Design Optimization of Electric Motor Frame and Its Study for Thermal, Dynamic and Modal Stability

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Abstract - *Induction motors are heart of all manufacturing industries without which process cannot take place. In this competitive world it becomes important to maintain the growth of industry by reducing the cost of the component. So in case of motor, optimization place an important role in reduction of material usage hence gives the tool for reducing cost of motor. Optimization in motor is mainly concerned to reducing the mass of motor, as large amount of components is used in the motor optimization can be concerned with any component. But before optimizing it is required to check all the parameters on which the component is dependent and the it is required to proceed further for optimization, where as in this paper frame of the induction motor is selected for optimization, which is one of the critical component of motor, hence by considering all the parameters of design an initiation is made to optimize and study the optimized frame under thermal, Dynamic and Vibration stability.*

Key Words: **Induction Motor, Optimization, Frame, Thermal stability, Dynamic stability, Modal Analysis ...**

1.INTRODUCTION

AC induction motor is a system in which the electrical energy is converted in to mechanical energy having electromagnetism as the intermediate principle. In which the electrical energy when passed through the stator windings will produce a rotating magnetic field which induces a force on the rotor in turn produces a torque, as the speed of the rotor is not same as the speed of rotating magnetic field the motors are also named as asynchronous motor. Any system can attain ideal working condition when all the elements of the system are ideal but in this practical world no elements can have 100% ideal behavior hence due to defects in the system. Behavior of the system changes, which may even lead to failure of the system, hence if this abnormal defects in the system is identified and rectified a system of optimum efficiency may be obtained.

In order to improve the material utilization in the motor system it becomes important to optimize the amount of material used in the system, in order optimize the component all the environmental conditions have to incorporated. So that improvement can be obtained in efficiency and life span of the system.

Concerned to the electrical system abnormal behavior may exists in all the 3 major environments, abnormal behavior in electrical environment leads to loss in the system which is in the form of heat, if this heat is not controlled and removed from the system it leads to windings failure which ends up with re-winding of the stamping, hence it becomes necessary to study the amount of heat dissipated in the system, with the help of [1], [2], [3], papers suitable thermal network was studied and temperature distribution and heat flow through the system was obtained.

Similarly, in the case of magnetism an abnormal behavior may exist in its distribution around the rotor because of abnormal air gap density, which leads to un-uniform magnetic flux around the rotor hence this may also lead to abnormal load which acts on the motor frame directly. With this magnetic field rotor experiences a pull due to which a deflection is observed in the shaft which in turn leads to centrifugal force on the frame.

On the other hand, in case of mechanical environment the energy which is imposed on the rotor through the magnetic energy, it is converted into torque which is being utilized in the useful work. During the machining of component if required tolerance is not reached then it leads to abnormal vibration in the system with respect to this their also exist a standard unbalance which also produces vibration in the system. Hence it is important to find the natural frequency of the system to predict the amount of vibration in the system, so that the resonating frequency should not coincide with the operating frequency, in order to incorporate smooth working of the system by maintaining operating frequency much below resonating frequency.

In this paper 315L 4 pole 160KW AC Induction motor frame is considered and an effort is made to optimize the frame and study the design safety of the motor with the help of Finite element modelling under different loading condition with the help of ANSYS workbench.

2. OPTIMIZING FRAME OF INDUCTION MOTOR

Optimization is a process of designing component which utilizes optimum quantity of material and can sustain any type of load in all type of working condition.

2.1 Existing design of motor frame

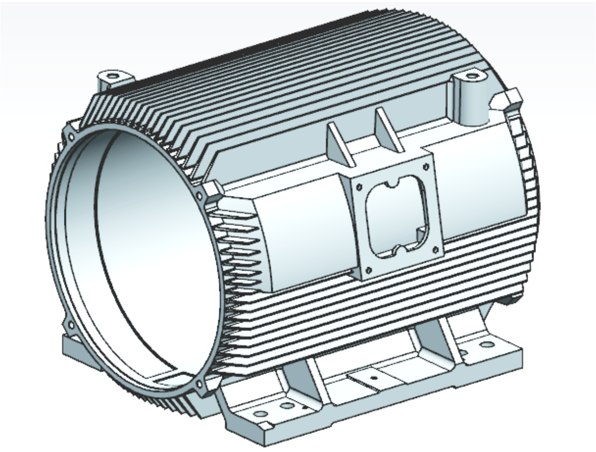


Fig -1: Shows the exsisting frame of 315L motor for 160 kW 4 pole motor

From above figure some assumption can be done that the amount of heat dissipated near the terminal box section is high hence it is required to increase the amount of surface required for convection heat transfer. With this, the another reason for updating the design is that the terminal box mounting in the early frame. It is found that it consists of only one position for mounting of terminal box. In case costumer requires terminal box at different position then total design need to be changed and fresh body is to be prepared, so in the new design care has to be taken to have flexible mounting position and with good aesthetic look too.

So by considering all above discussion and draw backs following changes were made to the frame design,

1. Firstly, in the position of terminal box fins were introduced by bringing terminal box mounting to driving end of the motor so that amount of area available for convention was increased drastically.
2. In case, that stamping is assembled in reverse manner then in order to take the leads to the terminal box a pocket was provided near the terminal box till the other end.
3. Terminal box mounting position was given at the top end of motor frame so that the flexibility in the mounting the terminal box was increased.
4. Another proposal was that in the early frame the thickness of frame was uniform only at the middle section of the frame only till 55 mm on both side of middle section this uniform section was increased to 150 mm on each side. After this the thickness increased till the end of motor, so that at the portion of spigot the thickness of frame was high and machining of spigot would be provided with more material, which would give good provision for machining with high strength.

2.2 Optimized design of motor frame.

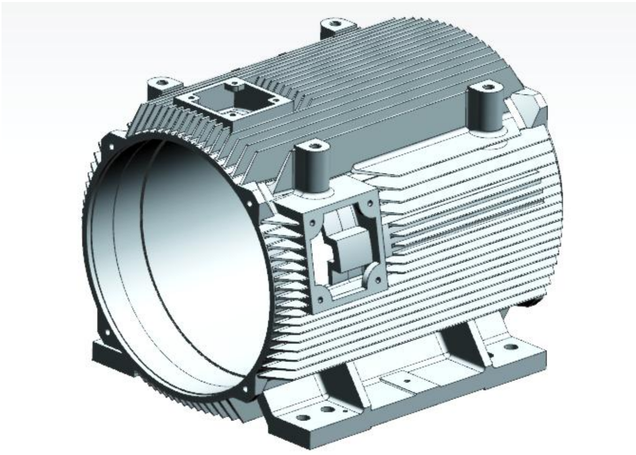


Fig -2: Shows the optimized frame of 315L motor for 160 kW 4 pole motor.

Here in the new frame the amount of area for convection was increased from 5.06 m^2 to 6.13 m^2 and also the mass of the frame is decreased from 377kg to 352 kg.

3. THERMAL ANALYSIS OF MOTOR SYSTEM.

In order to study the heat dissipation in the system. It is necessary to find out the contacts between the components so that the proper thermal network can be predicted.

3.1. Thermal Network of the Induction Motor

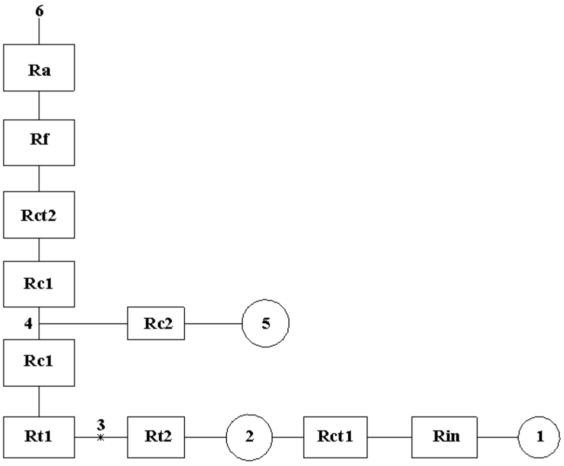


Fig -3: Thermal Network showing flow of heat in the motor system.

The network shows all the elements in the thermal network of a motor system. The numbered points represent the intermediate point between resistance, the points 1,2,5 are heat generating point, where 1 is the portion of winding, 2 represent the teeth and 5 represent core, The losses at each circled points is given by,

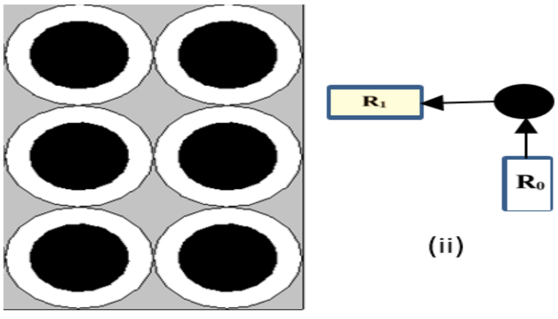
1) Stator copper loss=2800W
2) Core loss =2100W
    a. Loss at teeth=630W
    b. Loss at back iron= 1470W

The blocks between the numbering points represent the thermal resistance offered for the flow of heat in the system. Where R_{in} and R_{ct1} represent the resistance of insulation and contact resistance between winding and teeth of the stamping. Here as insulation includes all the components like resistance of insulation paper, slot liner, varnish, resin etc., R_{in} will be the effective resistance of all the components in series. Similarly, there is no perfect contact between insulation and teeth of the stamping so due to the imperfect contact the heat cannot be removed from the winding region effectively this resistance for heat flow is called contact resistance and is denoted as R_{ct1}.

In the next section the heat flow is in 2 directions. when heat reaches teeth surface it flows in to the teeth towards its center of the teeth and further as a small amount of heat is generated at the teeth too, both will flow radially outward towards the core so the resistance offered is in 2 forms one for flow towards the teeth center and other for flow radially outward both these resistances are represented as R_{t1} and R_{t2}.

From the bottom of teeth till the ambient air there exist resistance of R_{c1}, R_{c2}, R_{ct2}, R_f, R_a where R_{c1} are the resistance offered for the flow of heat in radial direction in the same way their also exists a resistance R_{c2} which offer resistance for heat developed in the core and R_{ct2} is the contact resistance between core and frame due to irregular overlap that is due to interference fit. R_f represents the resistance of frame for heat flow. R_a represents the resistance of forced convection of air.

3.2 Equations for all resistance with the help of lumped heat transfer. [3]



(i)

(ii)

Fig -4: showing arrangement of winding in slot and its effective modeling

$$R0 = \frac{R}{2} \qquad (A)$$

$$R1 = -\frac{R}{6} \qquad (B)$$

$$R_{i1} = R0 + R1 = \frac{R}{2} - \frac{R}{6} = \frac{R}{3} \qquad (1)$$

Where R is given as,

$$R = \frac{w}{2 * kav * h * l} \qquad (2)$$

$$R_{i1} = \frac{w}{6 * kav * h * l} \qquad (3)$$

$$Kav = ki * \left(\frac{d}{\delta} + \frac{\delta}{d'}\right) \qquad (4)$$

K_{av}= Average thermal conductivity of insulation over all copper wires, K_i= thermal conductivity of copper insulation, W= width of slot, **d**= dia of bare wire, **d'**= dia of wire with insulation, **δ**= thickness of insulation, **h**= height of slot,

Resistance for heat flow in external insulation is given by,

$$R_{in1} = \frac{t_i}{k_i * h * l} \qquad (5)$$

Now effective resistance for heat flow in slot is given by,

$$\text{Rin} = R_{i1} + R_{in1}$$

Resistance for heat flow due uneven contact is given by,

$$R_{ct1} = \frac{1}{h_{sl} * h * l} \qquad (6)$$

h_{sl} = contact resistance between teeth and insulation.

let the heat generated in the teeth is indicated as Q_{th} which is at point 2 from Fig 1.

Now as heat flow towards the center of the teeth from the slot, resistance for heat flow towards center, flow of heat towards core can be given as equation similar to A and B but the value of R for teeth changes [3],

$$R_{t2} = \frac{Wt}{2 * k_t * h * l} \qquad (7)$$

$$R_{t1} = -\frac{w_t}{12 * k_t * h * l} \qquad (8)$$

w_t= width of teeth, k_t= thermal conductivity of teeth material.

Total resistance of the teeth is given by sum of 7 and 8,

$$R_t = \frac{w_t}{6 * k_t * h * l} \qquad (9)$$

Now coming to back iron or core which also induces a certain amount of heat within itself and also resist the flow of heat form teeth, back iron can be modeled as cylindrical component generating heat of Q_c with in it and resistance for heat flow in back iron can be given as,

$$R = \frac{\ln(\frac{r2}{r1})}{2 * \pi * k * l} \qquad (10)$$

Heat is generated in the core this heat generation can also be separated into two forms as of teeth and winding, that is in the form of R0 and R1, as heat flow in the longitudinal direction R0 and R1 will be in the form of equation A and B where R1 is a negative value [1], [3].

Equation for R_{c1} and R_{c2} is given as,

$$R_{c1} = \frac{\ln\frac{r2}{r1}}{2 * 2 * \pi * kc * l} \qquad (11)$$

$$R_{c2} = -\frac{\ln\frac{r2}{r1}}{6 * 2 * \pi * kc * l} \qquad (12)$$

r_2= Outer radius of core, r_1= Inner radius of core at the end of teeth, k_c= thermal resistance for core, l= core length of stamping.

In between core and frame there exist an interference fit, which intern also resist the flow of heat from core to the frame which is included in the network as contact resistance R_{ct2} which is given as,

$$R_{ct2} = \frac{1}{hc * 2 * \pi * r2 * l} \qquad (13)$$

hc= thermal contact resistance.

Table-1: Gives thermal contact resistance between elements in contact [3]

Contact type	Minimum error of air gap	Contact heat transfer coefficient W/m^2_k
Winding and teeth of stack	0.10- 0.30	80 to 250
Frame and stamping	0.05-0.08	350 to 550
Rotor bar to rotor core	0.01 to 0.08	430 to 2600

Further, to find resistance for frame we assume it a uniform cylinder, and apply the same equation 10.

$$R_f = \frac{\ln\frac{r3}{r2}}{2 * \pi * k_f * l} \qquad (14)$$

r_3= outer radius of frame, r_2= inner radius of frame.

3.2 Modelling of Convection Heat Transfer for Flow of Air On Frame.

In order to remove the heat from the motor system, one of the way is to flow the air on the frame to remove the heat where fins are present on the frame to increase the area for convection. But if we see it, cross-section of the fin is complex and the surface of the fin is rough, so the air flowing on the surface of fin experiences turbulence effect, so for modelling convective heat transfer coefficient. it is necessary to include all the parameters in order to model the convection heat transfer.

But in this case, the surface roughness and the non-uniform cross-section of the fin will not allow to use of above formulation, so in order to compensate the above situation HELIES studied rigorously the flow of air in open channel and formulated an empirical formula to obtain the value of convective heat transfer coefficient of finned surface subjected to forced convection [6].

$$h = \frac{\rho * Cp * D * v}{4 * l * [1 - e^{-m}]} \qquad (15)$$

$$m = \frac{0.1448\ L^{0.96}}{D^{1.16}\left[\frac{k}{(\rho * Cp * v)}\right]^{0.214}} \qquad (16)$$

As surface was rough a turbulent factor of 1.7-1.9 was multiplied directly to the value of h, in order to include the effect.

3.3 ANSYS Model for Temperature Distribution in Motor

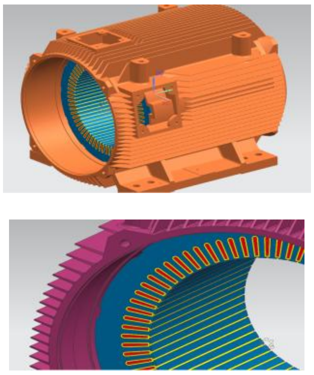


Fig-5: Showing the arrangement of copper, insulation, stack and frame used in ANSYS.

Table-2: Thermal properties of all component.

Components	Material	Thermal conductivity W/m_K	
Frame	Cast iron FG (200)	52	
Stamping	Electrical steel (orthotropic material)	K_x	33
		K_y	0.3
		K_z	33
Insulation of Electrical machine	Bonding epoxy	0.64	
	Glass fiber	0.8–1.2	
	Kapton	0.12	
	Mica	0.5–0.6	
	mica–synthetic resin	0.2–0.3	
	Nomex	0.11	
	Teflon	0.2	
	Treating varnish	0.26	
	Typical insulation system	0.2	

3.4 Application of Load And Boundary Condition.

Load are nothing but the heat lost at different section,

Stator copper loss=2800W.
Loss at teeth=630W
Loss at back iron= 1470W

Now to find the boundary condition nothing but convective heat transfer coefficient,

The properties of air are obtained at ambient temperature, according to design ambient temperature is considered as 50degrees [6].

$\rho = 1.060\, kg/m^3$

$Cp = 1.005\, KJ/kg\_K$

$\mu = 18.97 * 10^{-6} m^2/s$

$P_r = 0.696$

$P_c = (19 + 46) * 2 = 130$ mm

$A_c = 19 * 46 = 874$ mm^2

$D= (4*A_c/P_c) =26.8923$ mm

$L_f = 758.837*10^{-3}$ m

Now substituting these value in equation in 16

$$m = \frac{0.1448 * (758.837 * 10^{-3})^{0.946}}{[(26.8923 * 10^{-3})^{1.16} * (\frac{0.0289}{1.060 * 1.005 * 10^{-3} * 8.5})^{0.214}} = 110.7942$$

Now using value of m in equation in 15,

$$h = \frac{1.060 * 1.005 * 10^3 * 26.8923 * 10^{-3} * 8.5}{4 * (758.837 * 10^{-3}) * [1 - e^{-110.7942}]} = 80.31369\ W/m^2\_K$$

as it is given that turbulence effect has to be multiplied directly to value of h by an amount of 1.7-1.9 here 1.7 is used as turbulent factor in this case

$h = 80.31369 * 1.7 = 136.533\ W/m^2\_K$

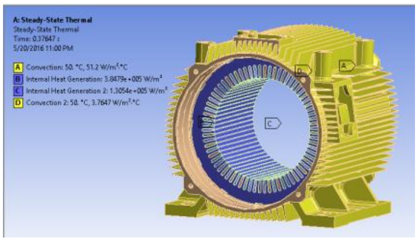


Fig-6: Applied loads and boundary condition.

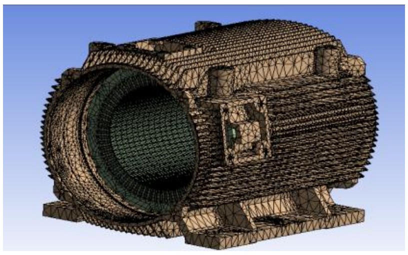


Fig-7: Genralized mesh applied to the body.

3.5 Result obtained for ansys solution.

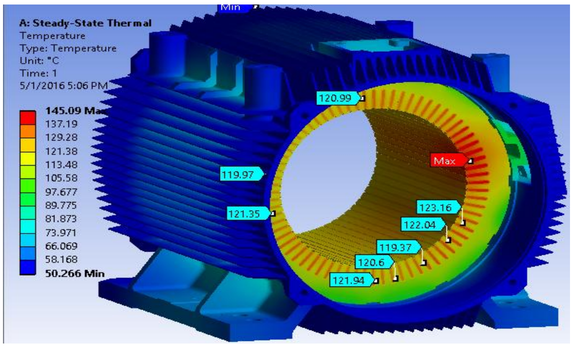


Fig-8 Result for temperature distribution in optimized frame.

4. DYNAMIC ANALYSIS OF MOTOR SYSTEM

In motor system as rotor rotates on its own axis, if the rotor which is manufactured is perfectly balanced dynamically then the amount of centrifugal force generated in the system and transferred to the frame would be negligible. But in practical rotor cannot be perfectly balanced on the bases of rotational velocity of the rotor the amount of unbalance is fixed.

Hence from the above discussion it is clear that any rotor which is balanced consist of some residual unbalanced load in the rotor, which in turn produces a centrifugal force which is in turn transferred to the frame through bearing contact.

With respect to this their also exist another phenomenon of unbalanced magnetic pull which is the result of magnetic flux generated in the electrical system, this UMP induced a pull on the rotor which in turn makes rotor shaft to undergo some deflection. This deflection in turn makes whole rotor to shift from its Center of gravity, which induces a centrifugal force when it is rotated to the speed of the system. Hence this centrifugal force is also transferred to the frame.

4.1. Force Produced Due to Residual Unbalance

For electric machine having height of 315mm from the base to the shaft and having the rotational speed of 1500 rpm, will have the balancing grade of G2.5.

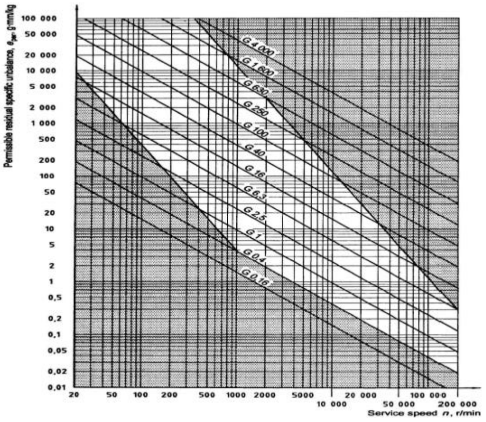


Fig-9 Relation between service speed and permissible residual unbalance.

Once the balancing grade is fixed now with help of grade and rotating speed the value of permissible residual specific unbalance (e_{per}) is obtained from the graph,
Now in the given case value of e_{per} is obtained as 15 g_mm/kg, from the assembly of the motor the mass of rotor is obtained as 300 kg so the value of U_{per} is given as,

$$U_{per} = e_{per} * m = 15 * 300 = 4500\ g\_mm$$

U_{per}= Residual unbalance in g_mm.
Equation for finding the centrifugal force is given by,

$$F = m * e * {\omega_n}^2 \tag{17}$$

$$F_{01} = m * e * {\omega_n}^2 = \frac{4500}{10^6} * \left(\frac{2 * \pi * 1500}{60}\right)^2 = 111.0194N.$$

4.2. Determination of Force Produced Due to Bending of Shaft.

In order to calculate the deflection accurately Finite Element Method is used in which whole shaft is divided in the form of elements which is shown in figure below,

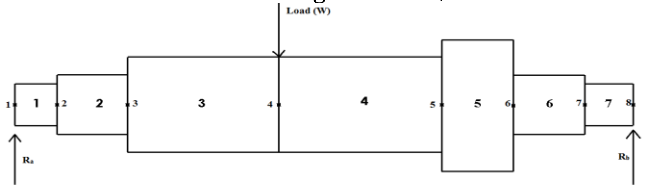


Fig-10 Representing Finite element model of shaft.

Table 6.2. Gives the information of dimension of the shaft.

Element number	1	2	3	4	5	6	7
Length of element	22.5	66	295	295	99	66	22.5
Diameter of element	95	108	120	120	128	108	95
MOI	3999621.733	6681081.568	10173600	10173600	13170114.56	6681081.568	3999621.733

Young's modulus of shaft material E = 210*10³ N/mm².

The matrices are written in form of following equation.

$$[K][\theta] = [W] \tag{18}$$

[K]=global stiffness matrix.
[θ]= deflection matrix to found.
[W]= Represents the load vector of loads acting on each node.

Stiffness matrix of elements is given as,

$$k = \frac{EI}{l^3}\begin{bmatrix} 12 & 6l & -12 & 6l \\ 6l & 4l^2 & -6l & 2l^2 \\ -12 & -6l & 12 & -6l \\ 6l & 2l^2 & -6l & 4l^2 \end{bmatrix} \tag{19}$$

Load is applied a node 4 W= 789 kg,

Solution for [θ] is obtained by solving equation 18 by using suitable boundary condition,

$$[\theta] = \begin{bmatrix} \theta 1 \\ \delta 2 \\ \theta 2 \\ \delta 3 \\ \theta 3 \\ \delta 4 \\ \theta 4 \\ \delta 5 \\ \theta 5 \\ \delta 6 \\ \theta 6 \\ \delta 7 \\ \theta 7 \\ \theta 8 \end{bmatrix} = \begin{bmatrix} 0.000181 \\ 0.00406 \\ 0.00018 \\ 0.015609 \\ 0.000168 \\ \mathbf{0.04846} \\ 0.000025 \\ 0.028606 \\ -0.00014 \\ 0.014164 \\ -0.00015 \\ 0.003674 \\ -0.00016 \\ -0.00016 \end{bmatrix}$$

$$\boldsymbol{\delta = 0.04846\ mm}$$

From above result it can be seen that the maximum value of deflection is obtained at node 4. Hence this becomes the eccentric value for the shaft under rotation which induces a centrifugal force on the motor frame. the value of force can be obtained as follows,

$$F_{02} = m * e * {\omega_n}^2 = 373 * 0.04846 * 10^{-3} * \left(\frac{2 * \pi * 1500}{60}\right)^2 = 445.997N.$$

Total force acting on system is the sum of both forces F_{01} and F_{02},

$$F = F_{01} + F_{02} = 111.0194 + 445.997 = 557.0164N.$$

Amount of force transmitted to the frame is calculated using vibration theory of force transfer which is given by,

$$\frac{F_t}{F} = \sqrt{\frac{1 + \left[2 * \varepsilon * \left(\frac{\omega}{\omega_n}\right)\right]^2}{\left\{1 - \left(\frac{\omega}{\omega_n}\right)^2\right\}^2 + \left[2 * \varepsilon * \left(\frac{\omega}{\omega_n}\right)\right]^2}} \tag{20}$$

In the system as there is no damping the value of ε is taken as zero, hence the equation is reduced as below,

$$\frac{F_t}{F} = \frac{1}{\left\{1 - \left(\frac{\omega}{\omega_n}\right)^2\right\}} \qquad (21)$$

$$\omega_n = \frac{1}{2\pi}\sqrt{\frac{9810}{.04846}} * 60 = 4296.493 \text{ rpm}$$

$$F_t = \frac{557.0164}{\left\{1-\left(\frac{1500}{4296.493}\right)^2\right\}} = 634.3327N$$

This gives the total amount of force transfer to the frame and this is used in ANSYS, in order to find the stress on the frame.

Table 6.3 Gives properties of material of components

Component	Material	Yield strength	Young's modulus	Poisson's ratio
Frame	FG200	200 N/mm^2	200*10^3 N/mm^2	0.3
Stamping	Electrical steel	250 N/mm^2	210*10^3 N/mm^2	0.3

4.3. ANSYS Solution for Dynamic Force Acting On Frame.

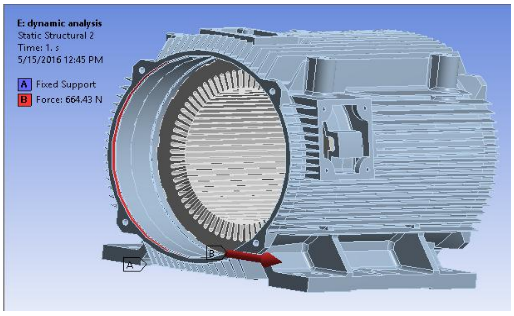


Fig-11 Gives the loading point and boundary condition for dynamic load

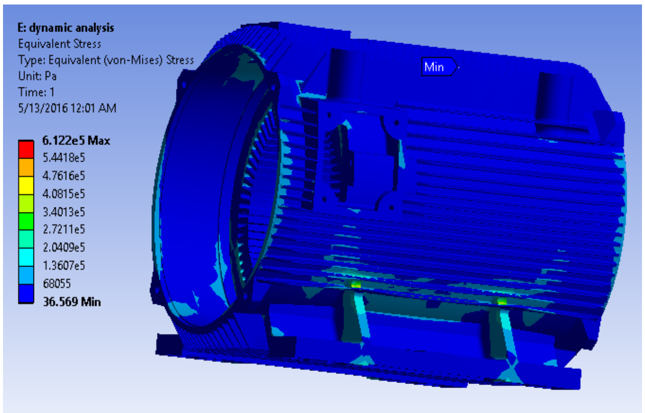


Fig-12 Stress built up in frame due to dynamic loads

5. MODAL ANALYSIS OF MOTOR SYSTEM.

If this vibration is related to motor, then in this context vibration in the motor is induced by external load so it may be said as externally induced forced vibration. Rotor is one of the part which is the major source of vibration phenomenon because when the rotor is die casted in the die aluminium is used as the binding material if this aluminium does not flow through the rotor casting uniformly means then the aluminium may get stored in peculiar region and have uneven distribution of the aluminium and also may end up with blow holes, voids etc. so due to this CG of the rotor gets shifted and produces eccentric distance between the theoretical CG and actual CG which during rotation will lead to large amount of vibration.

Hence here it becomes necessary to predict the natural frequency of the system so that resonance can be avoided, ANSYS software is used to predict the natural frequency of vibration.

5.1 Component consideration for modal analysis.

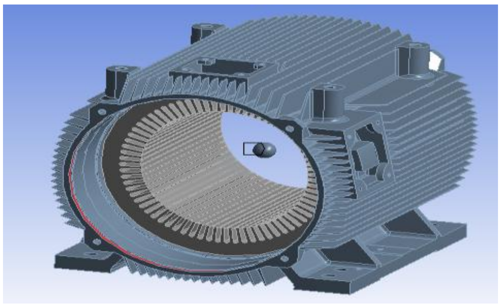


Fig-13 Shows the frame selected for the modal analysis.

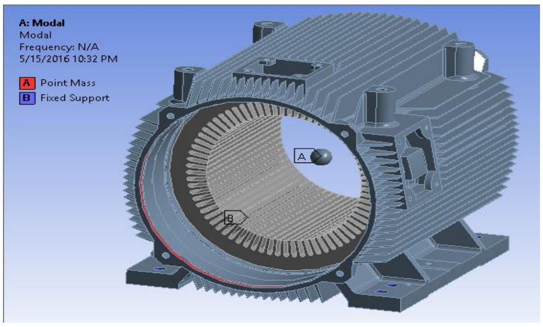
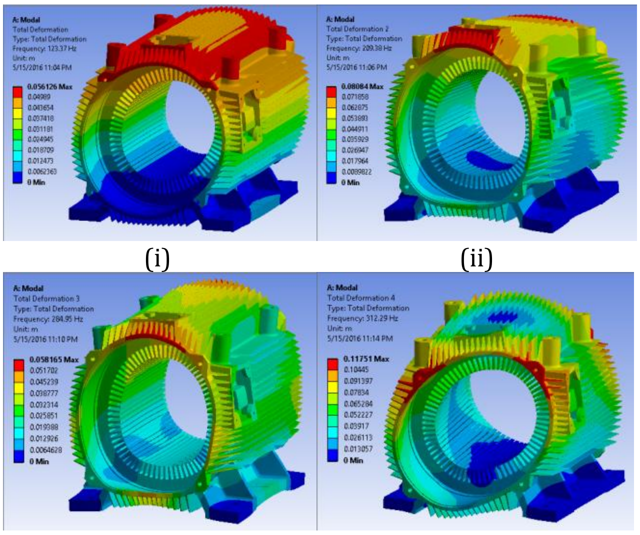


Fig-14 Shows the load and boundary condition applied on the frame.

Table 7.1 Shows the Material properties of components used in modal analysis.

Component	Material	Density (Kg/m^3)
Frame	FG200 (Cast Iron)	7200
Stamping	Electrical steel	7850

5.2. ANSYS Solution for Modal Analysis



(i) (ii)

(iii) (iv)

Fig-15 Shows the different modes of vibration.

6. RESULT AND DISCUSSION

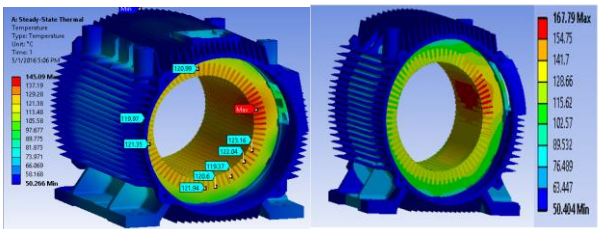


Fig-16 Showing temperature distribution in optimized and old body.

From above comparison it is clear that the temperature generated in the old body was very high and there was a drastic decrease in the optimized system. In older body the class of insulation that was used was of higher grade, but in new body the grade of insulation can be reduced and hence efficiency of the machine also increases.

Hence it can be said that the new design of frame effectively decreases the amount of temperature developed in the system.

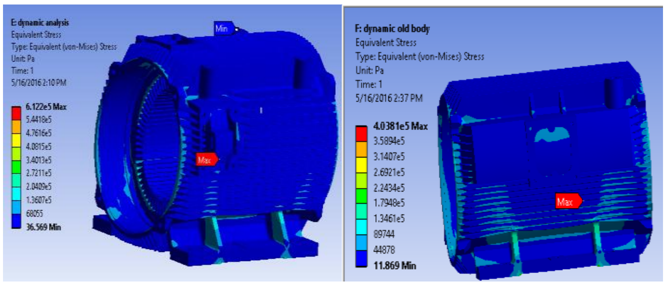


Fig-17 shows the dynamic result for optimized and old body.

From the above figure it is observed that dynamic stress in the optimized body slight greater compared to old body. Due to reduction in the mass deflection observed in the frame increases hence it will develop slightly high stress in the motor frame but seeing the stability of motor this small increase seems to be negligible over its Factor of safety.

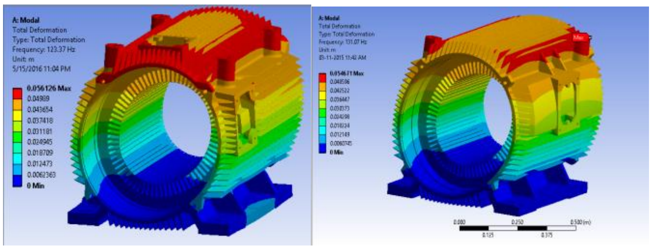


Fig-18 Shows the natural frequency of optimized and old body.

From the above result it can be said that the amount of natural frequency in old system is more compare to new body, this is because as during optimization small amount of mass of the frame was reduced with respect to old body. Hence due to this there was decrease in stiffness of system with small reduction in mass.

But if we compare the developed frequency with operating frequency of the system the difference between both of them is very large, hence even small reduction in the mass will not affect the performance of the system.

7. CONCLUSIONS

From above result it can be concluded that in the optimized body the amount of temperature developed is less compared to the old body, hence due to this the grade of insulation that was used to protect the winding can be reduced to lesser grade and with that efficiency of the motor system increases, Hence the life of the optimized body obviously increases.

In concerned to dynamic stress amount of stress induced in the optimized frame is more compared to the old body but by seeing the strength with respect to FOS the frame seems to be highly stable for the given loading condition.

With respect to modal analysis the amount of natural frequency in the optimized system was less compared to previous body because of its stiffness and mass, even though after optimization the difference between operating frequency and resonating frequency is high.

This paper gave a clear knowledge about the hot spots in the motor system and method of determining it and also studied about different types of loading condition in the motor frame. And parameter to be considered while optimizing the motor frame.

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