Research Article

Multiple Physics Design of Induction Motor

Serhat Dogan and Yasemin Oner

Abstract—**Today, induction motors which have a widespread usage network are constantly developed by manufacturers. It is frequently used in heavy industry, mines, household appliances and consumer electronics due to its cheap maintenance, efficiency, effective torque and easy control features. Designers go to increase productivity with various analysis methods. Moreover, designers want to check the manufacturability of their desired machines. In this study, the multi-physics design of an induction motor is discussed. Electromagnetic, thermal, modal and stress analyzes are carried out in the design. Various analysis methods are discussed for electromagnetic and thermal analysis. In this article, Finite Element Analysis (FEA) method is used for electromagnetic and thermal analysis. In addition, the components required in multi physics design are emphasized. Electronics Desktop, Ansys Workbench Steady-State Thermal, Modal and Static Structural software are used in the analysis. In this study, the necessary analyzes for the design of an induction motor are carried out.**

Index Terms—**Induction motor analysis, multiple physics design, electromagnetic analysis, thermal analysis, modal analysis, stress analysis, finite element analysis, coupling maxwell and steady-state thermal.**

I. Introduction

INDUCTION MOTORS are widely used today. Compared with other motors, it has always had a development area, as it has features such as high torque, low cost, robustness and low maintenance. Due to its wide usage area in the industry, it creates negativity regarding energy consumption. Therefore, studies on these motors are mostly focused on efficiency [1-3]. The efficiency is usually improved to reduce electrical losses. The losses generally occur in the stator core, stator winding, rotor core and rotor bars. These losses are stated as the main cause of temperature. In other words, reducing these losses during the development phase will also reduce the temperature. Therefore, the temperature distribution of the machine to be analyzed is important for designers. Designers often focus on thermal analysis. Because they want the isolation classes to be determined according to the temperature values and distributions. Further, they want to create integrity in the motor design stages by performing modal and stress analyzes structurally.

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In this study, the FEA method is used for electromagnetic analysis. The FEA method has several advantages compared to the Magnetic Equivalent Circuit (MEC) and Lumped Parameter Model (LPM) methods. The FEA method facilitates the analysis of complex geometries. Analyzes are performed by creating small mesh or part structures on the geometry. Analysis can be used in one, two or three-dimensional systems.

The simplified magnetic equivalent circuit of a machine is extracted with the MEC method. Elements in this circuit are compared to electrical equivalent circuit elements. Magnetic motor force, flux and reluctance elements in the magnetic equivalent circuit are compared to the voltage source, current and resistance elements in the electrical equivalent circuit, respectively. It is difficult to obtain the magnetic equivalent circuit on machines with complex geometries. However, it saves time compared to the FEA method. Moreover, it gives outputs closer to the experimental results. Regarding MEC analysis, Sudhoff aims to extract magnetic equivalent circuits of magnetic power circuits in his study [4].

The LPM method makes matching of different physical larges by analogy. This simplifies the behaviour of fragmented structures in the simulation. This method is used in various systems such as electrical, mechanical or heat transfer. It enables the simplification of components used in circuits, such as in electrical and electronic systems.

The LPM method creates an affinity between electrical and thermal systems [5]. Therefore, a close relationship can be established between electrical equivalent circuit parameters and real machine behaviour [6]. In the literature, FEA and LPM methods have been widely compared. For example, E. Ravaioli reports that the LPM method gives faster results than FEA analysis in nonlinear systems [7]. In fact, with this method, the mechanical components in the machine are assimilated to electrical circuit elements. The LPM method also helps to find losses in electromagnetic analysis.

Lumped Parameter Thermal Network (LPTN), Computational Fluid Dynamics (CFD) and FEA methods are mostly used for thermal analysis. The LPTN method is associated with the theory of heat transfer. This method takes advantage of the analogy between thermal and electrical circuits. In thermal analysis, simulation is likened to resistor and capacitor elements. While the capacitor element acts as energy storage, it helps to resolve transient behaviour. On the other hand, the resistor element refers to the heat transfer over the system. Its function is conduction, heat dissipation, and radiation events, and it helps to analyze steady-state temperatures [8].

With the LPTN method, the heat flows in the machine can be estimated. It enables the analysis of transient and steady states. In addition, the specific temperature of the machine components can be determined. [9, 10]. In order to obtain correct results, the mesh structure should be properly detailed [11]. As a result, comprehensive heat dissipation is obtained. Thermal analysis is performed with Ansys Steady-State Thermal software.

A negative situation that occurs in induction motors is vibrations. Depending on the duration and amplitude of these vibrations, structural changes such as bearing disintegration or fan friction may occur in the machine. Modal analyzes are performed to observe the changes in the machine. With the modal analysis, the dynamic properties of the system can be determined under the determined frequency conditions of a system. Due to the electrical frequency effect, the stator structure of the induction motor should be examined. Vibrations occur as a result of various losses [12]. The modal analysis allows to improve the dynamic characteristics of the structure. Almost all systems produce large amplitude vibration at the resonant frequency [13]. If the frequency applied to the motor is close to or compatible with the motor's frequency, the motor can pass in the resonance state. As a result, vibration and noise occur [14]. The natural frequency of the machine should be examined to eliminate these negative effects [15]. Ansys Modal software is used for modal analysis.

In addition to modal analysis, stress analysis should also be performed. It can be determined how a load exerting pressure on the machine shaft affects the rotor core and shaft. Stress analysis is performed to determine the deformations in the rotor structure. Ansys Static Structural software is used for this.

In this study electromagnetic, thermal, modal and stress analyzes are carried out, respectively. The geometry obtained by electromagnetic analysis is also used in later analyses.

II. METHODOLOGY

The FEA method is used for electromagnetic and thermal analysis. Electronics Desktop software uses equations obtained by J. C. Maxwell in 1864. Maxwell rearranged the laws of Gauss, Faraday and Ampere. These are the laws of electromagnetic induction, Ampere's law, and electric and magnetic fields, respectively. The edited statements are given below:

$$\nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t} \tag{1}$$

$$\nabla \times \mathbf{H} = \boldsymbol{J} + \frac{\partial \mathbf{D}}{\partial t} \tag{2}$$

$$\nabla . \mathbf{D} = \rho \tag{3}$$

$$\nabla . \boldsymbol{B} = 0 \tag{4}$$

Maxwell also added the expression ∂D/∂t to Ampere's law. The displacement expression is used for the estimation of electromagnetic waves. The above equations are in SI units. H and E express the magnetic and electric field strength in (ampere/m) and (volt/m) units. B and D express the magnetic and electric density in (weber/m^2) and (coulomb/m^2) units. It is also called B magnetic induction and D electrical displacement. Other expressions J and ρ are electric current and volume charge density, respectively. Its units are (ampere/m^2) and (coulomb/m^3).

Understanding the types of heat transfer will facilitate how thermal analysis is performed. Heat transfer is an energy process that occurs due to temperature differences. According to the law of thermodynamics, if a system loses energy, it is taken up by the environment. The same is true for vice versa. Namely, different structures transform into another form of energy without losing their energy [16]. This refers to the conservation of energy. Heat transfer phenomena generally take place in the form of conduction, convection and radiation.

- Conduction

The transfer of heat energy from a high point to a low point in a solid, liquid or gaseous medium is defined as conduction. The ability of the object to transfer heat in conduction is defined as thermal conductivity. In Fourier's law, the thermal conduction equation is expressed as:

$$q = -k\nabla T \tag{5}$$

$$q = -k\frac{dT}{dx} \tag{6}$$

where q is the heat flux density (W/m^2); k is the material conductivity W/(m.°K) or W/(m.°C) and *dT/dx* is the temperature gradient (°K/m). The heat transfer coefficient between the two materials is defined as h. The heat transfer coefficient expresses the power per unit area-Kelvin in SI unit.

$$h = \frac{W}{m^2 K} \tag{7}$$

- Convection

Convection, unlike conduction, refers to the spread of heat transfer from one point to another by the movement of fluids. It usually takes place in liquid and gaseous environments. In Newton's law of cooling, it is expressed as:

$$Q = hA(T - T_f) \tag{8}$$

where Q is the heat transferred per unit time; A is the area of the object (m^2); h, heat transfer coefficient (W/m^2K); T indicates the surface temperature of the object (°K or °C) and finally T_f indicates the liquid temperature (°K or °C).

- Radiation

The realization of heat transfer through electromagnetic waves is defined as a radiation event. Heat dissipation by radiation can occur in solid, liquid and gas environments. Radiation emission is expressed as follows according to Stefan Boltzman's law.

$$E_b = \sigma_b A T^4 \quad (9)$$

where E_b is the energy dissipated per unit time; T is the absolute temperature of the surface and σ_b is the Stefan-Boltzman constant and its value is $5.67\text{x}10^{-8}$ (W/m^2K^4).

Finally, the following equations are used for modal and stress analysis in FEA, respectively.

$$[M][\ddot{U}] + [K][x] = 0 \quad (10)$$

$$[K]\{x\} = \{F\} \quad (11)$$

where [M] is the mass matrix, [Ü] is the 2nd time derivative of [X] (displacement), [K] is the stiffness matrix (constant) and [F] is the force vector.

III. Electromagnetic Analysis

For thermal analysis, it is necessary to find electrical losses. In this study, an electromagnetic analysis of a 1.1 kW machine is carried out. The induction motor is 2-pole, 380 V (AC), 50 Hz, star connected and nominal speed is 1450 rpm. The analysis was carried out under constant power and full-load. In addition, the stator and rotor slot numbers are 36 and 28, respectively.

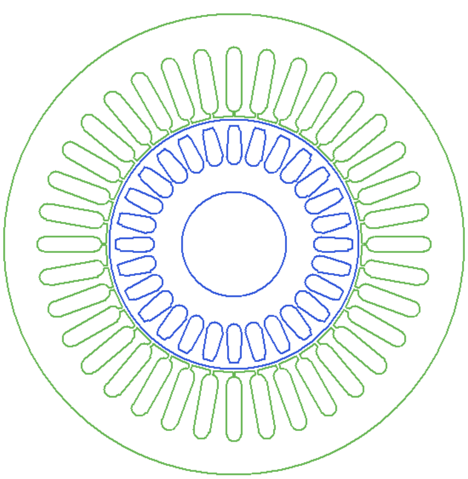

Fig. 1. 2D geometry of induction machine

Fig. 1 is the two-dimensional geometry of the machine. RMxprt software is used here. Magnetic analysis of the machine is performed with Electronics Desktop software. With magnetic analysis, it can be determined whether the machine is saturated or not.

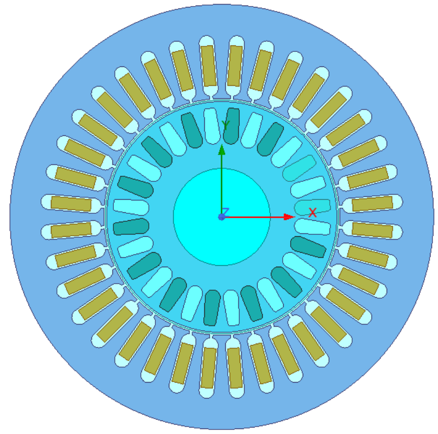

Fig. 2. Maxwell 2D representation of the machine

The magnetic flux density and flux distribution obtained according to the electromagnetic analysis are shown in the figures below. According to the results, while the maximum magnetic flux density is 1.87 Tesla, the magnetic flux value is found to be 0.0118 Weber/meter.

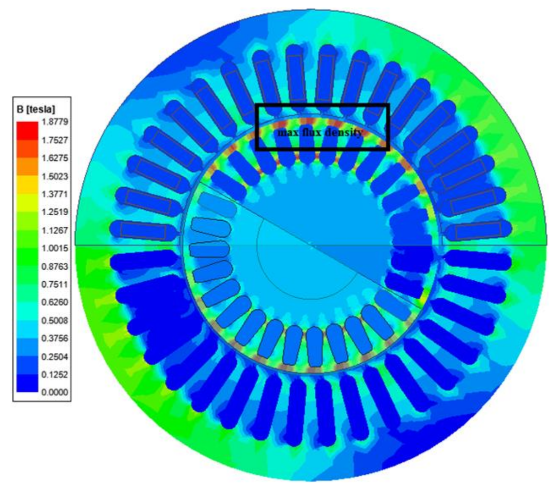

Fig. 3. Magnetic flux density distribution

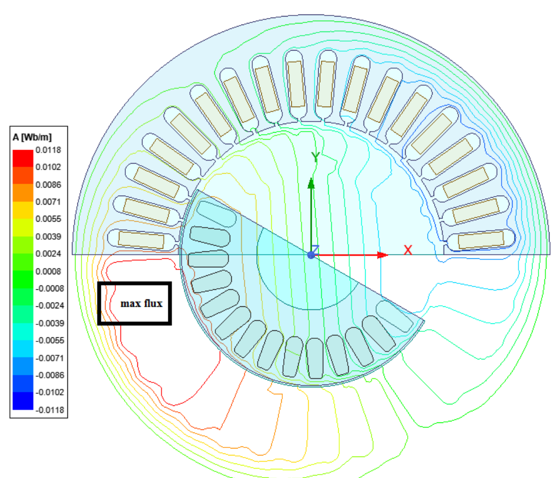

Fig. 4. Magnetic flux distribution

In the analysis, the average moment value is found as 3.91 Nm. Likewise, the current drawn by each phase is 3.08 A, in a steady state. Then, core, winding and rotor bars losses, which are critical, is calculated. The main factor causing temperature is usually losses. In addition, friction and wind losses also affect the temperature distribution. The Electronics Desktop software is used to find the stator and rotor core losses. The losses in the stator and rotor core are taken into account with the Electronics Desktop software. In addition, the eddy loss values of the rotor aluminum bars are calculated because of the thick cross-section. The total core losses consist of stator and rotor losses. When the steady state is examined, the average loss value is 19.44 W, while the average stator and rotor eddy losses are 5.65 W. It is determined that most of the eddy losses occur in the rotor bars.

IV. THERMAL ANALYSIS

The heat dissipation of a machine is an important parameter for determining the insulation class. In the basic insulation classes, the ambient temperature is taken as 40 °C. The three-dimensional geometry of the machine is obtained with Electronics Desktop Maxwell 3D software.

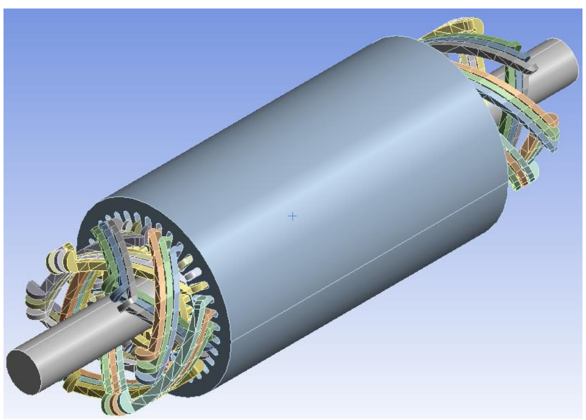

Fig. 5. Geometry of induction motor

Steel alloy M19_24G material is used in the stator, rotor cores. However, the rotor shaft was chosen from steel material and its magnetic effect was neglected while analyzing. The stator windings are made of copper. Rotor bars are aluminum. The properties of the materials used in this analysis are shown in Table 1.

TABLE I
MATERIAL PROPERTIES

Material	Thermal conductivity [W/m^2.°C]	Specific temperature [J/kg.°C]	Density [kg/m^3]
Steel M19_24G	45.0	481.0	7872.0
Copper	400.0	385.0	8933.0
Aluminum	237.5	951.0	2689.0
Air	0.026	1007.0	1.1614

The specific temperature value is the energy required to enhance the heat of a material by one degree. If attention is paid, the thermal conductivity value of air is quite low compared to other materials. Therefore, it negatively affects the heat dissipation between the rotor and the stator. Advanced cooling systems are used to reduce this negative effect.

In order to use electrical losses in thermal analysis, Electronics Desktop Maxwell and Steady-State Thermal software are coupled in the Ansys Workbench program. Then, the mesh structure of the geometry used is extracted as seen in Fig. 6.

Fig. 6. Mesh structure of the mechanical model

The heat generation values of the stator and rotor cores are calculated separately in order to conclude the losses accurately. The heat generation value is the electrical losses per unit cubed on the core. In other words, it is the conversion of any form of energy into thermal energy. Usually, these forms of energy are electrical, mechanical or chemical. Temperature distributions are found with these losses. The highest and lowest heat generation values are found in the stator and rotor cores. The heat generation value of each rotor bar is calculated in the software. However, the heat generation value of the total rotor bars is indicated here. The highest values in the rotor core are the rotor bars. The lowest values are the rotor core. In the stator core, on the other hand, it is observed that the heat generation values are high near the windings.

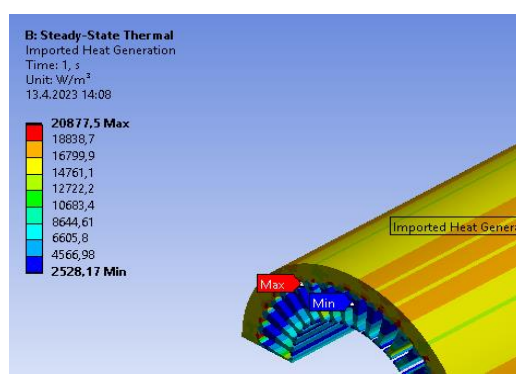

Fig. 7. Heat generation values of the stator core

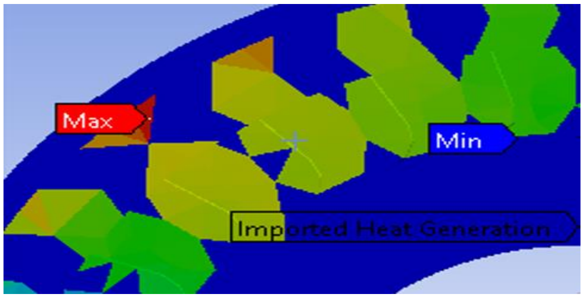

Fig. 8. Heat generation values of the rotor core

Losses per volume are obtained from heat generation values. These losses are listed in Table 2.

TABLE II
VOLUME LOSS DENSITIES

Structure	Total loss [W/m^3]	Scaling factor
Stator	10.9351	1.02266
Stator windings	43.5337	1.00
Rotor	0.438306	1.01047
Rotor bars	82.9701	0.999

Another important point in thermal analysis is boundary conditions. Material properties contribute to the determination of boundary conditions. There are two important components for determining the temperature dispersion: the heat dissipation and the heat source. The boundary conditions are as follows:

TABLE III
BOUNDARY CONDITIONS

Parameters		
Temperature source	Electrical losses	
Convection	Ambient temperature [40 °C]	Thermal conductivity coefficient [45 W/m^2.°C]

In the analysis, the heat generation values obtained from the stator and rotor structures are combined as a single structure as in Fig. 9. It is previously stated that the thermal conductivity coefficient for the M19_24G steel material is 45 W/m^2°C. For this reason, the same value is also used in the boundary conditions.

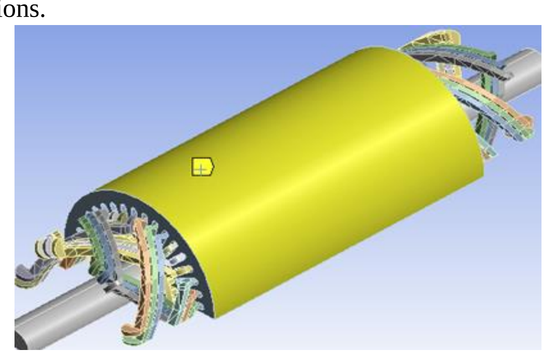
Fig. 9. Stator surface heat dissipation heat

Heat dissipation takes place through the stator surface. In other words, it is known that the cooling effect is effective on the stator surface. Therefore, the yellow region in Fig. 9 is determined as the boundary condition. The environment temperature is taken as 40 °C according to the determination of the insulation classes.

By establishing the boundary conditions, the temperature distribution is obtained, aligning with the results of the thermal analysis. In Fig. 10, while the maximum temperature value is 102.42 °C, the minimum temperature value is 95.015 °C.

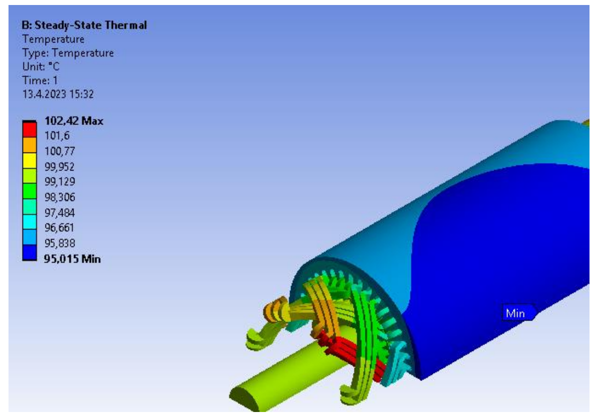

Fig. 10. Temperature dispersion

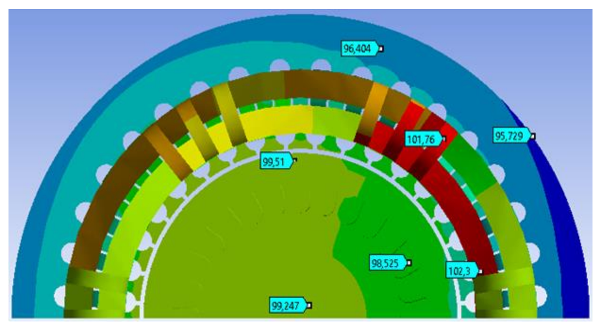

Fig. 11. Side section temperature dispersion

Fig. 11 is the side section of the machine structure. The highest values occurred in the stator windings. It is observed that the temperature distributions towards the stator surface decrease. Because of the air gap between the rotor and the stator, high-temperature values only show their effect on the windings. The temperature values around the rotor and shaft are lower compared to those around the windings. If a material with a higher thermal conductivity coefficient is selected in these analyses, the temperature distribution would change positively.

V. Structural Analysis

The natural frequency of the system is tried to be found by using the stator structure. The analysis is carried out in a condition where the stator core is kept stationary and free vibration. The stator core is shown in Fig. 12. The structural properties of the stator core are shown in Table 4. Here, young and volume modulus are values formed under hardness and pressure, respectively.

TABLE IV
STRUCTURAL PROPERTIES OF THE MATERIAL

Properties	Values
Density	7.85×10^{-6} [kg/mm^3]
Young module	2×10^5 MPa
Poisson ratio	0.3
Volume module	1.667×10^5 MPa

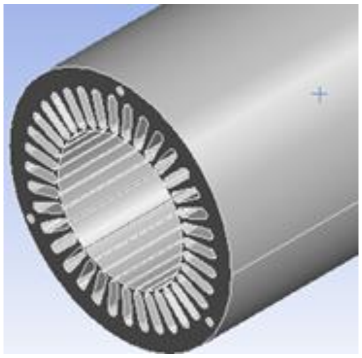

Fig. 12. Stator structure for modal analysis

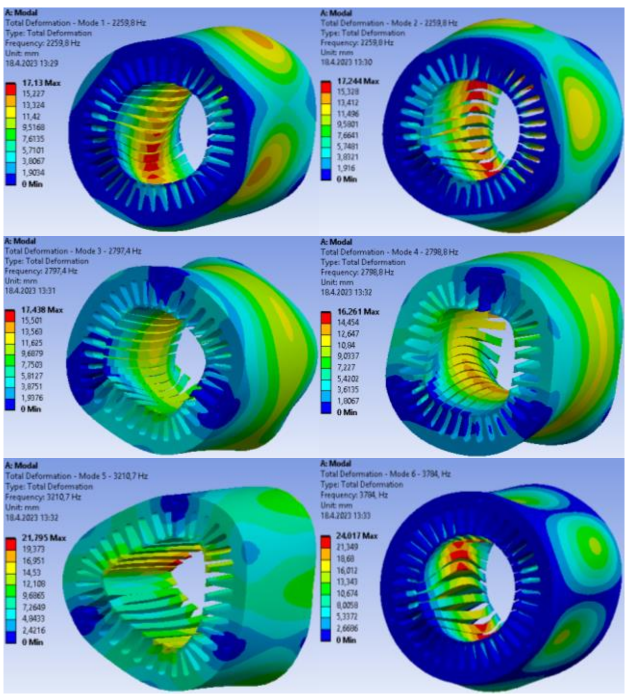

Fig. 13. Total deformation changes by modal analysis

According to the modal analysis, the natural frequencies of the system are found as 2259.8, 2797.4, 2798.8, 3210.7, and 3784.0 Hz. Images of the total deformation are shown in Fig. 13. When the results are examined, it is seen that the deformation ratio increase with the increase of the natural frequency value. The lowest deformation rate is 2259.8 Hz, while the highest deformation rate is 3784 Hz. Deformation rates occurred at high levels in the middle parts of the stator teeth.

In the electromagnetic analysis, the torque generated by the motor shaft is found as 3.91 Nm. In the stress analysis, it has been revealed how this moment value causes deformation in the rotor and shaft structure. For this, mechanical changes are applied to the rotor shaft. Fig. 14 shows the changes made to the motor shaft. There are two bearings and gears here. The boundary conditions required for the stress analysis are given in Fig. 14 and Table 5.

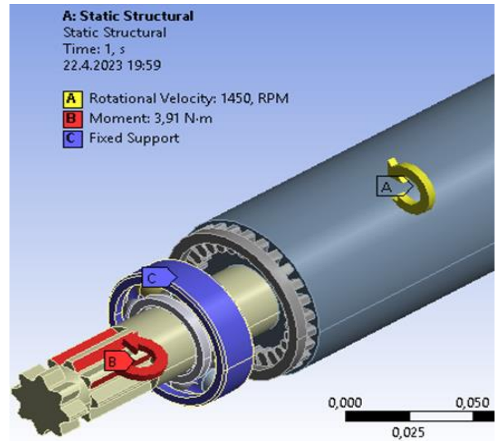

Fig. 14. Boundary conditions for stress analysis

TABLE V
BOUNDARY CONDITIONS FOR STRESS ANALYSIS

Parameters	Values
Rotation speed and direction	1450 rpm and counterclockwise
Applied torque and direction	3.91 Nm and counterclockwise
Fixed supports	The outer ring of the bearings

Looking at the stress analysis results in Fig. 15, it is seen that a maximum deformation of 0.0189 mm occurred in the middle parts of the rotor core. When this ratio is compared with the rotor diameter, it is determined that it is equal to a small value of 0.0144%. In the bearing and gear areas exposed to loads, there is almost no deformation effect.

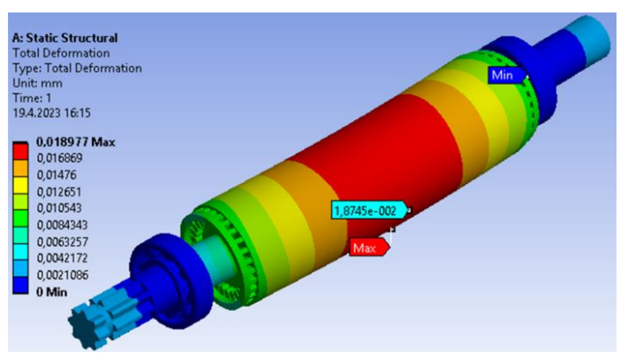

Fig. 15. Stress analysis results

VI. Conclusion

In this study, a multi physics design of a 1.1 kW induction motor is carried out. The parameters required at each design stage are emphasized. More focused on electromagnetic and thermal analysis. According to the literature, FEA is chosen as the analysis method.

Electronics Desktop software is used for electromagnetic analysis. In addition, the three-dimensional geometry of the machine is obtained from Electronics Desktop Maxwell 3D software. By calculating the electrical losses, the heat generation values required for the thermal analysis are calculated. Heat production values are used in thermal analysis by coupling Electronics Desktop Maxwell and Steady-State Thermal software in the Ansys Workbench program.

It is emphasized on which parameters the boundary conditions required for performing thermal analyzes depend. In the analysis made according to the heat production values of the induction machine, the temperature values of the materials in the stator and rotor structures are obtained. The highest temperatures occur in the stator windings, while the lowest temperatures occur on the stator core surface.

Structurally, modal and stress analyzes are carried out. In these analyzes, Ansys Modal and Static Structural software are used, respectively. The natural frequencies of the stator are obtained. Further, the total deformations caused by the natural frequencies are determined. In the stress analysis, the deformations caused by the load applied to the rotor shaft in the rotor structure are examined.

In this study, the points to be considered in the multiple physics design of an induction motor are emphasized. Moreover, the analysis that should be carried out in the process up to the production state is examined.

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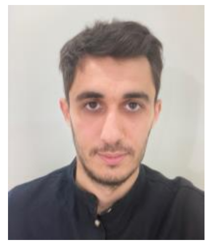
BIOGRAPHIES



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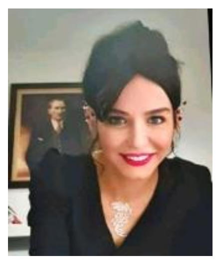

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