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Paper

Online Slight Inter-Turn Short-Circuit Fault Diagnosis Using the Distortion Ratio of Load Current in a Low-Voltage Induction Motor

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In recent decades, the use of induction motors in industrial environments has increased, and the demand for both maintenance management and condition monitoring has expanded. A literature survey shows that the inter-turn short-circuit insulation failure of stator windings is one of the most likely faults to occur in motor-drive systems. This short-circuit fault is mainly due to the damage or deterioration of electrical insulation. Moreover, the short-circuit failure of one turn will initiate stator winding insulation failure, leading to the breakdown of the entire system. Hence, identification of one-turn insulation failures in early stages is essential. Thus, the present paper deals with such failures of the induction motor. First, the frequency spectrum of the load current is analyzed by fast Fourier transform, and the characteristic frequency components are extracted. Next, the distortion ratio of the load current is calculated using the above characteristic frequency components. Finally, a new diagnostic method applying a support vector machine is proposed, and its advantages are described. The experimental and diagnostic results are presented to validate the proposed analytical procedure using the distortion ratio.

Keywords: diagnosis, distortion ratio, frequency analysis, induction motor, insulation failure, one-turn short-circuit failure, support vector machine

1. Introduction

Over the past decades, the role of induction motors in industrial environments has continuously grown. Moreover, such motor also plays a predominant role in normal human life, so failures and/or faults should be attentively considered. Due to improvements in the product quality, reliability, and performance of induction motors, the number of modern, complicated industries is increasing instantly. Some of the known advantages of induction motors include easy handling, low cost, high reliability and robustness. A literature survey [(1)] has shown that almost all industries use older motors that have been running for long durations for operations. In addition, maintenance management and condition monitoring have not been properly performed. Thus, the probability of industry shut-downs is elevated. To prevent this, faults occurring in induction motors should be identified at an early stage because replacing a faulty motor is cheaper than letting whole industries shut down. Thus, it is necessary to establish a fault diagnostic method to detect early-stage failures.

Various studies have been aimed at improving and/or upgrading the reliability of induction motors. Moreover, diagnostic technology has been developed for the purpose of motor failure detection. Numerous studies have been performed to detect electrical and mechanical failures in induction motors [(2)–(5)]. According to [(6)–(8)], short-circuit failure in the stator winding of an induction motor is a possible electrical fault in motor drive systems. This short-circuit fault is recognized as a crucial failure and is mainly caused by deterioration of electrical insulation. It is interesting to note that even the safety system used for detecting malfunctions in electrical motors cannot react to short-circuit failures because they only cause insignificant changes in the magnitude of the phase current. This problem can be addressed using digital diagnostic signal processing. This system looks after the motor condition and alerts the user at the initial stage of a fault [(9)(10)].

Some common diagnostic methods for detecting short-circuit inter-turn failures in induction motors are carried out using Park's vector and the air-gap torque [(2)–(5)]. Partial discharge characteristics are also considered essential elements in detecting such failures [(11)–(13)]. Motor current signature analysis (MCSA) is also used to detect short-circuit faults [(14)]. Also, guided waves and probability imaging approaches have been applied to detect the damage occurring in the insulation of a stator bar in a large generator [(15)]. An online method based on isolation testing can be used to detect faults when the motor is in running condition [(16)]. However, in the case of a low-voltage induction motor, most short-circuit inter-turn faults are detected using impulse testing [(17)(18)]. The high-frequency resonance fed by high-speed drives is also applied to detect stator winding insulation failure [(19)]. In turn, both negative-sequence current analysis [(20)] and load immune diagnosis [(21)] have been proposed for detecting minor level short-circuit failures occurring in the stator winding. Contrarily, a probabilistic diagnostic method has also been developed to detect

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these failures [22]. This analysis consists of characterizing the amplitude of the load current and considering it as the main feature for diagnosis. However, using this method, it is only possible to detect two or more such failures.

Generally, in the case of low voltage induction motor, if a minor short-circuit fault occurs, such as one-turn short-circuit insulation failure, the motor will not immediately result in a fatal electrical breakdown and continues to operate for a certain period even with the presence of a fault. However, the thermal deterioration of insulating material progresses gradually and certainly increases the number of short-circuit turns and finally the motor breakdown at some point of time. Thus, it is necessary and crucial to detect the slight insulation winding failure (one-turn) at the early stage to avoid the progression of insulation failure. Though the authors have diagnosed such failures, their method suffers drawbacks such as a convoluted process of selecting the combinational frequency components for diagnosis, and an accuracy rate that varies depending on this selection [23]. Hence it does not provide a permanent solution for diagnosing one-turn short-circuit insulation failures.

Thus, to overcome the disadvantages of previous works, the new clustering technique is applied to the diagnosis process of short-circuit fault. The present research is broadly classified into three distinct categories. First, frequency-spectrum analysis of the load current is performed, and characteristic frequency components are extracted by a Fast Fourier Transform (FFT). Then, the distortion ratio is derived using these components. Finally, a new diagnostic method is proposed using a support vector machine (SVM), and its advantages are described. The proposed method is then validated. The diagnostic accuracy of the present paper is considerably higher than that of Ref. (23).

2. Experimental Setup of the Proposed System

A three-phase induction motor (2.2 kW, 200 V, 8.9 A, 1680 min^{-1}, 4 poles) is used as a specimen. Power is fed to the induction motor from the three-phase line. The winding construction of the motor is shown in Fig. 1. The stator winding of the motor has a double-star connection; moreover, the number of turns for each phase winding and the number of slots are 60 and 36, respectively.

As it would be arduous and time-consuming to collect motors with insulation failures from factories, a one-turn short-circuit insulation failure is artificially introduced to the U phase of the stator winding, as shown in Fig. 2. The insulation between two adjacent turns is removed and soldered to induce a one-turn fault on the induction motor. A healthy motor is tested for reference and then the artificial insulation failure is induced to the stator winding and the similar testing is performed. In the present study, two healthy motor and a motor with short-circuit fault are used to carry out the insulation failure study.

The experimental setup used for this analysis is shown in Fig. 3. In the present study, a powder brake is used as a load. The fluctuation of commercial voltage is sometimes observed at the site. According to Japanese electricity business act, the allowed voltage fluctuation range lies between 182 V and 222 V. Hence, in the present study, the voltage fluctuation is generated using an autotransformer. The rotating speed of the induction motor is varied by changing the load as well as voltage. As a result, the instantaneous load current value of the U phase lies between 8 and 12 A. The load current and voltage of the stator winding are measured with current (HIOKI 9696-02) and voltage (HIOKI 9666) probes, respectively. The rotation speed is also monitored to ensure accuracy using a speed indicator (Ono Sokki HT-5500). Finally, the output from the available sensors is acquired simultaneously and connected with the measurement system developed by the authors. The current, voltage, and rotating speed data are received simultaneously and become readily available with the use of a high-speed recorder (HIOKI 8860). The obtained output signals from various sensors are transferred to a PC via measurement equipment and are recorded. The frequency of the power source is 60 Hz.

The measurement equipment developed by the authors has seven input terminals and eventually seven A/D converters.

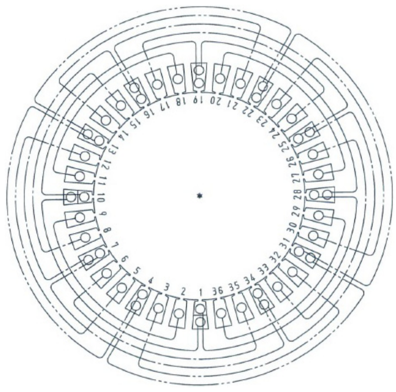

Fig. 1. Stator winding construction

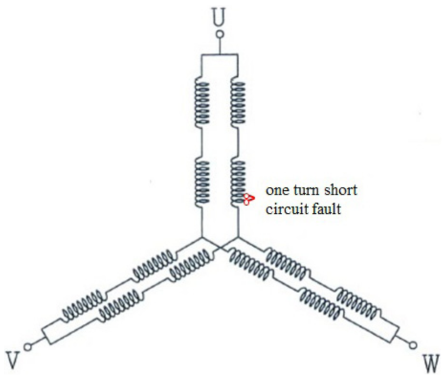

Fig. 2. One-turn short-circuit failure of U phase

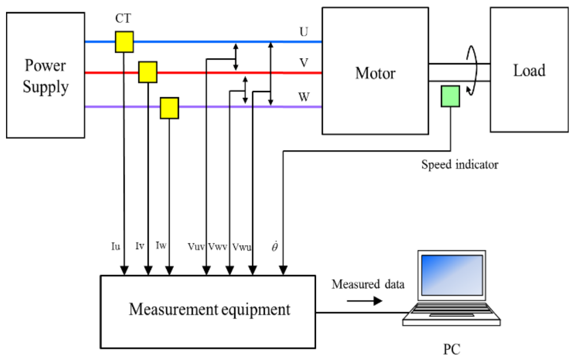

Fig. 3. Experimental setup of the proposed system

In the present research work, the three-phase load current, three line-to-line voltages, and corresponding rotation speed are recorded in seven channels. Generally, the frequency analysis resolution is determined by sampling time and data-recording length. It is always preferable to have a high-frequency resolution. Thus, the sampling time is about 10 μs, the frequency resolution is 0.76 Hz, and the data-recording length is 2^{17} sampling data per channel. Data acquisition is triggered every 30 s by the timer and data from the seven channels is transferred in 20 s.

3. Investigation and Discussion of the Frequency Spectrum

The load tests performed on both two healthy and one-turn short-circuit insulation failure windings are described below. Initially, FFT analysis for the measured load current is carried out continuously for current waveforms and the results are recorded. The examples of frequency-spectrum analysis on the U phase of a stator winding for healthy motor No1, healthy motor No2 and one-turn short-circuit failure motor is illustrated in Figs. 4–6, respectively. The amplitude of the vertical axis is normalized to take 0 dB as its maximum value. A remarkable difference in magnitude is observed between these windings (two healthy and faulty winding) at certain frequency components due to the occurrence of the short-circuit fault. Higher amplitude variation is observed at integer multiples of 30 Hz, because 30 Hz is the ratio of the power frequency (60 Hz) to the number of pole pairs in the induction motor (two).

The phenomenon for the appearance of signals at the integral multiple of 30 Hz and their mechanism is discussed below. Generally, asymmetry is created when the short-circuit fault occurs and leads to the generation of two opposite direction MMF (±f) inside the stator winding. Because of magnetomotive force, the following current harmonics (k/p±1)*f is generated in the rotor [24], where k = 1, 2, 3 takes the sequential value and p represents the number of pole pairs. Furthermore, due to the interaction caused between stator and rotor, the circulating current harmonics (k/p±1)*f of the rotor affects the stator of the induction motor just like the case of the broken rotor bar [25][26]. Therefore, it is considered that the current harmonics with an integer multiple frequencies f/p is generated in the stator current. In the case of low load that is a nearly no-load condition, the current harmonics flowing into the rotor part is very small and the stator is barely affected. In this condition, it is hard to measure the f/p signals in the load current. Indeed, the signals calculated at the low load condition is hardly measured during the experiment and this circumstance turns out to be the mechanism to support the appearance of the signals at the integral multiples of 30 Hz.

An amplitude difference larger than 15 dB is recognized for some frequency components, namely 30, 90, 120, 150, 210, 270, 330, 360, 390, 450, and 480 Hz. Since fluctuation often occurs in the frequency spectrum, it is better to choose multiple frequency components. Thus, attention should be paid to these eleven frequencies to identify the one-turn short-circuit insulation failure of the stator winding.

4. Introduction of Distortion Ratio

First, the order reduction of these frequency elements is carried out. Generally, the distortion ratio is defined as the ratio of the sum of the RMS amplitude of higher harmonic frequencies to the RMS amplitude of the fundamental frequency. It is defined as

$$D = \frac{\sqrt{\sum_i A_i^2}}{A_f} \quad (1)$$

where A_i and A_f stand for the RMS amplitudes of the harmonic and fundamental frequencies, respectively. In the present study, the RMS amplitude of eleven characteristic-frequency components is used instead of harmonics. Thus, the distortion ratio is defined as the ratio of the sum of the RMS amplitudes at selected frequencies to the RMS amplitude of the fundamental frequency. In the current case, the

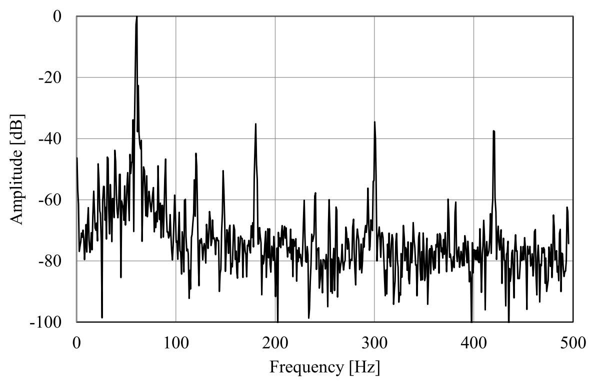

Fig. 4. Frequency-spectrum analysis of healthy winding (No1)

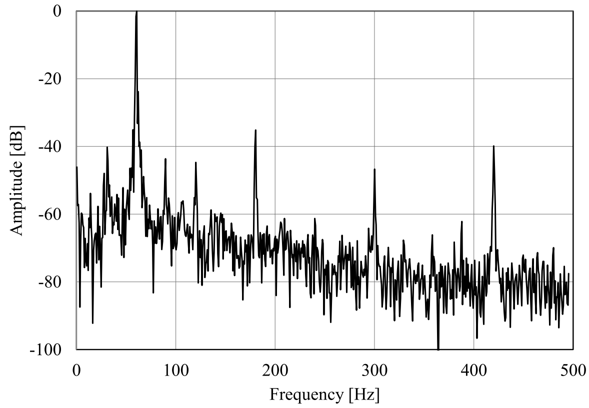

Fig. 5. Frequency-spectrum analysis of healthy winding (No2)

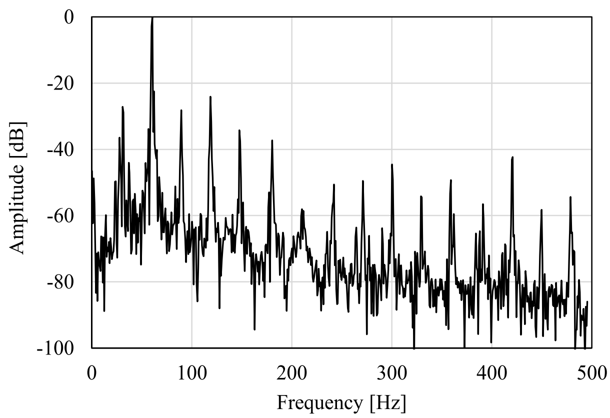

Fig. 6. Frequency-spectrum analysis of one-turn short-circuit insulation failure winding

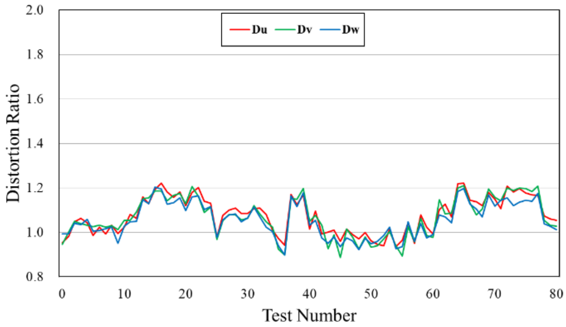

Fig. 7. Three phase-distortion ratios of load current (healthy)

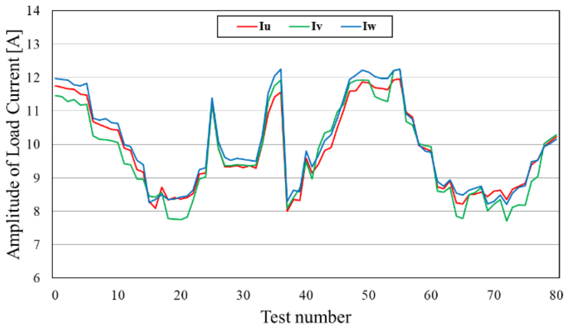

Fig. 8. Amplitude of the load current (healthy)

fundamental frequency is 60 Hz. Therefore, the distortion ratio of the load current is defined as

$$D = \frac{\sqrt{A_{30}^2 + A_{90}^2 + \cdots + A_{480}^2}}{A_{60}} \cdots\cdots\cdots\cdots\cdots\cdots (2)$$

The amplitude of frequency spectrum changes at all time. But with the result of using the distortion ratio, the amount of variation observed between the amplitude is small. Adding further advantages, irrespective of each phase current, the features of 11th order frequency can be reduced to one feature. Thus, the handling of the feature is made easy and the detection can be done flawlessly.

Figures 7, 8 show the distortion ratios of three-phases (D_u, D_v, and D_w) and the amplitudes for load currents of the healthy stator winding (No1), respectively. Figures 7, 8 clarify the fact that the amplitude of the load current between each phase varies intensely, whereas the distortion ratio has fewer changes between each phase. Similarly, Figs. 9, 10 show the distortion ratios of three-phases (D_u, D_v, and D_w) and amplitudes of load currents for the faulty stator winding, respectively. The result obtained is like that of the healthy winding. That is, the amplitude of load current between each phase varies intensely, whereas the distortion ratio has fewer changes between each phase.

An interesting fact is that the distortion ratios of each phase take nearly the same range. Moreover, a higher magnitude difference is observed between the distortion ratio of the normal winding and the one-turn short-circuit insulation failure winding. These magnitude differences will enable the distortion ratio to discriminate healthy and short-circuit windings. In the present study, the obtained distortion ratio is not influenced by the abrupt change of load current. This is a core feature of the proposed method and implies the advantages

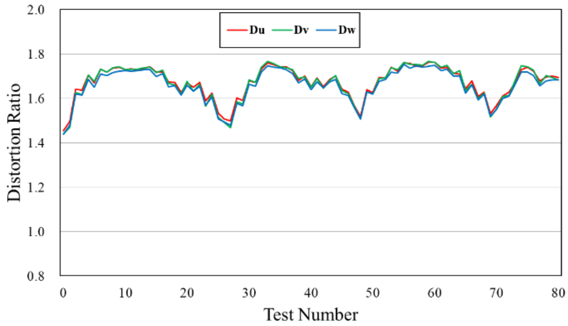

Fig. 9. Three phase-distortion ratios of the load current (one-turn short-circuit insulation failure winding)

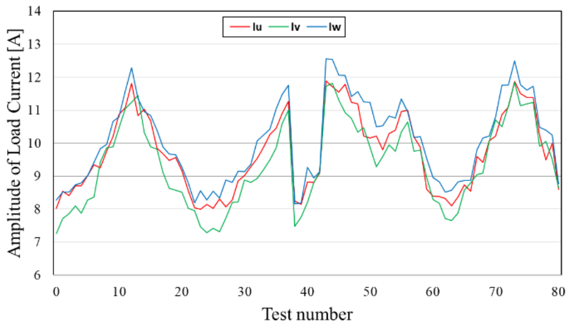

Fig. 10. Amplitude of the load current (one-turn short-circuit insulation failure winding)

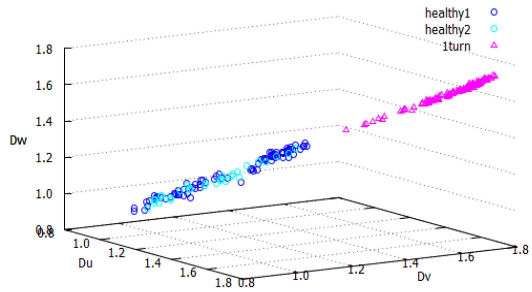

Fig. 11. Three-dimensional distortion-ratio analysis (Du, Dv, Dw)

of selecting distortion ratio.

Figure 11 shows the three-dimensional distortion ratios of the three classes of motors (two healthy, and one turn failure motor), respectively. One of the interesting note observed is that the condition of the motor is linearly distributed even when the load current changes continuously. The overlapping noticed between the different cases of the motor is negligible and they gather close to each other. The data of two healthy motors and one-turn short-circuit insulation failure motor are located according to their own classes. By representing the result of distortion ratios three-dimensionally, the winding condition can be visualized and identified conveniently.

5. Proposed Diagnostic Method for One-Turn Short-Circuit Insulation Failure

The diagnostic system proposed for detecting one-turn short-circuit insulation failures using SVM is described below.

5.1 Description of the SVM SVMs is generally used in pattern-recognition methods, particularly as diagnostic tools for classifying differences between categories [27]. SVMs

Table 1. SVM specification

Type of SVM	Soft Margin SVM
Kernel	Radial Basis Function Kernel
Cost parameter, C	1.0
Gamma parameter, γ	0.333
Number of support vectors	8
Number of classes	2

originated for linear classification of objects. Alternatively, they can also perform non-linear classification. This is made possible with the help of a Kernel function, which implicates the mapping of high input operates at high dimensional features.

SVM can be classified as "soft-" or "hard-margin" types, which are decided based on the linearity condition. The present study employs non-linear classification; hence the soft margin matches the prescribed condition. In Soft Margin SVM, cost parameter C is introduced, which controls the trade-off between maximizing the margin and minimizing the training error. If the value of C is lower, it tends to emphasize the margin, ignoring the outliers in the training data. Contrarily, larger C value tends to overfit the training data. Besides, Radial Basis Function kernel is also used commonly as gamma parameter γ and the boundary decision is established. Smaller γ value leads to a simple decision boundary and vice-versa. Thus, the cost and gamma parameters play a significant role and their tuning is accomplished.

In the present work, initially, data are divided into eight groups, the first seven of which provided training data. Data from group eight are used for evaluation. By alternating the groups, seven group diagnosis accuracy rates are obtained, and the average is calculated. The process is repeated for the different values of C and γ. Table 1 summarizes the SVM specification handled for present study of short-circuit fault diagnosis. The complete diagnostic process is undertaken using R programming-language software. A more detailed explanation of SVM type, Kernel type, and tuning parameters can be found in Ref. (23), (27).

5.2 Diagnostic Procedure Diagnosis based on SVM is performed using the distortion ratio of the load current, which is derived from the amplitudes at characteristic frequencies. This diagnosis is carried out by considering the distortion ratio of three-phases (D_u, D_v, D_w). For both the healthy and faulty windings, the datum consists of the amplitude of the distortion ratio under both conditions. Thus, the accuracy rate of diagnosis is defined as

$$\text{Accuracy rate (\%)} = \frac{\textit{Number of data diagnosed properly}}{\textit{Total number of data used for diagnosis}} \cdot 100 \qquad (3)$$

In other words, the diagnosis accuracy rate is defined as the percentage ratio of accurately diagnosed data points to the total data points used for diagnosis. By equation (3), diagnosis is made for both distortion-ratio cases.

5.3 Considering the Distortion Ration of Three Phases (D_u, D_v, D_w) In this section, diagnosis is performed by considering the distortion ratio of three-phases. In the present study, 90 (No1:60, No2:30), and 111 (1-turn) datasets are used to train the SVM as healthy and faulty windings, respectively. Newly measured 107 (No1:24, No2:83), and 89 (1-turn) datasets are used as diagnostic data to validate the method for each respective winding condition.

Table 2. Three-phase diagnosis results

		Data for evaluation	
		Healthy	1-turn
Results of diagnosis	Healthy	107/107	0
	1-turn	0	89/89
Accuracy rate (%)		100	100
Total accuracy rate (%)		100	

As a result of the diagnosis, the accuracy rates for individual winding conditions, as well as the total accuracy rate, are 100%, as shown in Table 2. The yellow cells indicate where the proper diagnosis is performed. The numerator of equation (3) takes the value present inside the yellow cell. Thus, a high accuracy rate can be obtained, even for one-turn insulation failure in the stator winding of an induction motor. Hence, the reliability of the proposed diagnostic system is high.

5.4 Discussion Table 2 shows the diagnostic accuracy rates for the three-phase condition of the distortion ratio. A high accuracy ratio is obtained under all phase conditions. In the proposed system, the diagnosis is performed using the amplitude value of the distortion ratio without considering the combinational frequency components. Thus, the drawbacks of the previous work [23] are eliminated in the present system. The diagnostic result in this paper is considerably better than that in the previous work.

6. Conclusion

The present paper presents a method for discriminating between healthy and one-turn short-circuit insulation-failure winding conditions using FFT analysis of load current and distortion ratio and diagnosis by an SVM. The proposed method is then validated.

Both the distortion ratio and the SVM play a significant role in diagnosing faulty windings. From the diagnostic result, the accuracy with which different winding conditions can be diagnosed is high (100%). Thus, the proposed method is beneficial for diagnosing one-turn short-circuit insulation failures in the stator winding of induction motors and can be considered effective. Moreover, the variation of the load current will not affect the value of the distortion ratio or the diagnosis process. This suggests the proposed method is applicable to actual cases with torque ripple.

The proposed method has difficulty diagnosing faulty motors under the no-load condition because the amplitude of the frequency spectra between the two motors shows no remarkable difference. In the future, a method for overcoming this drawback will be proposed.

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