TF bands corresponding to fault-specific components is very small, as opposed to faulty conditions when components with significant energy arise.

The central frequency of the band is calculated using (7) in [5], while the band width is chosen so that only the main-lobe of the considered window function is included. It is well known that the main lobe contains the greatest part of the window energy (e.g., 99.95% in Hann window and 99.81% in Gaussian window). Here, we can assume that fault-specific components are stationary within the window function, implying that their energy is concentrated within the main lobe. In this paper, the energy of the fault specific components is estimated by summing the periodogram values (squared modulus of the DFT) within the frequency band that corresponds to the main lobe of these components. In accordance with the definition of signal energy in frequency domain, the sum is additionally scaled by the number of periodogram samples.

The upper two plots in Fig. 8 correspond to the 3D time-frequency representation of the two fault-specific components selected for this analysis, second and third. The energies contained within frequency bands corresponding to these two components are shown in the lower two plots. Clearly, the fault induces a rise of energy within these frequency bands, which can be easily detected both visually and numerically.

Fig. 10 shows the frequency spectrogram for the speed profile shown in Fig. 9, for a short circuit case involving 7% of stator phase turns. As with the open circuit fault case, a significant rise in energy occurs for the same fault frequency components just after the fault takes place, as clearly illustrated Fig. 11. It should be noted that in this experiment, the maximum short-circuit current was limited to 50A in order to avoid machine winding damage, thus the differences in energy rise between the healthy and faulty conditions are severe limited compared with an actual short circuit. However, even with the self-imposed short circuit current limit, fault detection is possible using the proposed approach, thus further confirming its practical use.

![Fig. 8 Open circuit case frequency bands magnitude (top) and energy content (bottom) for two tracked fault frequencies](image)
6 Conclusions
This paper investigates the use of vibration signal analysis for the detection of electrical faults in a wound rotor induction. Numerical simulation is used to analyze the electromagnetic torque signal under transient conditions and experimental results were used to verify the induced effects in the machine vibration signal for different fault scenarios. The presented analysis demonstrates that electrical fault detection is possible using vibration analysis under variable speed operation by monitoring energy changes in fault specific frequency bands of interest.

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References


