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Investigation of Stator Windings Looseness of Polyphase Induction Machine after Rewinding in Workshop: Numerical and Experimental Analysis

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ABSTRACT:
Electric machines, particularly induction motors, are widely used in industry as they are robust in construction and require less maintenance. These machines are continuously operated under high loading conditions, which may result in machine vibrations. The Experimental-Modal-Analysis (EMA) technique is employed in this research to determine electrical machine vibrations. The hammer test is a popular EMA approach for locating the exact location of winding looseness. EMA test is executed on the stator winding to extract the modal parameters to find exact deformation in machine windings. Mathematical calculations and a numerical model are developed to validate the experimental data. The EMA's Operational Deformation Structure (ODS) validates the winding's looseness precisely. Two test machines' MA and MB windings are tested with EMA to evaluate the stator slot structure's looseness. Finally, the proposed technique is compared with the finite element technique along with mathematical calculations for verification.

KEYWORDS: Induction Machine, Machine-A (MA), Machine-B (MB), Vibrations, Finite-Element-Method, Experimental-Modal-Analysis, Operational Deformation Structure.

1. INTRODUCTION

Electrical machines are used in industries due to their long-term performance. Vibrations, noise, power density, and torque oscillations all have an impact on the machine's performance and efficiency [1]. These vibrations and noise are induced by electro magneto force, which is generated by machine component deformation [2]. Electromagnetic excitations such as force and torque oscillation have impact on the internal surfaces of a stator core. This creates electromagnetic vibration in electrical machinery [3]. Numerous studies have concentrated to determine the main cause of the vibration characteristics with the force excitations. However, it is preferable to use an electrical machine that has less vibration for industrial applications. If the vibration exceeds the allowable limit, it is important to determine the cause of the excessive vibrations. These vibrations are mainly due to electrical or mechanical faults [4]. Electrical faults are due to stator core and rotor bar defects. Mechanical defects are due to bearing, misalignment of components, eccentricity, and overloading. Fig. 1 shows the different faults in electrical machines according to the different surveys mentioned. It has been observed that stator windings problems are common defects in all surveys [5]. Therefore, the condition of stator windings is to be monitored for better performance of the machine. But in industries, the deformation of huge structures especially stators can produce strong force in the machine [6]. This force is caused due to deformation in the structure which is produced in the stator core and can vibrate the machine [7]. The vibration in windings during operation can cause extreme wear and tear and stress that possibly damage the machine. As a consequence, it is crucial to minimize and identify the deformation level in winding as low as possible to ensure the safety of the machine [8]. Therefore, it is important to find the deformation in the winding to avoid the sudden failure of the machine.

Machine deformation, vibration, and noise are to be restricted at an earlier stage. The above defects can be minimized by continuous monitoring of the machine. Advanced techniques should be used to inspect the machine's operation. Analytical and numerical methods

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have been used to quantify machine vibrations during the last few decades [9]. Numerical investigation with finite element method have been opted by many researchers to predict the faults of the machine. Since it is feasible to simulate the complex structures of the machine, the finite-element-method-FEM is widely employed to forecast the mode of vibration of machines [10].

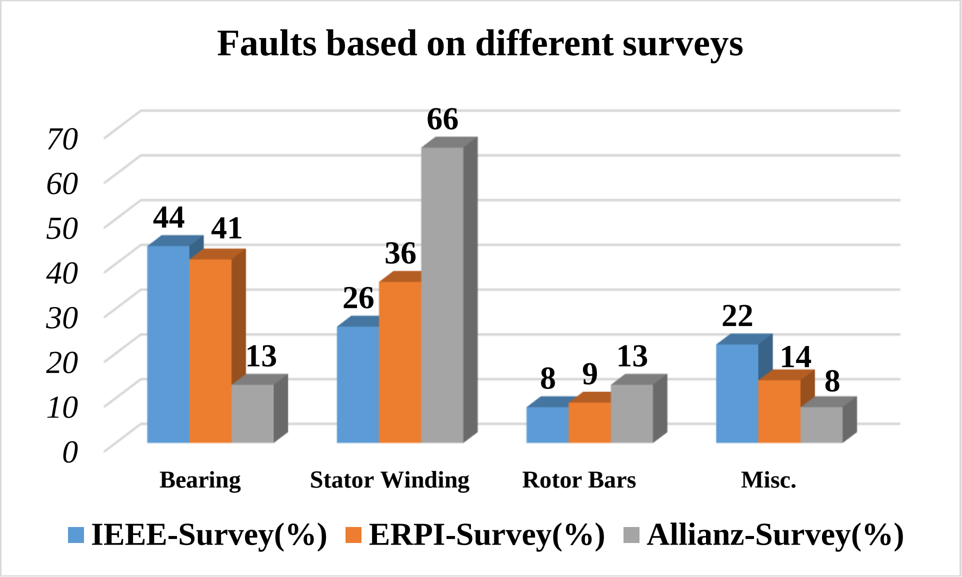


Fig. 1. Different Faults with surveys.

Obtaining the damping ratio is challenging using the FEM. To overcome this limitation, experimental-modal-analysis-EMA is used to calculate the damping ratio. EMA is a technique for predicting the deformation of massive structures applicable in industrial applications [11-12]. In practice, the hammering test (EMA) is a precise excitation method for determining the modal parameter [13]. These modal parameters represent the machine's state of vibration, which is a crucial part of this test. Modal parameters are determined by a gentle hit on the structure with the hammer which generates an impulse force [14-16]. Simultaneously the motor's vibration with acceleration should be monitored at the same time. Therefore, an advanced EMA technique is applied to the suspected structure to find deformation. This helps to quantify the looseness in windings and determine the exact slot number.

The proposed article investigates the accurate position of deformation in stator windings. Two test machines are re-winded in a workshop to find the deformation. Machine-A (MA) is a seventy-two-slotted machine and Machine-B (MB) is the twenty-four-slotted machine. The two machines are re-winded in a workshop. It is important to predict the deformation in the windings. Therefore, EMA is implemented on two machines (MA and MB) to predict the exact point of deformation in the winding. The mathematical calculation is done to find the looseness in the stator slot. Operational deformation structure (ODS) from EMA shows the looseness in the windings of the MA and MB. It is identified as the deformation of windings in slot number 51,52 and 1,4 of MA and MB, respectively. To validate the EMA, test the machines MA and MB are simulated in ANSYS software. There is a good validation between FEM and EMA results and the frequency percent error is nearly 2 %.

This paper is systematized as follows: In Section 2, the literature review and background of the work are discussed briefly. In Section 3, machine specifications and proposed work are explained. In Section 4, mathematical calculations to find the looseness in windings are computed. In Section 5, a numerical investigation is done to determine the modes of deformation. In Section 6, EMA is executed on stator windings to identify the looseness. Results are discussed in Section 7 and followed by a conclusion in 8.

2. LITERATURE REVIEW AND BACKGROUND OF THE WORK

Many researchers focused on monitoring electrical machines that have vibrations caused by stator windings. These vibrations are due to the looseness in stator windings which is difficult to predict. H. Fang et al., and C. Feng et al., present the force acting on the stator core which leads to deformation in the winding structure [1],[3]. These force leads to deformation in the winding structure and causes severe vibrations. According to Y. Zhao et al., and M. Rajesh et al., the deformation of stator windings with different modes is expressed [8],[11]. But looseness prediction for large machines is not mentioned. The looseness in the windings is caused due to electrical or mechanical defects. These faults are mainly due to resonance problems. Fig.2 shows the different vibration modes with deformation in the windings. Fig. 2 (a) is (0-mode) indicates there is no deformation in the windings.

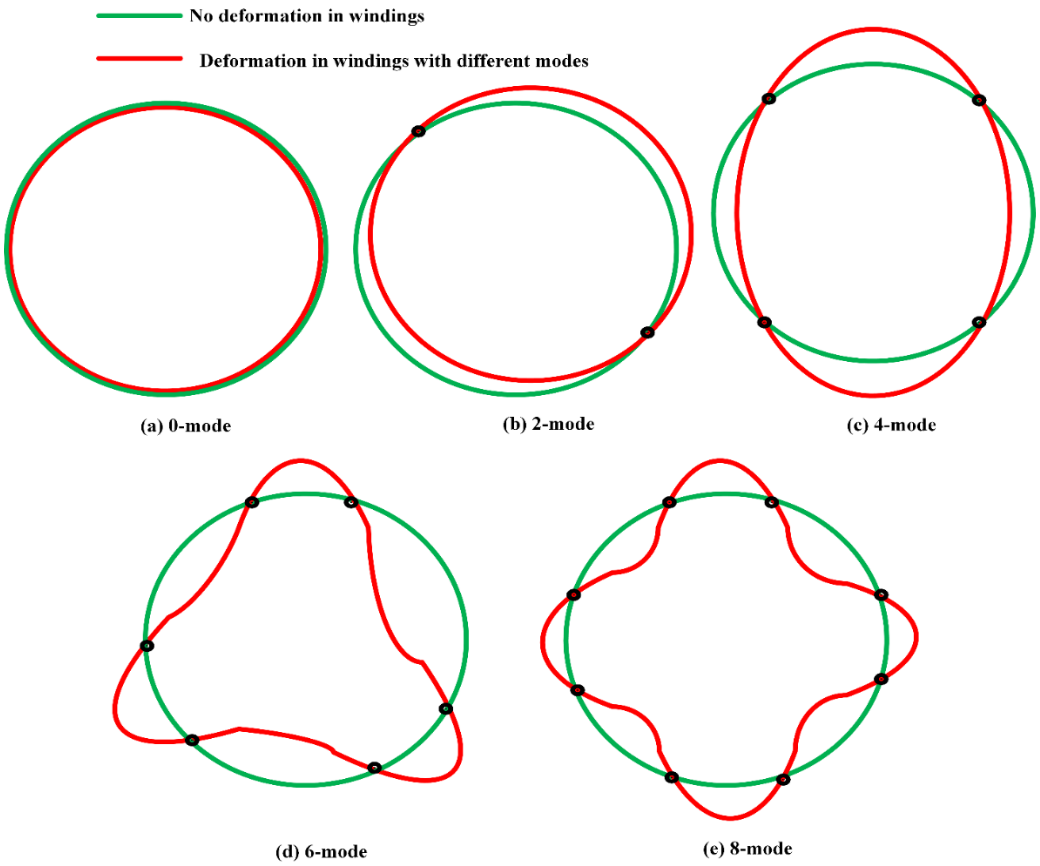


Fig. 2. Vibration modes of windings (a) 0-mode (b) 2-mode (c) 4-mode (d) 6-mode (e) 8-mode.

Fig. 2 (b) depicts the 2-mode or 1-lobe vibrational mode in the windings. Because of the looseness, substantial damage may occur if the windings come into contact with the stator core. As a result, 2-mode might cause more damage to the stator windings than the other modes. Fig. 2 (c) shows the 4-mode or 2-lobe mode of vibration in the windings. This type of mode can also damage the windings to a greater extent. Fig. 2 (d) and (e) demonstrate 6-mode (3-lobe) and 8-mode (4-lobe) looseness in all directions, indicating lower severity to hit the stator core. Y. Iga et al., and J. Zhao et al., predict the modes shapes and natural frequencies by executing experimental analysis (EMA) [9,12] to study the deformation in stator windings. Deformation in the windings with different vibration modes is expressed in the comparison of green and red circles as shown in Fig. 2. Whereas the red line indicates looseness of the windings of different vibrational modes. Many researchers had diagnosed faults due to stator windings but there is a constraint for identifying the deformation in the windings. The deformation and precise location in the windings has not been discussed. To identify the stator inter-turn faults [17], infrared (IR) thermopile sensor array (IRSA) and Hall-effect sensor array (HESA) are proposed. However, this approach is not focused on stator winding deformation. According to Y. Demir et al., the unbalanced winding layouts are created for minimum unbalance and maximum winding factors. Total MMF distributions in the airgap and their harmonic spectra were obtained. But looseness in the stator windings is not discussed. A fault-tolerant control (FTC) algorithm has been implemented on machines which is able to create the maximum possible performance recovery of the open and short stator winding faults, as well as speed sensor faults [19]. The main advantage of this work is to cease the motor with a protection stage activity in the worst-case operation of the machine. To evaluate phase-to-ground, phase-to-phase, and turn-to-turn faults, a digital signal processing device-DS1003 is used for data collecting to identify the electrical faults [20]. A fuzzy logic technique is also used to diagnose induction motor defects. This describes a reliable approach for detecting stator winding problems by measuring line/terminal current amplitudes. The fuzzy system can accurately identify the motor stator condition [21].

Apart from stator windings failures, rotor cage damage and prevention are crucial. The fault status of the rotor cage, according to Ali Saghafinia et al., can be stated in simulation using continuous wavelet transform-CWT and trained fuzzy logic controller-FLC. The trained FLC assesses whether the IM is faulty or healthy in real-time [22]. To estimate the rotor currents with broken rotor bars FEM is used to design the rotor bars (healthy and broken rotor bars), which are meshed in ALTAIR Flux software [23].

In this article, the looseness with exact location is determined to protect stator windings. To predict the looseness in the windings, EMA is a precise experimental method for determining deformation. For performance analysis, the EMA test is compared with a numerical method (FEM) and analytical calculation to identify the looseness in windings.

3. TEST MACHINE SPECIFICATIONS AND WORK EXECUTION

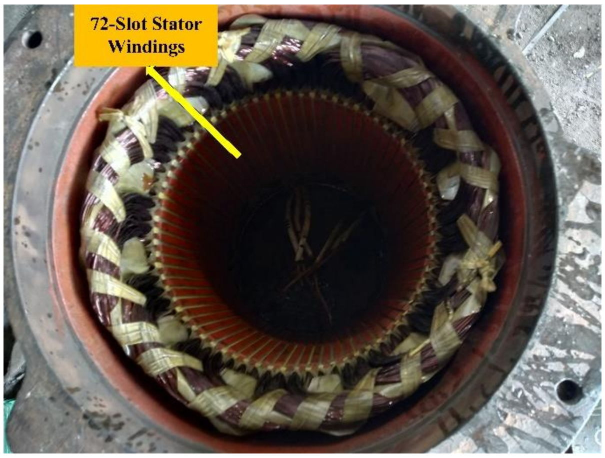
3.1. Machine Specifications

Faults in electrical machines are frequently observed in industries. Throughout the year, these machines are continuously operated. This causes the machine's parts to deteriorate and its efficiency decreases. As a consequence, early detection of various defects of electrical machinery can help to reduce the severity of the fault. Fault currents in stator windings can damage the machine causing the sudden shutdown. Fig. 3 (a) shows 72-slot stator windings of MA and Fig. 3 (b) represents a 24-stator slot machine of MB. These machines are winded in a workshop since the windings completely deteriorate in two machines. It is important to identify the deformation in the windings. The machine parameters are tabulated in Table 1.

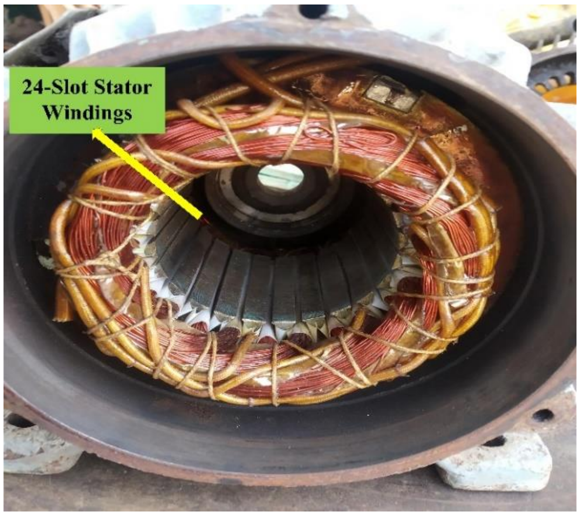
Table 1. Power rating of the machine.

Machine	MA	MB
P	74.5 (kW)	0.74 (kW)
V	440 (V)	440 (V)
I	140 (A)	1.6 (A)
f	50 (Hz)	50 (Hz)
No. of Slots	72	24
N	1500 (r.p.m)	2820 (r.p.m)
Poles	4	2

MA-Machine A, MB-Machine B, P-Power rating, V-Voltage, I- Current, f- Frequency, N-Speed



(a)



(b)

Fig. 3. Stator windings (a) 72-slot (b) 24- slot machine.

3.2. Work Execution

The work execution process for the proposed methodology is depicts in Fig. 4. This paper focuses on three aspects: experimental analysis- EMA, numerical investigation- FEM, and mathematical computations. The EMA assists in finding deformation in windings and determining the accurate position of the machine's major defect where it is under incredible stress. In ANSYS software- FEM is employed to simulate both machines. The frequencies of FEM and EMA are close, indicating that the work has been validated. The percentage error (frequency) is approximately 2% indicating good validation between the tests. In addition to numerical and experimental results, mathematical calculations are done to determine the displacement and the precise point in stator slots which are discussed in section 4.

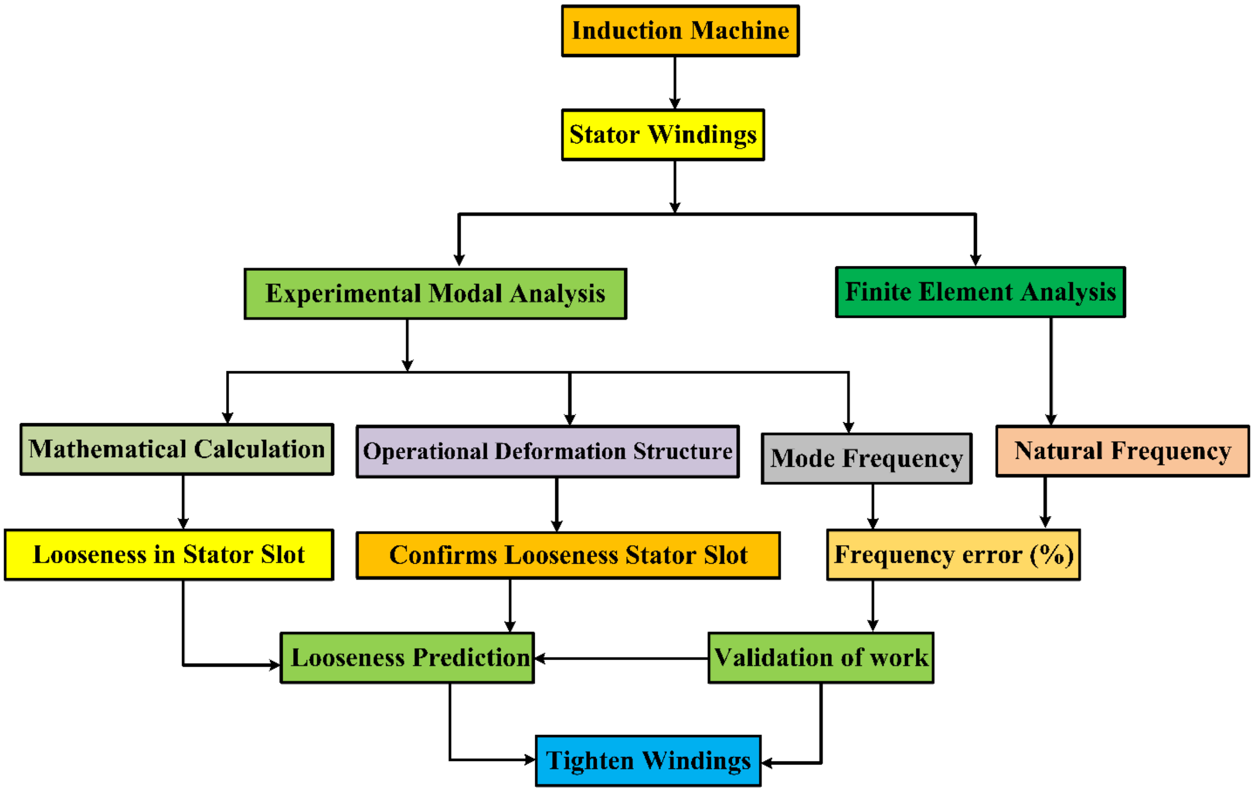


Fig. 4. Pictorial representation of work execution.

4. LOOSENESS CALCULATION IN STATOR WINDINGS

Winding problems are frequently observed in all rating (low to high) electrical machines. Looseness in stator winding is one of the primary causes of deterioration. It is essential to detect the greater magnitude of looseness in the windings of slots and their exact location before it causes severe damage. In this section, the looseness in the stator windings with exact location is discussed with mathematical calculations. The total displacement in windings that are caused due to deformation can be given by Eq. (1).

$$L_T = 2A\sin^3\alpha \qquad (1)$$

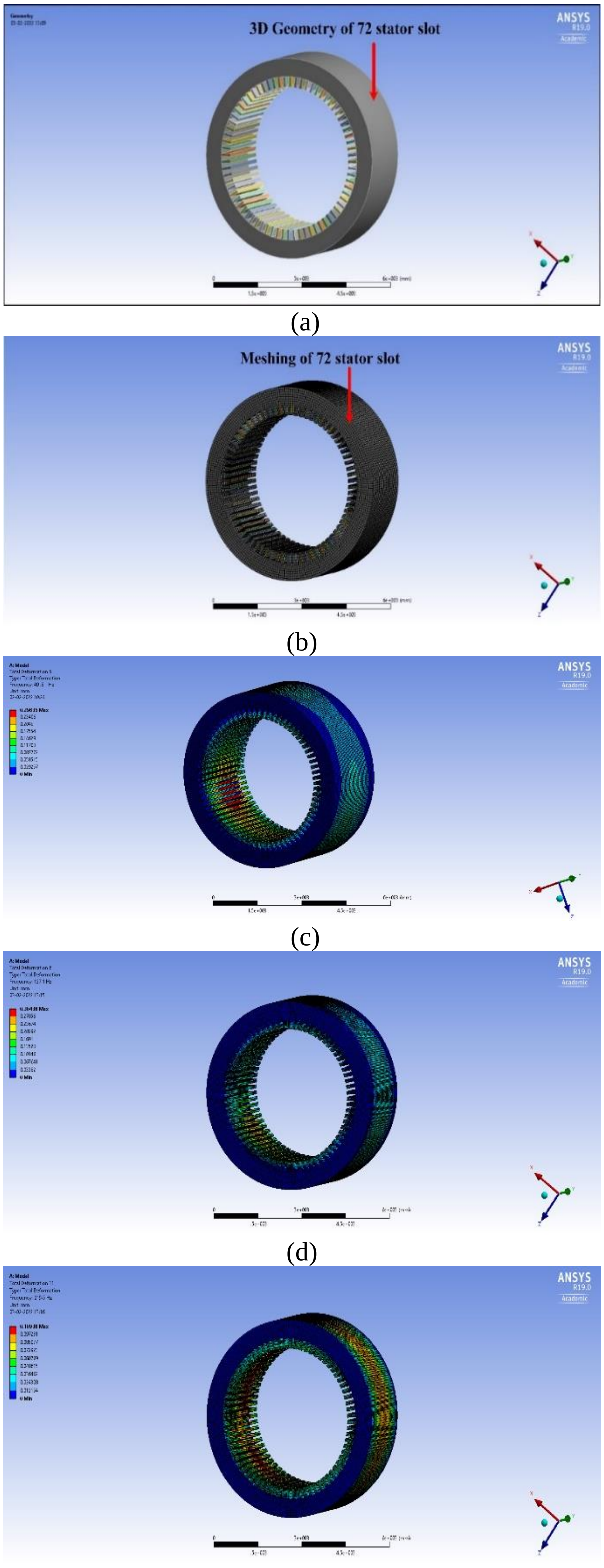
Where, L_T is total looseness in the windings of identified slot number, 'A' is the magnitude, and 'α' is the phase which is derived from the EMA test [4]. For 72-slot (MA) and 24-slot (MB), the maximum deformation is tabulated in Table 2. The mathematical computation of winding deflections of MA and MB of slots 51 and 52 for MA and slots 1 and 4 for MB have more looseness in windings. To confirm the looseness in windings, ODS from experimental analysis and numerical investigation is to be performed.

Table 2. Looseness in windings of MA and MB.

MA- 72 slots				MB-24 slots			
Slot No.	A	α	L_T (mm)	Slot No.	A	α	L_T (mm)
51	26.65	-31.56	7.46	1	18.69	39.95	9.71
52	14.65	42.53	8.79	4	13.27	48.67	11.14

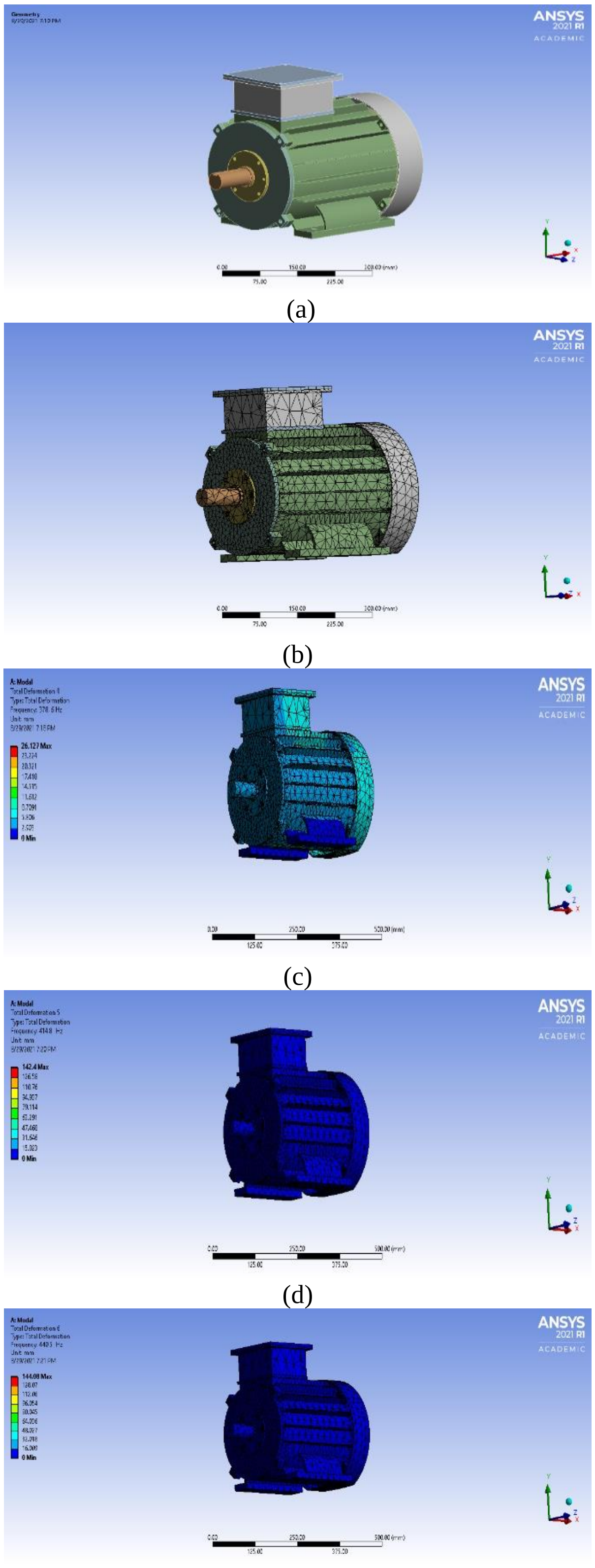
5. NUMERICAL INVESTIGATION-FEM

The finite element technique is employed as a numerical investigation for identifying structure deformation with different mode frequencies. This technique is used to design a large structure which is a less cost-effective procedure. The two test machines are simulated in ANSYS software, and the stator proportions are taken into account using the reverse engineering process. Fig. 5 depicts the model of MA and Fig. 6 shows the model of MB, for geometry, meshing, and natural frequencies at different modes. Since MA is a huge machine with 72 stator slots, therefore, the only model of the stator slot is shown in Fig 5; whereas MB is a small machine with 24 slots, therefore, the model of the whole machine is N-numerical frequency (Hz), E-experimental (Hz), e- percentage error depicted in Fig. 6.



(a) (b) (c) (d) (e)

Fig. 5: Model of MA stator slot (a) Geometry (b) Model (Meshed) 72-slot, mode frequency by FEM (c) 49.8 (Hz) (d) 127.1 (Hz) (e) 219.5 (Hz)



(a) (b) (c) (d) (e)

Fig. 6: Model of MB (a) Geometry (b) Model (Meshed) 24 slot machine, mode frequency by FEM (c) 378.6 (Hz) (d) 414.8 (Hz) (e) 448.6 (Hz)

Table 3. Meshing elements and size of MA and MB.

MA- 72 slots		MB-24 slots	
Nodes	460650	Nodes	116163
Elements	91425	Elements	61202
Elements size	75mm	Elements size	25mm

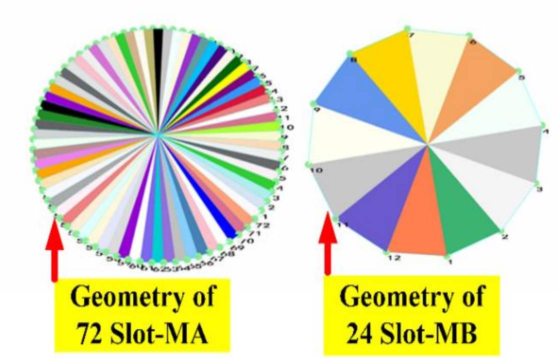
Table 4. Comparison of Numerical and Experimental Frequencies.

	MA			**MB**		
Mode	N	E	% e	**N**	E	% e
1	49.8	50.9	2.1	378.6	383.2	1.2
2	127.1	128.5	1.0	414.8	420.7	1.4
3	219.5	222.5	1.3	440.5	448.6	1.8

All structure’s elements are designed using a 3-D model as represented in Fig. 5 (a), (b) and 6 (a) and (b). After the modeling, the nodes, elements, and element size of MA and MB are tabulated in Table 3. A comparison of numerical and experimental frequency error of two machines is shown in Table 4. It can be seen from Fig. 5 (c) to (e) and Fig. 6 (c) to (e) that the observed frequencies obtained from FEM are close to experimental mode frequencies indicating the validation of the work. The variance, which is approximately 2%, demonstrates that these two approaches are in good conformity.

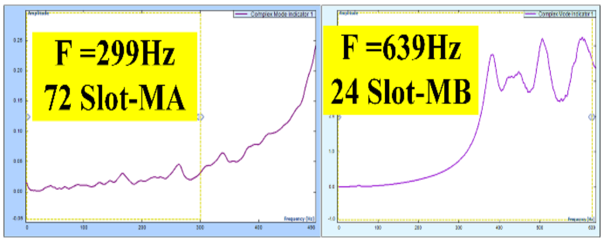
6. EXPERIMENTAL MODAL ANALYSIS (EMA)

The impact hammer technique is a part of Experimental Modal Analysis (EMA) to determine modal parameters. These parameters with different mode shapes represent the mode of vibrations. The tools needed to perform EMA are an impact hammer, sensor, and dynamic signal analyzer. The force and displacement characteristics are computed as a transfer function by a sensor. This gives winding deformation, which shows looseness in concerning slot number. The stator windings of MA and MB are considered to find the structure deformation from the test. To measure the looseness of two machines, the windings are gently struck with a hammer. The deformation is recorded by a sensor and signal analyzer CoCo-8oX. The crucial feature of this test is to determine the mode shapes using operational-deformation-structure-ODS indicating looseness in the windings. Because of the continuous operation of the machines, the windings of the machines may get ruined. The machines are re-winded in a workshop to handle heavy loading conditions to meet industrial applications. But looseness and deformation in windings can interrupt the machine. To avoid these failures, EMA is executed to identify the looseness in the windings.



(a) (b)

Fig. 7. Slots of test machines (a) 72-slot MA (b) 24-slot MB.



(a) (b)

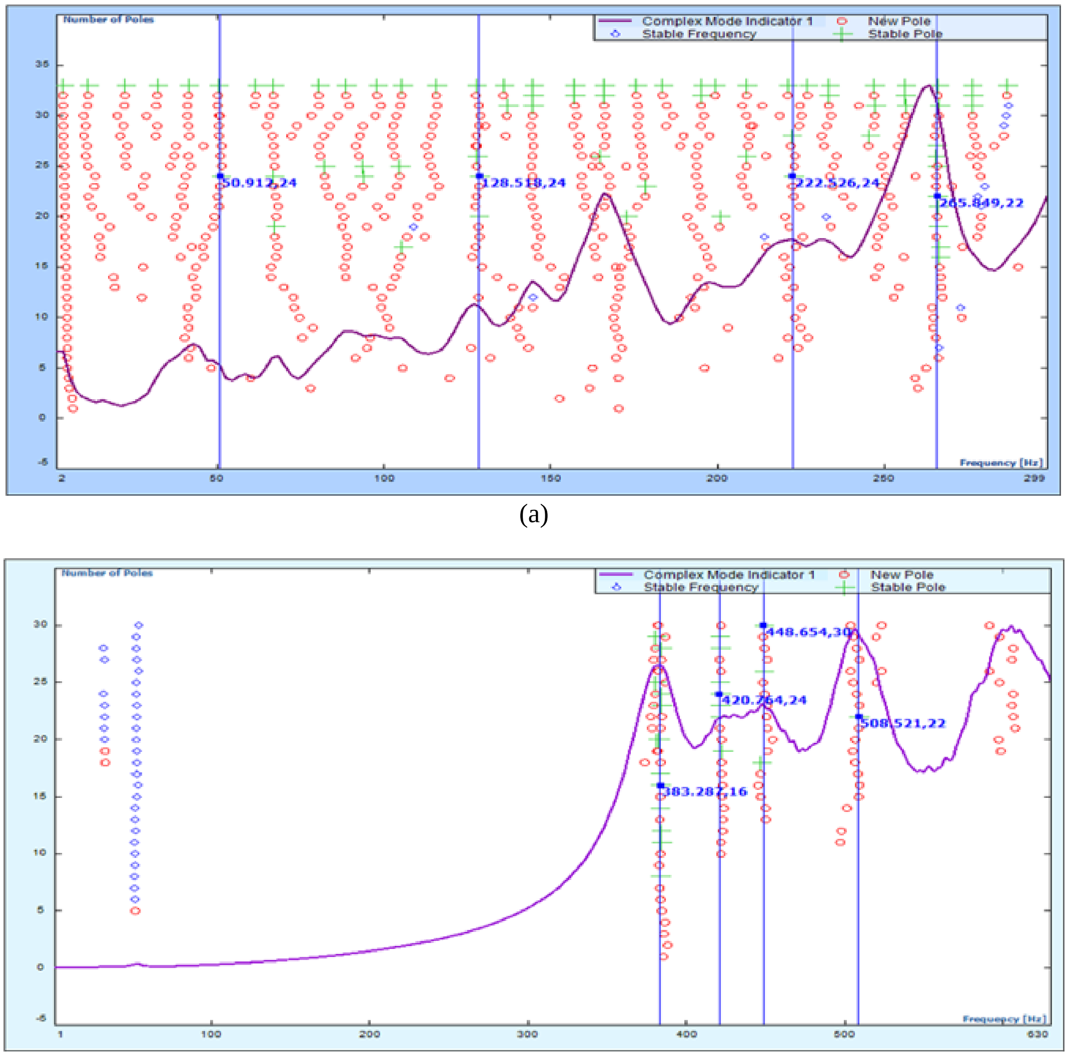
Fig. 8. Frequency selection (a) 299 Hz (b) 639 Hz.

7. RESULTS AND DISCUSSION

7.1. Preparation for EMA Test

To execute the EMA, the initial step is to consider the test structure and to determine the frequency responses by using EMA tools and finally identify the modes of the structure. For test machine-MA, 72 test points are considered (local mode) and for machine-MB 12-test points are considered (global mode) [13]. To predict the deformation in windings the modal parameters have to be identified. To perform this test the geometry and selected frequency of 299 Hz are considered for MA and 639 Hz for MB as shown in Fig. 7 (a), (b) and Fig. 8 (a), (b), respectively. After selecting a frequency, it is important to predict the modes with different frequencies. In EMA test modal parameters are identified with the help of a stability diagram. The stability diagram is a visual illustration to present new and stable poles to identify different modes which are shown in Fig. 9 (a) and (b). The modes identified from the stability diagram are 50.9 Hz, 128.5 Hz, 222.5 Hz, and 265.8 Hz for MA, respectively. Similarly, the modes identified from the stability diagram for MB are 383.2 (Hz), 420.7 (Hz), 448.6 (Hz), and 508.5 (Hz), respectively. The higher values of magnitude obtained from the EMA test of 72-slot and 24-slot machines are shown in Table 5. This higher magnitude specifies the deformation in windings. In both the machines, the windings are gentle strike with a force and the gravitational response is recorded by a sensor. Fig. 10

indicates the response of the hammer test for MA and MB. Fig. 10 (a) shows that thirteen slot winding is struck by a hammer and the response is recorded as a transfer function for MA.

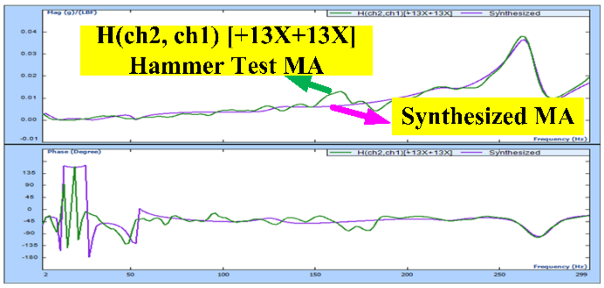


(a)

(b)

Fig. 9: Different modal parameters (a) MA (b) MB.

Similarly, the response is recorded as a transfer function for MB as shown in Fig. 10 (b). The magnitude from the EMA test represents the looseness in the winding. The highest magnitudes of both the machines are given in Table. 5. It is illustrated from Table 5 that for MA, the points 51,52 are observed with a higher magnitude whereas, for MB points 1,4 are observed with a higher magnitude. Further, the identified points L_T of MA and MB from EMA are similar to the points obtained from mathematical calculations as given in Table 2. Also, to validate the mathematical calculations, the operational deformation structure (ODS) is extracted from the EMA test. ODS proves the looseness in the windings of points 51,52 for MA and points 1,4 for MB with different modes, as illustrated in Fig 11 and Fig. 12. The experimental and mathematical values both validate the exact deformed position in windings of the two test machines MA and MB, respectively. After rewinding the MA and MB, EMA is executed on two machines and confirmed the looseness in the machine with ODS as shown in Fig. 11 and Fig. 12.



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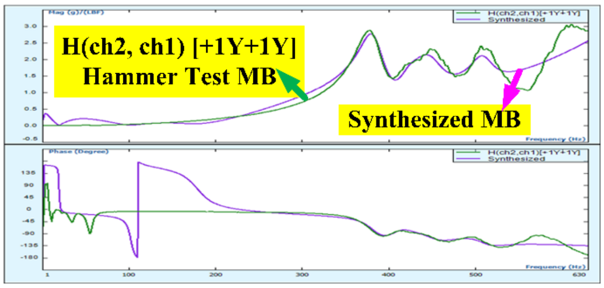
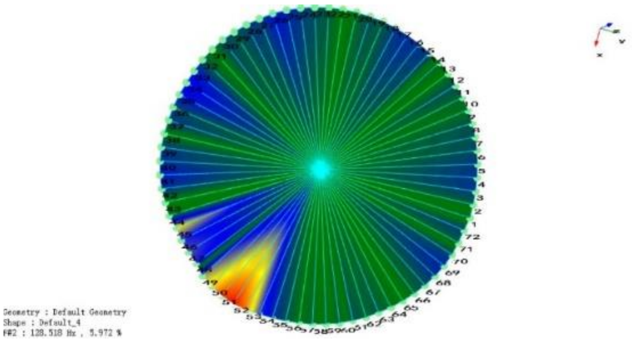


(b)

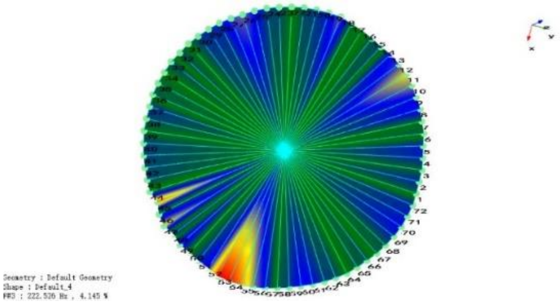
Fig. 10. Mag. And Phase of hammer test (a) MA (b) MB.

Table 5. Slot No. with highest Magnitude-A & Phase-α for MA and MB.

Point	MA 72-Slot		Point	MB 24-Slot	
	Mag.	Phase		Mag.	Phase
51	26.65	-31.56	1	18.69	39.98
52	14.65	42.53	4	13.27	48.67

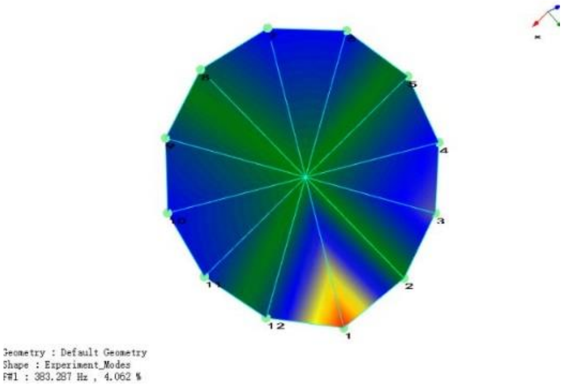


(a)

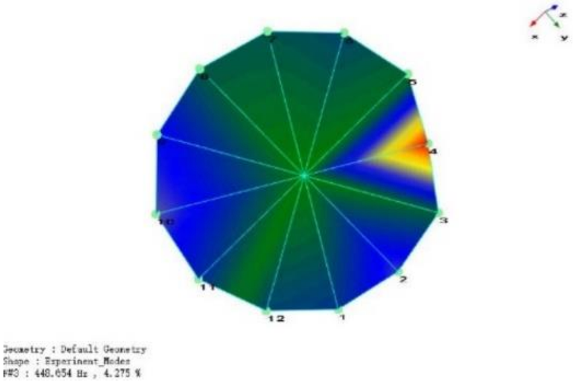


(b)

Fig. 11. Looseness in windings of MA with ODS (a) mode-2 (b) mode-3.



(a)



(b)

Fig. 12: Looseness in windings of MB with ODS (a) mode-1 (b) mode-3.

Table 6. Comparative Study with Literature Survey.

Cited Ref.	Methodology	N(Hz)	E(Hz)	% e	Findings	L.S.No.	L_T (mm)
[1] & 2019	FEM & EMA	4647.5	4535.4	2.4 %	Vibrations	-	-
[3] & 2020	FEA & EMA	1233.3	1210.9	1.8 %	Vibrations	-	-
[4] & 2022	FEM, EMA, & FVA	439.17	420.76	4.1 %	Vibrations	-	-
[5] & 2019	MVSA	261.36	267.9	2.4 %	RBE	-	-
[10] & 2018	FEM & EMA	1200	1496	19.7 %	Vibration mode	-	-
[11] & 2022	FEM & EMA	34.64	36.5	5.0 %	Vibrations	-	-
P	FEM & EMA	MA-127.1 MB-378.6	MA-128.5 MB-383.2	1.0% (MA) 1.2%(MB)	Looseness in windings	51 & 52 (MA) 1 & 4 (MB)	7.46;8.79 (MA) 9.71;11.14(MB)

N-Numerical Frequency (Hz), E-Experimental Frequency (Hz), e-percentage error between numerical and experimental frequency, RBE- Rotor Bearing Element, L.S. No- Looseness of SEW with Slot Number, L_T -displacement (mm), P-Present Work

7.2. Comparative Study with Literature

A comprehensive comparison is presented in Table 6, which shows a recent state-of-the-art investigation. The parameters considered for comparisons are vibration defects with numerical and experimental analysis. All of these investigations have concentrated on determining the frequency error. H. Fang et al. in [1] conveyed a 2.4 % frequency error between numerical and experimental results to predict the vibrations in machines. But this study does not predict the looseness in windings. C. Feng et al., in [3], used a similar procedure to obtain a frequency inaccuracy of 1.8 % while neglecting winding looseness. Kapu V. et al., in [4], S. Wang et al., in [10], and M. Rajesh et al., in [11] performed a numerical and experimental test and determined the error to be 4.1 percent, 19.7 percent, and 5.0 percent, respectively. However, the frequency error recorded in these methods is more than 4 percent. N. Bessous et al., predict the defects of rotor bearing elements by using motor vibration signature analysis. However, this method does not predict the looseness in the stator windings. Research cited in Table 6 covered FEM and EMA analyses but did not address the winding looseness. The proposed work exhibits the experimental test on two machines MA and MB. In 72 and 24 slot machines, a hammer (EMA) test is done on the MA and MB after rewinding in the workshop. To confirm the EMA test results, mathematical calculations and numerical investigation are performed, and good agreement between the tests is revealed. The major contribution of this work is that the frequency error observed in MA and MB is approximately 1.4 %. Operational deformation structure from the EMA test determines the exact deformation in windings at slots 51,52 for MA and 1,4 for MB. These deformations are observed in new windings and can deteriorate the machines if the looseness is not predicted exactly. The mathematical calculations signify the deformation in the windings of MA and MB. The validation of looseness in the windings is vital in avoiding stator breakdown due to faults. This methodology can also be used to anticipate the accurate fault location of the windings for huge-power rating electric machines equipment such as the alternator, pumps, and induction machines.

8. CONCLUSION

In this paper, the deformation in windings with different locations, of two electric machines is computed. To determine the looseness in windings EMA is executed to obtain the operational deformation structure-ODS. The deformation spectrum shown by ODS with different modes of two machines illustrates the exact looseness in the windings. Many industries and users do not perform winding tests on machines in the workshop, resulting in machine deterioration. The proposed work increases the machine's performance and longevity by eliminating unexpected interruptions by identifying the exact looseness points in the stator windings. The experimental findings confirm with mathematical approach and identify the looseness in windings effectively. The frequency deviation observed with element analysis is about 2%, which is confirmed by experimental data. The obtained results of MA and MB revealed that the windings were deformed in points 51,52 (MA) and 1,4 (MB), respectively. Machines are re-winded in the workshop, if the deformation in windings is not identified it seriously deteriorates the machine and its performance. As a consequence, the deformation in windings is estimated analytically and practically to avoid future interruption. Therefore, to avoid serious damage to massive electric machinery, this work forecasts the exact looseness location of stator slots that are deformed in windings.

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