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RESEARCH ARTICLE

Induction Motor Structure Design to Reduce Vibrations With Numerical (FEA) and Experimental (VA) Techniques

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ABSTRACT The resolution in the design of the machine structure can control vibrations that increase the lifespan of the induction motor (IM). This is feasible by retaining the machine's vibrations within acceptable ranges. To reduce these vibrations of an aged machine a vibration analyzer (VA), finite element approach (FEA), and experimental modal technique (EMT) are applied to an induction motor. The test on stator windings (SW) with global mode revealed that the windings in slots 7 and 8 are deformed. ANSYS software was used to model the machine with FEA numerically to predict the vibration velocity (VV) and found 18.3 mm/s. The vibration analysis was applied to IM and noticed a vibration velocity of 10.6 mm/s, indicating both the numerical and experimental vibration velocities are greater than 5 mm/s. This can reduce the reliability of the motor as per ISO Standard 10816 and cannot meet industrial needs. The test machine was numerically redesigned with a 6-hole reinforced frame and raised to 0.1 cm in thickness to reduce the vibrations then VV was recorded as 2.9 mm/s. Vibration analysis is carried out experimentally while the machine windings are tightened after modification and the vibration is 3.2 mm/s. Finally, both numerically (84.15%) and experimentally (69.81%), the test motor's vibrations are reduced, enhancing the test motor's reliability to meet industrial requirements and minimizing the plant's revenue cost.

INDEX TERMS Fault diagnosis, induction motor, modal test, finite element analysis, vibration analyzer, deflection shape, stator winding.

ABBREVIATIONS Vibration analyzer (VA), finite element approach (FEA), experimental modal technique (EMT), stator windings (SW), induction motor (IM), electro magnetic force (EMF), impact hammer (IH), motor drive end (MDE), deflection shape (DS), vibration velocity (VV), multiple-input and multiple-output (MIMO).

I. INTRODUCTION

For many decades, induction motors have been widely used in industries, electrical drives, and vehicles. It is likely to be used until and unless an alternative is discovered shortly. If the machine has fewer vibrations, it can attain robust performance and good torque characteristics. The machine's performance will likely worsen if it is used continuously for a very long time because vibrations will weaken the machine's structure. These electrical machines operate continuously at different temperatures and it is a challenge to protect their components in the long run. This has a different impact on structures, resulting in deterioration in the motor parts causing high vibrations which are to be restricted [1]. Vibrations in a motor (medium-sized) result in structural deformation, which affects the stator windings, due to strong electromagnetic force [2]. For continuous operation to meet industrial requirements fewer vibrations in motors are mandatory to achieve better efficiency. Discovering the cause for the increased vibrations is necessary if they exceed the

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permitted limit. This issue can be addressed by investigating the parameters (modal) accomplished by experimental tests (EMT). This analysis is used to pinpoint the fault's location and aids in a speedy redesign of the motor.

Many structural vibration evaluations utilizing FEA and EMT are carried out in the current study on electric motors to find the vibrations. Advanced methodologies are available to predict structural deformation with frequency considerations that can be used to assess machine performance. The stator, which is integrated with several components like the rotor, shaft, bearings, etc., is the most crucial section of an electrical machine. In some cases where there is a divergence between the fundamental frequency and the primary condition, the stator windings are susceptible to vibrate. This issue is raised due to looseness in the structure's robustness, which originates uneven vibration in the machine [3], [4]. The resonance is reduced and the SW vibration may be overwhelmed if the fundamental frequency and induced electromagnetic force (emf) frequency are sufficiently different. According to Lee et al., [5] and Logan et al., [6] the motor's vibration as an outcome of the structure's deformation leads to resonance as the motor runs uninterruptedly and needs regular maintenance to prevent the motor from various faults. The deformation in stator windings is to be identified in the test machine and the exact point can be predicted by EMT.

Apart from the experimental approach, mode frequencies of the electrical machine are predicted using numerical analysis on the ANSYS software platform. The frequencies at various structural modes using the numerical technique (FEA) are implemented [7], [8], [9], it is possible to reduce the defects caused by vibrations and ultimately redesign the machine with better structural features. The mechanical bend could be the main factor causing vibrations in the motor's various components. However, it is challenging to find the precise cause of the stator windings' looseness, which is crucial to the design. This looseness causes deterioration in motor stator bar components and causes complexity and damage to the motor. This problem can be overcome by the FEA model, and bindings with spring elements are added. This method concentrated on vibration-related issues using mathematical and experimental testing and specified an error (frequency) of seven percent and in the acceptable range (between FEA and EMT). The models of the electric motor are numerically evaluated to estimate the strong emf and the transient characteristics of the stator windings, which leads to significant errors for very huge machines are reported [10], [11].

The numerical approach created in the ABAQUS software is compared with the experimental test (vibrations). This vibration can lead the machine to electrical and mechanical faults in IM. According to an IEEE survey, induction motor stator issues are up to 30–40% of all electrical flaws, whereas rotor flaws make up 5–10% of all flaws. Motor defects with winding and rotor defects are considered electrical faults. The rotor is heavily stressed when operated at high temperatures, causing vibrations with poor electrical input that deteriorate the motor parts and misalignment in them. The resonance that is caused in various machine parts, such as the casing, base, fan cover, eccentricity, and bearing issues, is the primary cause of mechanical faults and accounts for 40–50% of failure rates [12], [13], [14]. Resonance can cause the machine to vibrate and reduce efficiency, which might harm the windings if deformations are not identified in the stator windings. These vibrations can damage the windings and can bend the structure of the windings, which results in an electrical problem in the motor. Furthermore, if the parts of the motor are not assembled due to manufacturing defects it causes more vibrations to occur in the motor at an early stage of erection. High motor vibrations cause inner weakening of the stator windings, which causes insulation breakdown with the mica layer, and semiconductor cracks.

A vibrational alignment problem arises when the machine's contacted parts are out of alignment. The motor vibrates more as the machine gets older and the manufacturer defects with misaligned motor parts. In some instances, the rotor's abnormal alignment in the machine results in an uneven electromagnetic field, which causes the motor to vibrate rapidly. Due to component misalignment and resonance issues, high-rating electric machines used in industries that are operated with these defects can lead to enormous vibration and noise. By using the numerical approach, FEA is implemented to simulate the motor in three-dimensional geometry to predict the frequency (fundamental) and vibration. Therefore, to control these vibrations and resonance the motor is to be modeled numerically and an experimental approach is to be performed to limit (vibrations) as per ISO 10816 [15], [16], [17]. If these vibrations are not restrained, the machine will develop electrical and mechanical faults [18], [19], [20].

A numerical approach with FEA is applied to predict the frequencies that reveal the resonance and improve the structure's stiffness [21]. The experimental approach with EMT which shows higher displacements in stator windings can identify the deformation of structures [22]. The stator end windings were reported to have high stresses by numerical and experimental evaluation. The authors mentioned above claim that numerical analysis cannot find the precise fault location or fault type. In this study, experimental analysis is implemented to predict the deformation in SW to restrict the vibrations in the machine. It is observed that there is a good comparison between the experimental vs numerical approaches in predicting the frequencies [23], [24], [25], [26], [27]. Therefore, reducing the vibrations in the test motor is important to increase the life of the machine.

The main contribution of this work is to implement vibrational analysis, finite analysis, and modal analysis to predict the vibrations of an aged test machine. The deformation in stator windings is to be predicted exactly in a twenty-four-slot motor. The IM specification is tabulated in Table 1 and the test motor is shown in Fig. 1. Foundation problems and deformation in stator windings are the major causes to vibrate the machine at more than 5 mm/s. Due to these vibrations, the test machine was designed with FEA in ANSYS software

TABLE 1. IM specification.

Parameter	Units
P (W)	745.5 W
Volts (V)	415 (V)
Ampere (I)	2 (A)
Speed (N)	295.30 (rad/s)
Poles	2
Frequency (F)	50 (Hz)
Slots (Stator)	24
Slots (Rotor)	20
Outer Diameter (Stator)	13.7 cm
Inner Diameter (Stator)	7.0 cm
Outer Diameter (Rotor)	6.0 cm

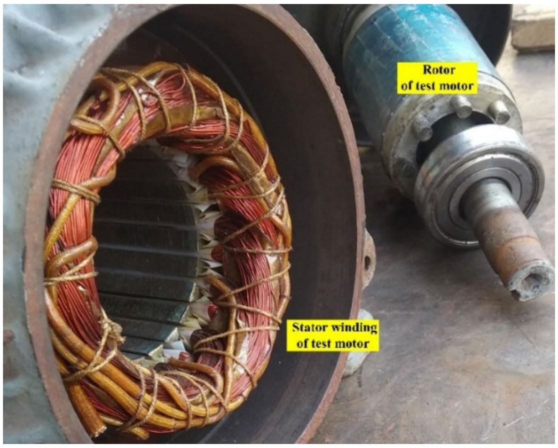

FIGURE 1. Test motor with stator and rotor.

by reverse engineering method and found the vibrations were more than 5 mm/s. Machine vibrations due to resonance, mechanical issues like the casing of the motor, and electrical issues with the winding deterioration are identified. Numerically the machine is designed in a three-dimensional of a 745.7 W motor, and statistical analysis is completed to predict the natural frequencies of the IM. The experimental technique is implemented to find the deformation in windings. Furthermore, the numerical approach is validated with the experimental results.

The proposed work focuses on identifying the root cause of vibrations related to various faults. This is made possible by the experimental results, which assist in determining the precise location of the stator winding bend. Consequently, the machine's electrical fault is identified and needs to be rewound. The mechanical defect is due to the vibration in the motor foundation and casing. The vibrations, which are measured in the vibrational analysis as 10.6 mm/s and numerically as 18.3 mm/s, are estimated using VA and FEA. Later, the machine was modified in ANSYS by thickening the base frame to 0.1 cm, which strengthened it. Additionally, the IM casing (base) was changed to 6 holes, which decreased vibration velocity (VV) to 2.9 mm/s. The machine stator windings are wounded tightly with overhauling and vibrational analysis is done and found the vibration velocity is 3.2 mm/s with an experimental approach which is less than 5 mm/s. The proposed work process is shown in Fig. 2. The brief comparison of EMT, VA, and FEA is tabulated in Table 2 where EMT and VA are experimental analyses and finite element analysis is numerical to identify the performance of the machine. EMT predicts the structure response and finds the precise location of deformation where severe stress acts with deflection shape. VA is an experimental approach to predict the vibration in the machine. Finite element analysis is a numerical approach to designing the machine and predicting vibrations of the structure.

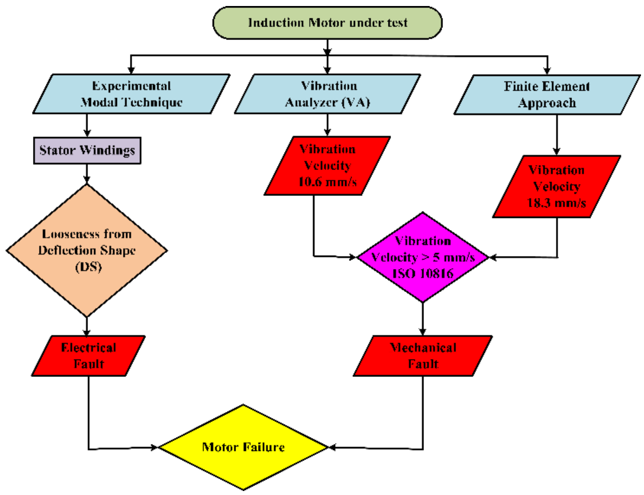

FIGURE 2. Flow chart of proposed work of test motor.

TABLE 2. Comparison of EMT, VA, FEA approaches.

Description	EMT	VA	FVA
Analysis	Experimental	Experimental	Numerical
Predicts	Structure Deformation	Vibration	Vibration
Parameter	Deflection Shape	Vibration Velocity	Vibration Velocity
Fault Type	Electrical	Mechanical	Mechanical

Therefore, to determine the cause of vibrations in the test motor, this work focuses on using the experimental modal technique (EMT), vibrational analysis (VA), and finite element approach (FEA). The EMT assists in locating any deformation in the SW and identifying the exact spot where the machine is most sensitive. To predict the VV numerically, FEA is used to simulate the test motor in ANSYS software. Experimentally, VA is applied to the test motor to forecast VV. Fig. 2 indicates the vibration velocity (VV) is more than the permissible limit (5mm/s) which can reduce the lifespan of the motor. The test motor is redesigned numerically and the stator windings are tightened to reduce the VV.

The paper is organized as follows, Section II presents the structure boundaries and faults, Section III discusses the experimental approach with EMT to predict the deformation in the SW. Structural boundaries and vibrations were discussed in Section IV. Results were discussed in Section V and finally, the conclusion is discussed in Section VI.

II. STRUCTURE BOUNDARIES AND FAULTS

Vibrations are mainly caused in electrical machines due to the deformation of the structure boundaries. It mostly occurs as an effect of stress, or more accurately, a force applied to the affected area. This affected area culminates in the structure's complex dynamic behavior and instability causing breakage. Moreover, the temperature variations and shrinkage effect in the structure (like stator winding, rotor bars, and bearings in machines) can damage seriously. Therefore, it is necessary to keep a focus on the structure's boundary condition and its properties, such as mass, damping, and stiffness. Moreover, when resonance causes the motor's structure to vibrate more intensely, making materials like stator windings more susceptible to tearing and eventual machine breakdown.

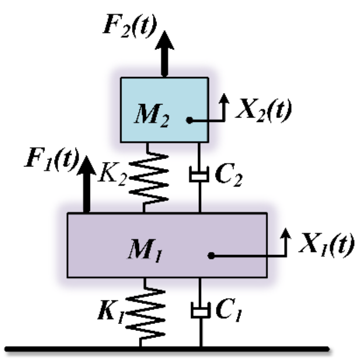

FIGURE 3. Multiple-input and multiple-output (MIMO) with force-displacement.

As illustrated in Fig. 3, let us consider a system where the structure is subject to multiple forces. Let 'M_1 and M_2' be the mass, 'C_1 and C_2' be the damping, and 'K_1 and K_2' be the stiffness of the structure. If $F_1(t)$ and $F_2(t)$ is the force acting on the masses M_1 and M_2 then,

$$M_1\ddot{X}_1(t) + C_1\dot{X}_1(t) + KX_1(t) = F_1(t) \quad (1)$$

$$M_2\ddot{X}_2(t) + C_2\dot{X}_2(t) + KX_2(t) = F_2(t) \quad (2)$$

where $M_1\ddot{X}_1(t)$ and $M_2\ddot{X}_2(t)$ are the inertial force, $C_1\dot{X}_1(t)$ and $C_2\dot{X}_2(t)$ are the damping force, $KX_1(t)$ and $KX_2(t)$ are the restoring force where $X_1(t)$ and $X_2(t)$ are the initial positions of the masses M_1 and $M_{2.}$ The total external forces $F(t)$ acting on the system have the potential to deform the structure and come into contact with surrounding elements, which could ultimately cause damage to the structure and the resultant force is

$$F(t) = F1(t) + F2(t) \quad (3)$$

Using the Laplace Transform in Equation (3),

$$F(s) = F1(s) + F2(s) \quad (4)$$

$$M\ddot{X}(s) + C\dot{X}(s) + KX(s) = F(s) \quad (5)$$

Eq. (5) can be modified as,

$$Z(s) * X(s) = F(s) \quad (6)$$

where $Z(s)$ the dynamic stiffness can be denoted by,

$$Z(s) = Ms^2 + Cs + K \quad (7)$$

The ratio of the output response concerning the displacements $X_1(s)$ and $X_2(s)$, related to input force vectors $F1(s)$ and $F2(s)$, defines the transfer function $H(s)$ of multiple-degree freedom, where the general equation is represented in Eq. 8,

$$X(s) * H(s) = F(s) \quad (8)$$

Multiple-input and multiple-output (MIMO) are shown in Fig. 3 with a force-displacement-related transfer function. These external forces acting on the structure can cause more vibrations with higher amplitude chronologically degrading the machine. This causes the boundary to deteriorate, damaging the original structure and resulting in deformation. These forces result from the machine's uneven vibrations, which alter the structure's mass, damping, or stiffness. This causes deformation as measured by displacement, which is derived from the transfer function and is caused by the forces enumerated in Eq. 8. The aforementioned equations show that the structure is subject to extreme stresses, which cause displacement that affects machine parts. The machine could experience several faults if these forces and displacement are not tracked and restricted.

An induction motor's faults can be broadly divided into two distinct groups: internal and external. Fig. 4 illustrates how the environment plays a role in ambient conditions that are crucial in the fault's occurrence. Electrical and mechanical issues are the cause of the internal breakdowns. Furthermore, eccentricity issues, bearing flaws, and foundation problems are the main causes of mechanical failures. On the other hand, magnetic circuit failures with rotor and stator defects cause electrical issues. In a similar vein, environmental, mechanical, and electrical issues cause external faults. The severity of these defects necessitates thorough maintenance or in the worst scenario, results in an abrupt machine shutdown.

The industries must rely on these prediction techniques to prevent errors through appropriate surveying and monitoring. The findings with various faults are compared with the surveys carried out by ERPI and IEEE-IAS. The results of both surveys indicate that bearing faults, approximately 40%, are the primary cause of machine failure. The percentage of stator winding faults is 30%, while the percentage of rotor-related faults is 10%. The stator short-circuited and broken rotor bar faults are modeled at various conditions [28]. The remaining faults, as shown in Fig. 4, are 20%. The severity of the fault can be classified into different categories based on the power ratings of the machine and the kind of load that is applied over time. Improper monitoring of these machines can cause damage to the sensitive parts, specifically, the stator windings, which can cause an abrupt breakdown. Therefore, an experimental modal technique EMT is used to predict the stator winding deformation.

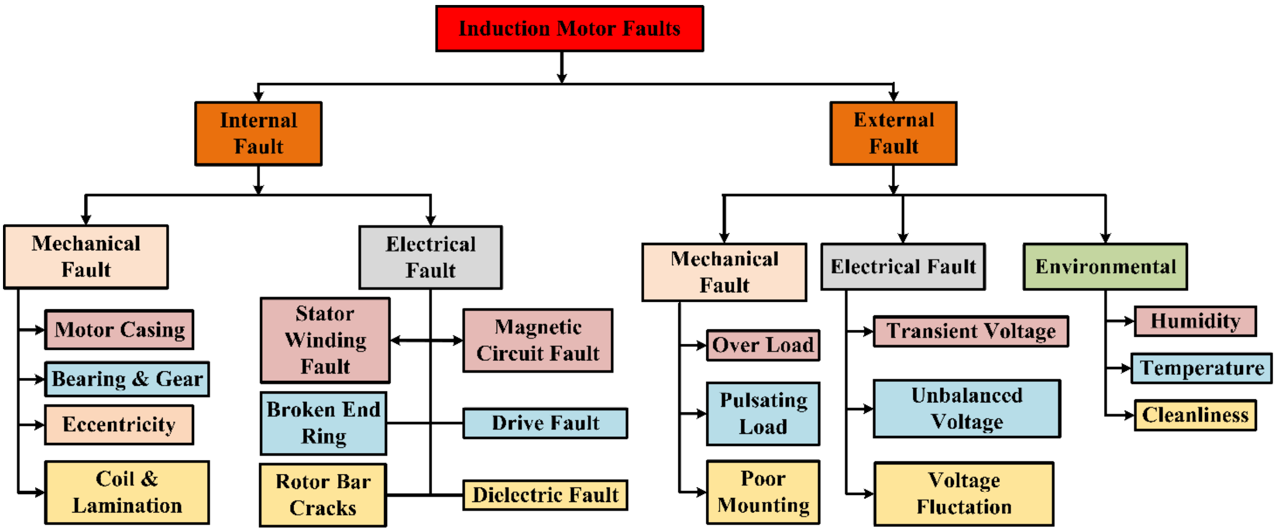

FIGURE 4. Major faults in induction motor.

III. EXPERIMENTAL APPROACH EMT

Experimental Modal Technique (EMT) is an advanced technique to determine the structure's dynamic properties. This approach forecasts its inherent frequencies and mode shapes that indicate a deformed structure. It is carried out using a sensor, impact hammer, and FFT analyzer on the machine's stator windings. The test is conducted with an Impulse Hammer (IH) type PCB086D05 which accompanies the first channel of the FFT analyzer and the sensor is kept in the second channel. The induction motor's stator windings are subjected to the EMT test, which involves hitting the stator with an IH. The force and displacement response are recorded as input and output by a sensor (accelerometer). To develop a transfer function, it is necessary to establish a relationship between the applied force and the deformation of the winding that is displaying looseness. The selection of the structure (windings) and its test points is the initial step to execute the experimental test.

The stator windings are gently hit by an impact hammer (IH) and the response is recorded as a frequency function that is quantified in magnitude and phase from the EMT test causing structural deformation. The highest magnitude obtained from the experimental approach should coincide with the deformation from the deflection shape (DS). This indicates the looseness in the windings identifying the exact location. The EMT is applied to the test motor the DS representing deformation in the windings is shown in Fig. 5. The test is performed in global mode by considering twelve test points where the hammer hit on the windings of 1,3,5,7,9,11,13,15,17,19,21,23 of twenty-four stator slot machine and found slot numbers 7 and 8 are deformed indicating looseness in the stator windings. Due to this deformation, it is important to find the root cause of vibrations in the motor by implementing vibration analysis experimentally and a finite element approach numerically which is discussed in the below section.

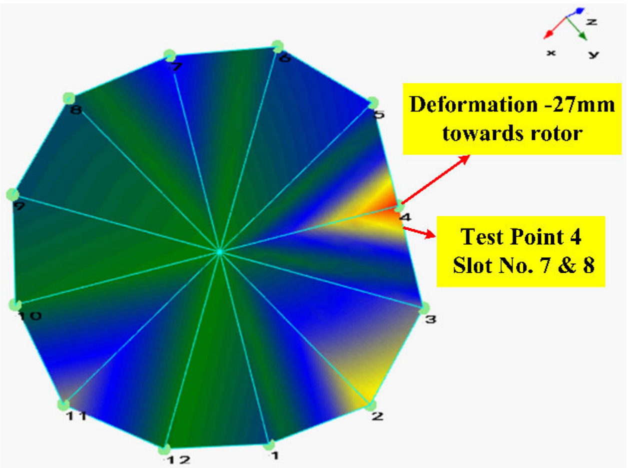

FIGURE 5. Deflection shape (DS) showing deformation in windings.

IV. STRUCTURE BOUNDARIES AND VIBRATIONS

To predict the vibrations in IM experimental and numerical methodology are performed. Experimental approaches with vibration analysis and numerical analysis by finite element approach are discussed.

A. VIBRATIONAL ANALYSIS

Vibration analysis involves tracking the levels and patterns of vibration signals within an element of equipment machinery, or structure. This method is employed to identify strange vibration occurrences and examine the overall status of the test object. The test motor is subjected to vibration analysis by using an accelerometer and an FFT analyzer on the motor driving end with the experimental setup shown in Fig. 6 (a) and instruments used shown in Fig. 6 (b). The predicted vibration levels were derived from a sensor of the motor (Model-9300) and four Channeled analyzers

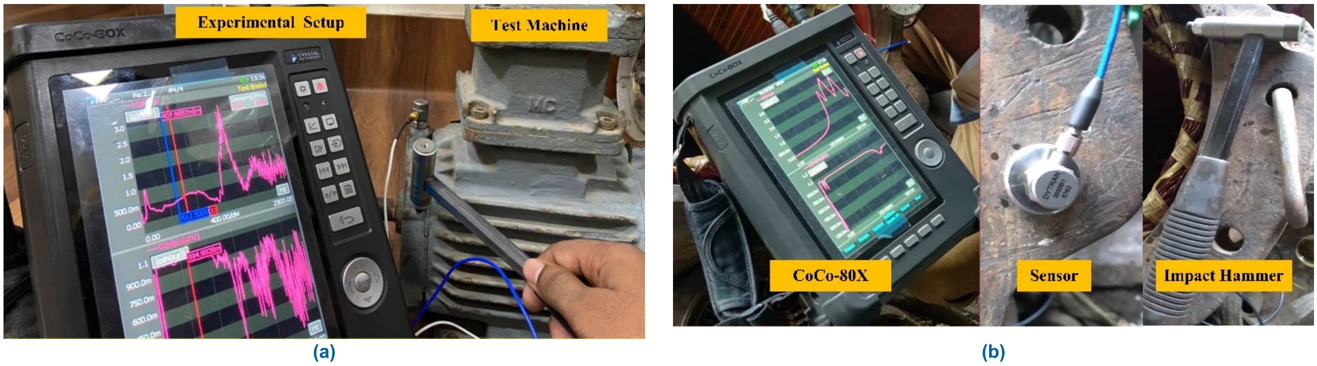

FIGURE 6. **(a) Experimental setup to predict vibrations (b) Instruments.**

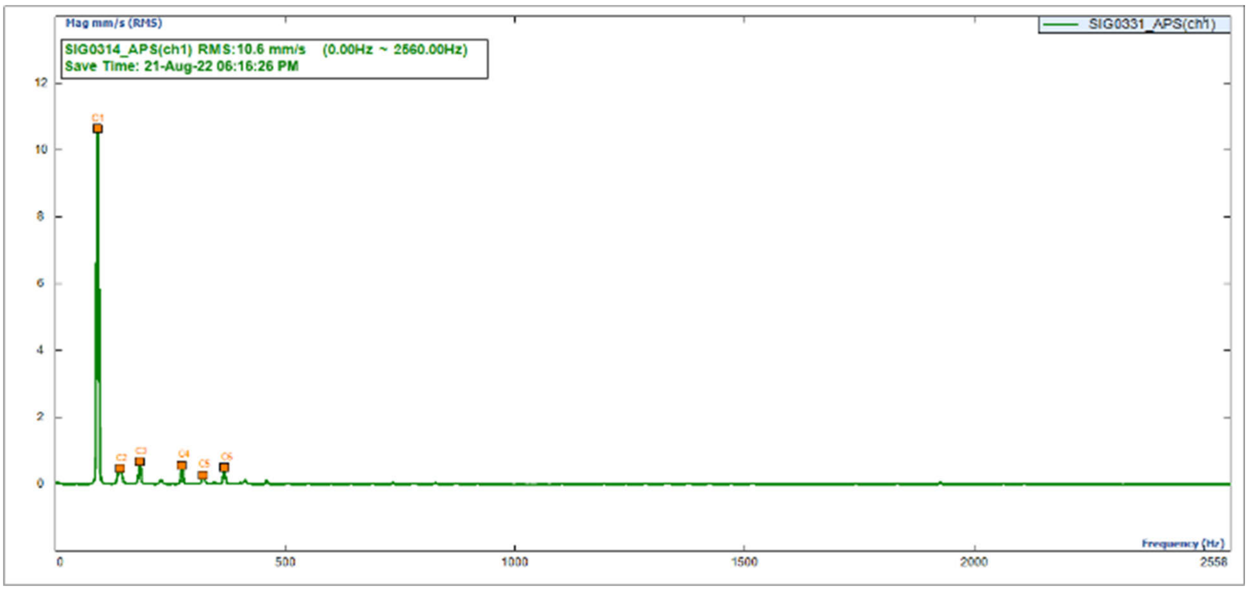

FIGURE 7. **Vibration velocity 10.6 mm/s from vibration analyzer.**

(CoCo FFT-Model 6348) in both the horizontal and vertical axes. The CoCo can serve as vibration data to analyze the vibrations in the test machine. The sensor is attached to the first channel of the FFT analyzer, where it takes into account 11 frequency range averages with a resolution of 1 Hz for calculating the frequency limit for the FVA, which is up to 2558 Hz. For the entire spectrum, 900 lines are utilized.

The Hanning window transforms signals captured in the time domain into signals captured in the frequency domain. Precision data are provided in the engineering data management (EDM) software for postprocessing to determine the force (gravitational) data which is converted to vibration response mm/s (velocity) by the software system. The FFT analyzer with a sensor measures the vibration of the machine at the motor drive end (MDE). Vibrations in the machine are plotted in the frequency spectrum with mm/s (vibration velocity) on the Y-axis and Hz (frequency) X-axis, respectively. From Fig. 7 it is observed the vibrations (mm/s) are 10.6 which exceeds the permissible limit (less than 5 mm/s).

B. NUMERICAL INVESTIGATION WITH FINITE ELEMENT ANALYSIS (FEA)

Finite element analysis (FEA) is used to simulate complex structures like motors more easily. This approach is frequently used to solve challenging problems in mathematical simulation and engineering for a unique solution. The motor's model is discussed in this section, and dimensions are taken into account to construct the three-dimensional in the software (ANSYS), as seen in Fig. 8. All of the components in this model (apart from the bandage) were created using a 3-D model. The motor is modeled with 1,06,264 nodes, 63,522 elements, and an element size of 2.3 cm. This technique is popular since it is less expensive than EMT. Numerical analysis is used to predict the precise frequency ranges and the ideal placement of the sensors during the process. This approach is a reliable and affordable tool for forecasting structural deformations. Vibrations are produced when a structure oscillates at a resonant frequency with a larger amplitude. The finite element approach is used to determine

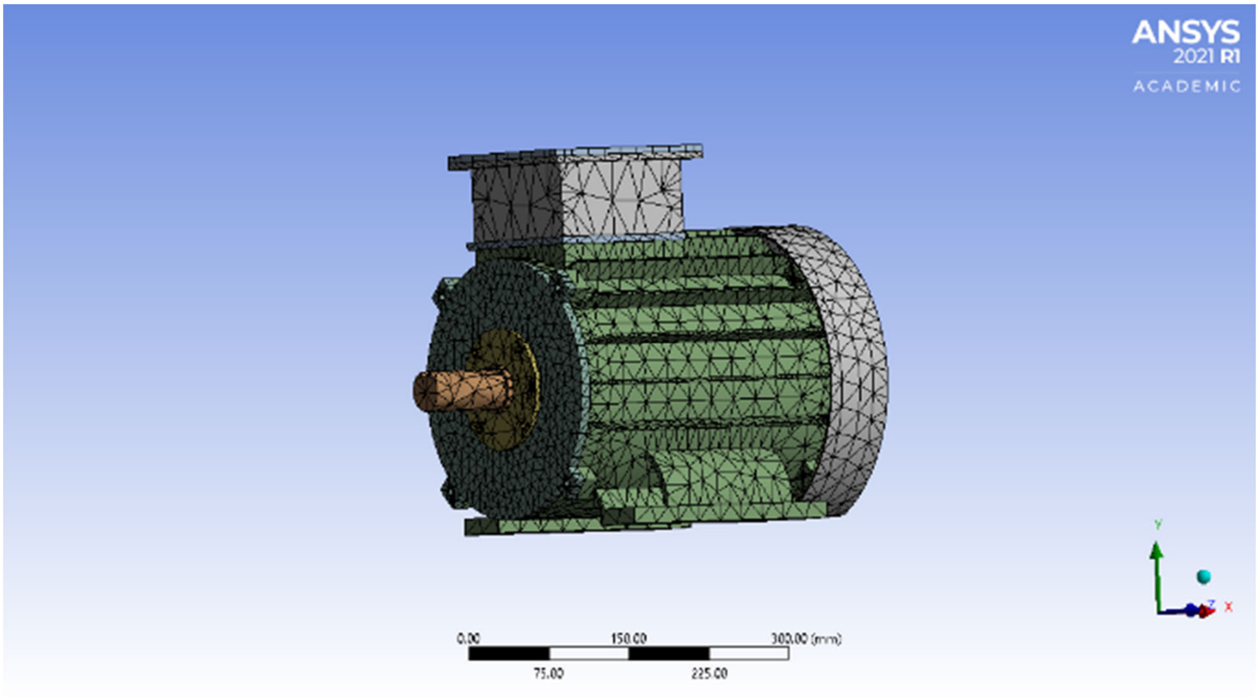

FIGURE 8. Motor model (Meshed) with FEA.

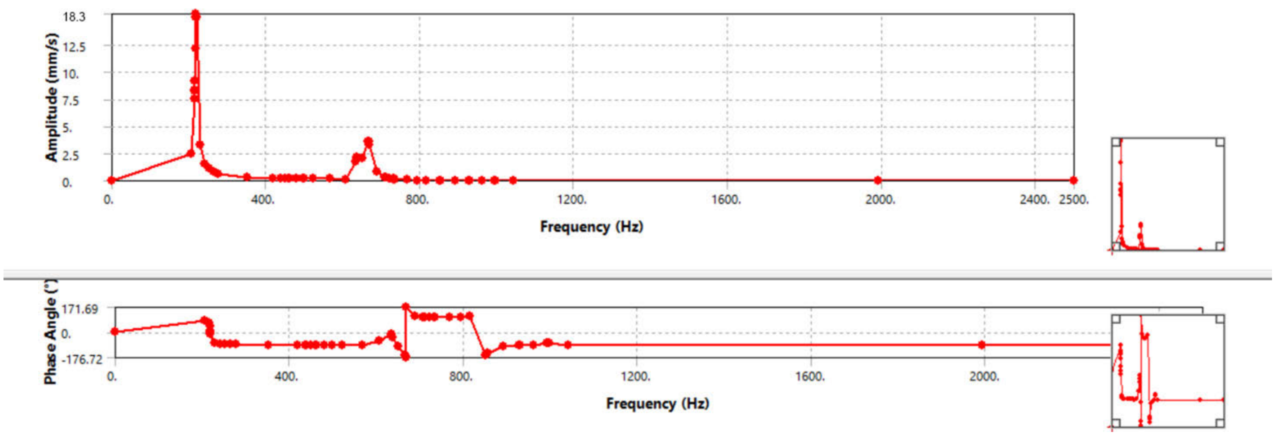

FIGURE 9. Vibration velocity 18.3 mm/s from FEA.

the vibrational velocity. This technique predicts VV on the MDEs is 18.3 mm/s. Therefore, the vibrations in the machine with numerical analysis is identified, and these vibrations are to be restricted to less than 5 mm/s. Both experimental and numerical approached vibration velocities are identified and found more than 5 mm/s. The experimental test is recorded at 98.6 Hz, and the peak VV of 10.6 mm/s. Similarly, the numerical test shows that the VV of 18.3 mm/s occurs at 241.35 Hz as shown in Fig. 9. Both tests show that the test machine is influenced by vibrations. To overcome this limitation the test motor is modeled by reverse engineering method in ANSYS to reduce the vibrations and the windings of the machine are tightened with overhauling then vibration analysis is executed to check the vibrations experimentally.

V. RESULTS AND DISCUSSION

The vibrations in the test motor are predicted by a finite (numerical) and vibrational (experimental) approach by knowing the precise location of component faults. The structural modification and motor redesign were considered in this section. To prevent motor vibrations and limit vibration levels as per standards (ISO 10816), the test motor casing and foundation are to be redesigned to reduce vibrations numerically. To identify the vibrations, harmonic analysis is performed and the frequency response is given at the motor drive end. Fig. 10 displays the boundary conditions after modifying the machine. Fig. 11 displays the frequency response provided at the motor drive end. As indicated in Fig. 12, the motor base is strengthened to 6 holes and the frame had reinforced

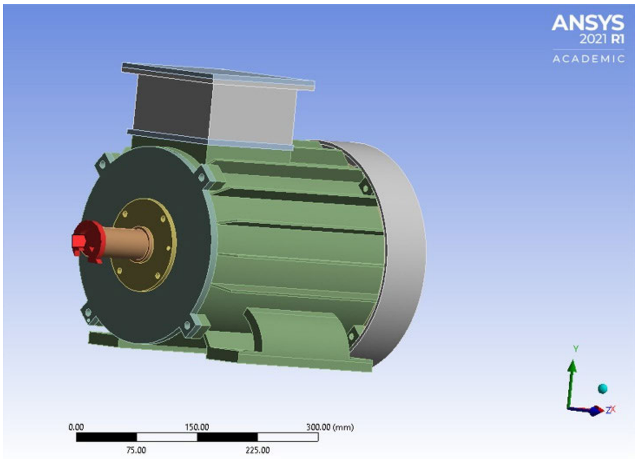

FIGURE 10. Boundary after modifying the machine.

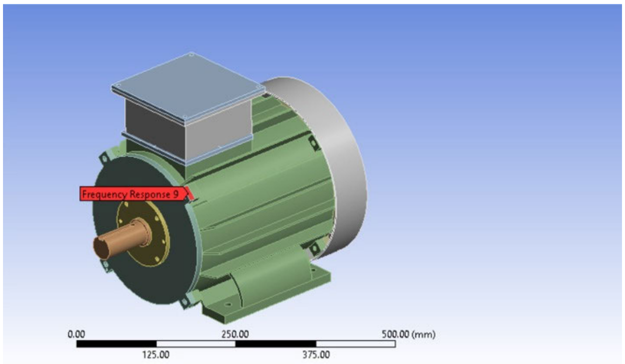

FIGURE 11. Frequency response on motor drive end (MDE).

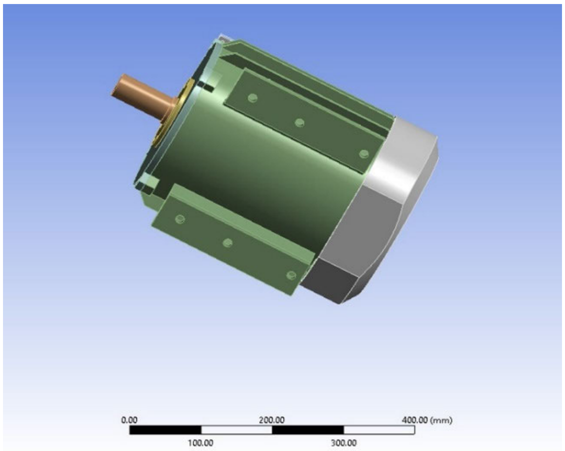

FIGURE 12. Redesign of a motor case to six holes to reduce vibrations.

and raised its thinness to 0.1 cm. The following modification in the motor casing is meshing with a 2.3 cm element size numerically, as shown in Fig. 13.

Redesigning the machine's structure is essential to avoid resonance and reduce vibrations. After the redesign of the machine, the VV is 2.9 mm/s. This lowers the vibration level numerically by designing the motor with a finite element

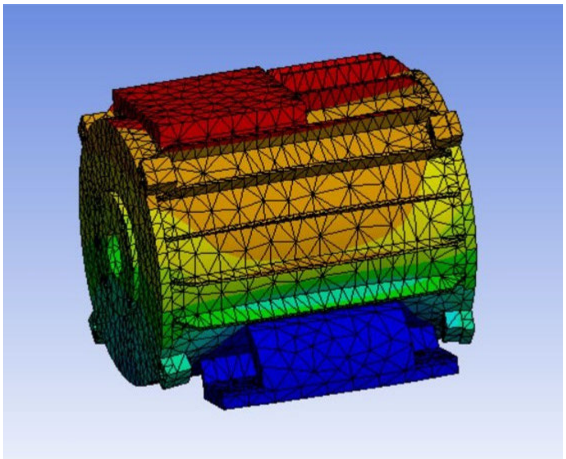

FIGURE 13. Modified motor casing with FEA.

approach. The VV after redesigning the test motor numerical is observed at 2.9 mm/s shown in Fig. 14. The percent of the vibrations numerically reduced up to 84.15 percent.

However, to meet industrial needs the test motor vibrations are to be restricted. The test motor windings are tightened and the vibration test is implemented experimentally and found the vibration is 3.2 mm/s, before tightening the machine windings it is observed 10.6 mm/s. Therefore, the percent of vibrations is experimentally reduced up to 69.81 percent. Fig. 15 shows the VV experimentally after modification of the test motor. The deformation of stator windings is determined after tightening to avoid looseness. Fig. 16 shows the reduced deformation of the SW indicating no looseness in the test motor that prevents deterioration in windings and increases the life of the motor. The reduced vibration between experimental and numerical are tabulated in Table 3. After redesigning the machine with six holes in the foundation and casing thickness is increased by 0.1 cm, the vibrations are reduced to 84.15 percent with FEA (numerically). The test motor windings are tightened to avoid deformation in stator windings and the machine is overhauled with proper lubrications and tightened all components to reduce the vibrations. Vibrational analysis was implemented and found vibrations were reduced by 69.81 percent experimentally. This validates the proposed work (numerically and experimentally) to reduce the vibration velocity to less than 5 mm/s as per ISO 10816.

TABLE 3. Reduced vibrations numerical (FEA) and experimentally (VA).

Vibration Velocity (mm/s)	Before modification	After modification	Reduced percent
Numerical (FEA)	18.3	2.9	84.15
Experimental (VA)	10.6	3.2	69.81

Table 4 gives an accurate assessment of the current state-of-the-art studies that have conferred vibration problems by taking into account numerical and experimental analysis. All of these investigators concentrated on estimating the different

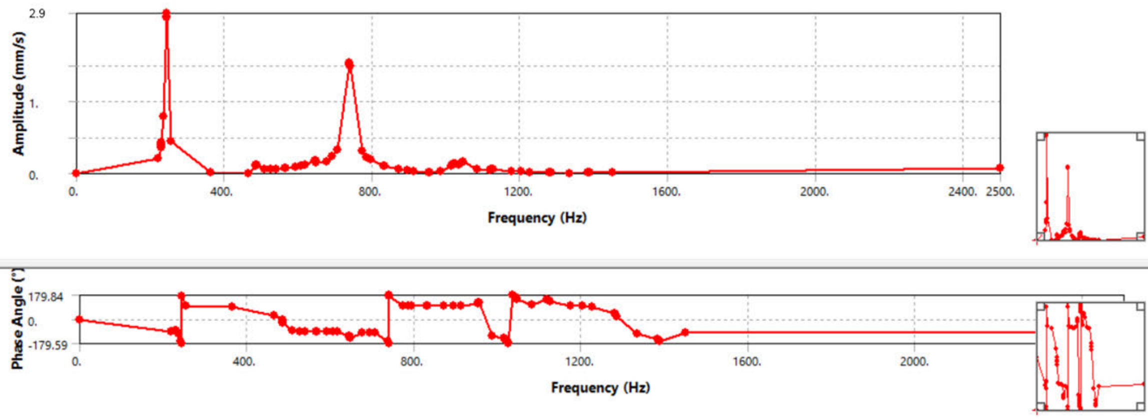

FIGURE 14. Vibration velocity 2.9 mm/s from FEA.

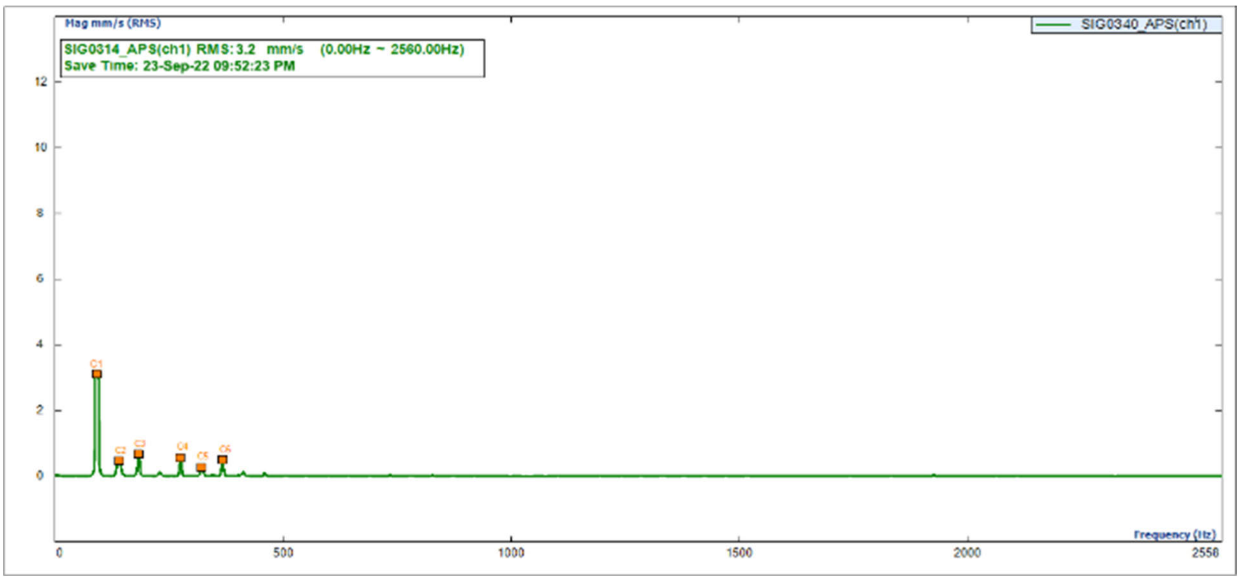

FIGURE 15. Vibration velocity 3.2 mm/s from vibration analyzer.

TABLE 4. Comparison of the present work with literature study.

Author	Methodology	Findings	Fault	VV (mm/s) BM	VV (mm/s) AM	Percent reduced
Sonje et.al [3]	DWT	Current	SW	-	-	-
Prasad et.al [4]	MT, FEM	Vibration	SW	15.3	4.4	71.24
W. Sun et.al [9]	MT, FEM	Vibration	Blisk	1.6	0.7	56.25
Rodriguez et.al [10]	DWT, IDWT	Vibration	Rotor, motor shaft	-	-	-
El-Gazzar [11]	FEA	Vibration	Bearing	19.5	10-	48.71
Irfan et.al [15]	IPA	Current	Bearing	-	-	-
Weidong et.al [16]	MCSA	Vibration	Bearing, Rotor	-	-	-
Proposed Work	EMT, FEA, VA	Vibration	SW, Motor casing, Foundation	18.3	2.9	84.15

DWT-Discrete Wavelet Transform, MT-Modal Test, FEM- Finite Element Method, IDWT- DWT-Inverse Discrete Wavelet Transform, FEA- Finite Element Analysis, IPA- Instantaneous Power Analysis, ANN- Artificial Neural Network, EMT- Experimental Modal Technique, VA-Vibrational Analysis, SW-Stator Winding. BM- Before Modification, AM- After Modification, VV-Vibration Velocity

faults that can occur in machines, but very few of them predicted the machine vibration and its cause. DWT (Discrete Wavelet Transform) was used by Deepak et al. to predict the inter-turn faults in SW using the current signal, but vibrations are not covered. Prasad et al., implemented MT, and FEM to predict the looseness in SW, and the machine is redesigned

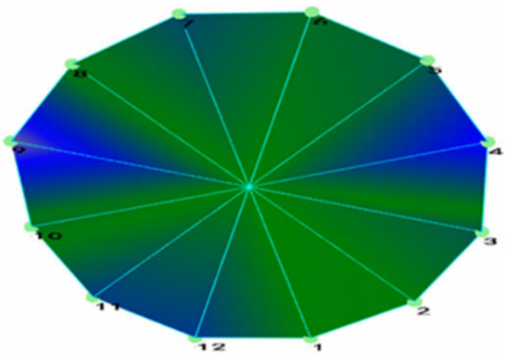

FIGURE 16. Deflection shape (DS) showing no deformation in windings after tightening.

to resolve the vibration, and the vibrations are reduced up to 71.24 percent numerically. W. Sun et al. stated the VV to be 1.6 mm/s and discussed MT and FEM. The structure has been modified by the authors to limit VV to 0.7 and confirms a vibration reduction of 56.25 percent.

Rodriguez et al., implemented online monitoring faults in IM with vibration analysis which is based on DWT and IDWT (Inverse Discrete Wavelet Transform). This technique predicts the condition of rotor bars but the vibrations in the motor are not discussed. Weidong et al., discuss the rotor condition with left and right sidebands indicating the condition of the rotor. Furthermore, this paper explains the condition of bearing with ball pass frequency outer race (BPFO) and ball pass frequency inner race (BPFI), but the percentage of vibration reduction in the machine is not discussed.

El-Gazzar used FEA to predict the vibration when a motor is replaced with a new one with a pump and found high vibrations. The motor is modeled numerically and the vibrations are reduced from 19.5 to 10 mm/sec. The vibrations are reduced by up to 48.71%, respectively. Irfan et al., and Srinivas et al., used IPA- Instantaneous Power Analysis and DWT to determine the bearing and rotor faults but vibrations were not discussed.

The proposed work implements EMT to find the deformed stator winding (SW) in the test motor. After tightening the windings of the machine, EMT is executed on the test machine and found no deformation. Secondly, FEA and VA are implemented on IM to predict the VV and the root cause of these vibrations. The test machine was modified in casing by increasing the frame thickness by 0.1 cm and the foundation of the motor was modified to six holes to restrict the vibrations not more than 5 mm/s as per ISO standards. Finally, the structure is modified and the machine is remodeled to resolve the vibrations issue, and the VV is 2.9 mm/s numerically. The vibration was reduced up to 84.15 percent (numerically) in the test motor after modification of the structure. The windings are tightened and the machine was overhauled with proper lubrications while tighten all components to reduce the vibrations and found VV 3.2 mm/s experimentally. Therefore, vibrations are reduced up to 69.81 percent (experimentally) which can increase the durability of the motor to meet industrial needs.

VI. CONCLUSION

The proposed work predicts the deformation in the SW (stator windings) by implementing EMT (experimental modal technique). The test was performed on SW (global mode) and found the windings of slot numbers 7 and 8 are deformed. The FEA (finite element approach) is modeled in ANSYS software to predict the vibration velocity numerically and found 18.3 mm/s. The experimental test is implemented on IM and observed at 10.6 mm/s which indicates both numerical and experimental vibration velocities are more than 5 mm/s which exceeds 5 mm/s as per ISO standards 10816. The test machine is redesigned numerically with a 6-hole frame reinforced and raised its thinness to 0.1 cm to reduce vibration velocity recorded as 2.9 mm/s. The machine windings are tightened at the deformed state and vibration analysis (experimentally) is implemented and noticed the vibration velocity is 3.2 mm/s. The vibrations of the test motor are reduced both numerically (84.15 percent) and experimentally (69.81 percent). If these vibrations are not controlled, they will cause damage to the motor components like stator windings, rotor damage, motor shaft alignment, and bearing damage. If these vibrations are restricted that increases the durability of the test motor to meet the industrial needs which can reduce the revenue cost of the plant.

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