A secure and sensitive wavelet transform based technique for stator fault detection in the cases of line-connected and inverter-fed induction machines

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Abstract
Here a new sensitive fault detection criterion is proposed, based on the stationary wavelet transform (SWT) decomposition components of the stator currents, for the online detection of stator winding turn-to-turn faults at an early stage of development. The energies of the desired detail components are calculated and the normalized Euclidean distance of the energy differences between the three phases is used as a new fault detection criterion. The robustness of the proposed technique against the presence of rotor turn-to-turn faults and loading variations is demonstrated. In addition, an adaptive threshold level as a function of the voltage unbalance factor is proposed to guarantee the robustness of the diagnostic technique against unbalanced voltage sources. Experimental results demonstrate the effectiveness and sensitivity of the proposed diagnostic approach for the detection of stator faults in line-connected and inverter-fed motors.

1 | INTRODUCTION

Three-phase induction motors are widely used for electromechanical energy conversion in industry. These motors are generally classified, based on the type of rotor construction, as squirrel-cage induction machines (SCIMs) and wound rotor induction machines (WRIMs). Due to their robustness, low weight, low repair and maintenance costs, among other factors, most induction motors in industry are SCIMs [1], usually being characterised by a low starting torque and a high starting current. On the other hand, there are some mechanical loads in specific applications such as in the cement and steel industries, cranes, etc., with high inertia at the motor startup. In such cases, WRIMs are the best choice to produce a high starting torque due to the possibility to connect startup resistors in series with the rotor windings via slip-rings and brushes [1–3].

The most common faults in induction motors can be classified as stator faults, rotor faults and mechanical faults. Among all types of faults, around 37% are stator faults [1, 2, 4, 5].

Stator and rotor winding turn-to-turn faults (STTF and RTTF, respectively) usually start with a few shorted turns caused by an insulation failure. The heat produced in the affected region will increase the local temperature which may lead to a more severe fault with more shorted turns in the affected phase, a coil-to-coil short circuit, or a coil to core (ground) fault. These faults must be detected as quickly as possible; otherwise the motor may be exposed to an irreversible damage in such conditions. Although the consumers are usually interested in the use of simple motor protection strategies against overvoltage, overcurrent or earth faults, such weak faults at an initial stage are not detectable by these simple protection methods [4].

To detect winding turn-to-turn faults in rotating machines, several non-invasive and invasive methods including non-invasive current-based, voltage-based and impedance-based, or invasive flux-based methods along with different fault detection criteria have been proposed, while each method has its own advantages and disadvantages. Due to the orientation and perspective of this article in using stator terminal currents as the main fault detection foundation, a brief review of the non-invasive current-based techniques is provided.

Some conventional current-based diagnostic methods are the positive-, negative- and zero-sequence current components analysis [6–8], motor current spectrum analysis (MCSA)
Another term of comparison for the different diagnostic approaches is the signal processing technique used in their implementation. Fast Fourier Transform (FFT) [22–25], Short Time Fourier Transform (STFT) [26, 27], Discrete Wavelet Transform (DWT) [4, 10, 11, 21, 26, 28–34], Stationary Wavelet Transform (SWT) [35–38], Dual-Tree Complex Wavelet Transform (DTCWT) [4, 34], Wavelet Packet Transform (WPT) [39–41], Rational-dilation Wavelet Transform (RADWT) [42], Artificial Intelligence (AI) [43, 44], Kalman filter [45, 46] and Hilbert-Huang Transform (HHT) [47–49] are some of the techniques presented in the literature.

As previously discussed, although any winding fault (including STTF and RTTF) usually starts with a low number of shorted turns, which represent a very weak fault at an early stage, a proper and quick action by the protection system is very important to deal with such faults. In this context, it is vital that a reliable protection system has the following two features:

- Capability to detect low intensity STTFs at their initial stage;
- Appropriate for a real-time implementation, with minimum calculation delay (computational burden);

In many current-based articles which applied sorts of wavelet transforms, the post-processing of the captured data window is the common problem [4, 26, 30, 32, 35, 37]. Indeed, proper selection of the signal processing technique is one of the important requirements when switching to an online diagnostic mode with minimum time delay for fault detection by using an appropriate technique such as the SWT [36]. Also, defining a suitable fault threshold level has a great impact on the performance of the protection technique from the security and sensitivity viewpoints. Generally, current-based methods are very sensitive to load level variations and/or unbalanced voltage sources (UVS) which lead to the circulation of a negative sequence current component that may create a challenge in the correct fault recognition [30]. Although an independent fault detection criterion can be defined in the case of load level variations, this procedure is impossible while the machine is fed by an unbalanced voltage source. Applying an adaptive threshold based on the severity of UVS percentage can be regarded as an acceptable solution in such a case, which has been less discussed in the recent research. Moreover, in some cases, despite the introduction of adaptive threshold, real-time results have neither been provided nor studied [30, 37].

UVS as one of the most challenging problems for online STTF detection in induction machines has been highly considered in recent research [4, 30, 35, 37], while it causes extensive asymmetrical components in the stator currents, which produce harmonics interfering with STTF. Although the effect of UVS is carefully analysed in these investigations, there is no solution provided to discriminate STTF from an UVS condition [30, 32, 35, 37]. Furthermore, the security of the proposed methods against other faults, especially rotor faults, is another important issue in STTF fault detection that is less discussed in articles [26, 30], while the rotor faults, including broken rotor bar in SCIM or RTTF in WRIM, will produce some harmonics on stator currents that can interfere with STTF ones. In fact, analysing the effect of rotor faults on the proposed STTF detection criterion has been ignored [4, 32, 35, 37, 41]. According to the diagnostic approach in this article, this issue is very important, especially RTTF in WRIMs and doubly fed induction generators (DFIG), which has not been addressed in similar articles [21, 28, 30]. The results of the above studies are carefully presented in Table 1.

In this article, a modified current-based method using the SWT is presented to detect STTF in WRIMs. By using a criterion based on the Euclidian distance of the energy

### Table 1: Current-based technique by WT to detect STTF

| Ref no.   | Signal process. technique | Faulty phase detection | Considering parameter | Security of the method against |
|----------|--------------------------|------------------------|-----------------------|--------------------------------|
|          |                          |                        | UVS                  | RTTF/BRB                       |
| [4]      | DWT                      | x                      | ✓ 1%–3%              | x                              |
| [10, 11] |                          | x                      | x                    | ✓                              |
| [26]     |                          | x                      | ✓                    | x                              |
| [30]     |                          | x                      | ✓ 1%–5%              | x                              |
| [32]     | DWT and SWT              | ✓                      | ✓ 1%–3%              | x                              |
| [35]     | SWT                      | ✓                      | ✓ 1%–3%              | x                              |
| [37]     | WPT                      | x                      | x                    | ✓                              |
| This paper | SWT                     | ✓                      | ✓ 0%–2%              | ✓                              |

Abbreviations: DWT, wavelet transform; RTTF, rotor winding turn-to-turn fault; STTF, stator winding turn-to-turn fault; SWT, stationary wavelet transform; UVS, unbalanced voltage sources; WPT, wavelet packet transform; WT, wavelet transform.
differences between the three phases, the machine condition is diagnosed. Although this technique is robust in the face of load variations and RTTFs, it may be activated when the motor is fed by a UVS. This major problem can be solved by utilising the idea of a biased characteristic curve (similar to transformer differential relays). To define such a curve for the diagnostic technique proposed in this article, the supply voltage unbalance percentage should be considered as the main criterion. Based on the permissible changes in this parameter, a variable threshold is obtained using the experimental results for the test motor to guarantee this technique in the face of UVSs.

The remainder of this article is organised as follows: Section 2 presents a brief overview of the theoretical concepts associated with the use of the wavelet transform and an online DWT filter is explained. The limitations of recent methods that have used wavelet transform for STTF detection are described in Section 3. The fault detection criterion is introduced in Section 4 and results of the experimental test and the security of the proposed fault detection method in the face of RTTF are shown and described in Section 5. The performance of the proposed method for the inverter-fed machine is presented in Section 6 and the paper is concluded in Section 7.

2 | USE OF DWT AND SWT FOR DIAGNOSTIC PURPOSES

2.1 | General remarks

Multi-resolution analysis is basically a technical approach to construct orthogonal wavelets, which cases the analysis of a signal that contains both low- and high-frequency components. The DWT is compatible with multi-resolution analysis and is a very common method to separate different frequency band components of a signal in a sequential procedure, offering high frequency resolution at low frequencies and high time resolution at higher frequencies. Thus, the DWT overcomes the resolution problems experienced when the STFT is used and aids in effective feature extraction for the purpose of fault detection. The discrete wavelet coefficients are calculated using two orthogonal discrete filters, a low-pass filter (H) and a high-pass filter (G). Such filters may be used consecutively over multiple levels at the outputs of the low-pass filters. By removing the high-frequency variations from the signal being processed, the low-pass filter secures slow trends. In a similar manner, the high-pass filter removes the slow trends and secures the higher frequency variations. Based on this nature of operation, the low-pass filter provides an approximation of the input signal while the high-pass filter extricates detail information from the signal [29]. The number of samples at each decomposition level is halved through a down-sampling process [36], as shown in Figure 1. Such a multilevel wavelet decomposition technique exhibits good sensitivity, short detection time, and easy application for online fault detection. Moreover, the wavelet coefficients enable better understanding of the signal and are useful in feature extraction applications [29]. As can be seen, the original signal is passed through filters H and G to generate the approximate and detail components at the first level of decomposition, where G and H are orthogonal vectors with N elements [10, 11, 36]. For the second level, the approximate component is down-sampled by two, that is, its samples are halved. After that, they are passed again through the same G and H filters to give the second detail and approximate components with halved frequency bands, respectively. Continuing this procedure up to the \( j \)th level decomposes the original signal into \( j \) detail components and an approximate one, as shown in Figure 1.

As can be seen, this procedure needs to access a filled data window of the original signal at the beginning and then decomposes it by the aforementioned sequential process. Also, the signal resolution will be halved at each decomposition level due to the down sampling process.

2.2 | The SWT

The SWT is another technique to implement an online decomposition of the original signal into various components using specific filters at each decomposition level. Since those filters are designed to directly decompose the original signal at the desired decomposition level with the specified frequency band, maximum resolution will be attained without any downsampling process. However, it should be noted that the length of the filters depends on the desired decomposition level, so that upper components are accessible using longer filters. As shown in [36], by using a mother wavelet (H) with \( N \) samples, filters \( G_i \) and \( H_i \), which take out the detail and approximate of the original signal at the \( j \)th decomposition level, include \( (2^j - 1)(N - 1) + 1 \) samples. For example, by using db2 as the mother wavelet with 4 samples, \( G_1 \) and \( H_1 \) are filters with 4 samples, \( G_2 \) and \( H_2 \) have 10 samples, and \( G_3 \) and \( H_3 \) include 22 samples. In fact, an online wavelet-based filter with the highest resolution implies more calculation burden. Such online implementation of the SWT is illustrated in Figure 2, which shows that the desired components can be extracted using the streamer of the original signal, sample by sample. Although the length of such filters can be reduced more than 50\%–60\% at higher decomposition levels by a simple technique [36] in order to obtain reduced order filters, full order filters are used in this article. For both DWT and SWT, each detail component at the \( j \)th decomposition level includes a predetermined frequency band as \( \Delta f = \left[ f_s/2^{j+1} - f_s/2^j \right] [36] \), where \( f_s \) is the signal sampling frequency. By considering \( f_s = 5000 \) Hz, the related frequency bands for various detail components are listed in Table 2.
The optimal decomposition level of a signal (motor stator current in this article) to diagnose motor faults can be chosen by comparing the frequency spectra of the healthy and faulty motor, operating at the same load level. The frequency range of the mentioned spectra where significant differences are found (by looking to the frequency bands of the SWT decomposition components) must be considered in order to determine an appropriate component to detect the fault.

3 | LIMITATIONS OF OTHER DWT-BASED METHODS

To investigate the challenges and limitations of the previous STTF detection techniques using the wavelet transform, the presented techniques in [32, 35, 37] are considered and the related outputs are discussed using the obtained experimental results for various motor load levels, UVS conditions and different STTFs. The percentage of the supply voltage unbalance is quantified by the voltage unbalance factor (UBF) [50] as in (1), where \( V_- \) and \( V_+ \) are the negative- and positive-sequence voltage components, respectively.

\[
UBF = \left( \frac{V_- - V_+}{V_- + V_+} \right) \times 100
\]

In [26], the stator currents are decomposed into seven level components, using \( \text{db}_{10} \) as the mother wavelet and a sampling frequency of 6 kHz, and the corresponding energy in all the mentioned levels is calculated. The increase of energy in the second and third details is proposed as the STTF detection criterion. However, the performance of the method in the face of UVS and load variations was not considered. Table 3 was generated using the introduced procedure in [26] for healthy (at no-load and medium load) and faulty (STTF_{5S} which means five shorted turns in the phase S) conditions. As can be seen, the variations of \( D_2 \) and \( D_3 \) components for medium load are higher than the ones for the STTF (energy of \( D_2 \) reduces for the case of STTF). Although it was mentioned in [26] that the load level must be considered to determine the energy level in various decomposition components, it can be concluded that the introduced method is a load-dependent technique which needs to use the speed of the motor or the related torque as an additional input signal.

In [32], the sixth DWT detail decomposition component (\( D_6 \)) of the stator current (i.e. the frequency band of 7~15 Hz with a sampling frequency of 1 kHz) using the db1 mother wavelet is considered for STTF detection. The normalized energy \( E_{\text{norm}} = \sqrt{\sum_{n=1}^{m} (D_6(n))^2} \) of this component is regarded as the main criterion (\( m \) is the total number of coefficients) to detect STTF. However, the proposed technique

| case          | Phase | \( D_1 \) | \( D_2 \) | \( D_3 \) | \( D_4 \) | \( D_5 \) | \( D_6 \) | \( D_7 \) |
|--------------|-------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Healthy No-Load | R     | 0.002     | 0.037     | 3.2       | 26.1      | 359.9     | 1.37e5    | 6.9c3     |
|               | S     | 0.002     | 0.033     | 2.7       | 13.9      | 364.2     | 1.37e5    | 6.9c3     |
|               | T     | 0.002     | 0.035     | 3.1       | 17.0      | 355.4     | 1.36e5    | 6.8e3     |
| STTF_{5S} No-Load | R     | 0.002     | 0.03     | 3.2       | 21.3      | 357.0     | 1.35e5    | 6.7c3     |
|               | S     | 0.003     | 0.04      | 3.4       | 13.5      | 397.6     | 1.52e5    | 7.5c3     |
|               | T     | 0.003     | 0.03      | 3.7       | 16.7      | 411.3     | 1.57c5    | 7.8e3     |
| Variation     | +33.3 | -4.7      | +14.4     | +6.1      | +8.0      | +8.3      | +7.2      |
| (Avg)%        |       |           |           |           |           |           |           |           |

Healthy medium load

| case          | Phase | \( D_1 \) | \( D_2 \) | \( D_3 \) | \( D_4 \) | \( D_5 \) | \( D_6 \) | \( D_7 \) |
|--------------|-------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
|               | R     | 0.003     | 0.085     | 6.0       | 58.9      | 581.2     | 2.14e5    | 1.1e4     |
|               | S     | 0.003     | 0.07      | 5.7       | 37.5      | 578.5     | 2.15e5    | 1.1e4     |
|               | T     | 0.004     | 0.087     | 5.5       | 46.9      | 577.9     | 2.16e5    | 1.1e4     |
| Variation     | +66.7 | +130      | +151.4    | +61.0     | +57.3     | +55.9     |           |           |
| (Avg)%        |       |           |           |           |           |           |           |           |
is neither evaluated in the face of the UVS condition nor in the face of load variations. To analyse the performance of this technique in the face of these conditions, the algorithm has been re-implemented by the obtained experimental recorded data, as shown in Figure 3. As can be seen, variation of $E_{\text{norm}}$ due to an unbalanced voltage source can result in a false STTF alarm. For instance, when the motor is fed by an unbalanced source with UBF = 1.5%, $E_{\text{norm}}$ is higher than the value obtained for STTF$_{3S}$ at a no-load condition.

In [35, 37] and [35, 37], the first detail of the DWT decomposition components (1650–3300 Hz) using the Bior5.5 as the mother wavelet is extracted as the fault index ($I_f$) as below for $n = 1 \sim N_1$:

$$I_f(n) = |\text{slope}_{d^x_i}(n)| + |\text{slope}_{d^y_i}(n)| + |\text{slope}_{d^z_i}(n)|$$

where $N_1$ is the total number of samples in the first detail, and the ratio between the difference in sample values and the difference in sample intervals is defined as a slope. This parameter is re-implemented for various conditions including the healthy, STTF$_{10S}$ and UVS (with UBF$_{1.5\%}$) at no-load level in Figure 4. As can be seen, this method is not able to distinguish STTF from an UVS condition, too.

The proposed technique in this article is an approximately load-independent method by considering a predetermined threshold curve in the face of UVS to exhibit a secure performance. In addition, it exhibits a secure behaviour in the face of RTTFs.

4 | THE PROPOSED METHOD FOR STTF DETECTION

An STTF in a motor creates a distortion in the air-gap rotational magnetic field with specific properties, leading to different induced voltages in the three windings (especially in the faulty phase). Consequently, the currents flowing through the three phases will also change, asymmetrically. Hence, in comparison to a healthy motor, the currents circulating in the three phases of a motor with a STTF will be asymmetrical.

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**Figure 3** Fault detection based on the percentage of the calculated energy ($E_{\text{norm}}$) for D6 component of DWT (left) for three phases and the related variation compared with the healthy (right) for various stator winding turn-to-turn faults and UVSs at no-load (top) and medium load (down) conditions.
Since on the basis of the experimental results obtained, (i) the energies of the currents in the three phases are approximately identical for a healthy motor and (ii) the energies of the currents in two phases will increase significantly after the appearance of a stator fault, the increase of the distance between these energies is regarded as a fingerprint for fault detection in this article. To quantify such property, the Euclidean Distance Criterion (EDC), after normalisation by the average value of the energies of currents in the three phases, is here introduced as an appropriate criterion to detect STTFs:

$$EDC(n) = \sqrt{\left(E_R(n) - E_S(n)\right)^2 + \left(E_S(n) - E_T(n)\right)^2 + \left(E_T(n) - E_R(n)\right)^2}$$

$$\times 100\%$$

(4)

where $E_{ave}(n) = (E_R(n) + E_S(n) + E_T(n))/3$ is the average value of the current energies in three phases and the related instant (n) in any detail component. Inserting the average value of the energies in the dominator makes the EDC a load-independent fault detection criterion.

5 | EXPERIMENTAL RESULTS

To evaluate the described diagnostic methodology, a three-phase WRIM with the technical specifications in Table 4 was used in the experimental tests. Several taps along one coil of phase S are extracted to the outside of the motor frame, allowing the introduction of different STTFs during the motor operation, for a short period of time. The extracted leads are connected to the beginning of the coil (taken as the reference point of STTFs) and to the 3rd, 5th and 10th turns of the same coil to simulate STTF3, STTF5 and STTF10, respectively. To measure the three stator currents and voltages, three 20:1 current transformers (CTs) and three 220:6 potential transformers (PTs) were used. As shown in Figure 5, these analog quantities are converted into digital signals and transferred to a laptop through a synchronous data logger. A synchronous generator connected to a resistive load plays the mechanical load role. STTFs are manually created on the motor by shorting the mentioned leads at various load levels including no-load, light load (0.7 kW mechanical power) and medium load (1.2 kW mechanical power). To generate an UBS, three single-phase varics are used to adjust the related voltages.

5.1 | Power spectrum density of the stator current

Figure 6 shows the stator current power spectral density for phase S in healthy (HC) and faulty (STTF10S) conditions, when
a medium load level is applied to the motor. As seen, the fault leads to a significant increase of the power spectral density for components in the low frequency range (often in the range of 0–200 Hz), which are obtainable in the D₅ and subsequent detail components. This means the related detail components can be considered as appropriate criteria for fault detection. However, the lower detail components are preferable over the higher ones because they have the lower number of elements (samples) and consequently require a lower calculation burden.

5.2 | Detail components and their energies at different decomposition levels

Figure 7 shows the stator currents in the three phases and their detail components for STTF₁₀S, STTF₁₀S, and STTF₁₀S, with the motor at no-load conditions, when db₂ with N = 4 elements (as a filter with the low calculation burden) is chosen as the mother wavelet and the fault is introduced at 100 ms. As seen, the variations of the detail components are more visible when more turns are shorted.

The first and second levels are ignored because at these levels of decomposition there are oscillations and thus are not suitable for fault detection. Also, D₅ exhibits a better resolution in the face of different STTFs in comparison with the other detail components. However, the discrimination between the healthy and faulty conditions is not possible for the weak faulty case (i.e. STTF₁₀S), especially when using D₁₀.

As mentioned before, the energy of the signal is a better quantity to evaluate these results. The energies of the three phase currents at several decomposition levels are shown in Figure 8. The following remarks can be made based on these results:

![Figure 6](image_url)  
**Figure 6** Power spectral density of the stator current in healthy and faulty (STTF₁₀S) conditions at a medium load level

![Figure 5](image_url)  
**Figure 5** The experimental setup (schematic)

### Table 4 Technical specifications of the sample wound rotor induction machine

| 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)   |
Energies of the three phases in HC are identical, while the energies of two phases increase considerably after the introduction of the fault.

The distance between the energies of the three phases, at each decomposition level, depends directly on the severity of the fault (longer distance for more shorted turns).

The energies of the 4th and subsequent detail components in faulty conditions are more stable than the 3rd, while the energy of the stator current in each phase at the 3rd decomposition levels oscillates.

The 4th and upper order detail components can be used as the more likely ones to allow the discrimination of a faulty condition from a healthy condition.
5.3 Condition assessment based on the EDC

Figure 9 presents the behaviour of EDC_{D5}, EDC_{D6} and EDC_{D7} for STTF_{3S}, STTF_{5S} and STTF_{10S}, at different motor load levels, including no-load, light load and medium load levels. For all decomposition levels, the results are approximately identical. However, they exhibit different delays to detect the faulty condition due to the use of longer filters at upper decomposition levels. A brief comparison of the time delays to detect the faulty condition is shown in Figure 10. As seen, the EDC at each of the three considered levels of decomposition is capable of detecting STTFs. Briefly, it can be concluded that any of the EDCs can be used to detect STTFs, while EDC_{D5} can be considered as the best one among all from the viewpoint of the related filter dimension and delay time.
### 5.5 The effect of UVS on the STTF detection

Unfortunately, the introduced EDC is sensitive to UVSs. UVS, even with its unbalance within its permissible range (i.e. 2.5\% [51]), leads to a remarkable increase in the EDC. So, by increasing the unbalance of the voltage supply system, and without any adaptation to the diagnostic process, the EDC would lead to a false STTF detection alarm. Hence, it is mandatory to find a procedure to distinguish an actual STTF from a UVS. This can be accomplished if a biased threshold level is used.

To evaluate the effects of the UBF on the value of EDC, a single-phase autotransformer is connected to each of the phases, in order to reduce the voltage applied to that motor phase. Although it was concluded in section 4 that the EDC is a function almost independent of the motor load level, the results in Figure 9 show that the EDC takes smaller values (slightly) at higher loads.

Since the maximum value of EDC with the motor in healthy conditions is required to be obtained a no-load motor was used to obtain the final biased threshold level. Figure 11 shows the obtained characteristic of the EDC versus UBF which exhibits a linear behaviour. As can be seen, the values of EDC obtained for a loaded motor are smaller than the ones obtained at no-load conditions. To achieve more security a 10\% increase in the obtained results was used to find the final threshold level characteristic: \( \text{Th} = 28.1 \times \text{UBF} + 5 \% \). For normal conditions, when UBF is zero, Th = 5\% is used as before.

In addition to the healthy conditions, the EDC values for three STTFs (including STTF\(_{3S}\), STTF\(_{5S}\) and STTF\(_{10S}\)) at three state UBF (about 0.55\%, 1.1\% & 1.6\%) for two load levels (no-load and light load) were obtained and are shown in Figure 11. As can be seen, the weakest STTFs (i.e. STTF\(_{3S}\)) are detectable. Figure 12 summarises in detail the proposed diagnostic technique to detect STTFs in online conditions.
Figure 13 shows the \( E_{DC_{DS}} \) for an UBS with \( UBF = 0.55\% \) for different STTFs, while the motor is at no-load. As can be seen, \( E_{DC_{DS}} \) in healthy condition has increased in comparison with the situation of a balanced voltage source. However, it does not exceed the biased threshold, as \( Th \cong 20\% \) for such UBF. So, by using a biased threshold level with the proposed method, it appears as a robust technique in the face of UVSs.

5.6 Identification of the faulty phase

To identify the faulty phase, two tests were carried out for two different faulty phases, that is, phases S and R. To achieve better results, a weak fault is introduced in phase R. The winding includes two parallel wires. To create a weak fault, just five turns of one path are shorted, while the other one is in healthy condition. The obtained results are shown in Figure 14.

The results show that:

- The severe STTF creates higher energies and more difference in the related values of the current signals;
- In the face of STTF5R, the energies of phases R and S increase while the energy of phase T does not change;
- In the face of STTF5S, the energies of phases S and T increase while the energy of phase R does not change.

Consequently, when an STTF occurs, the energies of the faulty phase and the next one will increase according to the phase sequence, thus allowing the identification of the faulty phase by following a simple procedure.

5.7 Security assessment

Any strategy aimed to detect faulty conditions in electrical devices (induction machines in this article) must be evaluated from a security point of view in the face of other faults or abnormal working conditions. RTTF is an example of other faults and abnormal conditions the proposed diagnostic method must be robust against.
Figure 15 shows the energies of the stator currents in the three phases and the related EDCs (EDC$_{D5}$ and EDC$_{D6}$ are similar to this one, as can be seen in the previous results) using db$_2$ as the mother wavelet, when an RTTF with seven shorted turns (RTTF$_7$) is introduced in the test motor. As can be seen, identical variations in the three current energies produces an EDC lower than the threshold value. In fact, the disturbed magnetic field rotates along the air-gap circumference and sweeps all three phases identically.

This means no difference can be found between the energies of the three phase currents, making the proposed diagnostic algorithm robust in the face of rotor faults.

6 | PERFORMANCE OF THE PROPOSED TECHNIQUE FOR INVERTER-FED MOTORS

As mentioned before, detail components from the 4$^{th}$ up to 7$^{th}$ level are appropriate for STTF detection in online conditions, when the motor is fed at rated frequency. Among them, the 5$^{th}$ one was chosen considering the calculation burden and the related resolution. However, if the calculation burden does not matter (by using powerful processors for instance), the 6$^{th}$ detail component with the higher resolution can be preferred. The 4$^{th}$-6$^{th}$ detail components include the frequency band of about 40-300 Hz, that is 0.8-6 times the motor rated frequency. Based on this analysis, for the inverter fed IM (at variable frequency), it can be expected that the diagnostic may be done using the current signals at higher decomposition levels (which correspond to the lower frequency bands). For instance, if the motor supply frequency is around 20-25 Hz, the 5$^{th}$-7$^{th}$ detail components can be used to achieve that goal. It must be mentioned at this point that at lower supply frequencies (and accordingly with lower flux variations), smaller currents will be induced in the shorted turns, and the windings are less likely to be damaged. However, it seems that the proposed method is able to detect the STTF even at such low frequencies using the previous detail component, that is, the fifth one.
To evaluate the performance of the proposed technique at lower supply frequencies, the tested IM is fed by an inverter using three output frequencies lower than the rated one (i.e., 20, 30 and 40 Hz). The obtained results, including the energies of different detail components (from the third up to the seventh ones) for STTF$_{15S}$ are shown in Figure 16.

As can be seen, although the performance of the proposed technique is acceptable, the STTF detection can be done using
the higher decomposition levels, which have superior frequency resolution. The energies of the signals at the higher decomposition levels (with lower frequency bands) are higher than the ones at the lower decomposition levels. The resulting EDCs for such conditions are shown in Figure 17. Although the energies at the 5th–7th decomposition levels change significantly, the resultant EDCs show that their sensitivity for fault detection is the same. It can thus be concluded again that the 5th detail can be regarded as an appropriate detail component to detect STTF, even at lower frequencies, when the machine is fed by an inverter. However, as can be seen, the performance of the proposed technique will be reduced at lower supply frequencies. In fact, although the extreme STTFs are detectable at all frequencies, the sensitivity of the proposed technique will be reduced at lower frequencies, especially for the weakest STTFs, due to the reduced fault effects at such frequencies.

7 | CONCLUSION

A new fault detection criterion, based on the SWT decomposition components of the stator currents, has been proposed in this article for the online detection of stator winding turn-to-turn faults. The energies of the desired detail components are calculated and the normalized Euclidean distance of the energy differences between the three phases is used as the fault detection criterion.

The experimental results have shown that even weak faults are detectable by this technique. The robustness and security of this technique against the presence of rotor turn-to-turn fault was also demonstrated. To ensure the robustness against UVSs, an adaptive threshold level has been introduced. Also, the performance of the proposed method for the inverter-fed machine with variable frequency has shown that this method can be used at lower supply frequencies, although it exhibits a lower sensitivity in this region.

As a whole, it can be concluded that the proposed technique of stator faults is a sensitive and secure method in the face of load level variation, UVS, rotor faults and variable frequencies.

CONFLICT OF INTEREST

There is no conflict of interest.

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