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Tajdinian, Mohsen; Behdani, Behzad; Chamorro, Harold R.; Sood, Vijay K.

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A Similarity Based Index for Stator Inter-Turn Fault Detection in Induction Motors

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Mohsen Tajdinian
Hitachi Energy Research Center,
Hitachi Energy,
Västerås, Sweden
Mohsen.Tajdinian@hitachienergy.com

Behzad Behdani, *Member, IEEE*
Department of Electrical Sustainable Energy,
Delft University of Technology,
Delft, the Netherlands
B.Behdani-1@tudelft.nl

Harold R. Chamorro, *Senior Member, IEEE*
School of Electrical Engineering and
Computer Science,
KTH Royal Institute of Technology,
Stockholm, Sweden
HR.Chamo@ieee.org

Vijay K. Sood, *Life Fellow, IEEE*
Department of Electrical, Computer and Software Engineering,
Faculty of Engineering and Applied Science,
Ontario Tech University, Ontario,
Ontario, Canada
Vijay.Sood@ontariotechu.ca

***Abstract*— Failures of Induction Motors (IMs) can lead to unscheduled downtime and interruption in industry processes. This paper concentrates on the detection of the stator's inter-turn faults which are one of the most frequent causes of failures in IMs. The proposed detection method is based on a similarity index that uses the current waveform. To be more specific, the proposed algorithm presents a full-cycle sliding-window-based index based on cosine similarity that only uses current signals for detection of the stator's inter-turn faults. The proposed index cuts the phase difference before/after the disturbance and, as a result, it only depends on the size variations of the current waveform. The proposed method is technically unaffected by non-fault transient conditions including voltage imbalance, voltage sag, voltage swell, and heavy load changes. The performance of the proposed method is validated with numerous simulated scenarios and has good accuracy and speed of convergence.**

***Keywords*— Cosine similarity, electrical motor protection, induction motors (IMs), short circuit, stator inter-turn fault.**

I. INTRODUCTION

The induction motors (IMs), due to their simple and strong structures while offering a wide range of capabilities, are among the most vastly utilized equipment for mutual conversion of electrical and mechanical energies in the industries. Despite their high reliability of operation, the IMs are prone to failures due to various mechanical, environmental, and electrical tensions [1]. Statistical studies show that nearly 30%-40% of the IM electrical failures have an origin in the stator winding whereas the rest arise from rotor-related causes [2]. One of the major reasons for stator-winding faults may be due to the absence of in-time stator inert-turn fault (SITF) detection, resulting in the growth of such occurrences into severely damaging faults such as coil-to-coil, phase-to-phase, or phase-to-ground faults [3]. The SITFs mainly occur when the voltage differences between the turns exceed their insulation withstand voltage, resulting in an inter-turn insulation breakdown in the IM stator-windings, and consequently, an arc short-circuit of the entire coil. Accordingly, it is of immense importance for the healthy operation of IMs and prevent the occurrence of costly damages to detect the SITFs while they are still in their initial stages.

Different methodologies have been proposed for IM SITF detection by employing model-based and signal-based techniques [4]. The model-based approaches rely on an analytical model which may, in most cases, be complex and not sufficiently correct for fault detection in comparison to the signal processing-based approaches [5]. The signal-based methodologies are constituted of two general groups of invasive and non-invasive methods [6], making use of special spectral analysis tools for harmonic assessment of signals, e.g., Fast Fourier Transform (FFT) [7] in the frequency domain, correlation functions [8] in the time domain, Short Time Fourier Transform (STFT) [9] and Wavelet Transform (WT) [10] in the time-frequency domain. The FFT, being the most well-known harmonic analysis technique, is only applicable for stationary signals and highly prone to inaccuracy for a non-stationary signal, being the case during dynamic conditions. This shortcoming is improved in STFT via mapping the signal in both frequency and time domains, making it suitable for both stationary and non-stationary signals. Despite this advantage, the STFT is also deficient in employing a fixed window-size for all frequencies, subjecting it to accuracy degradation. Such a disadvantage can be dealt with using a variable window-size WT method also offering the time-frequency analysis capability. However, the noise sensitivity of WT is highly problematic, resulting in the requirement of different sampling frequencies for each frequency sub-band to reduce the effect of the noise mounted on the signal.

The invasive methods are realized using the signals obtained from the sensors which require a physical connection to the IM structure, typically observing acoustic noise [11], vibrations of the stator frame [12], and temperature [13]. The invasive methods are associated with several shortcomings such as low reliability, poor fault detection capability, costliness, and disturbance of IM normal operation due to sensor installment [6]. On the contrary, non-invasive methods are also proposed in the literature based on the employment of various criteria, e.g., air-gap torque [14], instantaneous electrical power [15], stator current negative sequence component [16], zero-crossing of the stator current [16], instantaneous frequency [17], the instantaneous value of total harmonic distortion (THD) index

[18], the envelope of the stator currents [19], typically requiring the MCS and MVS features.

Despite the criteria described so far are the most used SITF approaches, yet they raise the same flag as for the fault conditions in case of other events such as severe variation of loads and power quality-related phenomena [20]. As for some examples, both the groups of methods based on the stator current's negative sequence and air-gap torque indicators are susceptible to misdetection in case of voltage source imbalance, and both the indicators based on the instantaneous frequency and instantaneous total harmonic distortion (ITHD) are unable to discriminate between fault condition and other disturbances, e.g., voltage sag or voltage swell phenomena.

Further on to the groups of methods introduced, various artificial intelligence (AI)-based techniques have also been proposed for SITF detection in IMs, e.g., fuzzy logic [21], evolutionary algorithms [22], and the conventional artificial neural networks [23]. However, there are several disadvantages in the usage of AI-based methods such as the requirement of a huge training dataset, and being unable to self-learn without feature extraction. Even though the latter issue has been improved by the introduction of deep learning techniques [24], these methods still struggle with the issue of requiring huge datasets.

This paper presents a current-only based method for detecting inter-turn faults in IM's stator. The proposed method presents an index based on the cosine similarity that uses current waveform characteristics. Mathematically proven, the nature of the proposed index is so that it can detect inter-turn faults while it has immunity against other transient disturbances. The proposed method is based on the full cycle sliding window that compares two half-cycles of the current signal. This paper has the following contributions:

- Due to the stator's inter-turn faults, the stator's fault current deviates from the sinusoidal waveform. As a result, the dissimilarity of the signal from a sinusoidal waveform is calculated by the newly proposed cosine similarity-based index. In the normal condition, the proposed index only depends on the difference of the phase angles before and after the disturbance occurrence. However, during the fault condition, the proposed index depends on the size of harmonics and the difference of the phase angles before and after the disturbance occurrence.
- During the non-fault condition, the sinusoidal waveform is almost preserved with some changes in the signal's size and phase angle. The cosine similarity index is sensitive to phase angle variation. Therefore, to immunize the proposed index from mal operation during the non-fault condition, it is mandatory to cut the dependency of the proposed index to phase difference. To such an aim, employing Discrete Fourier Transform the phase difference is calculated and then the phase-shifting procedure is conducted.
- The proposed method has low mathematical complexity and computational burden.

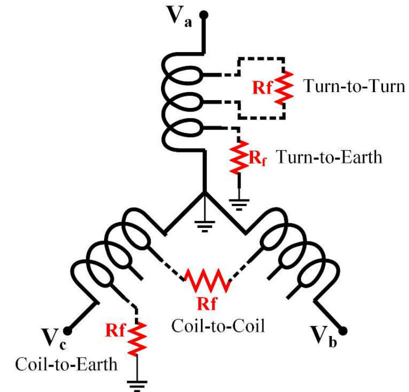

Fig. 1. Different types of inter-turn faults in IM's stator.

- Unlike [15] and [25], the presented index can single-handedly deal with diverse types of stator inter-turn faults with maximum immunity against other transients such as voltage sag, voltage swell, voltage imbalance.

The rest of the paper is organized as follows: *Section II* supplies a discussion about the different stator's inter-turn fault. *Section III* presents the proposed method and its corresponding requirements. *Section IV* supplies the validation of the proposed method based on simulation analysis. Finally, *Section V* discusses the conclusions of this paper.

II. Induction Motors Stator Inter-Turn Fault Types

Various modes and failure patterns can be considered for the SITF [26] , as shown in Fig. 1. In addition to the phase-to-ground faults which have the most severe impact, the turn-to-turn, coil-to-coil, and phase-to-phase short-circuits constitute the different types of faults associated with stator windings, e.g., single-phase, symmetrical, nonsymmetrical with grounding, and nonsymmetrical without grounding. To decide the cause of a fault occurrence, it is necessary to have an analysis of the diverse types and patterns of the faults.

A turn-to-turn fault is a short circuit of two or more turns of the coil, giving rise to a considerable increase of current in the short-circuited turns. Such an increased current would lead to significant heat generation and temperature rise to dangerous levels leading to severe damages and insulation breakdown of the windings. Particularly, one of the major causes of insulation failures is the development of turn-to-turn faults under such conditions. A turn-to-turn fault can also lead to other failures such as coil-to-coil faults by the short-circuiting of coils in the same phase, or phase-to-phase short circuits by the involvement of two or more distinct phases. Moreover, it is highly probable for a phase-to-ground fault, having a severely damaging impact on the IM due to because of such phenomena.

For the specification of IM fault causes, techniques other than analyzing the failure types and patterns can also benefit from, e.g., by visual inspection of the motor. In this context, inspecting the cleanness of the IM, presence of foreign materials, presence of moisture, and inspection of the rotor condition can be helpful. It is also important to consider the operating conditions susceptible to motor failure with respect to the general operating conditions. Moreover, the history of earlier maintenance data can be employed to guide failure rates. Taking these matters into consideration, a thorough method can be set up for the analysis and detection of the SITFs in IMs [26].

Throughout the literature, various SITF models with distinctive characteristics have been proposed [27]. The model employed in this analysis is based on the following assumptions as [28]-[29]:

- The motor temperature stays invariant so that the model parameters do not change.
- The magnetic core of the motor has a constant permeability while staying unsaturated.
- The motor air gap is constant and thin enough that the notching effect and space-harmonic generation can be ignored.
- The core hysteresis, eddy currents, and skin effects are negligible.
- The propagation of the magneto-motive force from the stator and rotor phases through the air gap is sinusoidal.

III. Proposed Stator Inter-Turn Fault Deection Method

Due to a stator inter-turn fault, several high-order harmonic components may appear in the air-gap flux density. Obviously, such an impact is reflected in the stator current. The additive components have the following frequency characteristics [29]:

$$f_{stator} = f_0[\frac{n}{p}(1-s) \mp k] \\ n = 1,2,3,\dots \ and \ k = 1,3,5,\dots \tag{1}$$

where f_{stator}, f, p, and s denote the SITF components, fundamental nominal frequency, number of pole pairs, and motor slip, respectively. Next, the cosine-similarity measure is presented followed by the proposed index.

A. Cosine Similarity Measure

In the context of the Vector Space Model, the similarity of two objects (characterized as vectors) is shown by the conventional cosine measure [31], calculated from a normalized dot-product of the two vectors. Such normalization is typically the Euclidian normalization where the normalized vector has a unit Euclidian length value. The cosine within the range of 0 to 1 interval. The cosine similarity measure between the two arbitrary vectors J_1 and J_2 are obtained as:

$$cosine(J_1.J_2) = \frac{J_1.J_2}{\|J_1\| \times \|J_2\|} \tag{2}$$

$$J_1 = [|i_1(1)|.|i_1(2)|.\cdots.|i_1(k)|.\cdots.|i_1(N)|] \tag{3}$$

$$J_2 = [|i_2(1)|.|i_2(2)|.\cdots.|i_2(k)|.\cdots.|i_2(N)|] \tag{4}$$

$$\|J_1\| = \sqrt{J_1 J_1^{Transpose}} \tag{5}$$

$$\|J_2\| = \sqrt{J_2 J_2^{Transpose}} \tag{6}$$

and N is the number of samples. Using (3) to (6), the expression (2) can be re-written as follows:

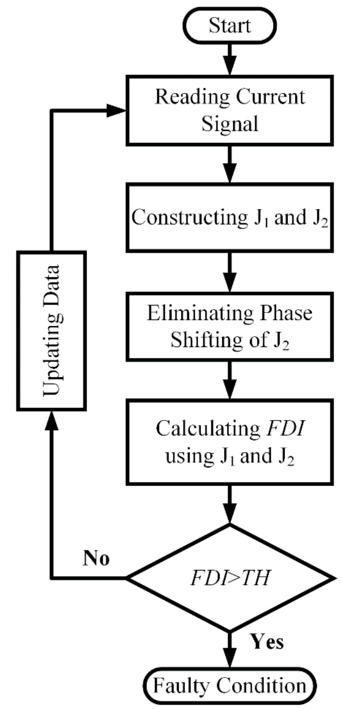

Fig. 2. Different type of inter-turn faults in IM's stator.

$$cosine(J_1.J_2) = \frac{\sum_{k=1}^{N}|i_1(k)||i_2(k)|}{\sqrt{\sum_{k=1}^{N} i_1(k)^2}\sqrt{\sum_{k=1}^{N} i_2(k)^2}} \tag{7}$$

According to (7), the similarity index (SI) is calculated as:

$$SI = 1 - cosine(J_1.J_2) \tag{8}$$

B. Implementation of the Proposed Algorithm

The procedure of inter-turn fault detection is presented in Fig. 2. The steps of inter-turn fault detection are described as follows:

1. Reading current data: A window equal to the full cycle data of the current signal is acquired from the signal. The sampling frequency is selected to be 5 kHz (100 samples/cycle considering 50 Hz nominal frequency).
2. Constructing vectors J_1 and J_2: The window data from step 1 is decomposed into two vectors, as stated in equations (3) and (4). Note that the length of vectors J_1 and J_2 are equal to a half-cycle.
3. Cutting phase difference between J_1 and J_2: Assuming $\Delta\varphi=\varphi1-\varphi2$, the phase difference between J_1 and J_2 is eliminated by phase-shifting J_2. To calculate $\Delta\varphi$, both J_1 and J_2 are fed to the Discrete Fourier Transform. After calculating $\Delta\varphi$, the samples corresponding to the phase-shifting $\Delta\varphi$ are calculated and J_2 is shifted accordingly to remove the phase difference.
4. Calculating FDI: To calculate fault detection index (FDI), vectors J_1 and J_2 whose phase difference has been eliminated previously, are then fed to equation (7). Then, according to equation (8), the FDI is calculated as follows:

$$FDI = \sum_{t_{start}}^{t_{end}} |SI| \quad (9)$$

where t_{start} and tend are the start and end times of the applying proposed algorithm. Eventually, a decision is made by comparing the FDI value and a certain threshold.

IV. Performance Evaluation

A. Simulation Results

In this section, the performance of the proposed algorithm is evaluated using a simulated model of a realistic three-phase IM adopted from [30] with the specifications given in Table I. The IM is simulated in MATLAB/SIMULINK using the model suggested in [28]. The threshold value TH is selected equal to 0.1. The threshold is obtained based on 500 simulated scenarios in various cases including inter-turn faults, voltage quality problems, and step load changes. The scenarios are introduced in Table II. Note that in all cases, the Gaussian noise level varies between 30 to 60 dB.

TABLE I. IM parameters [30].

Output Power	1.1 kW
Rated Voltage	230 V
Rated Current	4.5 A
Rated Frequency	50 Hz
Number of Poles	4

TABLE II. Consideations for Performance Comparison.

Scenario	Number of Scenarios	Type	Condition
Fault	250	- inter-turn fault (β=0.05) - coil-to-coil fault (β=0.1) - turn-to-earth fault (β=0.4) - coil-to-earth fault (β=0.6)	Fault Resistance (0 to 10Ω)
Voltage Sag	50		Voltage Variation (10 to 20%) Fault Duration (100 to 200 ms)
Voltage Swell	50		Voltage Variation (10 to 20%) Fault Duration (100 to 200 ms)
Unbalance Voltage	50		Voltage Imbalance (2 to 4%)
Load Change	100		Load Change (10 to 80%)

Next some of the challenging cases within fault scenarios including inter-turn faults, voltage quality problems, and step load changes as introduced in Table III, are graphically shown.

1) Performance Evaluation for Inter-Turn Fault Scenarios

This section provides a case study to evaluate the behavior of the FDI under internal faults in the stator of IM. Assuming that β denotes the severity of the fault, several fault scenarios

TABLE III. Accomplished Scenarios in Simulation and Experimental Studies.

Fault Scenario	Inter-Turn Fault (β=0.05)
Voltage Quality Problems	20% Voltage Sag
	10% Voltage Swell
	2.64% Voltage Source Imbalance
Step Load Changes	Load Changes from 0.7 p.u. to 1.5 p.u.

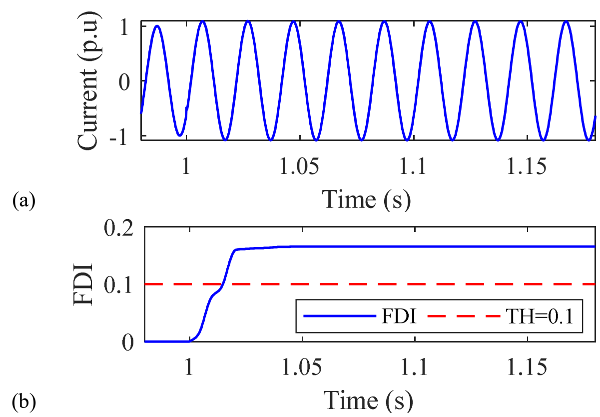

Fig. 3. Performance of the proposed indices based on simulation results for an inter-turn fault (β=0.05), (a) current signal, (b) fault detection index.

with different severities are generated. But as a hard case, only the low severity inter-turn faults (β=0.05) is discussed in this section. As it can be seen in Fig. 3a, a minor fault started at t=1s and the phase A of the stator winding is illustrated in Fig. 3a. Fig. 3b shows that the FDI quickly crosses the threshold after almost 10 ms. While the distortions in such a minor fault are exceptionally low, they are enough to cause significant variations in the FDI to cross the threshold. Obviously, the faults with higher severities result in higher values of FDI.

2) Performance Evaluation under Voltage Quality Problems

Not only in fault conditions but also during some non-fault transient conditions, the current may experience signal deformation. However, the FDI should be able to discriminate the inter-turn faults from these conditions. Such conditions are found during voltage quality problems including voltage sags, voltage swells, and imbalance of the supply voltage source.

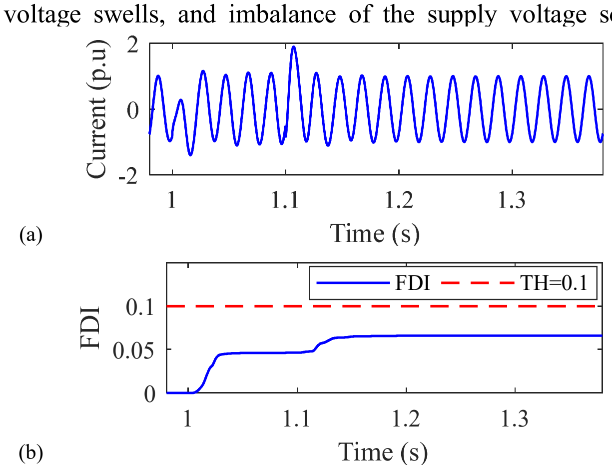

Fig. 4. Performance of the proposed indices based on simulation result for a 20% voltage sag, (a) current signal, (b) fault detection index.

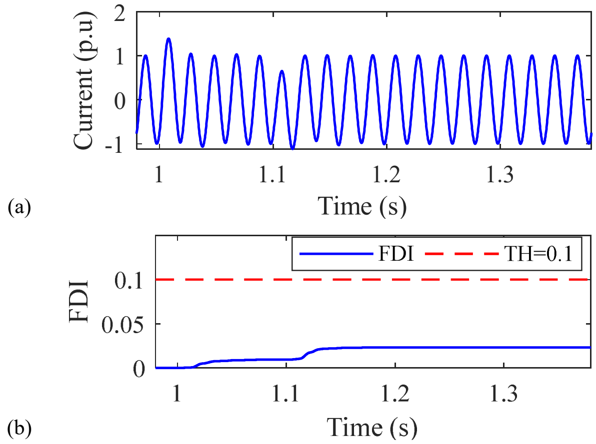

Fig. 5. Performance of the proposed indices based on simulation result for a 10% voltage swell, (a) current signal, (b) fault detection index.

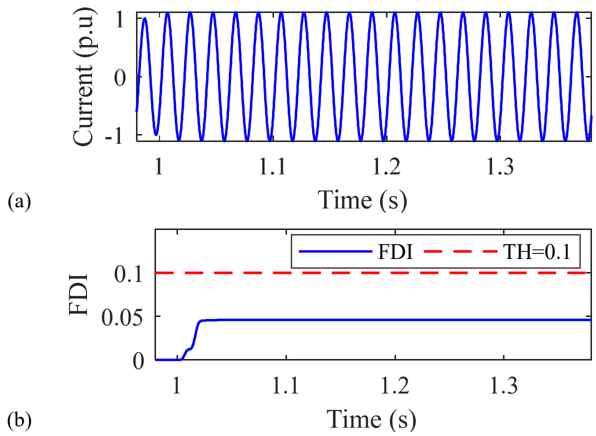

Fig. 6. Performance of the proposed indices based on simulation result for an unbalance voltage 2.64%, (a) current signal, (b) fault detection index (FDI).

Fig. 4 shows current signal during a 20% voltage sag from t=1s to t=1.1s. During voltage sag, phase A voltage signal's size changes from 1 p.u to 0.8 p.u. As shown in Fig. 4a, while the change in the current signal's size has led to a change in FDI, however, FDI does not exceed the threshold. The same results are obtained as shown in Figs. 5 and 6, respectively for 10% swell and 2.6% voltage imbalance. In general, in all three cases, the signal experiences changes in size, while almost preserving sinusoidal form during voltage quality problems. As a result, FDI which is sensitive to signal deformation from sinusoidal waveform has low changes and does not violate the threshold.

3) Performance Evaluation under Sudden Load Changes

To investigate the effectivity of FDI during sudden load changes, an 80% load change is studied. As shown in Fig. 7a, phase A current signal amplitude varies from 1 p.u to 2 p.u. Despite high variations, FDI does not exceed the threshold. During load change, the size of current signal changes, while the sinusoidal waveform is almost preserved. Therefore, the FDI which runs based on the signal deformation from the sinusoidal waveform does not cross the threshold.

B. Comparison of the Proposed Method with Previous Algorithms

Earlier sections dealt withevaluating the flexibility and effectivity of the proposed method under different fault and non-

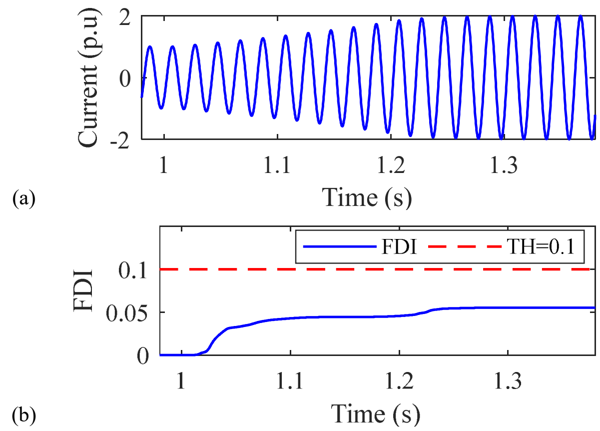

Fig. 7. Performance of the proposed indices based on simulation result for a load change 80%, (a) current signal, (b) fault detection index.

TABLE IV. QUALITATIVE AND QUANTITATIVE COMPARISONS BETWEEN THE FDI AND [15], [17], [18], AND [25]

Approach	[15]	[18]	[17]	[25]	FDI
Maximum Response Time (ms)	0.01	0.02	0.02	0.02	0.02
Required Signals	Current & Voltage	Current	Current	Current & Voltage	Current
Accuracy (%)	87	82	87	85	99

fault conditions. In this section, the performance of the proposed method is compared with algorithms that were previously suggested by references [15], [17], [18], and [25]. The comparison is conducted for 500 scenarios including fault and non-fault scenarios that are given in Table II. Table IV supplies qualitative and quantitative comparisons between the proposed method and methods given in [15], [17], [18], and [25].

From Table IV, the following conclusions can be derived:

- The proposed index has the highest accuracy among all the algorithms. Owing to the deformation of the current signal in the case of fault conditions, the cosine similarity-based index can robustly discriminate fault conditions from other cases considering voltage quality problems such as voltage sags, voltage swells, unbalanced supply voltages, and load changes. Note that the methods in [17] and [18] are not able to deal with voltage quality problems while the methods given in [15], [25], and the proposed method can deal with the problems.
- The proposed method requires 20ms of data which is higher than the method given in [15]. However, its response time is acceptable in comparison with methods given in [17], [18], and [25].
- Finally, the proposed method only uses the current signal, which in combination with other aspects of Table IV, makes the proposed algorithm much more efficient when compared with other algorithms.

V. CONCLUSION

Owing to the vital role of IMs in various industries, the condition monitoring of IMs has attracted lot of attention in research studies. This paper investigated the detection of the stator's inter-turn faults in IMs. To such an aim, an index based on the cosine similarity was developed that only uses the current signal of the IM's stator. An algorithm was presented to immunize the cosine similarity index against mal-operations due to voltage quality problems including voltage sags, voltage swells, and unbalanced supply voltages. Numerous simulation scenarios were generated and furthermore applied to the proposed index to confirm the efficiency of the proposed method. It was shown that the introduced index can detect different stator's inter-turn faults considering different fault resistances. Applying different voltage quality problems such as voltage sags, voltage swells, and unbalanced supply voltages, it was seen that the proposed method can deal with such circumstances. Also, during various sudden load changes, it was seen that the proposed index has good immunity against such conditions. Evaluating under different noise levels it was revealed that the proposed method has reliable operation in different circumstances. In comparison with the state-of-the-art algorithms, the proposed method can supply promising accuracy and fast response time, and therefore, it can be used for stator's inter-turn fault detection in IMs.

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