Comparison of rotor electrical fault indices owing to inter-turn short circuit and unbalanced resistance in doubly-fed induction generator

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Abstract: Doubly-fed induction generator (DFIG) is the dominant technology in the wind energy market. Rotor inter-turn short-circuits (RITSCs) and unbalanced rotor resistance (URR) are the main types of rotor electrical asymmetries in DFIG. The URR has already been considered as an electrical fault or asymmetry in the rotor of DFIG. Although the RITSC introduces URR into the rotor circuit its consequences are not similar due to the structure of the machine and presence of current controllers in the DFIG system. In this study, both RITSC and URR are proposed and compared, and the detection of these faults was performed using appropriate indices in the stator current, reactive power, and rotor modulating voltage signals, which are available in the control system of the DFIG. Furthermore, it is supposed that the discrimination between these two types of faults is feasible by utilising proper fault indices at various operating regions of the wind turbine. The performance of the defined fault indices, for different fault severities, is verified using an experimental setup with the DFIG operating under several conditions such as different power injection into the grid and different rotor speeds, including sub-synchronous and super-synchronous operation.

1 Introduction

Renewable power generation has proliferated in the last few decades, and wind energy is one of the most popular technologies in this field. Among the different wind turbine technologies, doubly-fed induction generator (DFIG)-based units are more common due to their advantages. The outstanding feature of the DFIG is the utilisation of a small converter (30% of the generator rating), which leads to a lower cost compared to other variable speed structures with the capability of active and reactive power control [1, 2].

Wind turbines (WTs) are usually located in harsh environments; therefore their components are subject to various faults. The failure of an individual element may lead to the malfunction of other components or breakdown of the whole system. The proper detection of faults at an early stage could help organise an appropriate maintenance schedule to reduce the maintenance expenses, decrease WT downtime, and increase its reliability and expected life span [3, 4]. These advantages lead to lower cost of energy which makes WT more competitive amongst other renewables [5]. Recently, for less complexity and cost, electrical condition monitoring especially based on electrical machine quantities such as the stator and rotor voltages and currents has been proposed [6].

The generator, as the energy conversion heart of the WT, is prone to mechanical and electrical faults. Eccentricity as a major mechanical disorder of DFIG has been addressed and some fault detection methods have been proposed [2, 7, 8]. Electrical faults could occur in stator or rotor side windings. Modelling and detecting of stator inter-turn short circuit fault as an electrical fault and one of the main roots of machine failures have been studied in DFIG [9–11]. However, detection of electrical faults of the DFIG rotor is also essential. WT’s are usually connected to weak grids, which are highly vulnerable to voltage dips. This event gives rise to over-voltages and over-currents in rotor windings and torque pulsations in the DFIG [12–14]. These phenomena, accompanied by the rotor side converter (RSC) switching, increase the risk of rotor inter-turn short circuit (RITSC) faults. The other electrical anomaly is high resistance connection (HRC), which mainly originated from the loosening of connections and damaging of contact surfaces. It is a widespread incident in industrial induction machines [15, 16], and is highly probable in the DFIG windings specially due to an improper connection between the slip ring unit and the rotor cable leads to a harsh situation [17, 18]. The HRCs in the rotor circuit leads to unbalanced rotor resistance (URR). It is important to discriminate between RITSC and URR, because of their different growth rates and consequences. RITSC develops much more rapidly compared with URR and could cause more serious failures. Although, each of these faults has been considered in the literature, their comparison has remained little explored. In this study, the effects of RITSC and URR on some special indices of DFIG are studied to facilitate their distinction.

The electric anomaly of the DFIG rotor has been investigated in different manners. The URR has been studied, and a rotor modulating signal has been proposed as a suitable index for a preliminary diagnosis [17, 19]. In these studies, the machine has been modelled by a coupled circuit model and wavelet transform has been utilised for improving the detection sensitivity under non-stationary conditions. Also, stator current and power spectra have been used for the detection of the URR and particular indices have been introduced [20]. Later on, it has been claimed that the dq current error signals, which are the inputs of the current controllers in the field-oriented control system applied to the RSC, are more appropriate for URR detection compared with current or power [21]. In [22], the DC component of a diagnostic space vector has been proposed as an index for the detection of URR. The diagnostic space vector is obtained based on space vectors of rotor current and voltage. In a case study [23], fault detection of an actual DFIG-based WT has been considered under different conditions of power and speed, based on the current signature analysis. Here, the rotor unbalance index has been more elevated. The extended Kalman filter-based method has been proposed in [18] to detect the URR under non-stationary conditions. It has been shown experimentally that the suggested approach has superior
accuracy compared with continuous wavelet transform and iterative localised discrete Fourier-transform, especially at a low load operation near-synchronous speed. It is noted that RITSC has been less investigated due to its hardware challenges. An offline method has been proposed in [6] for detection of RITSC faults. This method is based on the analysis of the current response to special voltage pulses applied by the RSC while the stator is shorted. The impact of the RITSC on the stator quantities and control signals has been explored when a magnetic equivalent circuit has been used to model the machine [13]. In this study, the sub-synchronous and super-synchronous operations of the DFIG have been considered.

In this study, both RITSC and URR are considered thoroughly and their effect on fault indices has been compared under various conditions. Then, a detection method is proposed for electrical faults in the rotor of the DFIG. As a consequence, the URR could be distinguished from RITSC and the immediate outage of the WT is avoided in the case of the URR.

The paper is organised as follows: following the presentation of the DFIG and its respective control system in Section 2, some explanations about the interaction between the current and flux in the DFIG are provided in Section 3. Then, significant indices for the detection of rotor asymmetries in the DFIG are introduced. Section 4 provides the experimental results of the faulty DFIG, affected by RITSC and URR. After the presentation of major spectra under the faulty condition, the dependence of the proposed indices on the fault severity and operating state of the DFIG (different power injection and speed involving sub-synchronous and super-synchronous modes of operation) is studied and discussed. In Section 5, the characteristics of wind turbine operation, preference of indices for detection of the URR and RITSC and discrimination between them are determined.

2 DFIG control system

As shown in Fig. 1, the rotor of the DFIG is connected to the RSC, and its stator is directly connected to the grid. Stator-flux-oriented vector control of RSC provides independent control of active and reactive powers. The control structure involves two outer and two inner control loops. The desired values of stator active and reactive powers dictate the reference values for rotor currents. Then, the inner control loops determine the rotor voltage applied to the DFIG based on these reference currents.

The stator active and reactive powers depend on the rotor current components as [12]:

\[
P_s \approx - \frac{3}{2} V_s L_m i_{d^s},
\]

(1)

\[
Q_s \approx \frac{3}{2} V_s^2 - \frac{3}{2} V_s L_m i_{q^s},
\]

(2)

where \( L_m \) is the mutual inductance between the stator and rotor windings, \( L_s \) is the stator self-inductance and \( V_s \) is the peak value of the stator phase voltage.

3 Electrical faults in DFIG

3.1 Interaction between currents and magnetic flux

A diagram of causes and effects between different the parameters/variables of the DFIG is shown in Fig. 2. To begin the analysis, let us assume that the rotor is in open-circuit. When the sinusoidal voltage is applied to the stator winding, sinusoidal currents circulate in this winding. The flow of current in the distributed stator winding produces a rotating magnetomotive force (MMF). Discrete slotting leads to the presence of space harmonics in addition to the fundamental component of the MMF. The MMF generates magnetic flux density in the possible magnetic paths. Assuming magnetic cores with high permeability, the air gap permeance, which is inversely proportional to the air gap length, mainly affects the magnetic flux density. Due to the slotting effect, permeance consists of rotating waves which means it has various space harmonics. By multiplying the air gap permeance by the MMF, stator-related air gap flux density \( (B_1) \) is achieved. A similar scenario is also valid for another case: rotor supplied and stator in open-circuit.

In the actual DFIG system, both stator and rotor windings are connected to supplies, so the total flux density waves are affected by both stator and rotor windings excitation. Since it is time and space dependent, the overall flux induces voltages in both stator and rotor windings, while the winding currents are influenced by any anomaly in the windings, in the machine geometry or in the supply system.

3.2 Major frequency components in an electrically asymmetric rotor

Faults in electrical machines can be diagnosed using different methods. In signal-based approaches, which are more common, fault signatures of some machine quantities are tracked with proper signal processing methods [15]. Hence, it is crucial to determine the fault signatures, which are usually specific frequency components of some electromagnetic quantities. Among these quantities, stator current is frequently used because the stator winding acts as a non-invasive search coil with proper location [24]. Therefore, for analysis of an electric rotor fault in the DFIG, the effects of the rotor asymmetry on the stator current are first considered.

3.2.1 Stator current: The following frequency components of the stator current in wound rotor induction machine with an asymmetric rotor have been proposed in [13, 20]

\[
f_{f^s_k} = \frac{k}{p} \left(1 - s\right) f_{s^r}, \quad k = 1, 2, 3, \ldots,
\]

(3)

where \( i = 1, 2, 3, \ldots \) is the order of supply harmonics, \( p \) is the number of machine pole pairs, \( s \) is the rotor slip and \( f_{s^r} \) is the fundamental frequency of the stator excitation.

3.2.2 Reactive power: In the field-oriented control system of the DFIG used in this work, the \( d \)-axis of the reference frame is aligned with the stator flux vector [12, 25]. So, \( \lambda_{ds} \) is almost zero while \( \lambda_{qs} \) is equal to the resultant flux-linkage of the stator. As a result, any irregularity in the magnetic flux manifests well in \( \lambda_{ds} \) [7]. Since the angular speed of the synchronous reference frame is \( 2\pi f_{s^r} \), the fault indices in the stator flux-linkage are as follows:

\[
f_{\lambda^d_{ds}} = \pm \frac{k}{p} \left(1 - s\right) \pm 1 f_{s^r}, \quad k = 1, 2, 3, \ldots
\]

(4)

However, monitoring the flux needs additional sensors, which leads to more cost and a higher failure rate. The \( d \)-axis component of the stator voltage can be written as follows:

\[
v_{ds} = R_s i_{ds} - \omega_s \lambda_{qs} + \frac{d}{dt} \lambda_{ds},
\]

(5)

where \( \omega_s \) represents the angular frequency of the stator voltage. The mentioned control system of the DFIG adjusts the quantities such that: \( \lambda_{ds} \approx 0 \) and \( v_{ds} \approx 0 \).

By rearranging (5), the \( d \)-axis component of the stator current is expressed as follows:

\[
i_{ds} = \frac{1}{R_s} \left( v_{ds} + \omega_s \lambda_{qs} \frac{d}{dt} \lambda_{ds} \right) \approx \frac{1}{R_s} \left( \frac{d}{dt} \lambda_{ds} \right).
\]

(6)

Equation (6) indicates that the frequency components of \( \lambda_{ds} \) are also present in \( i_{ds} \). Although this quantity is available in the control system, it is not usually supervised. On the other hand, the stator reactive power is a quantity that due to the DFIG control is directly proportional to \( i_{qs} \) and it is monitored in almost every WT system. The relationship between these two parameters is
Q_s \simeq \frac{3}{2} v_{qs} i_{ds}.

(7)

In an ideal grid voltage (with no harmonics), $v_{qs}$ has a DC value and adds no new component to the frequency spectrum of $Q_s$ compared with $i_{ds}$. On the other hand, multiplication of the frequency components by this DC value notably magnifies these components and makes their monitoring easier. In general, if harmonics of order $j$ in the grid voltage are considered, the fault indices of reactive power will be

$$f_{Q_s}^j = \pm \frac{k}{p} (1 - s) \pm j f_s, \quad j = 1, 2, 3, \ldots$$

(8)

3.2.3 Rotor modulating signals: A rotor asymmetry produces a negative sequence harmonic in the rotor current spectrum [13]

$$f_i^j = -sf_s.$$

(9)

In the closed-loop control system of the DFIG, current controllers are responsible for the establishment of sinusoidal and balanced currents in the rotor windings. When the rotor becomes asymmetric, this purpose is attained by applying unbalanced modulating signals to the RSC. Therefore, modulating signals involve the same component, which is appropriate for fault detection

$$f_v^j = -sf_s.$$

(10)

4 Experimental results and discussion

In this section, previously introduced fault indices are investigated for both the RITSC and the URR. Fig. 1b shows the connections diagram of the experimental setup used for verification of the simulation results. Available taps in the rotor windings facilitate the implementation of the RITSC while the URR is tested by adding a proper resistance for the desired unbalance resistance value. An additional set of slip rings and brushes connected to the taps of the rotor turns provides unchallenging monitoring of these turns from...
stationary terminals. With this setup, the RITSC can be easily investigated, and the short-circuit current of the affected turns can be supervised. A variable speed squirrel cage induction motor drive is mechanically coupled to the DFIG, imposing the desired rotor speed. The DFIG control system shown in Fig. 1a has been implemented in a dSPACE 1103 platform, which also enables data measurements and processing (Fig. 3). The data are sampled at 16 kHz with an acquisition interval of 10 s. The studied DFIG has the specifications presented in Table 1.

For a brief glance, the spectra of the suggested quantities obtained with the DFIG in healthy conditions and in the presence of the RITSC and URR are presented. At this stage, the DFIG operates at a sub-synchronous speed of 1350 rpm (10% slip) and injects 2 kW of active power into the grid. It is noted that the fast Fourier transform of the signal is normalised based on the fundamental component in the logarithmic scale to better compare spectrum components of diverse values.

4.1 Rotor inter-turn short-circuit

The major rotor asymmetry fault index in the stator current of the machine is the \((1 - 2s_f) f_s\) component, which corresponds to a frequency of 40 Hz in this test [19, 20, 26]. This index is obtained by substituting \(i = 1\), \(k = 4\), and \(p = 2\) in (3). It is seen in Fig. 4 that the amplitude of this component, compared with the healthy situation, has increased beyond 12.5 dB.

According to (8), the \(2s_f f_s\) component is the primary fault index in the stator reactive power, which corresponds to a 10 Hz component in this situation. Again, it is clear that this index has also been elevated (Fig. 5), although with a less increment (about 6 dB). The fault index of the rotor modulating voltage \((-s_f f_s)\), which corresponds to a \(-5 Hz\) component, has been less affected (about 4 dB) compared to other indices (Fig. 6). It is noted that for evaluating negative frequency components, the space vector of the signal has been used.

The capability of the fault indices, for different fault severities, different speeds, and different injected stator powers is now...
considered for a better evaluation. As presented in Table 2, the reactive power index is appropriately sensitive to the RITSC and it increases when the fault intensifies and this could be utilised in fault diagnosis. Although the stator current index is also well affected, it has a considerably less power spectral density (PSD) value. The rotor modulating voltage has the least sensitivity to this type of fault, and its index has low values for the different fault severities.

According to Table 2, the sensitivity of reactive power and stator current indices decreases when more power is injected and the index of rotor voltage gradually rises. Nonetheless, even at 2 kW, it is weaker than the two other indices. The last part of Table 2 presents the change of the index values when the rotor speed changes. It is evident that sensitivity of the reactive power and stator current is more pronounced at higher slips (lower speeds). At synchronous speed, the stator current and reactive power are not capable of detecting the fault. This happens because the stator current index coincides with the fundamental frequency and the reactive power index coincides with the DC component, which may not be zero due to a positive reactive power command. On the contrary to these two indices, the rotor voltage index is stronger near synchronous speed although again at zero slip it cannot be utilised due to the coincidence of the main component and fault component ($s_f = 0$).

4.2 Unbalanced rotor resistance

In this subsection, a similar study to the one shown in the previous section has been repeated using the frequency spectrum of the same quantities but for a URR of 50%. Like in the previous subsection, the DFIG is operating at 1350 rpm while injecting 2 kW into the grid.

As presented in Figs. 7 and 8, it is apparent that the fault indices of stator current and reactive power have been attenuated. It is obvious in Fig. 9 that the fault index of the rotor modulating voltage has been elevated by an amount as high as 11 dB. It is visible that the URR has an outstanding effect on the fault index of the rotor modulating voltage ($s_f$), which in this test corresponds to a $-5$ Hz component.

For a better evaluation, the capability of the indices is evaluated for different fault severities, different speeds, and different injected powers into the grid. As mentioned in Table 3, the modulating voltage index is appropriately sensitive to the URR and rises when

\[
\begin{align*}
\omega_{r}(1 - 2n)f_s &= -49.4 - 37.5 - 25 - 25.9 - 31.9 - 35.1 - 37.5 - 29.6 - 37.5 - 44.9 \quad 0 \quad -37 - 30.1 \\
\Omega_{r}(2n)f_s &= -24.8 - 25.3 - 18.8 - 12.5 - 13 - 16 - 17.7 - 18.8 - 15 - 18.8 - 22.4 - 51.5 - 18.4 - 15 \\
\nu_{r}\omega - sf_s &= -42 - 38.9 - 37.9 - 31.2 - 43.5 - 41.4 - 38.9 - 37.9 - 38.7 - 37.9 - 36.2 \quad 0 \quad -29.2 - 34.6
\end{align*}
\]

Table 2  PSD (dB) of RITSC fault indices under different operating conditions of the DFIG

<table>
<thead>
<tr>
<th>Number of shorted turns</th>
<th>Injected active powers, W</th>
<th>Rotor speed, rpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n = 1350$ rpm, $P_s = 2$ kW</td>
<td>$n = 1350$ rpm, seven shorted turns</td>
<td>$P_s = 2$ kW, seven shorted turns</td>
</tr>
<tr>
<td>0</td>
<td>500</td>
<td>1500</td>
</tr>
<tr>
<td>-50.2</td>
<td>-37.5</td>
<td>-25</td>
</tr>
<tr>
<td>-24.8</td>
<td>-25.3</td>
<td>-18.8</td>
</tr>
<tr>
<td>-42</td>
<td>-38.9</td>
<td>-37.9</td>
</tr>
</tbody>
</table>
the fault intensifies. Conversely, the reactive power and stator current indices decrease with the fault intensification, meaning that they are not proper indicators for the diagnosis of URR. It is apparent that power injection has little influence on the fault indices. Finally, the fault indices have been investigated at various speeds including sub-synchronous and super-synchronous operation. It is evident from Table 3 that the modulating rotor voltage index, which is very sensitivity to the URR, increases when the rotor slip approaches zero. On the other hand, the other indices weaken near zero slip. Again, it must be stated that at precisely zero rotor slip, none of the indices is capable of detecting the fault.

4.3 Discussion

Here, the results of the previous sections are summarised in order to better compare the RITSC and URR fault indices and introduce an appropriate scheme for rotor winding condition monitoring based on the real operating conditions of a DFIG-based wind turbine.

Table 4 compares the sensitivity of the fault indices to fault severity and variation of operating conditions. Based on the previous results, stator current and reactive power indices are not appropriate for URR detection. This phenomenon is mainly due to the power and current controllers which try to maintain constant power and balanced currents by introducing unbalanced modulating voltages to the RSC. On the other hand, in the RITSC case, the controllers cannot eliminate the effects of the rotor shorted turns because they create a permanent opposing flux which excites the stator current fault index. Indices of stator current, reactive power and modulating voltage have been compared for the RITSC fault detection but for the URR only modulating voltage has been considered.

According to Table 4, the stator current index has the highest sensitivity to the severity of RITSC. However, at the same time, it is also the most sensitive index to power variation which is not a desirable feature. Furthermore, at both sub-synchronous (<1500 rpm) and super-synchronous (>1500 rpm) operation, the speed change is accompanied by a broader change in the value of the stator current index which reduces its capability as an appropriate
The reactive power index is less sensitive to the RITSC, is a proper indicator for the URR with acceptable sensitivity to the speed and power change. It is seen that this index is more sensitive for higher output powers and smaller absolute values of rotor slip. It is noted that in Table 4, the absolute value of slip has been considered.

5 Final diagnostic procedure

Regarding the real operating conditions of a wind turbine, generator speed and its output power are prone to variations due to the inherent fluctuations of wind speed. According to Fig. 10, which shows the change of the generator speed and output power versus wind speed, four operating regions could be considered to study the performance of the previously presented fault indices. At region 1, the slip is high while a low active power is generated. At region 2, where power and rotor slip are low, the modulating voltage index is the most appropriate diagnostic index. The modulating voltage index, which has the least sensitivity to the RITSC, is a proper indicator for the URR. However, for discriminating the URR from the RITSC, simultaneous tracking of the stator current or reactive power is also necessary. If the origin of the rotor asymmetry is the URR, then the stator current and reactive power are excited while for the RITSC, stator current and reactive power are also necessary. If the origin of the rotor asymmetry is the URR, simultaneous tracking of the stator current or reactive power is also necessary.

Based on the previous results, the modulating voltage index is appropriate for detection of the URR. However, for discriminating the URR from the RITSC, simultaneous tracking of the stator current or reactive power is also necessary. If the origin of the rotor asymmetry is the URR, the modulating voltage index is excited while for the RITSC, stator current and reactive power are also necessary.
indices are also elevated even with more strength in some conditions.

6 Conclusion

Rotor electrical asymmetry in electrical machines originated from rotor inter-turn short-circuit (RITSC) or URR. Although these phenomena may have similar effects in common electrical machines; however, in the structure of the DFIG where the rotor is supplied by the controlled power converter, it is not the case. It is mainly due to current regulation conducted by RSC. In this study, RITSC and URR were investigated and their effect on fault indices was compared. The detection of these faults was conducted using appropriate quantities available in the control system of the DFIG such as the stator current, reactive power, and rotor modulating voltage. The validity of the fault indices was explored for several fault severities and for different DFIG operating conditions, including the operation at sub-synchronous, synchronous and super-synchronous speeds. According to the distinct behaviour of some fault indices in the presence of the URR and RITSC and based on different operating regions of a wind turbine, the discrimination between these two types of rotor faults could help the condition monitoring specialist to choose the best fault index according to the operating conditions of the wind turbine.

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8 References


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