Condition monitoring of a wind turbine doubly-fed induction generator through current signature analysis

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Abstract. Operation and maintenance (O&M) of wind turbines is recently becoming the spotlight in the wind energy sector. While wind turbine power capacities continue to increase and new offshore developments are being installed, O&M costs keep raising. With the objective of reducing such costs, the new trends are moving from corrective and preventive maintenance toward predictive actions. In this scenario, condition monitoring (CM) has been identified as the key to achieve this goal. The induction generator of a wind turbine is a major contributor to failure rates and downtime where doubly-fed induction generators (DFIG) are the dominant technology employed in variable speed wind turbines. The current work presents the analysis of an in-service DFIG. A one-year measurement campaign has been used to perform the study. Several signal processing techniques have been applied and the optimal method for CM has been identified. A diagnosis has been reached, the DFIG under study shows potential gearbox damage.

1. Introduction

Wind energy has been renowned as the fastest growing renewable energy source during the past years, with a global installed wind capacity of nearly 490 GW by the end of 2016, of which, around 15 GW are located offshore [1]. European countries are the leading players in the offshore wind energy market [2].

More modern and larger wind turbine generators are under continuous development. These exhibit more faults when compared to smaller ones [3], which becomes critical offshore [4]. Under this framework, operation and maintenance (O&M) [4] is key to improve reliability and availability. O&M activities represent between 25-35% of the total expenditure of a wind farm project [5], hence, it is mandatory to optimise them in order to reduce costs. There are three common types of maintenance strategies: preventive, corrective and predictive [6]. Downtime is avoided in the first strategy, while unnecessary resources and expenses may take place. For the second one, only the required resources are used but it can result in excessive downtime. New trends are moving from these two towards predictive maintenance, where condition monitoring (CM) determines the ideal balance between preventive and corrective actions [7], improving reliability and availability while reducing costs [8].
The generator is one of the major contributors to failure rates and downtime of wind turbines, together with the gearbox and the drive train system [9]. Doubly-fed induction generator (DFIG) is the dominant technology employed for variable speed wind turbines [10]. The most common faults of DFIGs are related to bearings (between 20% and 38%), stator (around 30%) and rotor (nearly 10%) [11,12]. Induction machine’s condition monitoring techniques include temperature, chemical and wear, mechanical vibration, electrical current, and power, electrical discharge and artificial intelligence, where electrical signature analysis is the most common one [13].

2. Methods

Electrically-based condition monitoring techniques include: current, voltage, instantaneous power and flux analysis, where stator current analysis is the most common of these techniques. It is based on the principle that each fault has its own effect on the current spectra [10]. Several signal processing methods can be applied to electrically-based techniques towards fault identification, typically classified into time-domain, frequency-domain and time-frequency [13].

In the present work, frequency-domain analysis will be applied on a real operating DFIG wind turbine via Fast Fourier Transform (FFT) to both stator and rotor instantaneous currents. This technique transforms the waveform signal from the time domain to the frequency domain. It is widely used for fault diagnosis because the variations of certain harmonic components in the frequency spectrum of a signal can be related to a specific fault type [14]. The formulae that provides the frequency components associated to various types of faults have been identified and demonstrated for different kinds of induction machines. A summary of such formulae was presented in [15, 16] by the authors. Particularly, the equation that provides frequency components related to gearbox damage is defined as (1):

$$f_{gb} = f_s \pm m \left( \frac{f_s}{G_r p/2} \right)$$

Where $f_s$ is the supply frequency, $m$ is the harmonic order, $G_r$ is the gearbox ratio and $p$ is the number of pole pairs.

Current Park Vector is another approach for fault diagnosis of electric machines. It is a fairly recent technique that can successfully diagnose rotor faults, inter-turn stator faults and unbalanced supply voltage and mechanical load-misalignment [17]. The instantaneous stator line currents are transformed into the Parks vector as per equations (2) and (3). An undamaged machine theoretically shows a perfect circle, and an unbalance one results in an elliptic representation.

$$I_d = \left( \frac{2}{\sqrt{3}} \right) I_a - \left( \frac{1}{\sqrt{6}} \right) I_b - \left( \frac{1}{\sqrt{6}} \right) I_c$$

$$I_q = \left( \frac{1}{\sqrt{2}} \right) I_b - \left( \frac{1}{\sqrt{2}} \right) I_c$$

Actual data from operating wind turbines is seldom presented. Much work has been published on modelled data, simulations and laboratory benches [18–22] but there is a lack of field measurement campaigns for current signature analysis. In the present work, an in-service DFIG wind turbine with potential gearbox faults has been analysed through electrically-based techniques. The data for the case study has been provided by the Spanish company Ingeteam Service S.A., specialising in power converters, generators, turbine controllers, CM systems and SCADA systems.
3. Results
The reported wind turbine has a doubly-fed induction generator with the following characteristics, Table 1:

| Characteristic                  | Value         |
|--------------------------------|---------------|
| Rated Power                    | 1545 kW       |
| Pole pairs                     | 3             |
| Synchronous Speed              | 1000 rpm      |
| Supply frequency               | 50 Hz         |
| Nominal stator voltage         | 12000 V       |
| Nominal rotor voltage          | 690 V         |

A test case with the wind turbine at 90% of its rated nominal power operating at super-synchronous speed with 8% slip has been chosen to illustrate the study. The waveforms of the stator and rotor currents are shown in Figure 1 and their main parameters extracted in Table 2.

**Figure 1.** Stator (left) and rotor (right) currents of the DFIG under super-synchronous speed operation (1 s zoom).

| Phase | Stator rms current [A] | Stator freq [Hz] | Rotor rms current [A] | Rotor freq [Hz] | slip   |
|-------|------------------------|------------------|-----------------------|----------------|--------|
| Phase a | 69.5792               | 50.0916          | 490.7019              | 511.4118       | 4.45   |
| Phase b | 70.1309               | 50.0916          | 511.4118              | 535.1995       | -0.08  |
| Phase c | 69.2850               | 50.0916          | 490.7019              | 511.4118       | 4.45   |

The generator slip is calculated dividing the supply frequency (main frequency of the stator) by the main frequency of the rotor, obtaining 0.08. The negative sign is the convention for super-synchronous speed.
3.1. Spectral Analysis of the Stator Currents

FFT is now applied to the stator currents, shown in Figure 2, in order to carry out fault frequency search.

The supply frequency is clearly seen in the spectrum with the highest amplitude. Two pair of peaks that are usually present in the spectrum due to the geometry of the induction generator itself are those related to broken rotor bars (41.48 Hz – 58.70 Hz) and rotor unbalance (31.96 Hz – 68.22 Hz). The sum of the stator main frequency (or supply frequency) and the rotor main frequency (4.45 Hz) can also be identified in the spectrum (54.54 Hz).

The mere presence of these components might not imply a fault. It has been reported that less than 25 dB difference must exist between the supply frequency and broken rotor bar components in order to be able to diagnose such fault [11, 23]. Similarly occurs for rotor unbalance components. A minimal degree of air gap is always introduced during manufacturing or assembly of the induction machine, which modulates the current at the rotational speed [19]. When the air gap degree increases, the rest of the sub-harmonics related to rotor unbalance appear, indicating the presence of the fault. In this case, only the first pair can be seen.

Differently occurs with gearbox related components, which shall not appear unless a fault is present. Table 3 summarizes the calculations for the frequency components as per Eq. 1 applied to the wind turbine under study.

$$\text{Table 3. Gearbox damage related frequency components for the DFIG under study.}$$

| $m$ | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|-----|-----|-----|-----|-----|-----|-----|-----|
| Freq [Hz] | 49.58 | 49.08 | 48.57 | 48.06 | 47.56 | 47.05 | 46.56 |
|       | 50.60 | 51.10 | 51.61 | 52.11 | 52.62 | 53.13 | 56.65 |

Zoom is applied around the supply frequency (Figure 3 left), where further peaks arise, in order to identify the potential fault frequency components calculated in Table 3. Three pairs corresponding to $m = \pm 2, 3, 5$ can be seen in the spectrum. For a better understanding of the
results, the frequency components are represented as a function of \( n \), (Figure 3 right). The presence of \( f_{gb} \) components indicate gearbox-related fault. This diagnose has been confirmed by the data owners, Ingeteam.

![Frequency components](image)

**Figure 3.** Zoom around supply frequency of the stator currents FFT (left) and gearbox related components by harmonic order (right).

### 3.2. Spectral Analysis of the Rotor Currents

The rotor shows electrical unbalance, which can be appreciated from the rotor currents previously presented (Figure 1 right) and the rotor rms values extracted in Table 2.

The spectrum analysis of the rotor currents is performed (Figure 4). Frequency components related to rotor asymmetry can be seen in the rotor spectra, corresponding to \( 3sf \) and \( 5sf \) respectively, pointing out the rotor electrical unbalance.

### 3.3. Current Park Vector Analysis

Finally, Current Park vector is applied, following Eqs. 2 and 3 previously defined. The results are shown in Figure 5.

![Current Park vector](image)

**Figure 4.** FFT of rotor currents.
4. Conclusions
A brief introduction on the state of the art of condition monitoring of doubly-fed induction generators of wind turbines has been given. The motivation being to optimise O&M activities by reducing costs and increasing reliability and availability.

The basis of current signature analysis and its application on DFIGs have been presented, including stator and rotor currents analysis as well as Current Park Vector approach, which have been applied on field measurements from an operating wind turbine. Faulty components related with gearbox damage have been identified on the spectral analysis of stator currents, and electrical rotor unbalance from the rotor analysis.

Both current and rotor spectral analysis show potential with regards to Condition Monitoring development for DFIG-based wind turbines, whereas Current Park Vector appears to provide scarce information for this purpose.

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