Impact of the Rotor on FRA Signatures and its Implications for Motor Health Assessment

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2024 International Conference on Green Energy, Computing and Sustainable Technology (GECOST) | 979-8-3503-5790-5/24/$31.00 ©2024 IEEE | DOI: 10.1109/GECOST60902.2024.10474882

***Abstract*—Electrical machine condition monitoring is essential in industrial processes for increasing workplace security, ensuring reliability, and cost-effective machine operation. The frequency response analysis (FRA) monitoring technique is gaining heightened popularity due to its reliability. The main purpose of this paper is to investigate the influence of the rotor on motor FRA signature. The frequency response is a highly sensitive technique. Therefore, any small defect in the motor condition will produce a unique frequency response which then can be analyzed and detected early. In this study, two motors are selected, and the corresponding frequency response is measured. To understand the impact of the rotor on the FRA signature two measurements are considered. FRA signature with and without rotor. The results obtained from both measurements are compared and analyzed. For a better understanding of the results, statistical indicators are used. The practical results are based on the measurements taken from the experimental setup.**

***Index Terms*—Frequency Response, Induction Motor, Rotors, Statistical Analysis.**

I. Introduction

An induction motor (IM) is an essential equipment in many industries, especially in oil and gas plants. A sudden failure on an IM will cause a complete stop to the production line. This will contribute to economic loss or production loss. Such a problem could be avoided if a proper diagnostic test is performed on the IM to detect early indications of developing failure on the IM winding. Three-phase induction motors (TPIM) are commonly used in the production of commercially available equipment. TPIM motors comprise about 95% percent of all industrial motors because of their advantages over other types of motors [1][2][3].

The rotor and stator faults that often occur in TPIM are termed electrical faults [4]. Conventional approaches are often not capable of detecting these kinds of faults while new, alternative ways are sometimes too complicated and in some situations impractical. Frequency Response Analysis (FRA) is utilized extensively for fault identification and condition evaluation in transformers [5][6]. Multiple investigations have demonstrated that the FRA method applies to transformers as well as rotating machines for fault detection. This tool can identify a variety of faults that impact the frequency response across different frequency ranges. As a result, the condition of the machine can be evaluated. Some authors suggested using FRA on induction motors [7] and synchronous generators. The applicability of this method would require the removal of the rotor to eliminate its effect on the analysis [8]. The requirement to remove the rotor reduces the industrial viability of this method.

In this paper, the main purpose is to investigate the influence of the rotor on motor FRA signature. The FRA is highly dependent on the structure of the winding. Therefore, any small defect on the winding will produce a unique frequency response which then can be analyzed and detected early. Initially, in this research, two motors are selected, and the

This research was supported by the Ministry of Higher Education (MOHE) through the Fundamental Research Grant Scheme FRGS/1/2022/TK07/UTHM/03/31.

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TABLE I
SPECIFICATIONS OF OSCILLOSCOPE USED IN THE TEST

Specification	Value
Analog Channels	2
Sample Rate Per Channel (max)	2 GSa/s
WaveGen	20-MHz Function Generator
Bode Plot	Standard
Maximum Memory Depth	2 M points (All Channels)
Waveform Update Rate	200,000 Waveforms/sec
Output Impedance	50 Ω
Input Impedance	50 Ω
Frequency	20 Hz to 20 MHz
FRA Method	Sweep Frequency

corresponding frequency response is measured. In order to better understand the influence of the rotor on the FRA signature, two measurements are considered. These are FRA signatures with and without rotor.

II. BIBLIOGRAPHY SURVEY

In the literature, few studies have discussed the application of the FRA for the assessment of IM's condition. Many FRA studies have focused on investigating the various failures of winding in the transformer. Studies were conducted on winding radial buckling [9],[10], winding axial displacement [9], and shorted turns in the winding [11] ,[12].There is a general agreement in [13], [14]–[17] that the FRA measurement on the transformer and the FRA measurement on the induction motor show similar FRA traces.The initial study that presented the use of FRA in diagnosing IM was proposed in [17]. It explains the influence of short circuits in the stator winding on the FRA pattern. In [17] and [18] provided a new research direction on FRA for its application on IM.

In [19], the response sensitivity for the insulation between windings was observed. It also showed that with the neutral terminal either joined or floating, this condition could influence the frequency response. In [20], the study revealed a significant change in response, suggesting that the FRA test is sensitive to non-mechanical factors as well. In [19] the FRA signature was observed to fluctuate between 1 kHz and 300 kHz due to a broken rod in the squirrel cage. However, faults in the stator winding were not examined. Additionally, the FRA test is also sensitive to other factors or parameters. Several factors that influence the frequency response other than winding damage have been investigated in [21]. It illustrates the impacts of shunt impedance, high voltage bushing, and FRA test cable length. Before a guideline on the use of FRA on IM can be established, a basic understanding of the characteristics of IM's frequency response needs to be investigated.

III. FRA IN ELECTRICAL MACHINE

This method is different from other common techniques due to its sensitivity to various types of errors and its ability to accurately detect very small deformations.

Additionally, it can identify changes that are not directly in the electrical or magnetic circuit of the measurement. The purpose of the experiments is to apply these benefits of FRA, which are typically used for power transformers, to rotating machines. Furthermore, there is no need to modify the design before testing, and the testing process itself is non-intrusive as it is performed with extremely low voltages.

A. FRA Principle

FRA is a non-intrusive diagnostic method used to assess a device's impedance response, such as the winding of a transformer or other electrical equipment. It allows engineers to detect potential damages or faults without causing any damage or adverse effects to the device. By subjecting the device to various frequencies and analyzing its response FRA provides valuable information about the device's condition and helps identify early signs of possible failures enabling timely maintenance and repairs. By conducting a comparative analysis of the measured FRA test result and a reference response, faults and differences in the device's condition can be identified [22].

By injecting a sweep frequency or impulse signal into one terminal and measuring the output signal at the other, the response of the winding can be determined. The magnitude and phase angles of the frequency response are subsequently calculated by comparing the output and input signals with the transfer function of preference. The FRA method performs on a comparative basis. The quality of the FRA results may be affected by the transfer function used, but the testing principle remains unchanged.

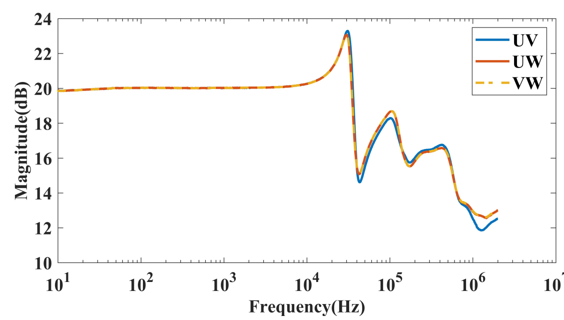

Fig. 1. FRA Comparison of Different Phases.

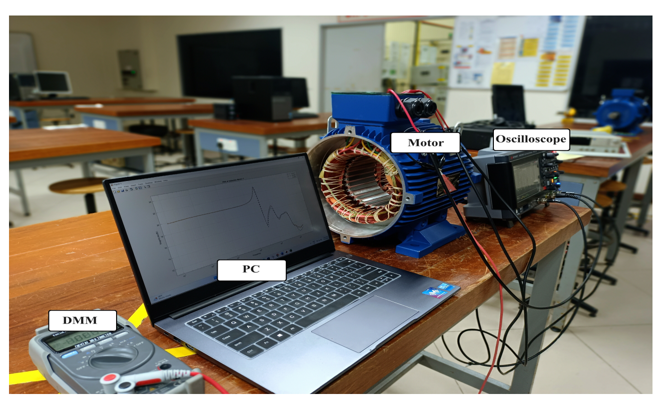

Fig. 2. Experimental Set up for FRA Measurement.

Different transfer functions may exhibit differing degrees of precision when identifying faults. Typically, the frequency response can be quantified using the input-to-output impedance, the voltage ratio between two terminals, or the admittance of a winding [22].

IV. Experimental Set Up

In this study, FRA measurements are performed on phases U, V, and W in order to diagnose and detect the effect of the rotor on TPIM. The measurements are conducted with and without the rotor. The frequency responses of windings are examined and interpreted by comparing the two responses. The FRA test is a powerful method to detect faults in transformer components such as transformer windings [23],[24].

The measurement method uses a star (Y) configuration of TPIM between phases U, V, and W. The star configuration has a common neutral point, which facilitates various measurements and analyses. Frequency response is measured with this type of connection between phase terminals (U-V, V-W, and U-W). Fig. 2 shows the experimental setup for FRA measurements. The measurement setup consists of two three-phase induction motors. The specifications of the motors are shown in Table II. FRA measurements are taken for both of the induction motors. First, frequency response for the motor having a rotor are recorded. The rotor is taken out, and then the same measurements are performed again. The same method is repeated for the second motor.

V. Influence of Rotor on FRA Signature

The FRA method compares the measured frequency response of a rotating machine to a reference curve. The reference curve is usually derived from a previous measurement in a known healthy state, from a sister unit, or another phase of the same unit. To ensure the credibility of the FRA, the elements that affect it must be identified, eliminated, or at least minimized. A comprehensive study was carried out to discover the influencing factors and their impact on the frequency response of rotating machines.

One of the main factors that affect the frequency response analysis (FRA) of three-phase induction motors is the rotor. The main purpose of this research is to investigate the influence of the rotor on the FRA measurements. In many cases, the researchers perform the FRA measurements on three-phase induction motors without the rotor. They remove the rotor to simplify the analysis and reduce the complexity. However, this raises the question of whether the absence of the rotor will affect the accuracy and validity of the FRA results. To address this issue, experiments are performed on two three-phase induction motors.

VI. Case Studies

A. Motor A

A series of tests are done using actual three-phase induction motors in order to verify the effectiveness of the proposed approach. The first series of tests is performed on an induction motor, with their respective specifications listed in Table

TABLE II
Specifications of the Induction Motors Used in Experiment

Specification	**Motor**	
	Motor A	***Motor B***
No. Phases	3-Phase	3-Phase
Model	IEC 60034-1	IEC 60034-1
Efficiency	90%	85%
Frequency	50 Hz	50 Hz
Rated Power	7.5 HP	7.5 HP
Rated Current	10.1 A	10.8 A
Rated Voltage	380-420 V	380-420 V
Power Factor	0.88	0.83
Pole Pairs	2	4
Rated Speed	2900 rpm	1440 rpm

II. Three different impedances are measured throughout the experiment. The impedance test is conducted on the frequency response between phase terminals (U-V, V-W, and W-U). Fig. 3 Shows the frequency response analysis comparison of three-phase induction motor A with and without a rotor.

B. Motor B

The experiments are performed on the same rating three-phase induction motor but with different poles. Detailed data of the induction motor is shown in Table II. The impedance measurements were carried out on the motor's windings using three configurations. To verify the accuracy of the test, it was repeated with the same connection of the phase terminals reversed. Fig. 4 shows the frequency response analysis comparison of a three-phase induction motor B with and without a rotor.

VII. Results and Discussions

The influence of the rotor on the FRA signature of three-phase induction motors is investigated in this study. This section presents and discusses the FRA response results for both with and without rotor configurations. Two induction motors with the same power rating but different rated speeds due to two and four poles are being selected. The frequency range of interest is from 10 Hz to 2 MHz. Because this range covers the dominant frequency regions that are affected by the short circuit faults in the TPIM. The winding resistance influences the low-frequency (LF) region, the winding inductance and capacitance influence the mid-frequency (MF) region, and the measurement setup and other factors influence the high-frequency (HF) region.

The results showed that the FRA signature without a rotor remained at a horizontal line between 10 Hz and 3 kHz, indicating no significant deviation from the FRA signature with a rotor. This implies that the rotor has negligible influence on the FRA signature at low frequencies, where the resistive component of the winding impedance dominates. However, between 3 kHz and 23 kHz, the FRA signature without a rotor started increasing exponentially, reaching the maximum deviation from the FRA signature of with rotor at 23 kHz. This suggests that the rotor has a considerable impact on the FRA signature at medium frequencies, where the inductive

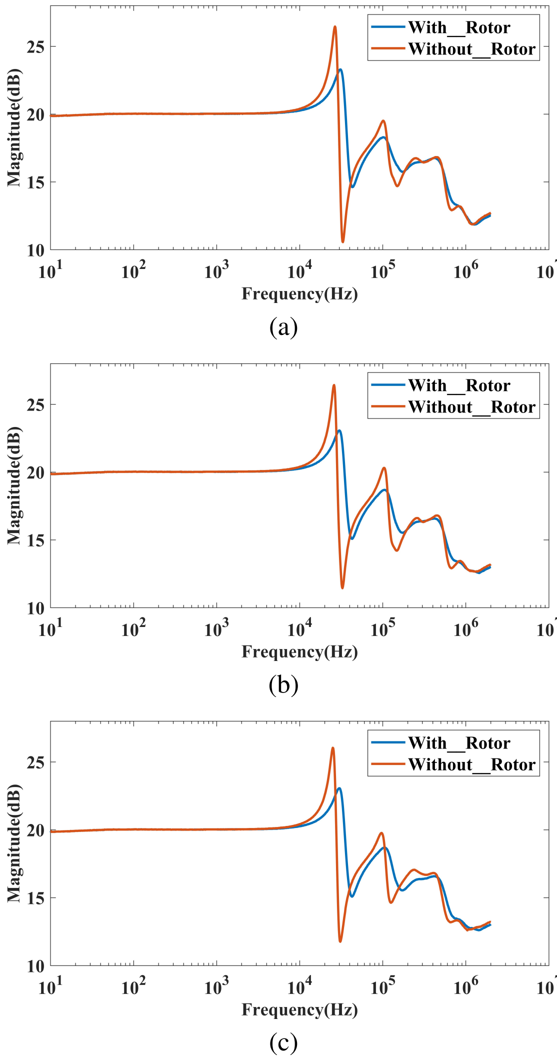

Fig. 3. FRA Results for Motor A With and Without Rotor. (a) U-V Phases (b) U-W Phases (c) V-W Phases

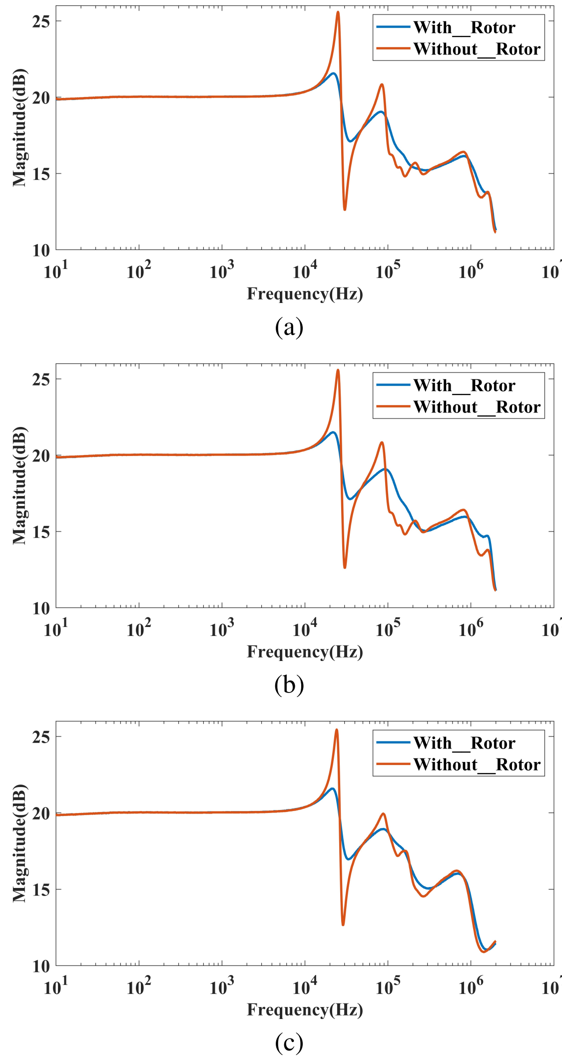

Fig. 4. FRA Results for Motor B With and Without Rotor. (a) U-V Phases (b) U-W Phases (c) V-W Phases

component of the winding impedance becomes dominant. The presence of a rotor reduces the inductance of the winding, resulting in lower impedance at these frequencies.

Between 23 kHz and 30 kHz, the FRA signature without a rotor started decreasing vertically, reaching the lowest deviation from the FRA signature of with rotor at 30 kHz. This indicates that the rotor has an opposite effect on the FRA signature at high frequencies, where the capacitive component of the winding impedance becomes dominant. The presence of a rotor increases the capacitance of the winding, resulting in higher impedance at these frequencies.

Between 30 kHz and 82 kHz, the FRA signature without a rotor again started increasing exponentially but did not reach the maximum deviation from the FRA signature of with rotor. Between 82 kHz and 105 kHz, the FRA signature without a rotor again started falling vertically but did not reach the lowest deviation from the FRA signature of with rotor. These oscillations in the FRA signature of without a rotor may be attributed to the resonance phenomena caused by the interaction between the winding parameters and the external circuit elements.

Between 320 kHz and 0.15 MHz, the FRA signature without a rotor showed a small deviation from the FRA signature with a rotor. Between 0.15 MHz and 2 MHz, the FRA signature without a rotor did not show any deviation from the FRA signature of with rotor. This implies that the rotor has no influence on the FRA signature at very high frequencies, where the winding impedance becomes constant. In Fig. 3 and Fig. 4, the FRA is compared in both cases with and without a rotor.

Therefore, it can be concluded that there is a significant effect of the rotor on the FRA signature of three-phase induction motors, especially at medium and high frequencies. The effect of the rotor depends on configuration, as well as on the frequency range. The effect of the rotor should be taken into account when analyzing the FRA signature of three-phase induction motors for fault diagnosis purposes.

VIII. Statistical Analysis

Advanced statistical indicators are utilized to analyze the patterns of IMs FRA in both with and without rotor data. These indicators determine the error ratio between two sets of data. However, the sensitivity of indicators can differ. In order to detect differences between normal and faulty FRA signatures in power transformers, statistical indicators were used to measure the differences between two responses [25]. As per standard procedures [26], calculations are typically performed within three FRA regions.

$$CC = \frac{\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{N}(x_i - \bar{x})^2 \sum_{i=1}^{N}(y_i - \bar{y})^2}} \quad (1)$$

$$ASLE = \frac{1}{N}\sum_{i=1}^{N}(x_i - y_i) \quad (2)$$

Here, x_i and y_i are the dB values of the ith frequency from responses x and y, respectively. Response x is the frequency response of the induction motor measured with the rotor, while response y is the frequency response of the same induction motor measured without the rotor. N is the number of data points (frequency points) in responses x and y.

The results show that the FRA signature without a rotor had different deviations from the FRA signature with a rotor depending on the frequency range and configuration. The deviations were quantified by two statistical indicators ASLE (Average Squared Logarithmic Error) and CC (Correlation Coefficient). ASLE measures the average difference between the logarithmic values of the FRA magnitudes, while CC measures the linear relationship between the FRA magnitudes.

It can be concluded that the rotor of three-phase induction motors has a significant impact on the FRA signature, especially in the medium and high-frequency ranges.

TABLE III
Statistical Indicators for Motor A

Frequency Range	ASLE (dB)	CC
10 Hz - 10 kHz	0.01	0.980
10 kHz - 300 kHz	1.413	0.592
300 kHz - 2 MHz	0.193	0.986

TABLE IV
Statistical Indicators for Motor B

Frequency Range	ASLE (dB)	CC
10 Hz - 10 kHz	0.006	0.996
10 kHz - 300 kHz	0.956	0.889
300 kHz - 2 MHz	0.248	0.975

IX. Conclusion

This paper investigates the effect of the rotor on the frequency response analysis (FRA) pattern of induction motors. Experiments were conducted on two induction motors with different winding connections and their FRA patterns were analyzed under various rotor conditions. The results revealed that the rotor has a significant impact on the FRA pattern, particularly in the high-frequency range. Furthermore, the results showed that the FRA pattern differs depending on the winding connection type. These findings imply that both the rotor condition and the winding connection type are crucial factors for interpreting the FRA results of induction motors. This paper contributes to the enhancement of the FRA technique as a reliable and non-invasive diagnostic tool for induction motor maintenance.

Acknowledgment

This research was supported by the Ministry of Higher Education (MOHE) through the Fundamental Research Grant Scheme FRGS/1/2022/TK07/UTHM/03/31.

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