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# Condition monitoring of wind turbine for rotor fault detection under non stationary conditions

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ABSTRACT

Condition monitoring of Wind Turbine based induction generators still faces challenges due to their operation in harsh and aggressive environments. The detection of anomalies at an initial stage is necessary for reducing the downtime of Wind Turbines. Depending on wind speed, the wind turbine generator operates continuously in non-stationary conditions. Under non-stationary conditions, the rotor fault frequency components present at generator output spreads out on bandwidth proportional to the speed which complicates its detectability. Therefore, this paper proposes a potential approach based on the use of wavelet analysis for diagnosing rotor eccentricity fault using WTG electrical signals. Its effectiveness under speed and load varying conditions is validated by experiments on a wind turbine condition monitoring test rig. The effectiveness of the setup was benchmarked with already proven WT test rigs.
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## 1. Introduction

There is a tremendous increase in the electric power generation from Wind Energy. However, due to the aggressive operating environment and variable load conditions, wind turbines are subject to relatively high failure rate. Wind turbine (WT) system mainly comprises of a gearbox, a generator, a rotor and several other electrical and mechanical sub-systems. Even a single component failure can result in the whole WT to fail, thus increasing its downtime. Right, diagnosis at an earlier stage of fault results in timely maintenance and shorter downtime of the system [1,2]. Condition monitoring of Wind Turbine Generator (WTG) is important as defects in generators have shown to be a major reason for WT downtime [3,4]. WT drive trains may have a catastrophic effect due to an undetected generator fault, so a proper diagnosis procedure is required. A proper diagnostic procedure should be non-intrusive and should be able to provide a clear indication of the incipient fault. Therefore, the progress of effective and reliable methods for condition monitoring of WTGs is gaining greater importance [5,24–28].

Among all the possible faults occur in WTG, faults related to rotor comprise a significant percentage [6]. The rotor of the generator has high thermal, mechanical, and electrical stresses, and is, therefore, prone to faults rising over long periods. Rotor faults can be categorized into rotor eccentricity, breakage of end-rings, rotor bow and breakage of rotor cage bars. Rotor eccentricity constitutes a significant portion of faults [2–6] in WTG. It is caused due to asymmetry which brings about some resultant failures causing system breakdown. Rotor eccentricity is classified by the terms static eccentricity, dynamic eccentricity, and mechanical load imbalance. The widespread imbalance faults in WTGs are shaft/blade imbalance that may be caused by manufacturing errors, deformation due to aging, icing or wear [7] and fatigue during the operation of the WTG. Aerodynamic asymmetry is another common imbalance fault caused by errors in the control mechanism and high wind shear. Imbalance fault can result in significant effects on the towers and the WTGs. Thus to prevent the serious operational problems, online monitoring of rotor eccentricities is highly enviable [5,8,9].

So far, many attempts have been made for monitoring of induction machines; this can be equally used to monitor wind turbine based induction generators. WTs are variable speed, variable load machines, as a result, standard analysis techniques like Fourier analysis cannot be directly applied simply to the monitoring of non-stationary signals produced by WT [2,10,11].

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In most of the earlier research papers, the various experimental setups are used for a non-stationary signal generation at the generator output. These setups include test rig controlled by aerodynamics forces [5,9,10], or hardware controlled methods - torque oscillator [12,13], wind tunnel [8], speed fluctuations by PLC [11], analog inputs [14]. Non-stationary signal fault detection by using current, voltage, power has been performed using advanced signal processing techniques such as instantaneous frequency [11], wavelet based techniques [5,7,12,15,16], the Wigner-Ville [13], quadratic distributions [14], power signature analysis [5], Short-time Fourier transform (STFT) [17].

Both stationary as well as non-stationary signals can be analyzed using discrete wavelet transform [7,15,18]. For various signal processing applications, wavelet theory provides a unified framework. One of its features, Multiresolution Analysis (MRA) has a vigorous function of both frequency and time localization. According to Mallet's algorithm the use of approximation signals resulting from discrete wavelet transform (DWT), constitutes an important advantage because these signals act as filters, which allows automatic extraction of the time evolution of the low-frequency components that are present in the signal during transient operation [19].

The main objective of this paper is focused on monitoring and diagnosing out rotor eccentricity faults in a wind turbine, which usually work under non-stationary conditions, because of wind speed fluctuations. Even though many researchers have worked on the rotor eccentricity fault both for induction motors as well as for induction generator, but a very few has done the research using the dynamic characteristic of the wind turbine. The fault diagnosis under these conditions is a different and much less studied problem than induction machine faults.

The novelties of this research paper are summarized as follows:

- For condition monitoring of wind turbines, a low-cost wind turbine emulator setup is designed and developed. The total cost of the setup is approx $1200. The low cost ($150) USB Advantech-4704 DAQ has been used. The CT's, VT's and driver circuits to interface and control the wind turbine emulator are designed in the lab.
- The real-time interface for monitoring and control of wind turbine emulator is designed in LabVIEW. It controls the prime mover according to the wind turbine principle and follows the torque-speed characteristics of the wind turbine. This setup is also benchmarked with the proven setup [9]. Multiresolution feature vector extraction for quantitative analysis of fault reduces the likelihood of false indications.

The organization of this paper is as follows. Section 2 presents the generalized approach for rotor eccentricity. Section 3 presents the DWT analysis using MRA and use of approximation signals for finding fault frequencies. The details of test setup which works on aerodynamic principle are described in Section 4. In Section 5, results using FFT, qualitative and quantitative analysis using DWT are presented. The conclusion is discussed in Section 6.

## 2. Rotor eccentricity

Unbalance fault occurs in WTG due to [2,3,5]:

- Impact/fatigue damage to the blade.
- Water in the blade,
- Blade surface can be covered with unequal icing.

At the shaft rotational frequency, strong vibration will be introduced once the rotor is unbalanced. It finally arrives at the generator after traveling along the wind turbine drive train. As a result, air-gap eccentricity fault is commenced into the generator. The most usual situation is the presence of mixed eccentricities in which the rotation axis of the rotor coincide neither with stator center nor with its geometric center Some of the important expressions for the computation of mixed eccentricities related frequencies available in the literature [13,17,21] are

$$f_{ecc} = f_e\left[1 \pm \mathrm{m}\left(\frac{1-\mathrm{s}}{\mathrm{p}/2}\right)\right] \tag{1}$$

where m = an integer, s = per unit slip, $f_e$ = input frequency and p = number of poles.

Any knowledge of machine construction is not required for detecting air-gap eccentricities through this technique. For m = 1 and four pole machine Eq. (1) reduces to

$$f_{ecc} = f_e\left[1 \pm \left(\frac{1-\mathrm{s}}{2}\right)\right] \tag{2}$$

This is equivalent to $\mathrm{f_e} \pm \mathrm{f_r}$ where $\mathrm{f_r}$(Hz) is the rotational frequency.

## 3. Wavelet

An efficient fault diagnosis requires the measurements of a quantity sensitive to the faults and a suitable method to obtain a diagnostic index and a threshold stating the edge between faulty and healthy condition. Dyadic band pass filtering process is the key idea underlying the use of DWT. If a certain sampled signal $= (i_1, i_2, \ldots, i_n)$ is provided, the DWT decomposes it onto several wavelet signals (an approximation signal $a_n$ and n detailed signals $d_j$) [15,16,18,19] as shown in Fig. 1. Each wavelet signal is related to a particular frequency band. The time progression of the frequency components of the original signal S is reflected by it's the wavelet signals, which are enclosed within its associated frequency band.

If $f_s$ defines the sampling rate in samples per second for capturing the signal s, then the detail $d_j$ includes the information concerned with the signal components with frequencies included in the interval.

$$f(d_j) \in [2^{-(j+1)} \cdot f_s, 2^{-j} \cdot f_s]\ \mathrm{Hz}. \tag{3}$$

The low-frequency components are included in the approximation signal $a_n$ of the signal belonging to the interval.

$$f(a_n) \in [0, 2^{-(n+1)}.f_s]\ \mathrm{Hz}. \tag{4}$$

As illustrated by Fig. 2, the logarithmically spaced frequency bands are obtained by dividing the frequency content of the original signal using DWT.

The approximation $a_j$ and detail $d_j$ has the same frequency bandwidth, equal to $\frac{f_s}{2^{(j+1)}}$. For fault analysis, the approximation $a_j$ is more suitable as it is less subject to overlapping effect than detail signals due to its proximity to 0 Hz [20]. If $f$ is included in the detail $d_j$, then the signal components with frequencies below $f$ are included in the approximation of this level ($a_j$). These components are negligible in the case of healthy machines, and $a_j$ remain almost null. In case of any fault, there is significant amplitude of the left sideband harmonic throughout the process; because its frequency is always under $f$, and it causes a considerable increase in the energy of the approximation signal $a_j$. Therefore, the frequency band $[0, 2^{-(n+1)}.f_s]$ is chosen to track the main fault components. The number of decomposition levels ($n_f$) is selected as below [16,20].

$$n_f = integer\left[\frac{\log(f_s/f)}{\log(2)}\right] \tag{5}$$

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