Detecting Generator Faults Using both Electrical and Mechanical Signals

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Abstract

With the rapid growth of wind energy based electric power generators, increasing the availability and reliability of Wind Turbines (WT) will aid in boosting energy production and minimise cost of energy. This paper presents a comparison of electrical and mechanical signals used in detecting both electrical and mechanical faults in induction generators. A series of experiments were conducted in steady state condition in order to obtain specific fault harmonic component present in the spectrum of the measured signals which are consistent and rise in magnitude with increasing generator speed when rotor winding imbalance and dynamic eccentricity were implemented on the test rig. This was then applied to a short period of variable speed condition. The spectral analysis was carried out using both Fast Fourier Transformation (FFT) and Continuous Wavelet Transform (CWT) algorithms to identify fault frequency components when faults were induced. The experimental results from the steady state condition shows a gradual rise in certain faulty frequency components magnitude with increasing speed. Rotor current was found to be very sensitive to rotor winding imbalance than vibration signal and vice versa when the test rig was operated under dynamic eccentricity condition. It was also revealed that the electrical and mechanical fault exhibit the same air gap flux distortion which reflected on the spectral analysis.

Keywords: Generator, Rotor Winding Imbalance, Dynamic Eccentricity, Current Signals, Vibration Signals

1 Introduction

Renewable energy generation is currently dominating in the energy policies of most developing countries. Ghana’s renewable energy target is to achieve 10% of its energy consumption from renewable energy sources (biomass, solar and wind) by the end of the year 2020 (Anon., 2015a). This is because renewable energy plays a vital role in reducing CO₂ emissions and the production of clean energy, which results in less dependence on imported conventional energy resources (Albizu et al., 2004). Several types of renewable energy technologies are emerging with different levels of growth and future potential. Wind energy has turned out to be one of the fast growing and promising renewable energy sources throughout the world (Albizu et al., 2004).

In wind energy generation, the energy from the wind is first converted into mechanical energy which is later converted into electrical energy by an electric generator which can be either asynchronous (induction) or synchronous. Induction generator is widely used in many industries because they are considered to be relatively reliable, less expensive and robust which is as a result of their simple and improved manufacturing technologies (Alwodai et al., 2012). However, they are liable to failure due to heavy load cycles, harsh working environment, and installation and manufacturing factors (Bhowmik et al., 2013). The current developments of power electronics for variable speed application have also increased the control and use of induction machines especially in the wind energy industries (Albizu et al., 2004). This is to enable wind turbine operates at its maximum power coefficient to obtain optimum energy over a wide range of wind speed (Kima et al., 2010). Induction generators are therefore constantly exposed to variable loads as a result of wind speed variation which could lead to failure due to high mechanical stress. The reduction in operation and maintenance costs and increasing the availability and reliability of wind turbines helps to improve the energy sector especially in cases where induction generators are installed in inaccessible areas. Detecting incipient faults of induction generators will therefore reduce its downtimes and extend its lifetime by applying condition monitoring systems (Anon., 2012).

A survey conducted by EU’s Reliawind on 4000 onshore wind turbines revealed that, 6% of the total turbine failures is caused by generators. Even though this seems to be minute, the downtime per failure is much greater as indicated in an onshore reliability data from Wissenschaftliches Mess- und Evaluierungsprogramm (WMEP) which is around 6 days (Anon., 2015b). Induction generators are subjected to major faults like stator faults, rotor faults, air gap eccentricity, and bearing failures. Stator faults are related to faults like opening or shorting of one or more of a stator phase winding while rotor faults include rotor winding insulation failure, broken rotor bar or cracked rotor end rings (Bhowmik et al., 2013).

Rotor winding fault is a form of electrical asymmetry which is usually related to the deterioration of the insulation of the windings.
which are mainly caused by thermal stresses as a result of aging and cycling (Duan, 2010). They normally occur as inter turn fault on the rotor phase winding causing distortion in the air gap flux. This generates excessive heat and eventually turns to rotor earth faults which result in an increase in vibration (Tavner et al., 2008; Wang, 2008). Air gap eccentricity is caused by the formation of an uneven air gap between the stator and rotor mainly due to improper positioning of rotor or stator core, shaft deflection, and worn bearing (Maruthi and Vishwanath, 2013). There exist two types of air gap eccentricity namely: static and dynamic eccentricity. Static eccentricity is the change in radial air gap along its length but fixed in space. Dynamic eccentricity occurs when the axis of the rotor is not positioned at the centre of rotation as shown in Fig. 1. There are cases where both eccentricities occur in the machine and is termed as mixed eccentricity (Maruthi and Vishwanath, 2013).

![Fig. 1 Air Gap Eccentricity (A) Static (B) Dynamic](image)

The presence of these faults in electrical machines exhibited one or more signs like imbalanced air gap voltages and line currents, increased torque pulsations, decreased average torque, increasing vibration, increased losses and reduction in efficiency, excessive heating and disturbances in the current/voltage/flux waveform (Darie and Darie, 2007) which helps in detecting the faults.

Hence, there are several diagnostic techniques for detecting electrical machines faults such as Current Signature Analysis (CSA) (Casadei et al., 2006), current negative sequence components, Park’s vector approach (Cheang, 2005), axial Flux Signature Analysis (FSA), vibration analysis, temperature measurements, chemical analysis, acoustic noise measurements, model by artificial intelligence and neural network based techniques (Darie and Darie, 2007). Most of these methods require high skills in computation and interpretation of results to implement them effectively. Therefore, simpler methods must be adopted to enable operators to monitor the condition of the machine and make reliable decisions.

CSA is a well-known and a reliable electrical monitoring technique for diagnosing faults in induction machine (Casadei et al., 2006). This technique detects faults based on the current harmonics with frequencies, which are peculiar to a type of fault (Alwodai et al., 2012). An advantage of using CSA is that current sensors are usually installed in wind turbines for control and monitoring purposes that helps to reduce costs and eradicate problems like fixing sensors on installed wind turbines (Casadei et al., 2006). When faults like rotor winding imbalance occur in the rotor winding, it produces an asymmetry of the rotor winding due to the reverse rotating magnetic field in the air gap induced by the current that circulate in the inter short circuit turns. As a result of the asymmetry of the rotor winding, the spectrum of stator or rotor current will change which can be used as an indicator for the presence of the fault.

Vibration is a natural phenomenon in induction machines due to the oscillations of mechanical parts of the machine, which are reflected in the machine frame attached to the rotating shaft (Djurović et al., 2014). Therefore, in the occurrence of a fault, there is an increase in vibration, which changes the frequency spectrum of the vibration signals. In comparison to the frequency spectrum of a healthy machine, it can be used as a fault detection and diagnostic technique (Darie and Darie, 2007).

The technique used in processing signal is very important in order to obtain accurate and reliable information to ascertain the operating condition of the machine. There are various ways to process signals from sensors, which range from time domain analysis to time-frequency analysis (Alwodai et al., 2013). This can be achieved by using Fourier transformation, wavelet transformation, and empirical mode decomposition. The use of power electronics and the variation of wind speed enables induction generators to operate continuously in non-stationary condition. Therefore, Fourier transformation will not be effective as a signal processing technique due to it been used in processing stationary signals (Crabtree and Tavner, 2011). According to Gritli et al. (2009), Short Time Fourier Transformation (STFT) can be used to overcome the shortfalls in Fourier transformation to some extent. This is done by analysing the signal over a short time interval but its shortcoming is the use of a fixed size window. Wavelet transformation has proved to be efficient in analysing signals from non-stationary conditions, which provide greater resolution in time for high frequency and greater resolution in frequency for low frequency components of a signal (Gritli et al., 2009).
In most studies, electrical signals (stator current) have been used in diagnosing both electrical and mechanical faults (Alwodai et al., 2012, Casadei et al., 2006, Crabtree and Tavner, 2011, Darie and Darie, 2007, Popa et al., 2003). However, in this paper, the use of rotor and stator current, and vibration signals to detect faults were considered. The study also considered the use of Fast Fourier Transformation (FFT) and Continuous Wavelet Transformation (CWT) techniques for signal processing as well as comparison between the two techniques.

2 Resources and Methods Used

2.1 Fault Detection Technique

Faulty frequencies in either stator or rotor current and vibration spectrum due to rotor winding imbalance and dynamic eccentricity were determined using expressions in Table 1. However, not all the fault frequency components given by the expressions can be seen on the signals’ frequency spectrum. These fault frequency components depend on the layout of a particular machine winding design and the response to the induced air gap distortion due to faults (Djurović et al., 2012a). Therefore, to determine frequency harmonic components in both current and vibration signals, series of experiments at different constant speed to identify specific fault frequency components related to the signals were conducted.

Table 1 Expressions used in fault detection

<table>
<thead>
<tr>
<th>Signals</th>
<th>Expressions</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator current</td>
<td>$f_t = \frac{k}{p} (1 - s)$</td>
<td>$k = 1, 2, 3 \ldots$</td>
</tr>
<tr>
<td></td>
<td>$\pm j f_s$</td>
<td>$j = 1, 2, 3\ldots$</td>
</tr>
<tr>
<td>Rotor current</td>
<td>$f_t = \pm k j f_s$</td>
<td>$k = 1, 3, 5\ldots$</td>
</tr>
<tr>
<td>Vibration signals</td>
<td>$f_t = \frac{k}{p} (1 - s)</td>
<td>f_s$</td>
</tr>
</tbody>
</table>

where $f_t =$ faulty frequency, $f_s =$ supply frequency, $p =$ number of pole pairs, $s =$ slip, $j =$ order of the grid supply induced current harmonic components, $k =$ any positive integer (Cheang, 2005, Crabtree, 2011, Wang, 2008, Saad et al., 2014).

2.2 Description of Experimental System

The experimental set-up is a model of a wind turbine system. The test rig consists of a three-phase 30 kW, 50 Hz, 390 V, 4-poles Wound Rotor Induction Generator (WRIG). The generator was mechanically coupled to a 54 kW DC variable speed drive controlled motor through a 5:1 two-stage gearbox (see Fig. 2). The DC motor was used to emulate the wind turbine rotor in the test rig.

Fig. 2 Photograph of the WT Condition Monitoring Test Rig

The speed of the DC motor was controlled by an external variable speed drive using a National Instruments LabVIEW environment, which allows the test rig to be driven under either constant or variable speed conditions. The induction generator was driven at super synchronous speed from 1510 rpm to 1600 rpm within intervals of 10 rpm at both healthy and faulty conditions. This was done to determine the specific faulty frequency component.

Six current and six voltage transducers were installed in a cabinet, which were used to measure stator and rotor current signals. These transducers measured the phase current and phase voltage signals output from the induction generator. Two accelerometers were mounted horizontally and vertically on the induction generator drive end outer case for measuring vibration signals at the various speeds. The rotational speed of the DC motor was measured by using a tachometer that was installed at the end side of the rotating shaft. All the signals were conditioned to provide accurate input to two National Instruments data acquisition pads (DAQ card) which were connected to a computer to monitor the condition of the induction generator. For each different speed, three tests were conducted and signals from all the transducers were compared. The signals with least variation in the supply voltage was chosen for processing.

The specific frequency components obtained from the constant speed experiment were applied to a variable speed condition to determine faults. The variable speed condition was operated using speed range from 1580 rpm to 1585 rpm. The signals obtained from the test rig were sampled at 5 kHz for 50 s.

2.2.1 Fault Implementation

The test rig was designed to enable both electrical and mechanical faults to be implemented on it.
Considering rotor winding imbalance fault, one of the phase rotor resistance was increased to 30% of the rotor resistance which increased the impedance along that phase and signals from each transducer were recorded. Mechanical fault was simulated by attaching a weight to a balance plane fixed to the generator rotor shaft. The balance plane contained holes at four different radii directions. A total mass of 412 g was attached to one of the radii direction to simulate dynamic air gap eccentricity fault on the test rig.

2.2.2. Signal Processing

The signals obtained from the various experiments were processed using both Fast Fourier Transformation (FFT) and Continuous Wavelet Transformation (CWT) algorithms in Matlab. The results obtained from the FFT algorithm were in bandwidth of 400 Hz while CWT were in the range from 20 Hz to 300 Hz.

3 Results and Discussion

3.1 Faulty Frequency Components

The fault frequency expressions given in Table 1 are slip and machine dependent. Therefore, to identify frequency harmonic components in the measured signals that are very sensitive to specific faults for a particular induction machine, the induction generator was driven at fixed super synchronous speed from 1510 rpm to 1600 rpm within intervals of 10 rpm at both healthy and faulty conditions. The signals from the sensors were processed using the FFT algorithm to obtained the magnitude of specific frequency harmonic components (k) which increase with generator rotor speed as shown in Figs. 3 - 5.

![Fig. 3 Variation of Magnitude of Specific Frequency Harmonic Components of Stator Current with Increasing Generator Speed under Rotor Winding Imbalance Fault](image)

![Fig. 4 Variation of Magnitude of Specific Frequency Harmonic Components of Rotor Current with Increasing Generator Speed under Rotor Winding Imbalance Fault](image)
The results showed that not all fault frequencies obtained from the expressions in Table 1 can be found in the signals spectra as shown in Figs 3 – 5. Faulty frequency components that showed a gradual rising trend in magnitude with increasing speed are presented in Table 2. Most of these faulty frequency components were also observed in the frequency spectrum of a faulty WRIG (Djurović et al., 2012a, Popa et al., 2003, Crabtree et al., 2010, Djurović et al., 2012b).

Table 2 Specific fault frequency components for different signals

<table>
<thead>
<tr>
<th>Signals</th>
<th>k values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator current</td>
<td>1,4,7,8,12</td>
</tr>
<tr>
<td>Rotor current</td>
<td>1,3,5,11,31,35</td>
</tr>
<tr>
<td>Vibration signals</td>
<td>1,2,3,4,6,7,12</td>
</tr>
</tbody>
</table>

NB. additional integers for detecting dynamic eccentricity using vibration signals, j = 1

3.2 Rotor Winding Imbalance

The fault frequencies obtained from the faulty machine at variable speed condition are labelled in Figs. 6 and 7 for stator and rotor currents, respectively.

The spectrum from the FFT algorithm contains noise due to the transducers used in generating signals and the measurement environment. The measured fault frequency components were seen to be in good relation with the expressions given in Table 1 for each signal even though it might not be the exact frequency obtained from the expressions. This is due to the supply frequency assumed to be 50 Hz and the variation in the measured speed, which in real time, slightly differ, that is, the supply frequency varies with time and limitation in the accuracy of the measured speed (Djurović et al., 2012a).

Comparing the frequency spectrum of stator and rotor currents of the faulty machine to that of the healthy condition as shown in Figs. 6 and 7, it can be observed clearly from the faulty current spectrum that labelled fault frequencies are above the noise level even though some of them have lower magnitude as compared to the healthy state. This is due to the construction imperfection, imbalance in the supply voltage (Robertson and Ong, 1995), and the inherent rotor electrical imbalance in generator, which also generate reverse rotating magnetic field. It can also be observed that there are higher spikes in the current spectrum that are not labelled. These are present in both
conditions as a result of high order harmonic content in power supply and can also be caused by magnetic saturation within the generator (Djurović et al., 2012a).

The fault frequency components for rotor current (see Table 2) are found at lower frequency, although they contain higher frequency which can also be used in detecting fault. Therefore, in comparing the magnitude of these fault frequency components in the stator and rotor current, it can be seen that the rotor current is very sensitive to rotor winding imbalance fault.

Figs. 8 and 9 present the CWT of stator and rotor current under rotor winding imbalance, respectively. The results clearly show that the rotor current is very sensitive to fault even when the imbalance is less severe as compared to the results from the FFT algorithm. Fig. 8 shows no clear evidence that the induction generator has developed any fault since the sidebands around the supply frequency of the stator current exist in even healthy machine. The CWT analysis of the rotor current showed that high frequencies can be obtained in the frequency spectrum which can be used to indicate the present of the fault.

The sensitivity of rotor current to the fault may be because rotor current produces rotating magnetic field, which interacts with that of the stator field, introducing faulty harmonic into the stator current. In addition, since the rotating magnetic field of the rotor is weak, there will be more distortion in the rotating magnetic field as compared to the stator rotating magnetic field. Therefore, rotor current can be used as a good indicator for very low rotor asymmetry.

Figs. 10 and 11 show the frequency spectrum under rotor winding imbalance for two vibration signals obtained from the vertical and horizontal transverse direction of the generator, respectively. The fault frequency components sensitive to the fault are identified and labelled in the graph.

Examining the frequency spectrum from the two vibration signals for both healthy and faulty condition, it is clearly visible to see fault frequencies. Although some appeared on the
healthy state spectrum with high magnitude especially in the signal obtained from the vertical direction due to the inherent rotor electrical imbalance in the generator. The spectra from the vibration signals show that, the position of the accelerometers on the generator is very critical and must be considered when installing them. From the results, it can be seen that the vibration signal obtained from the horizontal direction contain more fault frequency components with higher magnitude as compared to the vibration signal from the vertical direction. This can be due to the fact that the outer casing of the generator was bolted vertically to a workbench giving rise to high vibration in the horizontal direction.

Fig. 10 FFT of Vibration Signal under both Healthy and Rotor Winding Imbalance Conditions in the Vertical Direction

The CWT analysis from the vibration signals showed a clear indication that the signal from the horizontal direction is sensitive to the fault than the vertical direction but was not sensitive in the detection of the fault as observed in the rotor current. It was therefore not included. However, the frequency bandwidth in the CWT analysis which showed the indication that the fault fell in line with the FFT spectra of the vibration signals which present a high magnitude at a lower frequency of about 26 Hz.

Therefore, comparing electrical and mechanical signals in detecting electrical fault (rotor winding imbalance), it can be observed that even though both signals were able to detect the fault, the electrical signal (rotor current) showed a large number of rich harmonic components with higher magnitude which can be used to detect the fault even when the fault is less severe.

3.3 Dynamic Eccentricity

Figs. 12 and 13 represent the frequency spectrum under dynamic eccentricity condition of stator and rotor current, respectively. The frequencies of interest are labelled on both graphs, which give a clear indication of the presence of the fault as it can be seen above the noise level. Looking at both electrical signals, the rotor current indicated the presence of the fault with higher magnitude and clear visibility above the healthy state condition.

Fig. 12 FFT of Stator Current under both Healthy and Dynamic Eccentricity Conditions

The analysis from the CWT for both stator and rotor current also showed a similar result. This indicates that rotor current is more sensitive to the fault than stator current when compared with the
healthy state. However, they were not presented since the detection of the fault was not clearly visible. The sensitivity of rotor current to the fault implemented could be due to the weak rotating magnetic field experiencing more of the air gap flux distortion between the rotor and stator.

The frequency spectra from the vibration signals are presented in Figs. 14 and 15 with frequencies of interest labelled. It can be clearly observed that, there is increase in vibration when dynamic eccentricity was implemented on the test rig. Also, the vibration signal introduced two additional frequency components which were not all that visible when rotor winding imbalance fault was implemented.

The analysed vibration signals using the CWT algorithm are shown in Figs. 16 and 17. The CWT analysis from the vibration signal gave a clearer indication that the vibration signal from the horizontal direction is more sensitive than the signal from the vertical direction. The CWT analysis indicated the presence of the fault at lower frequency which is in line with that of the frequency spectrum obtained from the FFT algorithm.

![Fig. 14 FFT of Vibration Signal under both Healthy and Dynamic Eccentricity Conditions in the Vertical Direction](image1.png)

![Fig. 15 FFT of Vibration Signal under both Healthy and Dynamic Eccentricity Conditions in the Horizontal Direction](image2.png)

![Fig. 16 CWT Analysis of Vibration Signal under Healthy Condition (a) and Dynamic Eccentricity Condition (b) in the Vertical Direction](image3.png)

![Fig. 17 CWT Analysis of Vibration Signal under Healthy Condition (a) and Dynamic Eccentricity Condition (b) in the Horizontal Direction](image4.png)
3.4 Findings

In comparing electrical and mechanical signals, it can be observed that vibration signals are more sensitive to dynamic eccentricity than the electrical signals (stator and rotor current). Among the electrical signals, the rotor current also performed better than the stator current in the detection of dynamic eccentricity.

Also, from the results obtained, it can be seen that both rotor winding imbalance and dynamic eccentricity faults exhibit the same symptoms and air gap distortion. Therefore, the same frequencies of interest appear on the spectra of the measured signals for both faults.

The CWT analysis gave a clear indication of the presence of both faults for only signals, which are sensitive to the fault as compared to the FFT analysis. However, the challenges in using CWT analysis are that, it is computationally intensive, which requires huge memory for processing high sampling rate data and has a longer processing time (Crabtree, 2011). In addition, the frequency domain in wavelet analysis is an approximation of the time-scale domain of the wavelet that makes interpretation of the results require high skill of knowledge since the conversion depends on the type of wavelet used. On the other hand, FFT is less computationally intensive but can only process data with short time interval when considering variable speed condition, which therefore generates many results to be considered.

4 Conclusions and Recommendation

The study presented a comparison of electrical and mechanical signals used in detecting both electrical and mechanical faults in induction generators. Electrical and mechanical faults were implemented on a test rig, which were detected using both electrical and mechanical signals. The results showed that rotor current was very sensitive to the rotor winding imbalance faults while vibration signals were sensitive to dynamic eccentricity. The frequency spectrum analysis showed that the air gap flux distortion was similar in both faults. Also, the results from the vibration signals revealed that the horizontal position of the accelerometer on the generator was sensitive to both faults implemented than the vertical direction.

FFT and CWT algorithm was applied to the measured signals from the test rig to detect the occurrence of the fault. Results from the FFT analysis showed a clear detection of faults implemented in both electrical and mechanical signals measured. However, the CWT analysis clearly detected faults, which are very sensitive to the measured signals.

Future work will consider the monitoring of electrical and mechanical signal when multiple faults are implemented.

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References


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