Stator and rotor turn-to-turn fault detection in wound rotor induction machines based on the air-gap magnetic field distortion

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Abstract: An efficient online flux-based diagnostic approach is proposed to detect turn-to-turn faults in the stator and rotor windings of wound rotor induction machines, at an early stage of development, which can be applied in the online mode. Some flux sensors are installed in the stator slots to detect the rotational magnetic field at various positions along the air-gap circumference. These sensors measure the flux linked to all winding coil groups, in the three phases. Any fault occurring either in the stator or rotor windings will disturb the air-gap flux and create an asymmetry in the rotational magnetic field, which is detectable through the difference of the induced voltages in the corresponding flux sensors. The proposed diagnostic technique is evaluated by finite element analysis as well as by multiple experimental tests. The obtained results show that such an invasive technique is able to detect and discriminate various faults in the stator and rotor windings with high accuracy, low calculation burden, proper sensitivity and appropriate robustness in the face of machine load level variations.

1 Introduction

Three-phase induction motors have been ruling the industrial world for many decades because they are relatively inexpensive, rugged, highly reliable, and easy to maintain in comparison to other options. According to the National Electrical Manufacturers Association (NEMA) [1], around 50% of the global electricity consumption is due to induction motors. Based on the rotor construction, squirrel-cage type induction machines (SCIMs) are extensively used due to their simple structure and low manufacturing costs. On the other hand, they have major disadvantages such as difficult speed control and low starting torques. The induction machines used in hoist, cement, and steel industries usually have high inertia loads with long acceleration times [2]. Wound rotor induction machines (WRIMs), also known as slip-ring induction machines, are another type of induction motor that is used in those mentioned industrial applications. In comparison to SCIMs, although WRIMs are more complicated in structure, they are more costly and need more frequent repairs and maintenance sessions, mainly due to their use of brushes, they have important advantages such as [3] low starting currents, high starting torques due to the start-up series resistance bank connected to the rotor circuit, smooth acceleration and proper speed control. Moreover, WRIMs have found their applications in wind turbines, especially in large wind farms, working as generators, in a comparison configuration known as doubly fed induction generator (DFIG) [4].

Induction motors are subjected to different types of undesirable internal and external stresses which may cause various kinds of faults, leading to unscheduled motor and driven load interruptions. They can disrupt the production of industrial units, resulting in significant financial losses. To avoid such unpleasant circumstances, proper protection, on-line condition monitoring and scheduled preventive maintenance is crucial. Statistical studies conducted by IEEE and EPRI (Electric Power Research Institute) highlight the proportion of the different fault types in relation to the total number of faults [5]. The results of these studies that were carried out on various types of motors used in industrial applications show that 36–45% of the faults are located in the stator and rotor windings [6, 7].

Winding faults generally start by some shorted turns caused by an insulation failure. Due to the high circulating current in the shorted turns, the generated heat will increase the temperature in the affected area and the fault may spread and lead to other more severe types of faults, such as coil-to-coil and coil-to-core (ground) faults.

For a stator winding fault, the induced voltage in the shorted turns leads to a circulating current up to twice of the locked-rotor current [8, 9], which results in intensive heat in the faulty region, exposing the motor to irreparable damages [10, 11]. However, for a rotor fault, there is neither considerable heat nor extensive rotational magnetic field (RMF) distortion, as the frequency and amplitude of the induced voltage (and accordingly the current) in the shorted turns is low. The increase of the rotor slip (due to heavy loads or during the startup period) will increase the rotor winding currents in the three phases, and so, a higher rotor slip results in a higher unbalance in the rotor currents. In brief, one can state that a rotor turn-to-turn fault (RTTF) is a weaker fault and has a lower detectability than a stator turn-to-turn fault (STTF). Other differences between STTFs and RTTFs in WRIMs can be listed as follows:

(i) The RMF distortion level is a function of the motor load level for RTTFs, while it is almost an independent function of it for STTFs.
(ii) The RMF distortion rotates along the air-gap circumference for a RTTF, while such distortion is stationary for STTFs.
(iii) The distortion in the currents drawn from the three supply phases in the face of RTTF is identical, while that distortion will be asymmetrical in the case of STTFs.

Several techniques, including invasive (e.g. measuring the magnetic flux, stray flux, or temperature in various regions) and non-invasive ones (based on current, voltage, power, impedance, vibration etc.) have been proposed in the literature to detect different types of faults in induction machines [12]. Among the non-invasive methods, stator current spectrum analysis [13–15], voltage signal [16], current and voltage positive, negative and zero sequence components [17–20], active and reactive powers [21–23], impedance sequence components [24–26], air-gap torque [27, 28], Park's vector approach [29, 30], magnetic fields [31, 32], motor frame vibration [33, 34], thermal analysis [35, 36], discrete wavelets and Hilbert transform [37–41], artificial intelligence and
deep neural network techniques [42, 43], and equivalent model-based methods [44, 45] can be highlighted. Nevertheless, almost all of them have low security in the face of unbalanced and/or disrupted voltage sources and load level variations, are incapable of identifying the faulty region (or even faulty phase), and are incapable of discriminating STTFs from RTTFs. In addition, they need to use CTs (current transformers) and PTs (potential transformers) for measuring the current and voltage signals with a probable risk of CT saturation or PT fuse burning.

There are also other non-invasive flux-based techniques which use some sensors installed on the motor frame to monitor the stray magnetic flux [46–48]. Such techniques are not suitable for RTTF detection as the stray flux due to RTTFs in WRIMs is very small and probably undetectable [49]. In [46], several harmonic components of the voltages induced in those sensors are used to identify STTFs. Since such sensors detect the leakage flux that crosses the stator core-back and motor frame, achieving a high sensitivity cannot be expected. With a similar technique [47], the 17th harmonic component (850 Hz) of the induced voltage in two external sensors is used to detect TTFs. The diagnostic technique proposed in [48] uses a specified range of low-frequencies (up to 1 kHz) of the induced voltage in an external flux sensor with the same aim, being the interpretation of the obtained frequency spectrum difficult due to the presence of significant harmonics not directly related to the fault [12].

In contrast, some invasive methods have also been proposed to detect TTFs, as reported in [49–51]. The method in [49] measures the flux crossing each stator tooth, meaning that numerous sensors (as much as the number of stator slots) are needed to measure the air-gap flux. In a similar manner, the total harmonic distortions (THD) of the induced voltages in the sensors are used in [50] to detect TTFs, by comparing the obtained THD with the related value in the healthy condition (HC).

Temperature measurement by special embedded sensors is another technique to monitor the machine status from various viewpoints, as proposed in [52–54] for stator and in [55, 56] for rotor windings temperature tracking. In the presented method in [54], special thermal sensors such as Fibre Bragg grating (FBG) have been used to measure the stator winding temperature increase due to STTFs. As a brief comparison between invasive flux-based and thermal-based techniques, it can be noted that although thermal-based techniques can measure the stator winding temperature at several winding locations and assess the machine health condition, they have some disadvantages in comparison with the flux-based technique proposed in this paper as follows:

- Thermal-based techniques inevitably lead to delays in the fault detection process as STTFs create an increase of the winding temperature, especially in the surroundings of the fault, but the existence of a non-negligible thermal time constant means that if the sensors are installed far from the faulty point, they will take some time until they are able to sense the increased temperature.
- Motor overloading conditions or unbalanced voltage supply sources can lead to an increase and asymmetric distribution of the winding temperature, resulting in false tripping. In other words, the security of thermal-based techniques is lower than the flux-based one.
- Although monitoring the rotor winding temperature in rotational machines by using such sensors is not impossible, it is very complicated [55, 56] and needs special instruments to transmit the obtained signals from the sensors installed on the rotational rotor.

The use of flux sensors is not a novel approach to detect the RMF in motors, and their use was introduced in previous research works [12, 51, 57–59] to detect TTFs in stator and rotor of SCIMs. However, the diagnostic approach proposed in this paper uses the distortion of the RMF along the air-gap circumference to detect STTFs as well as RTTFs in WRIMs, by focusing on RTTF detection. The distortion of the RMF is accessible through the comparison of the induced voltages in corresponding sensors which must sense identical/symmetrical flux when the machine operates in HCs. The presence of each type of fault will disturb this symmetricity. For each stator coil group of each phase, one sensor is installed, being the induced voltage in each sensor linked to the resultant flux in the related region. In the face of STTFs, the faulty phase and faulty region can be identified by the analysis of the differential voltages induced in the corresponding sensors and by the comparison of the amplitude of the fundamental frequency component of the voltages induced in the sensors related to the faulty phase/rotor.

Since a fault occurrence in the rotor winding creates a rotational distortion in the air-gap magnetic field, all sensors will sense such distortion, sequentially, at different instants in time. The source of this distortion rotates at the rotor speed, which is a function of the number of pole-pairs and load level.

Although the proposed flux-based technique is not new in the detection of STTFs and faulty region identification, the application of this technique to detect RTTFs in WRIMs was not evaluated yet. In fact, the detection process of STTFs using this method is identical for all types of rotating machines, but in the face of rotor winding faults, there is a significant difference between them. While synchronous machines have individual pole windings, fed by a DC voltage source, which rotate at a constant synchronous speed, and SCIMs have rotor bars shorted by end rings, WRIMs have three individual windings on the rotor that can be regarded as a combination of the faults of the aforementioned machines. In comparison with SCIMs, the RTTF detection in WRIMs is more difficult and needs to be more sensitive.

The main benefits of this diagnostic technique is that it is robust to unbalanced or disrupted voltage supply systems, load level variations, and its implementation does not require complicated mathematical processing in the time or frequency domains. These properties of the proposed diagnostic technique are proven by the results shown later on in this paper.

2 Basics of the proposed technique

2.1 Air-gap RMF behaviour and current signature analysis in healthy and faulty conditions

A three-phase WRIM fed by a three-phase balanced voltage supply system, assuming ideal sinusoidal distributed windings, results in a constant amplitude and symmetric RMF along the air-gap circumference. However, in practice, some harmonics exist in the RMF of a real motor due to the non-ideal sinusoidal distributed windings, harmonics in the voltage source, the effects of stator and rotor teeth, among other factors [60].

Any kind of winding faults, whether in the stator or rotor, will disrupt the RMF symmetricity along the air-gap circumference. In the case of STTFs, there will be an air-gap flux density reduction in the vicinity of the faulty region, while it remains almost constant in the healthy regions [12]. For RTTFs, the air-gap flux density will drop slightly in the vicinity of the faulty coil while it remains almost constant in other parts. It should be noted that the faulty region is fixed to the stator for the case of STTFs, being the RMF asymmetry observable in the affected area, while the asymmetric RMF generated by RTTFs is not limited to a specific zone and will rotate, according to the rotor speed and direction.

Based on the current signature analysis, rotor faults, whether broken rotor bars (BRBs) in SCIM or RTTFs in WRIMs, produce specific components in the stator current spectrum, at frequencies of \( f_{\text{brb}} = (1 \pm 2k_s) \times f \) (for \( k_s = 1, 2, \ldots \)), where \( f \) is the fundamental frequency, \( f_{\text{brb}} \) is the sideband frequencies associated with the BRB, the rotor slip and the fundamental supply frequency, respectively [60].

Regardless of the rotor structure, the frequency components appearing in the stator currents due to STTFs are well-known, being \( f_s = n/p(1 - s) \pm k \times f \) for \( n = 1, 2, \ldots \) and \( k = 1, 3, 5, \ldots \) where \( p \) is the number of pole-pairs [61]. Similar harmonics will also be present in the air-gap and leakage flux.

2.2 Proposed diagnosis approach

The main idea behind the proposed diagnostic approach is to use the magnetic flux instead of other unessential signals (e.g. electrical current, vibrations etc.) as the main state variable of the electric machine. In fact, the original factor which subsequently

\[ f_{\text{brb}} = (1 \pm 2k_s) \times f \]

\[ f_s = n/p(1 - s) \pm k \times f \]
creates unbalanced motor supply currents, increase of the harmonic content of current signals, increase of the machine frame vibration etc. under the presence of any internal defect in the electromagnetic system of rotating machines is the distorted RMF along the air-gap.

The scientific background and the way how this technique can detect and discriminate STTFs and RTTFs in WRIMs and distinguish them is described in this paper, although with more focus on RTTFs. The sample 4-pole WRIM under analysis has 36 slots in the stator. Each stator phase winding has two coil groups series-connected and each coil group contains three coils, each one with 36 turns. On the other hand, the rotor core has 48 slots, and each rotor phase winding is made of two coil groups. Each coil group contains four coils of eight turns each. Fig. 1 shows the stator and rotor windings arrangement and the installed flux sensors in each phase. Each sensor contains five turns. The slots for the coil groups of each stator phase and the corresponding sensors are shown in Table 1.

It should be clarified that by using a lower number of turns, the induced voltages in the sensors and, accordingly, the accuracy/sensitivity of the proposed method will be reduced. In this context, a higher number of turns is preferred. However, there are limits to be considered in the use of a higher number of turns. Firstly, it may not be possible to install sensors with a high number of turns in the stator slots and isolate them from the main stator windings due to space restrictions. Secondly, analogue/digital (A/D) converter cards have a maximum permissible input voltage level in their analogue inputs. By using sensors with more turns, although a higher induced voltage is obtained across the sensors terminals, the maximum permissible input voltage of the A/D card has to be met. By considering all these limits, the optimal number of turns in this study was chosen as 5.

Due to the identical RMF sensed along the magnetic axis of each coil group in one phase of the machine, it can be anticipated that in HCs an identical flux will be observed in those regions and, accordingly, equal induced voltages (\(E_{i,HC} = i = 1, 2, \ldots, 6\)) in the corresponding sensors (e.g. \(S_1\) and \(S_2\) for the phase A): (see (1)) . However, in practice, considering the non-ideal construction of the motor and sensors, there are small differences in the amplitudes of the induced voltages in the corresponding sensors, which may affect the sensitivity of the diagnostic method. In addition, some distortions in the induced voltages are predictable. To solve these problems, firstly the obtained voltages are filtered by appropriate low-pass filters (e.g. simple resistor–capacitor (R–C) analogue or digital filters) and secondly, proper correction factors \(CF_j\) are applied to the obtained induced voltages.

Let us consider that \(E_{i,HC}\) is the induced voltage in the \(j\)th sensor (measured after the low-pass filter) with the motor in HCs. The next step is the extraction of the fundamental component (FC) of this voltage through the discrete Fourier transform (DFT), thus obtaining \(E_{i,FC}^{HC}\). To compensate the effects of the aforementioned residual unbalance in the induced voltages, modified induced voltages in the sensors \(E_i^{FC}\) during the motor operation can be obtained as follows [12]:

\[
E_i^{FC}(t) = \frac{\max\{E_{i,k}^{FC}\} \mid k = 1:6}{E_{i,FC}^{HC}} \times E_i(t).
\]

Equation (2) shows that the modified induced voltages are equal to the original ones, after their normalisation in relation to the voltage with the highest FC. Such a process is important to improve the sensitivity and accuracy of the proposed diagnostic algorithm. The effects of the low-pass filtering and modification process by the CFs on the obtained signals are shown in Fig. 2.

The distortions in the FC of the RMF can then be observed through the calculation of the differential voltages, obtained as the difference between the modified voltages induced in the corresponding sensors, i.e. \(\Delta E_A = E_i - E_i^{FC}\), \(\Delta E_B = E_i^{FC} - E_i^{FC}\) and \(\Delta E_C = E_i^{FC} - E_i^{FC}\).
The fundamental frequency component of each $\Delta E$ ($\Delta E_{25Hz}$ or $\Delta E_{50Hz}$) is then extracted with the aid of the DFT, being these components used to detect STTFs. With this aim, the obtained $\Delta E$s will be compared with the related threshold level ($Th_b$). This threshold is found in a worst-case scenario while the motor is run in HCs, with the highest probable unbalanced voltage source, at different load levels, and by applying a safety margin factor of 1.1. Indeed, $Th_b = 1.1 \times \Delta E_{max}$ where $\Delta E_{max}$ is the maximum value of the $\Delta E$s in the worst-case scenario. On the other hand, a rotor fault creates an RMF distortion which rotates approximately at the rotor speed, consequently, all $\Delta E$s will detect it sequentially. Since the 4-pole sample motor has two pole pairs, the RTTF detection can be realised through the monitoring of $\Delta E_{50Hz}$ (generally, the component at the frequency $f/p$). The related threshold level for such fault type, $Th_b$, is obtained similarly to $Th_b$, but in this case using the 25 Hz component of the $\Delta E$s [51].

When the $\Delta E_{50Hz}$ or $\Delta E_{25Hz}$ components increase above the respective threshold values ($Th_b$ for one phase or $Th_b$ for all three phases), this in an indication that an STTF or RTTF has occurred in the motor, respectively. In the case of STTFs, the highest $\Delta E$ among them determines the faulty phase [12]. In the case of RTTFs, the differences between the $\Delta E$s are negligible and all of them will exceed $Th_b$. Fig. 3 summarises the proposed diagnostic technique in the detection and discrimination of STTFs and RTTFs, step-by-step.

There are two points that need further clarification. One point is about the safety margin factor and the other one is concerned with the harmonic content of the induced voltages, as described as follows:

- Although the safety margin factor is an arbitrary value, it should be remembered that the selection of a high safety margin factor will decrease the sensitivity of the protection scheme while increasing the security of the proposed method and vice-versa. The safety margin factor in the paper was chosen to attain the highest sensitivity while maintaining the related security.

- Although STTFs or RTTFs in general increase the level of the inherent harmonic content in the induced voltages across the sensors due to the created distortion in the RMF, such harmonics lose their importance in the proposed technique because specific frequency components (calculated by DFT) are used as fault diagnosis criteria. It should be emphasised that the air-gap magnetic field (even with the machine in a HC) does not have a pure sinusoidal waveform. There are several space harmonics which are affected under the presence of any fault in the machine.

### Table 2 Technical specifications of the simulated WRIM

| Specification         | Value   |
|-----------------------|---------|
| rated power, kW       | 2.2     |
| rated line-to-line voltage, V | 380     |
| rated speed, rpm      | 1487    |
| rated frequency, Hz   | 50      |
| number of poles (pole-pairs) | 4 (2)   |
| inner diameter of the stator core, mm | 109     |
| outer diameter of the stator core, mm | 169     |
| axial length of the stator core, mm | 87      |
| number of stator slots | 36      |
| stator windings connection | Y      |
| stator turns/slot in series | 36      |
| number of stator turns/coil group (phase) | 108 (216) |
| rotor type             | wound rotor |
| inner diameter of the rotor core, mm | 29.37   |
| outer diameter of the rotor core, mm | 108.5   |
| axial length of the rotor core, mm | 87      |
| number of rotor slots  | 48      |
| rotor turns/slot in series | 8      |
| number of rotor turns/coil group (phase) | 32 (64) |

Fig. 3 Flowchart of the proposed diagnostic procedure

### 3 Simulation results

To demonstrate the performance of the proposed technique applied to a WRIM, a finite element model of the sample motor was implemented in Ansys Maxwell v.16 software. Embedded sensors were considered in specific stator slots, as shown in Fig. 1. The sample WRIM technical specifications are provided in Table 2. This information also applies to the motor used in the experimental tests.

As discussed before, any TTF, either in the rotor or in the stator windings, will cause a flux density distortion and an RMF asymmetry along the air-gap circumference. Fig. 4 clearly illustrates the change in the air-gap flux density in the case of STTFs and RTTFs, compared to the HC, over a certain period of time. The second row in each rectangle of this figure indicate the difference of the flux density in the healthy and faulty conditions for a better visualisation of their differences. As can be seen, the flux distortion zone rotates along the air-gap circumference in the case of RTTFs, while it is stationary in the case of STTFs.

Since the induced ampere-turns in the rotor windings is a function of the rotor slip (or load level) and the number of shorted turns, in order to obtain more visible results, the simulation of the rotor fault was carried out for seven shorted turns (RTTF$_7$) in a coil at a slip of 5.33%, while the STTF was simulated for five shorted turns in the first coil of phase A (STTF$_5A$), at the same slip.

As mentioned in the introduction, the main cause of the adjacent insulation failure and fault expansion is the circulation of the current in the shorted turns. The circulating currents in the shorted turns for the cases of STTF$_5A$ and RTTF$_7$ from the starting moment up to the rated speed are shown in Fig. 5.

As can be seen, for the case of STTF$_5A$ this current will increase to about twice the motor locked rotor current (at the starting moment), while in the case of the RTTF$_7$, the difference between the currents flowing in the rotor winding in the HC and the current flowing through the faulty portion of the rotor winding during an RTTF is insignificant, thus allowing to conclude that the detection of RTTFs is more challenging than the detection of STTFs.

The induced voltages in all sensors, the $\Delta E$s, and the related 25 and 50 Hz components for the HC, RTTF$_7$ and STTF$_5A$, are shown in Fig. 6. As expected, the induced voltages in all sensors are approximately equal in magnitude and phase in HCs, while the 25 and 50 Hz components are almost zero. However, some disturbances are seen in the $\Delta E$s when a RTTF or a STTF is introduced, so that $\Delta E_{25Hz}$ or $\Delta E_{50Hz}$ excels the related threshold values under a RTTF or a STTF, respectively. As can be seen, $\Delta E_{50Hz}$ is not triggered by a RTTF, and $\Delta E_{25Hz}$ is not activated by a sensor.
conditions to detect and discriminate RTTFs and STTFs, an generator (SG) which acts as a mechanical load. The armature shown in Table 2, mechanically coupled to a synchronous

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R–C low-pass filters, and the output signals are then converted to terminals of the SG are connected to a variable three-phase mechanical power and speed of the WRIM, can be controlled by regulating the field current of the SG. The leads of the sensors installed in the stator slots of the WRIM are connected to simple R–C low-pass filters, and the output signals are then converted to digital ones by using an ADC card (Advantech USB-4711a), being sampled at a frequency of 2 kHz. Various RTTFs in one rotor winding and STTFs in one coil of phase A are applied to the WRIM at different load levels (to perform the tests at various rotor slips) to fully test the proposed diagnostic approach.

4.2 Determination of the threshold levels

To obtain the threshold levels, several tests conducted at different motor conditions (including different load levels, with and without a series startup resistor of 1 Ω connected to the rotor circuit) were performed. The maximum values of $\Delta E_{50Hz}^R$ and $\Delta E_{50Hz}^S$ were recorded as a function of the mechanical load in order to obtain $Th_R$ and $Th_S$ (Fig. 8). As can be seen, the variation of the mechanical load in HCs does not have a significant effect on these components. Although it seems that the ramp of $Th_R$ versus the load level is incremental, the related slope is very small, hence $Th_R$ is regarded as a constant value in this paper, similarly to $Th_S$. By looking to the maximum values of $\Delta E_{50Hz}^R$ and $\Delta E_{50Hz}^S$ at different conditions, and using a security margin of 10%, the related thresholds were set as $Th_R = 0.195$ V and $Th_S = 0.063$ V.

4.3 Detection and discrimination of various TTFs

Experimental results

4.1 Experimental setup

To verify the performance of the proposed technique in real conditions to detect and discriminate RTTFs and STTFs, an experimental setup has been prepared as shown in Fig. 7. It consists in a 2.2 kW WRIM with the technical specifications shown in Table 2, mechanically coupled to a synchronous generator (SG) which acts as a mechanical load. The armature terminals of the SG are connected to a variable three-phase resistive load. The mechanical power of the SG, and thus the mechanical power and speed of the WRIM, can be controlled by regulating the field current of the SG. The leads of the sensors installed in the stator slots of the WRIM are connected to simple R–C low-pass filters, and the output signals are then converted to digital ones by using an ADC card (Advantech USB-4711a), being sampled at a frequency of 2 kHz. Various RTTFs in one rotor winding and STTFs in one coil of phase A are applied to the WRIM.

![Fig. 4](image_url) Air-gap flux density variations over time for the STTF_{SA} in comparison with the HC, at a medium load level with a slip of 5.33% and their difference (upper rectangle), and for the RTTF_{R} in the same conditions but for a different instant in time (lower rectangle)

![Fig. 5](image_url) Circulating current in the shorted turns for STTF_{SA} (left) and RTTF_{R} (right) along with the corresponding faulty phase current from starting moment up to the rated speed

STTF. Such behaviour shows that the proposed technique discriminates RTTFs from STTFs and has an acceptable security.

As an interesting point about RTTFs is the simultaneous oscillation of $\Delta E_{50Hz}^R$ for all three phases, while the entire air-gap circumference will be sweep by the distorted RMF.

It should be noted that the maximum increase of the $\Delta E_{50Hz}^R$ for an STTF occurs in the faulty phase, i.e. phase A. Indeed, $\Delta E_{50Hz}^A$ is bigger than $\Delta E_{25Hz}^R$ and $\Delta E_{50Hz}^C$.

![Fig. 5](image_url) Rotor current in the healthy turns and the faulty turns during RTTF

4 Experimental results

4.1 Experimental setup

To verify the performance of the proposed technique in real conditions to detect and discriminate RTTFs and STTFs, an experimental setup has been prepared as shown in Fig. 7. It consists in a 2.2 kW WRIM with the technical specifications shown in Table 2, mechanically coupled to a synchronous generator (SG) which acts as a mechanical load. The armature terminals of the SG are connected to a variable three-phase resistive load. The mechanical power of the SG, and thus the mechanical power and speed of the WRIM, can be controlled by regulating the field current of the SG. The leads of the sensors installed in the stator slots of the WRIM are connected to simple R–C low-pass filters, and the output signals are then converted to digital ones by using an ADC card (Advantech USB-4711a), being sampled at a frequency of 2 kHz. Various RTTFs in one rotor winding and STTFs in one coil of phase A are applied to the WRIM at different load levels (to perform the tests at various rotor slips) to fully test the proposed diagnostic approach.
medium load level. As can be seen, $\Delta E_{25Hz}^{\text{RTTF}}$ exceeds $\text{Th}_S$, while the 25 Hz components remain securely below $\text{Th}_R$.

Briefly, these experimental results show that the proposed diagnostic technique detects RTTFs and STTFs and discriminates them, as well. Weak RTTFs (e.g. RTTF_1) can also be detected at higher load levels (higher rotor slips).
Fig. 9 $\Delta E_s$ (left), $\Delta E_{25\text{Hz}}$ (mid) and $\Delta E_{50\text{Hz}}$ (right) for the HC at no-load and medium load (first row), RTTF at no-load (second row) and medium load conditions (third row), STTF at no-load (fourth row) and medium load conditions (last row)
4.5 Effects of the load level on the TTF diagnosis

Fig. 11 (top-left) shows the variations of $\Delta E_{25Hz}$ for STTFs (left) and RTTFs (right) versus the mechanical load level (top) and number of shorted turns (down).

Fig. 11 (down-left) shows the variations of $\Delta E_{25Hz}$ for all three phases, with the motor running in steady-state at no-load, with $R_{ad} = 1 \Omega$, versus the number of shorted turns.

Fig. 11 (top-right) shows the variations of $\Delta E_{50Hz}$ versus the number of shorted turns in the rotor for three levels of the mechanical load. Clearly it can be seen that $\Delta E_{50Hz}$ is not affected by the mechanical load level, and again shows that more shorted turns create a higher $\Delta E_{50Hz}$.

Fig. 11 (down-right) shows the variations of $\Delta E_{23Hz}$ versus the number of shorted turns in the rotor for three levels of the mechanical load. In opposition to $\Delta E_{50Hz}$, it depends on the mechanical load level and number of shorted turns in the rotor.

Based on these experimental test results, the following conclusions can be drawn:

- RTTFs with more shorted turns result in the higher $\Delta E_{23Hz}$.
- The detection capability of the rotor faults will be increased for the higher mechanical load levels.
- RTTF as the minor fault is detectable at a medium mechanical load and above it; while RTTF is detectable even at a very light-load condition. In other words, RTTFs are more easily detected at the higher loads (higher rotor slip), as expected.

It must be emphasised that WRIMs are designed to start-up under load. Running them at no-load is mostly used just for pre-commissioning tests. Therefore, the low performance of the proposed diagnostic technique at a no-load condition cannot be regarded as a major disadvantage.

5 Conclusion

An invasive flux-based diagnostic technique is proposed for the online detection of turn-to-turn faults in the stator and rotor windings of WRIMs. The differences of the induced voltages in the corresponding flux sensors (as an appropriate criterion to detect the RMF distortion) are used to detect the faults: the related 25 Hz components allow to detect rotor winding faults and the 50 Hz components permit the detection of stator windings faults. Simulation and experimental results have shown the ability of such a technique to detect and discriminate these two types of faults. Furthermore, the obtained results show that weaker rotor faults are more detectable at higher rotor slip values, while a single turn fault in the rotor of the sample motor with 64 turns per phase can be detected for load levels higher than 80%, but a rotor fault with 7 shorted turns is detectable even at 5% of the rated load. The proposed technique is a general diagnostic tool that allows the detection of stator and rotor faults in SCIMs and WRIMs.

6 References

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