

CONDITION MONITORING ARTEFACTS FOR DETECTING WINDING FAULTS IN WIND TURBINE DFIGs

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Abstract:

Monitoring the condition of doubly-fed induction generators (DFIG) is growing in importance for Wind Turbines. This study presents the results of a comparison of DFIG steady state stator line current and instantaneous power when used as a means for generator condition monitoring, based on an examination of their frequency spectrum. For the purpose of this work, a detailed analytical model that makes it possible to simulate DFIG operation under a range of supply and winding balanced/ unbalanced operating conditions, was developed. Additionally, a purpose-designed DFIG test rig was built to facilitate the experimental validation of model results. The faulty machine current and power spectra are compared using experimental and model results.

Keywords: Wind Turbine, DFIG, condition monitoring, current, instantaneous power, frequency spectrum.

1 Introduction

At present doubly-fed induction machines are the dominant technology used for generators in variable speed wind turbines with ratings in excess of 1MW [1,2,3]. Monitoring the condition of such machines is an important aid to maintenance and improved reliability. Stator line currents and instantaneous power are commonly used as the basis of detecting electrical faults in induction machines [4,5,6]. The condition monitoring technique that is usually used in conjunction with these quantities is based on examining the frequency content of their steady state spectra and detecting the presence of tell-tale harmonic components or unexpected changes that may be linked to the

presence of a fault within the machine. The aim of such an analysis is, if possible, to identify clearly defined fault-specific current and/or instantaneous power harmonic components that have the potential to constitute reliable fault indicators. The practical advantage of this approach is that it is non-invasive. The machine windings are used, in effect, as search coils, and only a small number of additional transducers is needed to establish an efficient data acquisition system.

In order to monitor the condition of electrical apparatus it is essential to characterize the monitored signal so that the most likely faults can be unambiguously identified and appropriate action taken. The authors have developed a time-stepped coupled-circuit model expressly for this purpose. In this paper we compare current and power spectra for a DFIG operating with a stator open-circuit fault, using simulation data obtained from the time-stepped model. We also further substantiate the analytical findings with corresponding data measured experimentally on a specially-constructed test-rig.

2 DFIG Modeling

Machine modeling in this work is based on coupled-circuit theory and takes into account the precise distribution of the winding conductors, as well as the instantaneous values of the line voltages for both stator and rotor. As such the analytical model is capable of representing winding unbalance and/or excitation unbalance on either the stator or rotor. Additionally, model considerations account for higher order air gap fields unlike most other conventionally used methods [8]. The set of model voltage and flux linkage matrix equations is defined as:

$$V = RI + \frac{d\psi}{dt} \quad (1)$$

and

$$\psi = LI \quad (2)$$

where: V - is the machine voltage matrix, R - is the machine resistance matrix, I - is the machine current matrix, ψ - is the machine flux linkage matrix and L - is the machine inductance matrix. The machine mechanical operation is described by:

$$T_e - T_{LOAD} = J \frac{d\omega}{dt} \quad (3)$$

$$\omega = \frac{d\theta}{dt} \quad (4)$$

$$T_e = \frac{1}{2} I^T \frac{dL}{d\theta} I \quad (5)$$

where:

- T_{LOAD} : load torque including losses;
- J : combined rotor inertia;
- T_e : electromagnetic torque;
- ω : rotor speed in mechanical radians per second;
- θ : angular displacement of the rotor in mechanical radians.

Equations (1-5) describe the machine mathematical model and are solved in an iterative time-stepping numerical procedure. The model inputs that need be defined in order for a solution to be achieved are the machine supply voltages, load torque and the machine inductance and resistance values along with the rotor inertia. The model is especially sensitive to calculation of fixed and time varying winding inductances so the evaluation of these needs to be performed with the utmost care. The theory behind the modeling approach explained here is presented in more detail in [9]. Based on the presented model this work examines stator instantaneous power and line current spectra under machine operation with balanced as well as unbalanced windings and in steady-state conditions.

3 Experimental apparatus

The model described in Section 2 has been extensively verified experimentally on a specially-constructed test-rig [8,9,10]. The rig consists of a 4-pole 30kW wound-rotor induction machine, coupled to a converter-controlled d.c. machine. The induction machine stator was re-wound with several tapping points brought out to an external connection board. This enables the test machine stator winding to be readily re-configured. By this means, a range of faults, including short- or open-circuited coils or groups of coils, can be introduced for experimental purposes. The DFIG rotor circuit is excited from an active front end converter consisting of two industrial four-quadrant converter units coupled by a dc link. This setup allows for bi-directional power flow in the rotor circuit, depending on the speed regime in which the DFIG is operating. DFIG shaft torque is measured by means of an in-line torque transducer while primary and secondary current and voltage RMS values are evaluated using three phase power analyzers. The stator current and instantaneous power data is acquired through installing current and voltage transducers in the primary circuit and then sampling and recording the signals with a precision digital oscilloscope. The measured data is subsequently imported in MATLAB and analyzed using the built-in FFT function. The test rig schematic diagram is shown in Fig. 1.

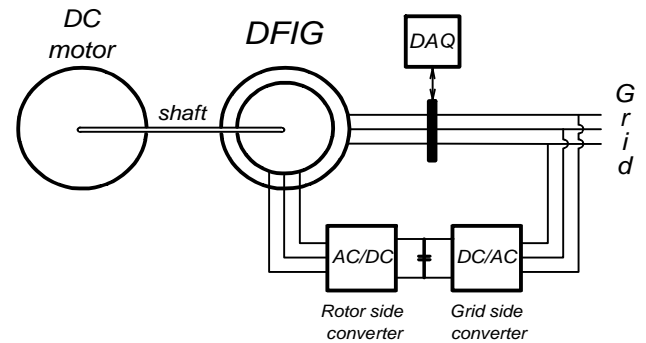


Fig. 1 Test Rig block diagram

4 Results and discussion

4.1 Correlation of Experimental Measurements and Model Predictions

A comparison of the predicted and measured stator line current and total stator instantaneous

power frequency spectra is given in this section. The DFIG winding configuration modeled in the simulations is for a faulty stator winding, where an open-circuit fault is introduced by opening one of the two parallel winding groups comprising a phase winding. The faulty stator winding configuration is shown in Fig. 2. This configuration was realized experimentally by open-circuiting part of the winding in the test rig.

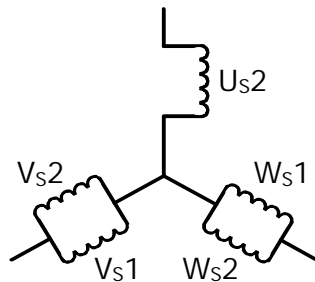


Fig. 2 DFIG Stator open-circuit fault winding configuration

The unbalanced stator and rotor voltages and the shaft load torque were measured during experiments and used as data inputs to the time-stepped model. In addition, two line currents and two line voltages were synchronously sampled and recorded. The instantaneous power signal was realized through multiplying the appropriate line currents and voltages and then summing their products.

The measurements were performed at a DFIG operating speed of 1651 rpm . Model results generated for faulty DFIG stator line FFT current and a DFIG operating point corresponding to the experimentally measured operating conditions are shown in Fig. 3a. The accompanying measured stator line current FFT spectrum is shown in Fig. 3b. The data shown in the graphs demonstrates good agreement between model predictions and experimental measurements in terms of the presented spectra harmonic frequency content. The dominant higher order harmonic components found in the calculated current spectra are seen to be at 114 Hz , 214 Hz , 278 Hz , 378 Hz , 444 Hz and 544 Hz . Comparison with experimental data shown in Fig. 3b indicates that these components are indeed present and can be clearly identified in the measured current spectrum. The obvious difference between predicted and measured data is noticeable in the content of harmonic components that are present at multiples of supply frequency, some of which are labeled in the experimental data at 150 Hz and 350 Hz for illustrational purposes. The existence of these components in experimental results originates from two causes, the first being the saturation present in the machine magnetic circuit, while the second is the influence of the existing supply voltage higher order harmonics that are consequently

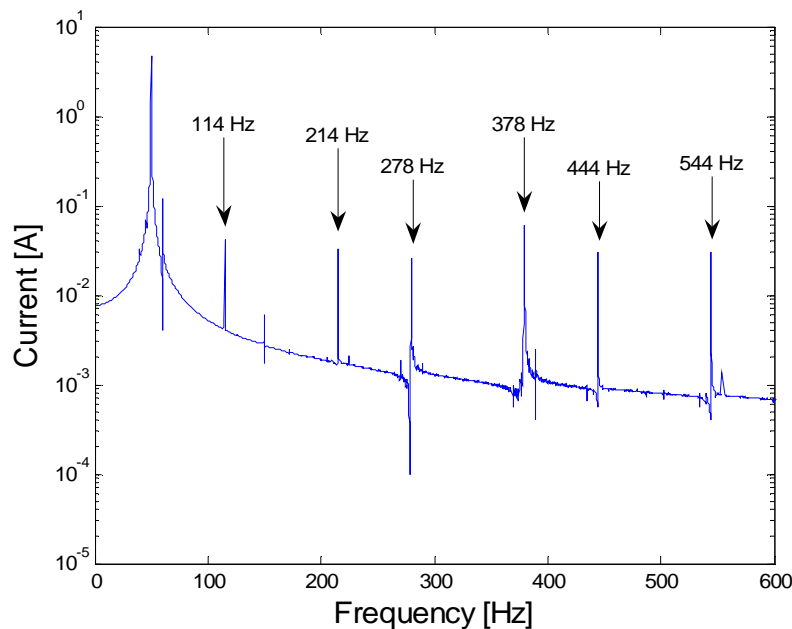


Fig. 3a) Calculated stator current FFT spectrum for DFIG operating with stator open-circuit fault and a speed of 1651 rpm

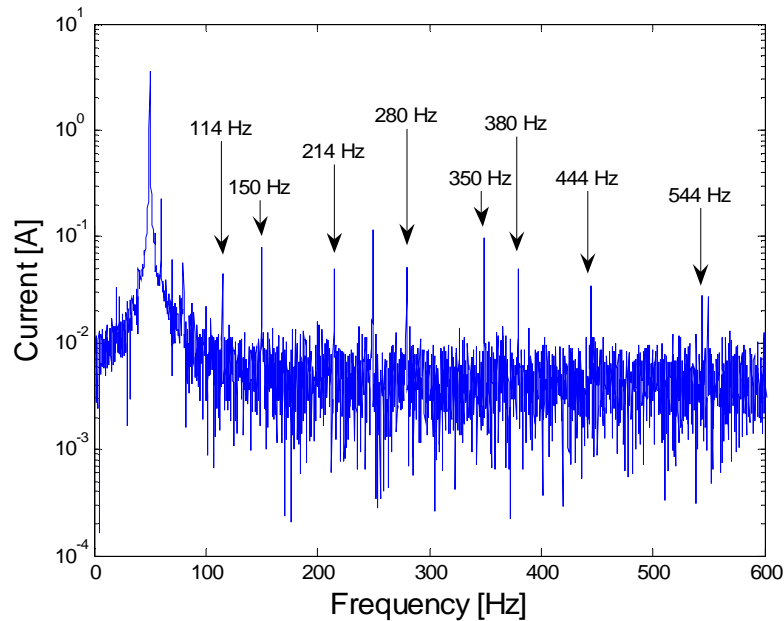


Fig. 3b) Measured stator current FFT spectrum for DFIG operating with stator open-circuit fault and a speed of 1651 rpm

reflected in the current spectrum. The analytical model used here does not account for any of these factors. The voltage supply is represented in the calculations as a pure sine wave. Magnetic saturation is dealt with in a conventional manner, through introducing the air-gap length correction factors. However, as harmonic components at multiples of supply frequency are not usually employed for condition monitoring purposes their absence in the model predictions is not considered to present a significant disadvantage to the approach taken in this work. The general noise level is another evident difference between predictions and measurements. For the most part, this is a consequence of the converter switching and measuring equipment, which are not taken into consideration in the model.

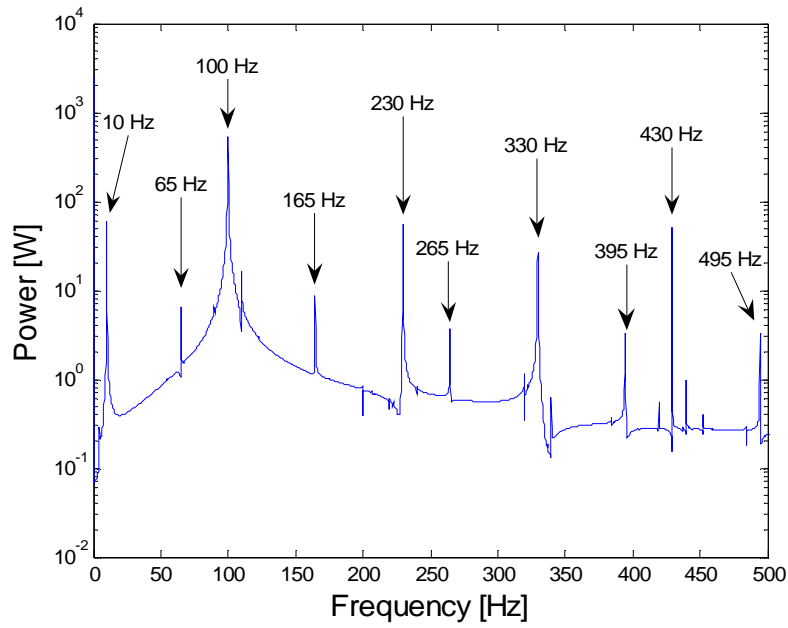
Figs. 4a and 4b give model predictions and test measurements for the stator total instantaneous power spectrum, for the same operating conditions. The data presented is again seen to show good agreement between calculation and measurement. The dominant harmonics found in model predictions at 10 Hz, 100 Hz, 230 Hz, 330 Hz and 430 Hz are also clearly visible in the experimental data.

The measured power spectrum is noticeably noisier than the current spectrum due to the effects of current and voltage multiplication, and

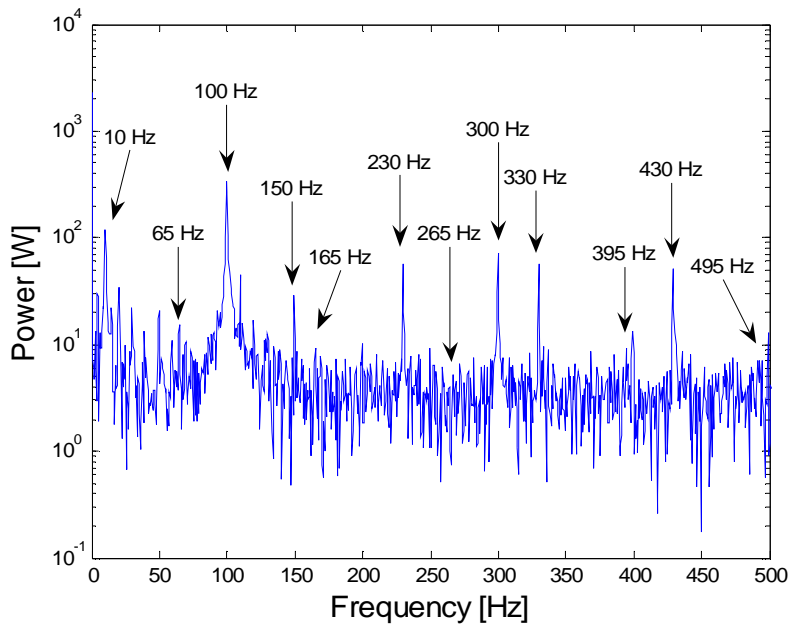
most of the harmonic components of smaller magnitude found in the model predictions are buried in the noise level in the experimental data. In addition some of the instantaneous power harmonic components that appear at multiples of supply frequency in experimental data, most obviously the harmonic component at 300 Hz, are not found in model predictions. The reason for this is that the existence of these components in the instantaneous power spectrum is mostly a reflection of the interaction of the current and grid voltage spectra harmonic components found at multiples of line frequency. These effects are not predicted in model calculations because the stator voltage is modeled as a pure sinusoid, and as was previously mentioned, the model predictions do not yield the existence of current harmonic components at multiples of supply frequency. The current and power data shown in Fig. 3 and Fig. 4 show good agreement between prediction and measurement, and demonstrate the validity of the model used in this work.

4.2 Comparison of Current and Power steady state FFT spectra content

In order to compare the potential use of line current with that of instantaneous power, as a medium for DFIG condition monitoring, a study



a) Calculated stator instantaneous power FFT spectrum



b) Measured stator instantaneous power FFT spectrum

Fig. 4 Calculated and measured stator total instantaneous power FFT spectrum for DFIG operating with stator open-circuit fault and a speed of 1651 rpm

was undertaken using the analytical model. DFIG operation was simulated at a typical super-synchronous speed of 1552 rpm for three seconds with balanced windings, after which a stator winding group was open circuited for another three seconds, corresponding to the winding configuration shown in Fig. 2. Finally

the open-circuited winding group was reconnected to the appropriate phase winding and DFIG operation then simulated with balanced windings for a further couple of seconds. The supply voltage used in the simulation was unbalanced, reflecting that measured in our experiments. As before, the

supply voltage is modeled as a single frequency sinusoid. Study results for stator line current and total instantaneous power were then analyzed with a short time Fourier transform (STFT).

Model results for stator faulty phase current are shown in red at the bottom of the graph in Fig. 5, with the top figure in the graph showing the frequency content of the current on the common time scale obtained from STFT analysis. Temporary transients are noticeable at $t=8$ sec and then again at $t=11.5$ sec, corresponding to the instant at which the open-circuit stator fault was introduced in the model and that where stator winding balance was re-established. The data presented shows that a significant change in stator line current harmonic content is induced by the presence of a winding fault. This is clearly noticeable in the STFT results between $t=8$ sec and $t=11.5$ sec. The harmonic components present in the faulty current spectrum clearly have the potential to be used as fault indicators.

Study results for stator total instantaneous power are shown in Fig. 6. Analogously to Fig. 5, the model results for instantaneous power against time are presented in the bottom figure

in the graph while the top figure gives the STFT frequency spectrum of instantaneous power for the same time vector. As before, brief transients are evident at the times when the fault was introduced and removed. Again, it is clear that the presence of the fault introduces additional lines in the spectrum. This obvious change in the spectrum may be utilized as a fault indicator.

Also, the comparison of study results in Fig. 5 and Fig. 6 shows that although the presented spectra demonstrate some common features, the steady state instantaneous power frequency seems to carry more potential fault information when compared with the steady state stator line current spectrum. This higher number of the induced harmonic components in power spectrum is largely due to the fact that the harmonic components found in the current spectrum are modulated with those existing in the supply voltage and so the instantaneous power spectrum yields more harmonic components. That is, if the line current contains a component, the model results shown in this study take into account the interaction of current harmonic components with only the fundamental voltage component, i.e. each

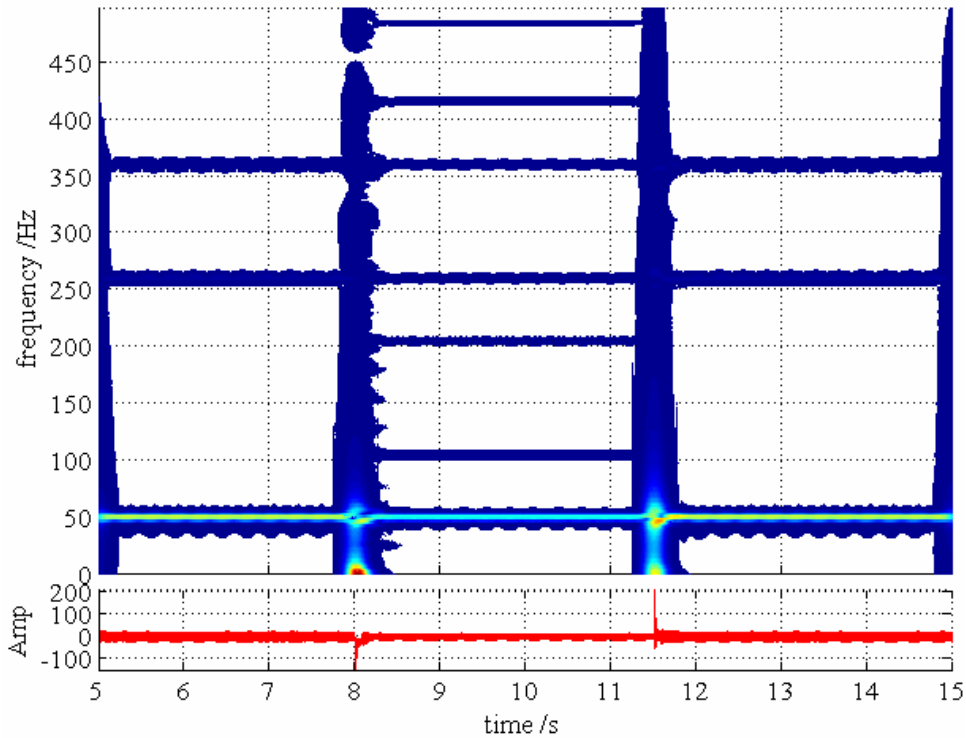


Fig. 5 Stator line current data and its STFT spectrum for healthy and open-circuit fault DFIG operation

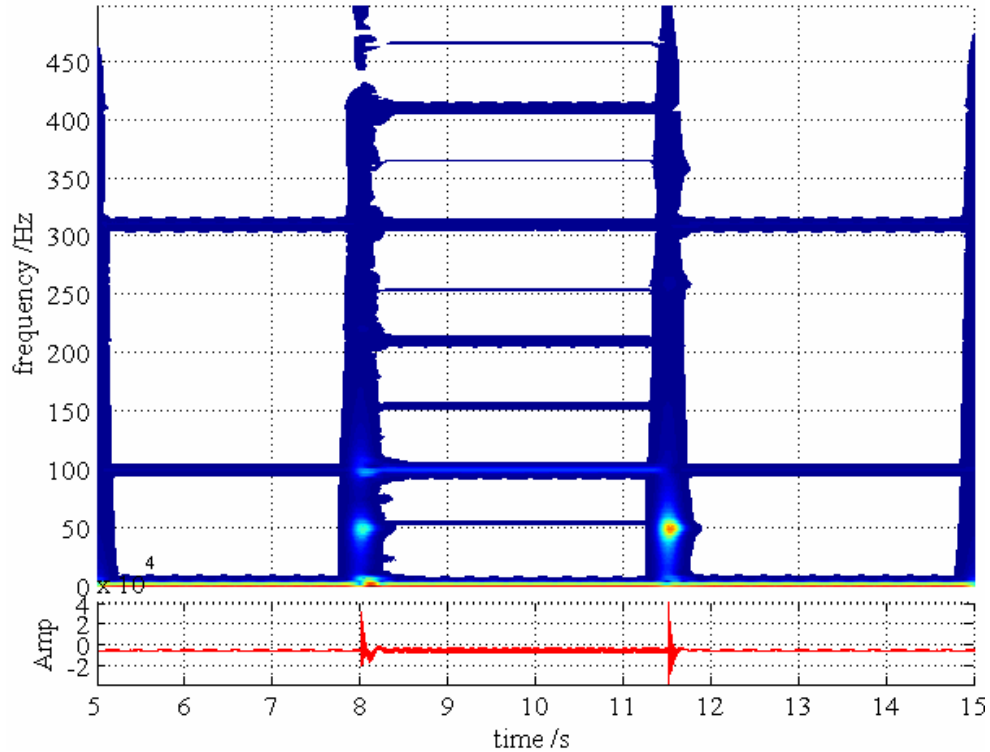


Fig. 6 Stator total power data and its STFT spectrum for healthy and open-circuit fault DFIG operation

current harmonic component is modulated with a 50 Hz signal in the calculations, as can be seen from the correlation of the presented STFT results for current and power. Furthermore when performing voltage and current signal multiplication to obtain the instantaneous power signal various components that exist at multiples of supply frequency in current and voltage spectrum due to effects of saturation and power quality also interact with each other and other components found in the spectra, and mostly give rise to additional components in the power spectrum at multiples of line frequency, as can be seen in experimental data in Fig. 4b. Since higher order supply harmonics and current harmonics at multiples of line frequency are not accounted for in analytical considerations the aforementioned effects are not found in the model predictions.

A difficulty when monitoring power is that the signal is derived from a number of voltage and current transducers and this has the potential to introduce additional noise, compared to monitoring current, which relies on only one transducer. This noise could be reduced by using the 2 wattmeter method and reducing the number of transducers, and by selecting low

noise transducers. Another noise problem for the power signal arises when the generator is unbalanced and the signal contains a 100 Hz component which varies in amplitude with time with the unbalance. However, the power signal has some advantages, as shown in Figure 6 compared to Figure 5:

- The 50 Hz component is greatly reduced in the faulty power signal compared to the faulty current signal.
- As described above the faulted power signal contains 7 harmonic components of interest, compared to Figure 5, where the faulted current signal contains 5 components of interest.

Based on this discussion the study suggests that in comparison with the line current, the instantaneous power could constitute a superior condition monitoring medium.

5 Conclusions

A detailed comparison of stator line current and instantaneous power spectra for a DFIG operating with a stator open-circuit fault is presented in the paper. The experimental and simulation results indicate that there are harmonic components in the current and power

spectrum whose existence is directly related to the presence of the type of winding unbalance that would arise in the case of a winding fault. A model study is undertaken which has demonstrated that the instantaneous power spectrum contains more potential fault-specific information when compared with the line current spectrum. However, measurement of the power spectrum requires more careful instrumentation to reduce noise. Advanced instrumentation and spectral analysis techniques may be capable of resolving these issues and utilizing the information found in the power spectrum more efficiently. In fact the authors are currently using wavelet transforms to extract fault data from the power signal under varying speed conditions [11] as arises in real wind turbines.

6 References

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