Investigation of wound rotor induction machine vibration signal under stator electrical fault conditions

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Abstract: This paper investigates wound rotor induction machine torque and vibration signals spectra for operation with and without a stator short-circuit or open-circuit winding fault. Analytical expressions that enable the healthy and faulty machine pulsating electromagnetic torque frequencies to be related to shaft speed are derived and validated for operating conditions of interest. A coupled-circuit machine model is used to investigate the healthy and faulty electromagnetic torque signal. Shaft torque and stator frame vibration are measured on a laboratory test rig comprising a 30 kW wound rotor induction machine. It is shown that the existence of a stator winding inherent electrical unbalance or that arising from fault gives rise to a range of pulsating torque frequencies that are transmitted to the machine frame and can be detected in the measured vibration signal. The magnitudes of the resulting vibration components are demonstrated to be largely determined by the unbalance severity and the mechanical system response. The presented experimental results clearly validate the analytical and simulation analysis for the operating range of the investigated industrial machine design.

1 Introduction

Wind energy remains the dominant form of sustainable electricity generation. With a significant increase in wind energy penetration levels projected in the near future for a number of national markets [1], the development of effective wind turbine (WT) condition monitoring (CM) techniques is becoming crucial for minimising the downtime and maintenance cost of production systems. A considerable proportion of installed and currently manufactured megawatt size WTs use wound rotor induction generator (WRIG) drives for electromechanical energy conversion. Recent fault surveys [2–6] report high rates of winding failures in WT generators and indicate that these may make a large contribution to WT downtime.

The common approach to academic research on ac machinery non-invasive electrical fault detection is based on techniques utilising spectral analysis of machine electrical signals [7]. In this context, a number of authors have recently reported that WRIG winding fault specific spectral changes can be identified in WRIG currents for different industrial designs [8–10]. When WT drive train CM in the field is concerned the commercially available monitoring systems (CMSS) today are almost exclusively focused on generator vibration signal monitoring [11]; this technique can provide mechanical fault detection and general indications of the generator electrical fault. The existing commercial CMS solutions have however been reported to suffer from a high degree of diagnostic unreliability [12]. This indicates a distinct need for a better understanding of the fault information contained in the vibration signal, and in particular whether it can be used to better recognise and assess the generator electrical condition. In addition, the success of future CM platforms in delivering the required improvements in diagnostic reliability will largely depend on how effectively fault signatures can be identified in multiple electrical and mechanical signals. Vibration and torque signals monitoring and analysis for electrical fault detection was shown to be feasible in the literature [13–17]. However, these methods have received considerably less attention in comparison with electrical signal monitoring because of reported lower sensitivity of mechanical signals to electrical fault signature. Li and Mechefske [13] showed that a rotor broken bar fault will induce sidebands in the frame vibration spectrum; monitoring of these was however reported to provide lower sensitivity fault detection when compared with that achieved by current analysis. The estimated air-gap torque observation requires multiple generator signals to be monitored, but was shown in [14] to be an effective tool for recognition of cage rotor machine faults. The research in [15] presents a theoretical study that indicates that vibration signal spectral changes can occur with a stator winding fault in wound rotor induction machines. In [17] finite element analysis methods are applied to investigate the changes in air-gap force stress waves through cage rotor induction machine vibration measurement. This paper reports stator winding and rotor bar fault induced changes in low-frequency vibration signal components.

Given the extensive use of vibration analysis-based CMS in WT installations and their reported limitations in effective recognition of generator electrical fault, this paper investigates the electrical unbalance fault induced spectral effects in the WRIG vibration signal. The aim of this research is to clarify the nature of the WRIG vibration signal spectrum and the electrical fault and unbalance information it contains. This paper extends the work presented by Djurovic et al. [18] by providing an in-depth examination of the effects of a range of electrical faults on the shaft torque and frame vibration signals of an industrial WRIG. This paper also experimentally investigates the influence of the rotor converter on the WRIG vibration signature for operation with stator electrical fault in a doubly fed induction generator (DFIG) configuration. The work presents a generalised theoretical analysis of the WRIG electromagnetic torque signal spectrum that provides analytical expressions linking possible pulsating torque frequencies to machine operating conditions. A harmonic modelling technique [19] is employed to develop a WRIG model capable of predicting pulsating electromagnetic torque frequencies. The model is then used to investigate the torque signal spectrum under healthy and faulty operating conditions. The predicted pulsating torques are shown to be clearly detectable in shaft torque and stator frame vibration signals measured on the laboratory WRIG test rig. Both model and experimental results for the investigated machine design indicate the existence of a range of pulsating torques and vibration signal components that are stator winding unbalance specific. The magnitudes of these are shown to significantly increase with the presence of electrical fault. Propagation of winding fault harmonic effects in the shaft torque signal through to the frame vibration signal is
clarified by undertaking impact testing to characterise the mechanical response of the examined system. The consistency of the identified fault effects and developed theoretical principles are validated for the laboratory machine’s rated operating range.

2 Electromagnetic torque signal

Considering a general case of a three-phase \( p \) pole-pair wound rotor induction machine with no rotor excitation, a single frequency excited three-phase stator winding system will give rise to a range of air-gap fields with pole numbers \( v \) determined by the existing stator windings and supply arrangement. These can be expressed in general form by

\[
b_{gs}(\theta, t) = \text{Re} \left[ \sum_{n} \sqrt{2} B_{gs} e^{j(\omega_n t + \theta_n)} \right]
\]

(1)

where \( \theta \) is the angular coordinate in the stator reference frame, \( \omega = 2\pi f \) is the angular frequency and \( f \) is the stator supply frequency. For the rotor mechanical speed \( n_r \), the transformation between the rotor coordinate system (\( \theta' \)) and the stationary stator reference frame coordinate system (\( \theta \)) is given by: \( \theta = n_r t + \theta' \). Substituting the above in (1) and considering the fundamental slip relationship, \( n_r = \omega/\omega_s - 1 \) allows for the stator current driven air-gap field to be expressed in the rotor reference frame

\[
b_{gs}(\theta', t) = \text{Re} \left[ \sum_{n} \sqrt{2} B_{gs} e^{j(\omega_n (1 - s) t + \theta_n)} \right]
\]

(2)

Each individual stator harmonic field in (2) will induce an electromagnetic force of corresponding frequency in the rotor three-phase windings. The stator driven air-gap fields in (2) can therefore set up a range of harmonic rotor currents. Each induced rotor current will in turn create a range of harmonic fields in the rotor reference frame, with pole numbers \( \mu \) defined by the rotor winding arrangement. The resulting rotor current driven air-gap field will therefore take the following form in the rotor coordinate system

\[
b_{gs}(\theta', t) = \text{Re} \left[ \sum_{\mu} \sum_{v} \sqrt{2} B_{gs} e^{j(\omega_{\mu v} (1 - s) t + \theta_{\mu v})} \right]
\]

(3)

Transferring (3) to the stator reference frame gives

\[
b_{gs}(\theta, t) = \text{Re} \left[ \sum_{\mu} \sum_{v} \sqrt{2} B_{gs} e^{j(\omega_{\mu v} (1 - s) t + \theta_{\mu v})} \right]
\]

(4)

The induced rotor current driven air-gap fields’ angular frequencies in the stationary reference frame are defined by (4) as

\[
\omega_{\mu v} = \left( 1 - \frac{v - \mu}{p} (1 - s) \right) 2\pi f
\]

(5)

In the stator reference frame these rotating harmonic fields will interact with a range of stator current driven air-gap fields of supply angular frequency

\[
\omega = 2\pi f
\]

(6)

Each stator driven field with pole number \( v \) at frequency given by (6) can interact with a range of rotor driven air-gap fields with an identical pole number rotating at frequencies given by (5) and created by the induced rotor currents. The interaction of any two stator and rotor driven magnetic fields with identical pole numbers will establish an electromagnetic torque component. The angular frequency of the torque component created by two fields with identical pole numbers travelling in the same direction is given by the absolute value of the relative difference between their respective angular speeds, that is,

\[
| \omega - \omega_s | \quad (7)
\]

Similarly, for identical pole number fields travelling in opposite directions, the resulting torque angular frequency will be equal to the absolute value of the sum of the individual field angular velocities, that is,

\[
| \omega + \omega_s | \quad (8)
\]

Considering (7) and (8), the resulting electromagnetic torque signal angular frequencies can be established directly from expressions in (5) and (6) by considering the balanced or unbalanced winding operating conditions of interest and introducing appropriate constraints for possible values of \( \mu \) and \( v \). This analysis neglects the effects of stator supply higher-order harmonics, which need to be investigated separately. The presented derivations also neglect the influence of the machine’s mechanical system and consider only the air-gap field origins of the torque signal spectrum. An unbalanced stator/grid supply is assumed in the analysis, as is generally the case for online operating ac machinery. Electromagnetic torque frequencies can now be derived for the operating conditions investigated in this paper.

2.1 Balanced windings and unbalanced supply

When the machine operates with an unbalanced stator supply, for each stator driven harmonic air-gap field there will exist a forwards (\( + \)) and a backwards (\( - \)) rotating component. These stator field components will give rise to forwards and backwards rotating components of the rotor driven harmonic fields. Consequently, for every harmonic order, there will exist a range of field waves having the same pole number and travelling in forwards and backwards directions in the air-gap at speeds \( \omega^+ \), \( \omega^- \), \( \omega^+_s \) and \( \omega^-_s \). Therefore, for each considered harmonic order in the stator reference frame, forwards with backwards rotating field components interaction will be possible, as well as the interaction between field components travelling in the same direction. The resulting torque frequencies can therefore be determined from the following interactions

\[
| \omega^- - \omega^+_s |; \; | \omega^+ + \omega^-_s |; \; | \omega^- - \omega^-_s |; \; | \omega^+ + \omega^+_s | \quad (9)
\]

For unbalanced supply conditions, the pole numbers \( \mu \) and \( v \) are given by: \( \mu = \pm \mu (1 - 6m) \) and \( v = \pm v (1 - 6n) \), where \( m = 0, \pm 1, \pm 2, \pm 3, \ldots \) and \( n = 0, \pm 1, \pm 2, \pm 3, \ldots \). Substituting these expressions into (5) and considering (9), the possible torque angular frequencies for operation with unbalanced supply and balanced windings are derived as

\[
| 6k(1 - s) | 2\pi f \quad (10)
\]

and

\[
2 \pm 6k(1 - s) 2\pi f \quad (11)
\]

where \( k = 0, 1, 2, 3, \ldots \)

2.2 Unbalanced stator windings and unbalanced supply

A stator winding fault will give rise to air-gap field components and interactions identical to those described in (9). However, for the investigated faulty winding configurations, shown in Fig. 1, the considered short-circuit and open-circuit faults, as well as any electrical unbalance between individual phase winding parallel groups,
The harmonic effects of such a field distortion will be manifested in the possible presence of all harmonic orders over the air-gap perimeter of the analysed four-pole machine. Consequently, $\mu$ and $\nu$ will take a different form to that in Section 2.1, and all pole values can be assumed to exist, that is, $\mu, \nu, \pm 1, \pm 2, \pm 3,...$ A general expression for torque angular frequencies of a machine operating with a stator winding electrical unbalance can now be derived by substituting the above condition into (5) and evaluating the field interactions given by (9)

$$\frac{|k|}{p} (1 - s) \frac{2\pi}{f}$$  \hspace{1cm} (12)$$

and

$$|2 \pm k| (1 - s) \frac{2\pi}{f}$$  \hspace{1cm} (13)$$

where $k = 0, 1, 2, 3,...$ The expressions in (12) and (13) are derived under the general assumption that all winding unbalance induced harmonic fields will be equally manifested in the air-gap and predict all possible torque signal frequencies that can originate from the considered conditions. However, not all frequencies given by (12) and (13) will necessarily be present in the torque signal, as how each of these is manifested will be highly dependent on a particular machine winding layout and how it responds to the unbalance induced air-gap field distortion. The derived expressions for possible torque signal frequencies are summarised in Table 1.

### Table 1: Electromagnetic torque frequencies

<table>
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<th>Windings</th>
<th>Torque frequencies</th>
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<tr>
<td></td>
<td>$</td>
</tr>
<tr>
<td>unbalanced</td>
<td>$</td>
</tr>
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<td></td>
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</table>

A model study was undertaken to explore the spectral content of the laboratory machine electromagnetic torque signal for the examined healthy and faulty winding conditions. A typical super-synchronous operating speed of 1590 rpm was investigated in the calculations for illustration purposes. The simulations assume a stator phase voltage root-mean-square unbalance of ±1%, equal to that measured in the laboratory grid supply during experiments. It is important to point out that the model calculations neglect any time-varying interactions between the electromagnetic torque and the machine mechanical system (inherent rotor and/or shaft unbalance, natural/resonant frequencies) and therefore any pulsating torque damping or excitation that may result from these [15].

Machine operation with balanced windings and unbalanced supply was first simulated and numerical model predictions for the steady-state torque signal spectrum are shown in Fig. 2. In addition to the dominant DC component, the spectrum is seen to contain a number of pulsating torques at harmonic and inter-harmonic frequencies. These originate from the interaction of healthy machine harmonic air-gap fields, as discussed in Section 2. To understand and evaluate the influence of inherent stator winding unbalance, machine operation with a 3% resistive unbalance between parallel winding groups in individual stator phase windings was simulated in the model and the resulting torque spectrum shown in Fig. 2. The considered resistive unbalance value was measured between individual phase winding groups on the laboratory machine. The inherent winding unbalance is seen to result in a number of additional low magnitude frequency components in the electromagnetic torque spectrum: balanced windings (top) and inherent winding unbalance (bottom), unbalanced supply, 1590 rpm

**Fig. 2 Electromagnetic torque spectrum: balanced windings (top) and inherent winding unbalance (bottom), unbalanced supply, 1590 rpm**
predicted torque spectrum. These arise because of interaction of the unbalanced field harmonic components analysed in Section 2.2. The predicted torque spectra for machine operation with unbalanced supply and open-circuit and short-circuit faults shown in Figs. 1b–c, are presented in Figs. 3 and 4, respectively. The model study suggests that, even under perceived ‘healthy’ machine operation, the existence of inherent machine stator winding asymmetry can produce distinct small magnitude torque pulsations. However when an actual stator winding fault takes place, the resulting field distortion is significantly amplified and the magnitudes of these pulsating torques are much increased, becoming several orders of magnitude larger. Monitoring these changes may therefore provide useful information on the integrity of stator windings.

The pulsating torque frequencies identified in the model study results in Figs. 2–4 confirm the theoretical principles established in Section 2. The observed torque frequencies can be calculated for the corresponding operating conditions using the appropriate closed-form expressions from Table 1, coupled with the knowledge of the machine operating speed and the supply frequency. For the considered operating conditions, Table 2 lists the calculated pulsating torque frequency values in ascending order with the corresponding equations and parameters that yield the identified frequencies.

4 Torque and vibration measurements

4.1 Laboratory test-rig description

The laboratory test rig, shown in Fig. 5, comprises a four-pole 30 kW wound rotor induction machine coupled to a 40 kW DC motor. The DC motor torque and speed are controlled using a DC speed drive to operate the induction machine as a generator. The rig can be driven in WRIG or DFIG configuration; it contains a 40 kW back-to-back converter that can be used to inject/recover slip power into the rotor circuit to establish steady-state DFIG operation. The converter open loop controller enables the output magnitude and frequency to be separately set to a desired value. The converter switching frequency in this application was set to 8 kHz. For the purpose of this research, the WRIG rotor windings were either short circuited or interfaced to the grid via the back-to-back converter. The stator windings were connected to the grid via a three-phase variable transformer. To enable experimental emulation of stator winding faults, the WRIG stator was wound so that the individual coil connections are taken out to an external terminal box. The desired healthy and faulty winding configurations can be achieved by appropriate connection of the accessible coil ends. The available laboratory machine imposes the limit for the minimum amount of turns that can be shorted at seven. This enables the emulation of a practical short-circuit fault comprising 6% of the effective phase winding turns. Healthy WRIG winding configurations corresponding to manufacturer’s specifications, along with the investigated short-circuit and open-circuit fault scenarios are shown in Fig. 1. To avoid irreparable damage to the stator windings during short-circuit experiments, a variable resistor was used in the short-circuit path to limit the current. Different levels of incipient fault severity were investigated by adjusting the variable resistance to manipulate the magnitude of short-circuit current. Three-phase power analysers were used in the WRIG stator and rotor circuits to monitor and record currents and voltages. The rotational speed was measured by a stub shaft mounted 1024 ppr incremental encoder. The electromagnetic air-gap torque signal for a balanced machine was estimated from recorded stator voltage and current measurements [14, 22]. To accurately measure the dynamic shaft torque, the IM was mounted on a Kistler 9281B force platform containing three-axis piezoelectric transducers [23]. The stator frame vibration signal was recorded by installing a Bruel & Kjaer accelerometer (DT4394) on the top of the drive end bearing in the radial direction. The accelerometer output signal was conditioned using the Bruel & Kjaer Pulse vibration analysis platform. The vibration signal FFT analysis was performed using the Pulse platform proprietary routine at 6400 line resolution for the investigated 0–1 kHz bandwidth. The air-gap and shaft torque FFT measurements were performed for the identical bandwidth with a resolution of ±0.1 Hz.

4.2 Experimental results

The analysis in Sections 2 and 3 indicates that stator winding faults can increase torque pulsations at predictable frequencies that can be numerically determined. The identified electromagnetic torque pulsations will be transferred to the machine shaft, but can also be manifested mechanically on the machine frame as radial vibrations, because of the interaction of forces produced by torque pulsations with the machine’s mechanical system [15, 16]. Not all frequencies

<table>
<thead>
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<th>#</th>
<th>Balanced windings</th>
<th>Winding unbalance/fault</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Equation number/k</td>
<td>Frequency, Hz</td>
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<tr>
<td>1</td>
<td>(11)/0</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>(11)/1</td>
<td>218</td>
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<tr>
<td>3</td>
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<td>4</td>
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<td>854</td>
</tr>
<tr>
<td>9</td>
<td>(10)/3</td>
<td>954</td>
</tr>
</tbody>
</table>
observed in the torque signal will be equally present as vibration, since how the electrically excited vibration components are established largely depends on the considered machine’s frame mechanical response. Excitation forces acting near natural frequencies of the machine’s mechanical system are likely to result in a pronounced motion response [16].

To verify the spectral phenomena observed in numerical simulations, a series of experiments were undertaken on the laboratory test rig. The generator was driven at a typical operating speed of 1590 rpm and vibration, shaft torque, stator voltage and current signals recorded. Stator short-circuit fault was simulated by shorting seven turns in laboratory tests. The open-circuit fault was established by open circuiting one leg in a phase winding. To avoid damage to machine windings and because of laboratory supply limitations (≤60 A), the short-circuit current was limited to being approximately equal to the machine rated current (50 A) by adjusting the variable resistance in the short-circuit path to 0.3 Ω.

The estimated air-gap torque spectrum obtained from stator voltage and current measurements for the machine operating with balanced windings is shown in Fig. 6. The electromagnetic torque

![Figure 5](image1.png)

**Fig. 5** 30 kW WRIG laboratory test rig

![Figure 6](image2.png)

**Fig. 6** Estimated torque spectrum for balanced windings and unbalanced supply, 1590 rpm

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frequencies predicted by the model simulation in Fig. 2 for the same operating conditions and calculated using the equations in Table 2 are clearly present in the experimental results. This observation confirms the validity of the developed frequency expressions and the efficacy of the numerical model. There exist additional components in the estimated torque signal, which are believed to mostly originate from the supply harmonic effects and unbalances that this paper neglects [24]. The estimated air-gap torque signal does not account for unbalanced operation or mechanical interactions in the system so the shaft torque signal measurements are used in further analysis in this paper.

To investigate the influence of the mechanical response of the laboratory test rig on the electromagnetically induced vibrations, a series of impact tests were performed recording the mechanical response of the machine frame to vertical axis excitation. Fig. 7 presents the measured frequency response obtained from impact testing for the vertical acceleration component; this corresponds to the frame vibration measurements on the vertical plane investigated.

---

**Fig. 7** Test-rig impact test frequency response, vertical acceleration

---

**Fig. 8** Measured shaft torque spectrum, 1590 rpm

a Balanced windings

b Open-circuit fault
c Short-circuit fault
experimentally in this paper. The frequency bands containing each of the nine slip dependent fault frequencies identified in Table 2 are mapped in the figure for the machine rated operating speed range (≈1500–1620 rpm).

The recorded response indicates that frame excitation at the second unbalance induced frequency [(12), \(k=6\) from Table 2] can be expected to exhibit the strongest response in the vibration spectrum for the machine rated operating region. The 1st, 3rd and 6th fault frequency excitations can also be expected to exhibit a moderately strong response. It is interesting to note that, in addition to being present for machine operation with healthy windings (Fig. 6), the excitation at twice supply frequency \(2f\) (100 Hz) that is commonly monitored for global electrical fault detection [17] is not expected to exhibit the strongest response in vibration as result of a stator winding failure. This implies that, depending on machine design, alternative frequency components may be better suited for electrical fault detection using vibration analysis.

The measured vibration and shaft torque signals spectra for machine operation with balanced windings, open-circuit and short-circuit faults are shown in Figs. 8 and 9, respectively. Frequencies corresponding to the electromagnetic torque signal components identified in Table 2 are labelled in the measurements. Minute discrepancies between the numerical data in Table 2 and frequencies measured in Figs. 8 and 9 are because of an assumed ideal 50 Hz supply and 1590 rpm speed; the measured values of these two quantities are slightly different and time-varying because of inherent supply frequency oscillations and limitations in velocity measurement accuracy. The measured vibration and shaft torque data account for the mechanical effects in the test-rig drive train, as well as the supply harmonic effects, and are therefore significantly noisier than the estimated air-gap torque signal. A number of components seen in the measured spectra originate from inherent unbalances in the

![Fig. 9 Measured vibration signal spectrum. 1590 rpm](image)

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<th>Frequency, Hz</th>
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<th>Vibration [normalised]</th>
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machine mechanical system and are found at frequencies equal to integer multiples of the rotor mechanical speed.

The measured shaft torque signals are seen to be in good agreement with the spectral content patterns observed in the model predictions of electromagnetic torque in Figs. 2–4 and the measured air-gap torque spectrum in Fig. 6. All relevant torque signal components predicted by the model are clearly manifested in the measured shaft torque spectrum for the considered healthy and faulty operating conditions. As expected, the mechanical response of the machine frame is seen to have a moderate effect on how the existing shaft torque pulsations are transferred to machine frame as vibration. All shaft torque signal spectral components identified as originating from the interaction of air-gap fields are clearly present in the corresponding measured vibration signals shown in Fig. 9.

The experimental results in Figs. 8 and 9 indicate a clear relationship between the magnitude of all electrically excited vibration signal spectral components and the presence of winding fault. The recorded increase in individual component magnitude averaged from three separate vibration measurements is summarised in Tables 3 and 4 for winding unbalance-specific components and those existing for healthy windings, respectively. The data in Fig. 9 and Tables 3 and 4 demonstrate a general vibration level increase in presence of winding fault. However, on examination of the individual components magnitude change with fault, it becomes clear that the winding unbalance-specific components exhibit a significantly higher rise in relative magnitude when compared with other electrically excited vibration components. The unbalance-specific components are seen to be manifested at different levels for short-circuit and open-circuit faults at the investigated load point, indicating different sensitivity to the existing unbalance intensity. This is especially evident for the 477 and 577 Hz components that exhibit the highest increase for a short-circuit fault. Similarly, the magnitude increase of 695 and 795 Hz components is dominant for an open-circuit fault. The latter pair of components is also seen to exhibit a much higher sensitivity to fault than the component at double supply frequency, which is a commonly used stator electrical unbalance indicator. The 418 Hz component is also seen to have a strong presence in the spectrum with existence of winding fault. All these high sensitivity frequency components were found to be in close proximity to local resonances of the mechanical systems.

To provide a more clear illustration of the winding fault induced effects, a detailed side-by-side comparison of the measured shaft torque and vibration signal spectra is shown in Fig. 10. To separately identify the influence and highlight the natural modes of the laboratory rig mechanical system, the figure also includes the WRIG vibration and shaft torque spectra measured with no excitation and the rotor driven at constant speed. For the presented narrowband spectra, a clear increase in the magnitude of ≃59 Hz torque and vibration component occurs with the presence of a winding fault. A much less significant fault induced magnitude variation is present in other spectral components.

To assess the impact of rotor converter noise on the observed spectral phenomena when WRIG is configured for DFIG operation, a series of experiments were conducted with the machine’s rotor circuit interfaced to the grid via the back-to-back converter. Fig. 11 shows the shaft torque and vibration signals frequency spectra for DFIG operation at 1590 rpm and the test rig operating conditions consistent with those analysed in Fig. 10. The converter operation is seen to induce the appearance of additional low magnitude frequency components and general noise in the shaft torque and vibration spectra of the WRIG. These effects are clearly

<table>
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<th>Frequency, Hz</th>
<th>Vibration, m/s²</th>
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illustrated in the frequency spectrum below the fundamental rotational frequency (26.4 Hz) for the measured bandwidth shown in Fig. 11. More importantly, the observed effects were not found to have a significant detrimental influence on the identified fault specific components, suggesting these could be used as fault indicators for DFIG operation.

4.3 Sensitivity assessment

The results of an experimental study investigating the magnitude sensitivity of the nine winding unbalance induced components identified in Table 2 to different short-circuit fault levels are shown in Fig. 12. The data clearly indicate that the 2nd frequency component is exhibited at the highest magnitude level suggesting that its monitoring would be most feasible for the investigated machine design. It is interesting to note in Fig. 12 that, although good correlation exists between the shaft torque and vibration signals, the relative magnitude differs considerably between some torque and vibration components at matching frequencies. This difference may be explained by the fact that the shaft torque measurement is established by considering the interaction between forces acting in both horizontal and vertical planes [23], whereas the
vibration signal is reported for the vertical component of acceleration only.

A load dependency study was conducted, where a series of signal measurements were taken in uniform steps within the machine’s rated operating region, that is, from no load conditions until rated current (~59 A stator) was achieved. For each different steady-state load levels, three separate measurements were taken for stator short-circuit fault and averaged in order to minimise the sensitivity to variations in the grid supply. The study results are presented in Fig. 13 for the nine winding unbalance induced components. The data show a predominantly rising trend in magnitude of components with increasing load. However, individual components exhibit different load dependencies and some are seen to be more pronounced than others. In concordance with Fig. 7, the results in Fig. 13 highlight the 2nd fault frequency component as having the highest magnitude throughout the operating range. In combination with the sensitivity study results this data confirm that, for the investigated machine design, the 2nd [(12), $k=6$] unbalance-specific vibration component would be the most suitable for providing winding fault information.

## Conclusions

This paper investigates the electromagnetically induced shaft torque and vibration signal pulsations for wound rotor induction machine operation with and without stator winding unbalance or fault. These effects are first examined through developing a generalised theoretical analysis of the machine air gap fields’ interaction and the resulting electromagnetic torque pulsations. A detailed harmonic model of the investigated industrial machine design is then employed to perform a numerical study of the winding fault and electrical unbalance effects in the electromagnetic torque signal. This paper then uses a purpose built fully instrumented 30 kW wound rotor induction machine laboratory test rig to undertake an in-depth experimental study of winding unbalance and fault effects. The measured shaft torque and stator frame vibration signals are examined for the rated operating range of the laboratory machine. The test rig can be configured to operate in steady-state DFIG regime and was used to investigate the influence of the rotor circuit converter on the observed spectral effects.

It is shown that a stator winding asymmetry gives rise to a range of theoretically and numerically predictable pulsating electromagnetic torques that are detectable in the machine shaft torque and stator frame vibration signals. These are demonstrated to be significantly amplified by the presence of stator short-circuit and open-circuit faults. Monitoring of these components may therefore provide useful information on the stator windings electrical condition. Further investigation of the observed effects on a wider range of industrial wound rotor machine designs would be required to confirm the generality of the reported phenomena.

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## References


## Appendix

### 8.1 Appendix 1: Machine parameters

MarelliMotors E4F-225 wound rotor induction machine. About 240 V, 50 Hz, 30 kW, 3phase, 4 poles, 59 A stator rated current and 56 A rotor rated current.
8.2 Appendix 2: Machine model connection matrices

8.2.1 Healthy

\[
C = \begin{bmatrix}
1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\]

8.2.2 Short-circuit fault

\[
C = \begin{bmatrix}
1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\]

8.2.3 Open-circuit fault

\[
C = \begin{bmatrix}
0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\]