Investigation of Rotor Impact on FRA Signatures in Induction Motors with Different Poles and Connections

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***Abstract*—The non-destructive nature of the Frequency Response Analysis (FRA) test is one of the reasons for gaining interest in the application of condition monitoring in rotating machines. The FRA technique is highly sensitive. Any small changes in the motor will generate a distinct frequency response, enabling early detection of the defect. This paper presents an in-depth experimental investigation of the rotor impact on FRA signatures of three-phase induction motors with different numbers of poles and connections. The experimental analysis was carried out using a frequency response analyzer, from which two distinct sets of measurements were taken. 1st set of measurements was taken to observe the effect of rotor presence on a 2-pole motor connected in star and delta. The same measurements were then repeated for 2nd motor with 4 poles. The results obtained from both sets of measurements are compared and analyzed. To enhance the comprehension of the results, statistical indicators are utilized. The finding highlights that the presence of a rotor can greatly influence the FRA signature. This helps further understand the FRA in motor and assists in accurate interpretation.**

***Index Terms*—Frequency response analysis, induction motor, rotor, statistical analysis**

I. Introduction

Three-Phase Induction Motors (TPIMs) comprise about 95% percent of all industrial motors because of their advantages over other types of motors [1] . The rotor and stator faults often occurring in TPIM are termed electrical faults [2]. Conventional approaches often cannot detect these faults, while new, alternative ways are sometimes too complicated and impractical in some situations [3, 4]. Frequency Response Analysis (FRA) is a standard method for diagnosing power transformers on-site [5, 6]. Typical applications of FRA include transformer installation or relocation, factory short-circuit testing, and protocol-based diagnostic measurements [7]. The fundamental concept of this technique relies on broadband measurement of a transformer's impedance or admittance, which can be modeled as an RLC circuit across a frequency spectrum extending from a few Hz to the MHz range [8]. A transformer's health is monitored by comparing various measurements taken throughout its operational life to a baseline representing its optimal condition. Deviations from this reference indicate potential faults or malfunctions. The use of FRA for diagnosing rotating machines is still novel and lacks a standardized application [9]. In the literature, several studies have discussed the use of FRA for diagnosing different short circuit faults [10, 11]. However, the study did not consider the effects of rotor position. This research trend has persisted in studies such as [12, 13], where FRA is used to diagnose faults in low-voltage electric motors.

Lamarre and Picher [14] suggests using FRA to identify insulation aging in hydro generators and highlights the benefits of winding reversal. The potential of FRA for identifying winding aging is further explored in studies [15, 16], which investigate variations in impedance curves caused by different insulation aging mechanisms, including thermal and moisture-related factors. Another research focus involves utilizing FRA to diagnose short-circuit faults within the salient pole of synchronous machines [17, 18]. Witjoanes and Yousof [19] studied the impact of stator winding turn-to-turn faults on TPIM frequency response. Perisse *et al*. [20] developed a novel monitoring system capable of identifying minor variations in the resonant frequencies of motor windings powered by an industrial inverter. Yousof *et al*. [21] used various statistical indicators for the FRA curve. The author suggested that the Absolute Sum of Logarithmic Error (ASLE) is the most suitable indicator for this application. They also benchmarked limits for ASLE and Standard Deviation (SD) to diagnose stator winding faults. Uhrig *et al.* [22] mentioned that the FRA method can detect faults

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in the TPIMs. Further, it was proposed that the FRA curve deviates from the fingerprint due to different short circuit faults. Off-line FRA is a promising tool for various diagnostic and condition monitoring applications. A vital advantage of this test is its adaptability, rapid execution, and cost-effectiveness, especially for MVA-sized machines. The main challenges in standardizing the methodology are the limited expertise on various faults and aging effects, as well as the method's sensitivity to machine geometry and rotor position [23].

Online FRA provides the benefit of continuously monitoring the electrical signature of the winding. Lambert-Torres *et al.* [24] presents a directly connected coupling that facilitates the online connection of the measurement apparatus. Sant'Ana *et al.* [25] extends this work by using the active cancellation technique. Bucci *et al.* [26] presented a setup for online monitoring of the health condition of the induction motor using FRA. A different approach is presented in [27], where a cost-effective passive coupling method for online FRA is proposed. The disadvantage of online FRA is the noise in the results, which can arise from electromagnetic couplings or the impact of the rotor position in the inductive frequency bands. Rotor position is a significant uncertainty source for offline and online FRA applications. The impact of rotor position displacement on single-phase admittance curves is presented in [28]. The authors attribute the impact of rotor position on FRA measurements to variations in airgap size. They emphasize maintaining a consistent rotor position during testing to prevent misdiagnoses. A similar phenomenon is observed in [29], which compares the FRA of the motor both with and without the rotor. Sant'Ana *et al*. [30] demonstrate that the rotor position influences even machines with a constant air gap (i.e., cylindrical rotor induction machines). A recent study investigates the broadband impedance characteristics of all three phases in a low-voltage, randomly wound induction machine [31].

Many authors have removed the rotor during experimental work to eliminate its influence on the FRA analysis [32]. The requirement to remove the rotor makes this method less attractive from an industrial perspective. In this paper, the main focus is to investigate the influence of the rotor on the FRA signature of both star and delta-connected motors. It expands the recent work presented in [33]. The experimental work utilized two three-phase induction motors as a case study, rated at 7.5 HP, one with 2 poles and the other with 4 poles, respectively.

II. Methodology

During the FRA test, a low input voltage $U_{\text{input}}(f)$ is applied to one end of a phase, and the output voltage $U_{\text{output}}(f)$ is measured at the other end of the same or a different phase while the remaining terminals are left open. As the windings are an RLC distributed circuit, if we keep increasing the frequency of the input voltage without changing its magnitude, it will give us different output voltages for different frequencies, depending on the RLC behavior of the windings. The frequency range typically spans from a few Hz to several MHz [8]. But in this paper, the frequency range is selected from 10 Hz to 2 MHz because this range covers the dominant area in the FRA signature affected by the rotor. The transfer function $H(f)$ is dependent on both the Device Under Test (DUT) and the measurement equipment's impedance, which are influenced by the input signal frequency as in (1). The ratio of the output voltage to the reference signal gives the frequency response (2). The phase angle between the signals can be calculated using (3):

$$H(f) = \frac{U_{\text{output}}}{U_{\text{input}}} = \frac{Z_{\text{FRA\_equipment}}}{Z_{\text{FRA\_equipment}} + Z_{\text{DUT}}} \tag{1}$$

$$k = 20\log\left(\frac{U_{\text{output}}}{U_{\text{input}}}\right) \tag{2}$$

$$\varphi = \tan^{-1}\left(\frac{|U_{\text{output}}|}{|U_{\text{input}}|}\right) \tag{3}$$

The research methodology of this paper relies entirely on experimental work. Two TPIMs were utilized to investigate the impact of the rotor on FRA signatures. Both star and delta connections were considered for the research to be thoroughly explored. The methodology is summarized in the flowchart shown in Fig. 1. Initially, the first motor (motor A) with 2 poles is selected for the measurement. The motor is connected to a star connection, and FRA measurement is performed on the motor in the presence of a rotor. Then, the rotor is removed, and the FRA measurement is repeated without the rotor. Secondly, the procedure in motor A is repeated on the second motor (motor B), which has 4 poles. Next, both motors are connected in a delta connection, and the procedure is repeated with and without the rotor. Finally, the results are analyzed and interpreted using statistical indicators.

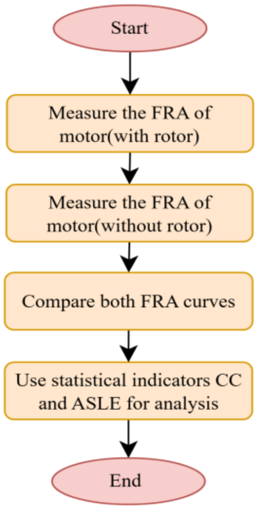


Fig. 1. Flowchart of the methodology.

III. Experimental Setup

The setup includes two TPIMs, an FRA Analyzer, and a PC. The FRA connection diagram for the measurement is shown in Fig. 2. The figure shows two different connections for star and delta-connected windings. For star-connected winding, terminals U_2, V_2, and W_2 are connected to make a star point. Typically, the star point of TPIM exists inside the motor, which is inaccessible. In that case, FRA measurement can only be performed between U_1-V_1, V_1-W_1, and W_1-U_1 terminals. The measurement was repeated on these three terminals to validate the test's accuracy. For delta-connected winding, similar measurements can be performed on the terminals. The actual experimental setup is shown in Fig. 3. The motors used in this study are listed in Table I, and the specifications of FRA equipment are listed in Table II. The results obtained from these measurements were plotted using MATLAB to visualize the differences and similarities in the FRA signatures.

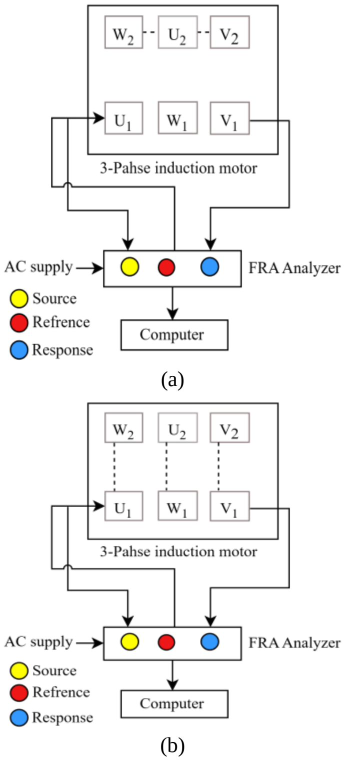


Fig. 2. Measurement diagram of FRA. (a) Star-connected motor, (b) Delta-connected motor.

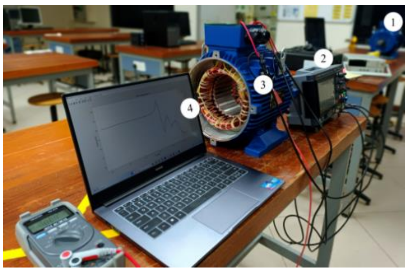


Fig. 3. Experimental setup (1: Motor A, 2: FRA measuring equipment, 3: Motor B, 4: PC).

TABLE I: MOTORS USED IN THE TEST

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

TABLE II: SPECIFICATION OF FRA ANALYZER

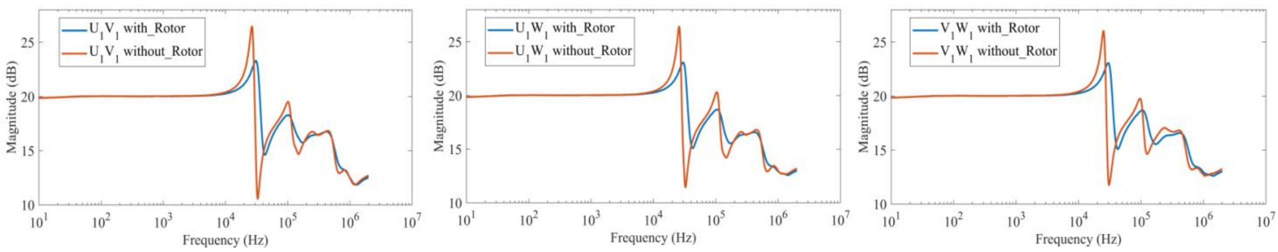
Specification	Values
Analog Channels	2
Sample Rate Per Channel	2 GSa/s
Wave Gen	20-MHz
Bode Plot	Standard
Maximum Memory Depth	2 M points
Waveform Update Rate	200,000 Waveforms/sec
Output Impedance	50Ω
Input Impedance	50Ω
Frequency	10 Hz to 20 MHz
FRA Method	Sweep Frequency

IV. RESULTS

This study investigates the influence of the rotor on the FRA signature of TPIMs. This section presents and discusses the FRA results for motors with and without rotors under star and delta configurations. Furthermore, it also discusses the effect of a number of poles on FRA signatures.

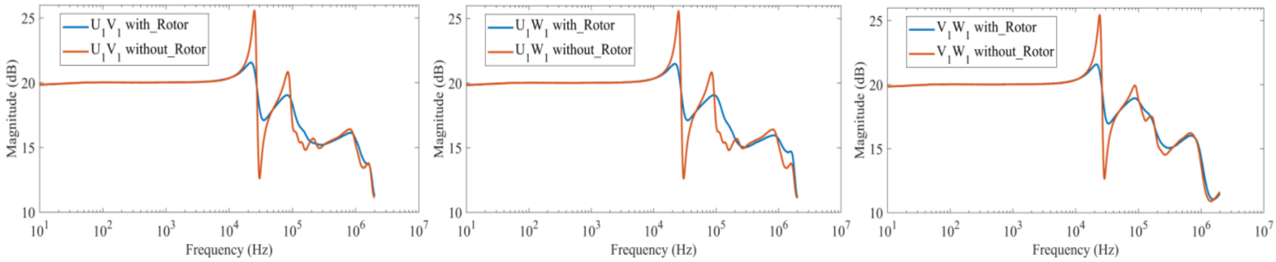
A. Rotor Effect on the FRA of the Star-Connected Motors

The results from Fig. 4 and Fig. 5 show no significant impact of the rotor on the FRA signature at low frequencies, as both curves display the same magnitude. However, in the medium-frequency range, a considerable effect of the rotor is observed, where the magnitude of the signature decreases. As we move into the high-frequency range, the rotor's influence becomes more dominant, further lowering the magnitude and shifting multiple resonant peaks to the right. Therefore, it can be concluded that the rotor significantly affects FRA signature of TPIMs, especially at medium and high frequencies. The effect of the rotor depends on configuration, as well as on the frequency range. Thus, the presence of a rotor introduces additional inductance (L), resistance (R), and capacitance (C), behaving as a complex RLC circuit. This interaction with the stator winding alters the motor's overall impedance, consequently affecting its FRA across various frequencies.



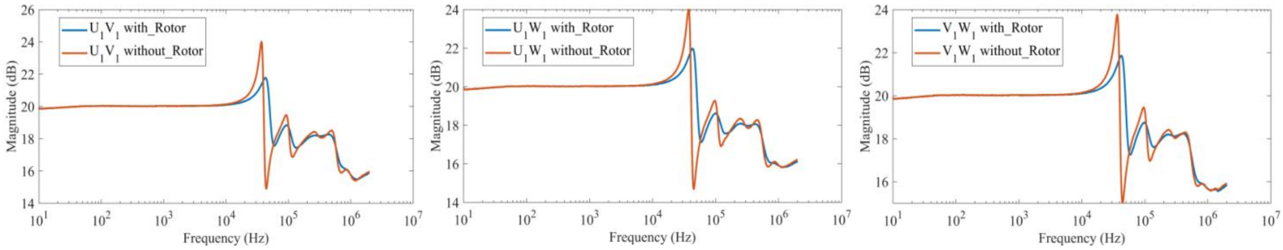
(a) (b) (c)

Fig. 4. FRA results comparison for motor A connected in star: (a) U_1V_1, (b) U_1W_1 and (c) V_1W_1.



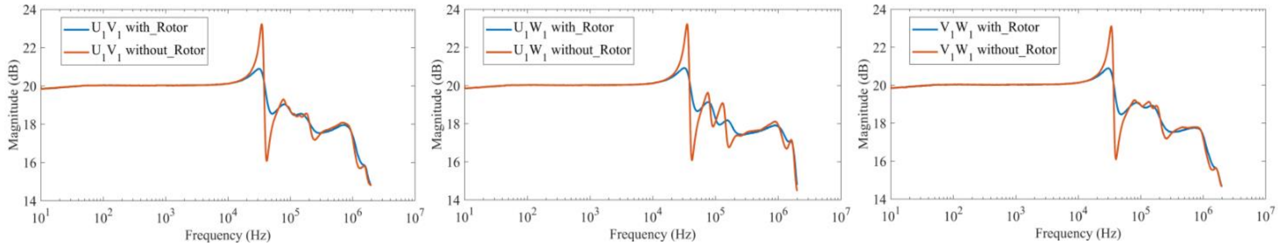
(a) (b) (c)

Fig. 5. FRA results comparison for motor B connected in star: (a) U_1V_1, (b) U_1W_1, and (c) V_1W_1.



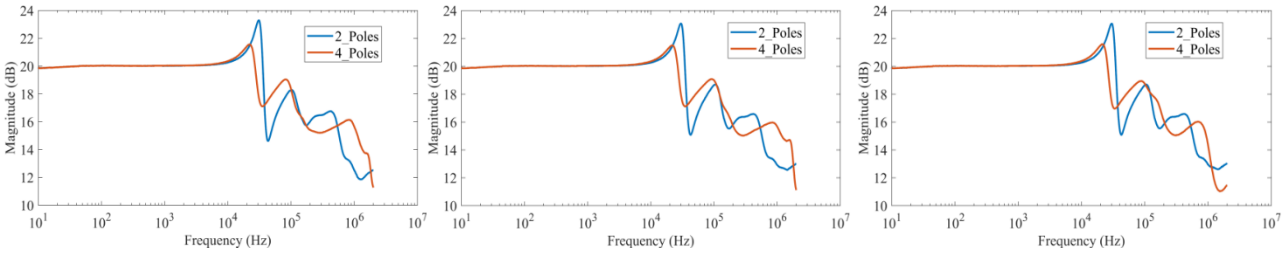
(a) (b) (c)

Fig. 6. FRA results comparison for motor A connected in delta: (a) U_1V_1, (b) U_1W_1, and (c) V_1W_1.



(a) (b) (c)

Fig. 7. FRA results comparison for motor B connected in delta: (a) U_1V_1, (b) U_1W_1, and (c) V_1W_1.



(a) (b) (c)

Fig. 8. FRA results comparison for 2-pole and 4-pole motors: (a) U_1V_1, (b) U_1W_1, and (c) V_1W_1.

B. Rotor Effect on the FRA of Delta-Connected Motors

The results from Fig. 6 and Fig. 7 show no significant impact of the rotor on the FRA signature at low frequencies, as both curves display the same magnitude. However, in the medium-frequency range, a considerable effect of the rotor is observed, where the magnitude of the signature decreases. As we move into the high-frequency range, the rotor's influence becomes more dominant, further lowering the magnitude and shifting multiple resonant peaks to the right. Therefore, it can be concluded that the rotor significantly affects FRA signature of TPIMs, especially at medium and high frequencies. The effect of the rotor depends on configuration, as well as on the frequency range. Thus, the presence of a rotor introduces additional inductance (L), resistance (R), and capacitance (C), behaving as a complex RLC circuit. This interaction with the stator winding alters the motor's overall impedance, consequently affecting its FRA across various frequencies.

C. Poles Effect on the FRA of Motors

Two induction motors with the same power rating but different numbers of poles were selected to investigate the effect of a number of poles on FRA signatures. The results in Fig. 8 show that different numbers of poles do not affect the FRA signature at low frequencies (10 Hz to 5 kHz). However, significant effects are observed in the medium frequency range (5 kHz to 200 kHz). Increasing the number of poles increases the curve's magnitude and shifts the resonant peaks to the left. Similarly, in the frequency range (200 kHz to 1 MHz), increasing the number of poles increases the magnitude of the curve and shifts the resonant peaks to the right. Thus, it can be concluded that the FRA test for motors is sensitive enough to distinguish between different pole numbers for motors with the same rating.

V. Statistical Indicators

Statistical indicators are utilized to analyze the patterns of TPIMs FRA both with and without rotors. In [19], Statistical Indicators (SIs) were employed to measure the differences between faulty and healthy FRA in TPIMs. The study revealed that the FRA signatures of faulty motors exhibit variations in SI values. Another investigation [12] also utilized SIs to differentiate between normal and faulty FRA signatures, concluding that SIs are effective tools for interpreting these differences. These indicators determine the variation ratio between two sets of data. However, the sensitivity of indicators can differ. In this study, two indicators are selected since they had been previously used in literature and were proven suitable[15, 30] . Equations for ASLE and CC are shown in (4) and (5).

$$\text{ASLE} = \frac{1}{N}\sum_{i=1}^{N}(X_i - Y_i)^2 \tag{4}$$

$$\text{CC} = \frac{\sum_{i=1}^{N}(X_i-\bar{X})(Y_i-\bar{Y})}{\sqrt{\sum_{i=1}^{N}(X_i-\bar{X})^2}\sqrt{\sum_{i=1}^{N}(Y_i-\bar{Y})^2}} \tag{5}$$

In (4) and (5), 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. Table III, Table IV, Table V, and Table VI show the computed indicators, which compare the responses with and without a rotor.

Table III shows the statistical indicators (SIs) values for the FRA of motor A (2 poles) connected in a star configuration. For the frequency range of 10 Hz to 5 kHz across all connection types (UV, UW, VW), the CC values range from 0.97 to 0.98, which is very close to 1, indicating a strong correlation. The ASLE values range from 0.0116 to 0.0123, which are relatively small. These values suggest that the presence of the rotor does not significantly influence the FRA of the motor in this frequency range. In the frequency range of 5 kHz to 200 kHz, the CC values decrease from 0.98 to 0.50, and the ASLE values increase from 0.0123 to 1.61. This indicates that the rotor significantly impacts the FRA signature within this range. In the higher frequency range of 200 kHz to 1 MHz, the CC values slightly decrease from 0.97 to 0.96, and the ASLE values increase from 0.0123 to 0.2358. These changes suggest that the rotor has a minor effect on the FRA signature in this range.

TABLE III: STATISTICAL INDICATORS FOR MOTOR A CONNECTED IN STAR

Frequency	Phases	CC	ASLE (dB)
10 Hz to 5 kHz	U_1V_1	0.9807	0.0121
	V_1W_1	0.9773	0.0123
	U_1W_1	0.9813	0.0116
5 kHz to 200 kHz	U_1V_1	0.5922	1.4138
	V_1W_1	0.5092	1.6186
	U_1W_1	0.6149	1.4538
200 kHz to 1 MHz	U_1V_1	0.9869	0.1932
	V_1W_1	0.9630	0.3258
	U_1W_1	0.9780	0.2184

Table IV illustrates the SIs for the FRA of motor B (4 poles) in a star connection. In the frequency band of 10 Hz to 5 kHz for all connection types, the CC values are consistently at 0.99, indicating a very high correlation, while the ASLE values range between 0.0056 and 0.0063, which are quite minimal. This suggests that the rotor does not substantially influence the FRA in this frequency range. For the frequency range of 5 kHz to 200 kHz, the CC values drop from 0.98 to 0.85, and the ASLE values increase from 0.0063 to 1.130. This demonstrates that the rotor considerably impacts the FRA signature in this range. However, in comparison with motor A, the absence of a rotor is more significant in 2-pole motor than in 4-pole motor. In the higher frequency range of 200 kHz to 1 MHz, the CC values slightly reduce from 0.99 to 0.91, and the ASLE values rise from 0.0063 to 0.4985. This indicates that the rotor has a minor effect on the FRA signature within this frequency range.

TABLE IV: STATISTICAL INDICATORS FOR MOTOR B CONNECTED IN STAR

Frequency	Phases	CC	ASLE (dB)
10 Hz to 5 kHz	U_1V_1	0.9961	0.0061
	V_1W_1	0.9958	0.0063
	U_1W_1	0.9957	0.0056
5 kHz to 200 kHz	U_1V_1	0.8890	0.9563
	V_1W_1	0.9007	0.7636
	U_1W_1	0.8590	1.1306
200 kHz to 1 MHz	U_1V_1	0.9756	0.2486
	V_1W_1	0.9900	0.2358
	U_1W_1	0.9163	0.4985

TABLE V: STATISTICAL INDICATORS FOR MOTOR A CONNECTED IN DELTA

Frequency	Phases	CC	ASLE (dB)
10 Hz to 5 kHz	U_1V_1	0.9850	0.0060
	V_1W_1	0.9864	0.0052
	U_1W_1	0.9883	0.0051
5 kHz to 200 kHz	U_1V_1	0.5670	0.7853
	V_1W_1	0.5826	0.7719
	U_1W_1	0.5823	0.8069
200 kHz to 1 MHz	U_1V_1	0.9758	0.1389
	V_1W_1	0.9728	0.0900
	U_1W_1	0.9750	0.1184

Table V presents SIs for motor A connected in a delta configuration. For the frequency range of 10 Hz to 5 kHz across all connection types, the CC values remain consistently at 0.98, signifying high similarity. The ASLE values are minimal, ranging from 0.0051 to 0.0060. This indicates that the rotor's presence does not significantly affect the FRA within this frequency range. In the frequency band of 5 kHz to 200 kHz, the CC values decrease from 0.98 to 0.56, while the ASLE values rise from 0.0060 to 1.8069. This indicates a notable impact of the rotor on the FRA signature within this frequency range. For the higher frequency range of 200 kHz to 1 MHz, the CC values slightly reduce from 0.98 to 0.97, and the ASLE values increase from 0.0051389 to 0.4985. This suggests that the rotor has a minor influence on the FRA signature in this frequency interval.

Table VI outlines the SIs for motor B configured in a delta connection. Within the 10 Hz to 5 kHz frequency range across all connection types, the CC values remain consistently at 0.99, reflecting high similarity. The ASLE values are minimal, ranging from 0.0034 to 0.0043. This indicates that the rotor's presence does not significantly affect the FRA in this frequency range. In the frequency range of 5 kHz to 200 kHz, the CC values decrease from 0.99 to 0.84, while the ASLE values increase from 0.0043 to 0.5868. This demonstrates a dominant influence of the rotor on the FRA signature within this frequency. For the higher frequency range of 200 kHz to 1 MHz, the CC values slightly reduce from 0.99 to 0.96, and the ASLE values rise from 0.0043 to 0.1684. This suggests that the rotor has a minor effect on the FRA signature in this frequency interval. This finding is similar for star-connected motors as in Tables III and IV. Additionally, this also shows that the effect of the rotor on the response of the star and delta-connected motors is the same.

TABLE VI: STATISTICAL INDICATORS FOR MOTOR B CONNECTED IN DELTA

Frequency	Phases	CC	ASLE (dB)
10 Hz to 5 kHz	U_1V_1	0.9928	0.0034
	V_1W_1	0.9915	0.0039
	U_1W_1	0.9907	0.0043
5 kHz to 200 kHz	U_1V_1	0.8633	0.4235
	V_1W_1	0.8701	0.4178
	U_1W_1	0.8439	0.5868
200 kHz to 1 MHz	U_1V_1	0.9873	0.1565
	V_1W_1	0.9891	0.1230
	U_1W_1	0.9696	0.1684

Thus, it can be concluded that the rotor impacts the FRA signature between 5 kHz to 1 MHz. This analysis helps to identify the specific ways in which the presence or absence of the rotor influences the FRA signatures. The overall summary of rotor and pole impact on FRA at different frequency ranges is shown in Table VII.

TABLE VII: SUMMARY OF ROTOR AND POLES EFFECT ON FRA SIGNATURE

Connection type	**Motor**	**Frequency Range**		
		Low	Medium	High
Star Connection	A	No significant changes	Multiple peaks shifted right, lower magnitudes	Lower magnitudes
	B	No significant changes	Lower magnitudes	Peaks shifted right, and higher magnitudes
Delta Connection	A	No significant changes	Multiple peaks shifted right, lower magnitudes	Lower magnitudes
	B	No significant changes	Lower magnitudes	Multiple peaks shifted right, and lower magnitudes
Different Poles	A vs B	No significant changes	Peaks, shifted left, higher magnitudes	Peaks shifted right, and higher magnitudes

VI. CONCLUSION

This paper investigates the effect of the rotor on the FRA signature of induction motors. Experiments were conducted on two induction motors (2 pole and 4 pole) with different winding connections (star and delta), and their FRA signatures were analyzed under various rotor conditions. The paper presents an interesting finding that, although the rotor is not physically connected to the stator winding, its influence on the FRA signature, which is measured at the stator winding, is significant. The influence of rotor is more dominant in 2 pole motor compared to 4 pole motor. Additionally, the results showed that the FRA pattern varies depending on the winding connection type (star and delta). These findings suggest that both rotor condition, number of poles, and winding connection type are crucial factors in interpreting the FRA results of induction motors. Therefore, it can be concluded that the rotor's effect must be considered when analyzing the FRA signatures of induction motors. Furthermore, the results demonstrate that the FRA technique is so intelligent that it can distinguish between motors with different numbers of poles, even if they have the same rating. This highlights the FRA technique as a reliable and non-invasive diagnostic tool for induction motor condition monitoring.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Rizwanullah Khan and Mohd Fairouz Mohd Yousof conducted the research, analyzed the results, and wrote the paper; Rahisham Abdu Rahman and Zawar Khan improved the writing; Norhafiz Azis and Salem-Alameri assisted in conducting the electrical test at the laboratory. All authors approved the final version.

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