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Efficiency Improvement of Induction Motor Through Altered Design

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Abstract: Three phase squirrel cage induction motors are widely used in industries and hence in this paper we have aimed to increase a motor's efficiency by augmenting its cooling process. The motor chosen was of 3 HP rating. Motor structure was altered to improve its efficiency and its performance characteristics were analysed to compare with the conventional motor design. A dynamic model was constructed in Matlab Simulink to observe the changes in speed and phase currents on varying load. After successful dynamic modelling, the motor is simulated using Motor Solver and various performance parameters are observed and monitored. This is followed by improving the efficiency by using Aluminium as material for the stator housing and rotor bar and end ring. Silicon steel is used for stator back iron. High cost of Aluminium used to design the stator casing is compensated by the nullification of high maintenance and operational costs.

I. INTRODUCTION

Induction motors are widely used in industrial applications because of features such as self-starting property, simple construction, robustness, economical, reliability and less maintenance. Some of the applications of 3 phase induction motors include lifts, cranes, hoists, traction etc. The modified motor designed in this paper is specific to applications that require high torque at high speed.

The main limiting factor in the fine operation and life time of an electrical machine which can be operated continuously on load is the temperature of the various circuit elements that constitute the machine. In these motors if the efficiency can be increased by just a few percentages, it will still have a major impact on the energy consumption and operation. Hence in this paper, a new casing for the stator is designed using Aluminium as opposed to the conventional cast iron, stator back iron is made of Silicon steel and rotor bar and end rings are made of 61%Alminium IACS to increase efficiency. As the conductivity of aluminium is poor as compared to copper, 61% aluminium is used[2]. Although [3] discusses that increase in silicon in the core leads to decreased saturation flux density which in turn decreases efficiency, we found that by changing the stator back iron material to silicon steel, the efficiency increases. In addition to this, stator slot liner material is changed from epoxy resin to Nomex 430 for higher shear adhesion property.

The technique used for dynamic modelling of the conventional machine is stationary stator reference frame method. MotorSolve has been used to alter the motor structure.

The results in [4] show, that for the same frame size, mechanical or electrical loading must be increased to increase torque which in turn leads to greater copper losses and lower efficiency. As the rotor of the modified motor is made up of Aluminium, the losses have reduced and the efficiency has increased. A novel approach of including permanent magnet in the rotor was explored in [5] for high efficiency remanufacturing, however due to the cost of permanent magnet only a low efficiency approach could be explored.

Efficiency improvement with the help of structural alteration was explored in [6] as well by incrementing stack length of prototype motors however significant increase in efficiency could not be achieved as the motors were already built for premium efficiency ratings.

The technique used for dynamic modelling of the conventional machine is stationary stator reference frame method. After successful dynamic modelling of the conventional motor, its physical parameters are calculated using [7]. On calculation of the physical parameters of the motor, the values are entered in Motor Solver and its performance characteristics are observed and monitored. Following this, the aforementioned structural changes are made to the motor and simulated. The performance characteristics of the modified motor have been shown and comparisons of different behavioural characteristics have been tabulated for better understanding.

II. ANALYSIS OF EXISTING MOTOR

A. Dynamic Modelling Of Motor

A 3HP motor was chosen. The name plate details of the motor as shown in Table I. Dynamic modelling techniques are based on reference frame theory. Reference frame theory is widely used as it reduces the complexity of differential equations that describe the machine model by transforming variables to either rotor or stator side. There are two models in this theory: synchronous rotating reference frame and

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stationary stator reference frame.

TABLE I
NAME PLATE DETAILS OF 3HP MOTOR

Rated speed	1440rpm
Rated voltage	415V, 3 phase supply
Rated Current	4.5A
Frequency	50Hz
Insulation	F class
Make	Crompton Greaves
Rated power	2.2kW

We have used stationary stator reference frame method to make the thermal model of the induction motor as it offers easy computation because there is no involvement of PI regulator tuning and linearization of small signal model as opposed to synchronous rotating reference frame. This dynamic model was constructed in Matlab Simulink[4] with the help of the mathematical model of the motor described the following equations and matrices.

$$Vs\alpha = Rs * Is\alpha + Ls * \frac{dIs\alpha}{dt} + Lm * \frac{dIr\alpha}{dt}$$

$$Vs\beta = Rs * Is\beta + Ls * \frac{dIs\beta}{dt} + Lm * \frac{dIr\beta}{dt}$$

$$Vr\alpha = Rr * Is\alpha + Lr * \frac{dIr\alpha}{dt} + Lm * \frac{dIs\alpha}{dt} + \omega r * Lr * Ir\beta + \omega r * Lm * Is\beta$$

$$Vr\beta = Rr * Ir\beta + Lr \frac{dIr\beta}{dt} + Lm \frac{dIs\beta}{dt} - \omega r * Lm * Ir\alpha - \omega r * Lm * Is\alpha$$

	$Is\alpha$	$Is\beta$	$Ir\alpha$	$Ir\beta$	$\frac{dIs\alpha}{dt}$	$\frac{dIs\beta}{dt}$	$\frac{dIr\alpha}{dt}$	$\frac{dIr\beta}{dt}$
$Vs\alpha$	Rs	0	0	0	Ls	0	Lm	0
$Vs\beta$	0	Rs	0	0	0	Ls	0	Lm
$Vr\alpha$	0	ωrLm	Rr	ωrLr	Lm	0	Lr	0
$Vr\beta$	- ωrLm	0	$-\omega rLr$	Rr	0	Lm	0	Lr

$$\frac{dI}{dt}[L] = -[R][I] + [V]$$

$$\begin{bmatrix} Ls & 0 & Lm & 0 \\ 0 & Ls & 0 & Lm \\ Lm & 0 & Lr & 0 \\ 0 & Lm & 0 & Lr \end{bmatrix} \frac{d}{dt} \begin{bmatrix} Is\alpha \\ Is\beta \\ Ir\alpha \\ Ir\beta \end{bmatrix} = - \begin{bmatrix} Rs & 0 & 0 & 0 \\ 0 & Rs & 0 & 0 \\ 0 & \omega rLm & Rr & \omega rLr \\ -\omega rLm & 0 & -\omega rLr & Rr \end{bmatrix} * \begin{bmatrix} Is\alpha \\ Is\beta \\ Ir\alpha \\ Ir\beta \end{bmatrix} + \begin{bmatrix} Vs\alpha \\ Vs\beta \\ 0 \\ 0 \end{bmatrix}$$

Simulation circuit :

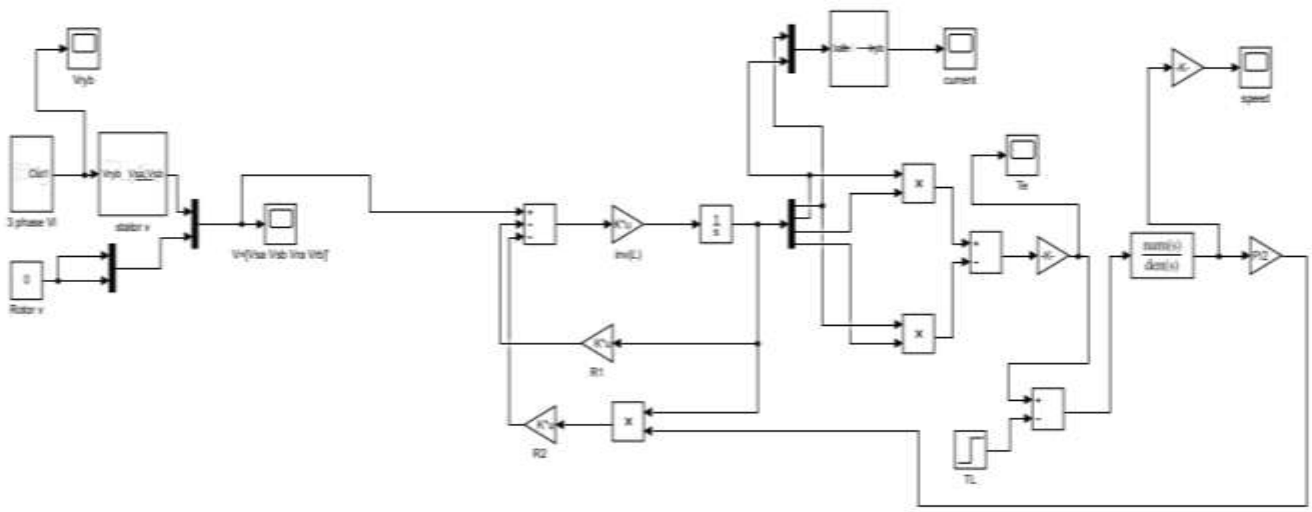

FIG. 1. MATLAB SIMULATION CIRCUIT

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Model Parameters:

The following parameters were used for model initialization in Matlab Simulink.

Line voltage, V_L = 415V
Power frequency, pf =50 Hz
Stator resistance, R_s=3.45Ω
Rotor resistance, R_r=3.6141Ω
Stator inductance, L_s=0.3246H
Rotor inductance, L_e=0.3252H
Mutual inductance, L_m=0.3117H
Moment of inertia, J=0.02kg m^2
Friction coefficient, B=0.001
No. of poles, P=4

$$L = [L_s, 0, L_m, 0; \; 0, L_s, 0, L_m; \; L_m, 0, L_r, 0; \; 0, L_m, 0, L_r;]$$

$$R1 = [R_s, 0, 0, 0; \; 0, R_s, 0, 0; \; 0, 0, R_r, 0; \; 0, 0, 0, R_r;]$$

$$R2 = [0, 0, 0, 0; \; 0, 0, 0, 0; \; 0, L_m, 0, L_r; \; -L_m, 0, -L_r, 0;]$$

Where L is the inductance matrix, R is the resistance matrix which is expressed as the sum of two separate matrices R1 and R2.

Experimental Setups And Results:

(a)

(b)

Fig. 2. (a) Setup for load test. (b) Motor used in the paper.

In order to obtain model parameters various tests such as load test, no load test, blocked rotor test were performed.

The parameters measured during these tested are given below.

TABLE II
NO LOAD TEST PARAMETERS

No load Voltage(V)	No load Current(A)	No load Power(W)
415	2.25	304

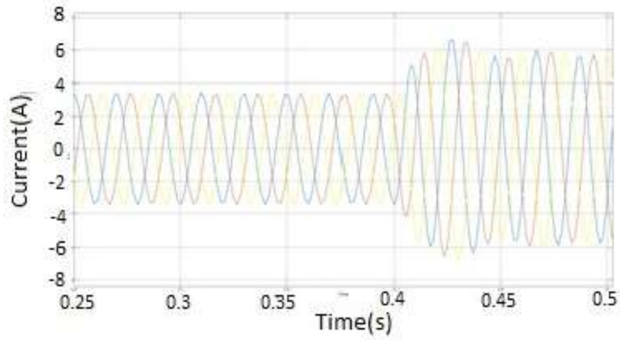
Table III
BLOCKED ROTOR VOLTAGE

Blocked rotor Voltage(V)	Blocked rotor current(A)	Power(W)
142	4.5	640

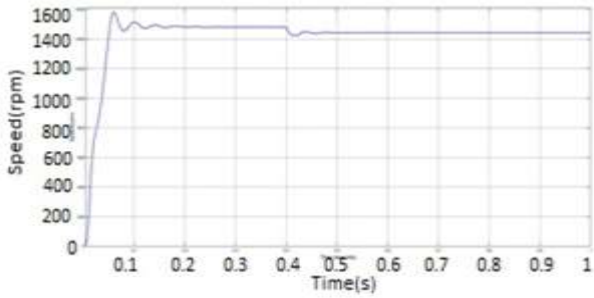
TABLE IV
LOAD TEST MEASURED VALUES

Current(A)	Speed(rpm)	Load(Nm)	Output Power(W)	Efficiency
2.2	1486	0.88	137.39	17.17
2.75	1478	2.83	437	36.416
3	1470	3.53	543.3	37.73
3.45	1462	4.77	729	45.594

Results Of Simulation



(a)



(b)

Fig. 3. (a) Current vs time. (b) Speed vs time.

The motor was given a step signal for changing the load torque. Initially a torque of 20 Nm was applied and then it was increased to 40 Nm. All the three phase currents are plotted against time and it was observed that for a constant load torque at 20Nm the current was 3A and after 0.4 second when the torque is changed to 40Nm the time, the current increases with oscillations which settle down after a few milliseconds to a value of 6A. Thus on increase of load torque, the amount of current drawn by the motor increases.

Similarly, when speed vs time curve was plotted it was observed that initially the speed curve had many oscillations due to start of the motor which settled down after a few milliseconds and reached a steady value upon application of 20Nm torque. Upon increase of the torque to 40Nm, the speed curve oscillates and reaches a value lower to the previous value. Thus as the load torque of the motor increases the speed of the motor decreases.

B. Modelling Of Motor In Motorsolve

The following parameters were calculated from [7] and used in MotorSolve[8].

TABLE V
DIMENSIONS OF MOTOR USED IN MOTORSOLVE

Parameter	Value	Dimension
Stator outer diameter	245	mm
Length of air gap	0.454	mm
No. of stator slots	36	
Outer diameter of rotor	143	mm
Inner diameter of rotor	97.02	mm
Stator inner diameter	143	mm
Depth of rotor core	23.9	mm
Depth of stator core	33.8	mm
Depth of stator slots	16.9	mm
Housing thickness	14.2	mm
Left bearing width	28.5	mm
Right bearing width	28.5	mm
Rotor slots	19	

Performance curves of the conventional motor:

Supply voltage:

During the entire course of the simulation of the motor in MotorSolve, the supply voltage was kept constant as shown in Fig. 4.

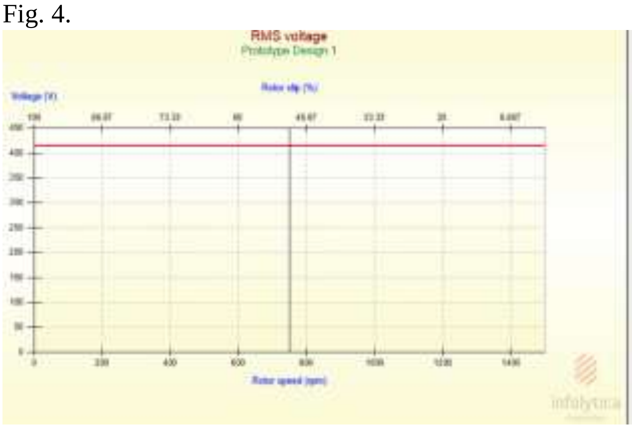


Fig. 4. Supply voltage vs Rotor speed for conventional motor.

Efficiency:

The overall efficiency of the conventional motor was observed to be 38.9%.

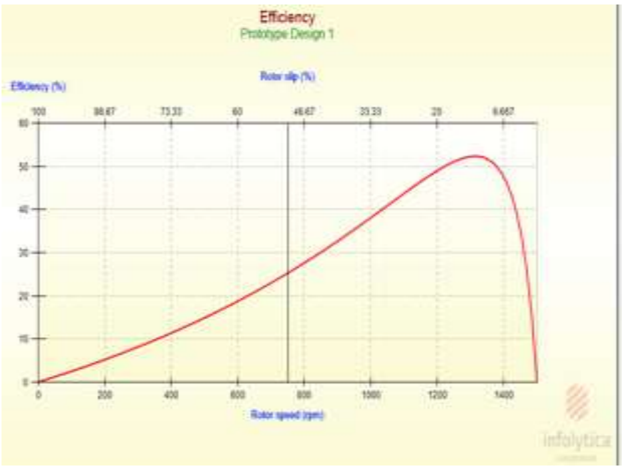


Fig. 5. Efficiency vs rotor speed curve of conventional motor.

The maximum efficiency of the motor was observed to be 52.4% at a speed of 1304 rpm.

Torque:

Fig. 6. Torque vs Rotor speed curve for conventional motor.

The maximum torque was observed to be 43.8Nm at rotor speed of 1136rpm.

Flux Distribution :

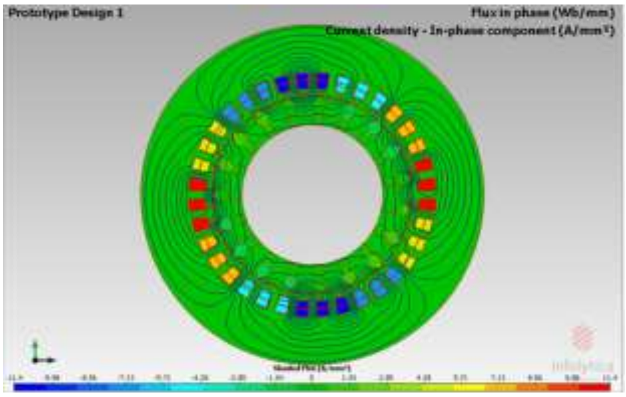


Fig. 7. Flux distribution of conventional motor.

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III. PERFORMANCE ANALYSIS OF MODIFIED MOTOR

In order to improve the motor performance, the housing of the motor which was initially made up of CR10: Cold rolled steel is replaced by Aluminium 61% IACS. Aluminium has good corrosion resistance due to the formation of an oxide layer on the metal on reaction with different materials. Steel casings have to be painted from time to time to avoid corrosion. The cost of this regular maintenance can be saved by using Aluminium as the casing material even though the material cost of Aluminum is higher. In addition to this property it is more flexible than steel thus aiding in design of casing ridges. Due to technological advancements Aluminum extrusions can be designed easily than the tedious process of casting iron.

61% Aluminium IACS is used for the Rotor bars and end ring. Usage of Aluminium decreases losses that occur in various parts of the machine and increase cooling. This has been used instead of steel laminations. Aluminium is lighter in weight.

Carpenter: Silicon steel has been used for stator back iron material instead of M-19-Ga Steel. This particular metal has good electrical resistivity and also is vital to decrease eddy current and hysteresis loss. Nomex 430 has been used instead of epoxy resin for stator slot liner material as it has higher shear adhesion than epoxy and is relatively inexpensive.

This motor can be used for applications requiring high torque at high speed and good efficiency at high speed regions for example in crashing plants and in locomotives.

The supply voltage used was the same as for the conventional motor i.e. 415V. Fig. 7 shows the flux distribution of the modified motor.

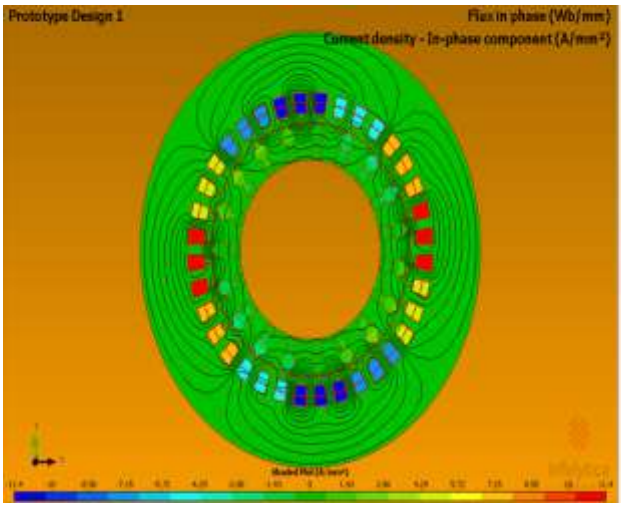

Fig. 8. Flux distribution and current density of altered motor.

IV. COMPARISON OF CONVENTIONAL MOTOR AND MODIFIED RESULTS

After the material changes were made to the motor the following simulation results were obtained. The overall efficiency of the motor was increased by 5%. The power of the motor increased from 3HP to 3.5HP. The overall losses were observed to have decreased. Various parameters such as torque, efficiency, losses, energy and coenergy were analyzed.

TABLE VI
COMPARISON OF EFFICIENCY OF MOTOR AT DIFFERENT SPEEDS (CONVENTIONAL VS MODIFIED)

S.no	Speed	Conventional motor efficiency	Modified motor efficiency	Percentage improvement
1	200	5.18	5.16	
2	400	11.4	11.7	
3	600	18.8	19.	
4	800	27.6	28.2	
5	1000	38.2	38.6	
6	1200	49.1	49.8	1.4
7	1250	51.1	51.6	0.9
8	1300	52.3	53.8	2.9
9	1350	51.8	54.5	5.2
10	1400	47.7	51.7	8.4

Fig. 9. Efficiency curve of altered motor.

The overall efficiency of the motor has been increased by 5%. The conventional motor had an efficiency of 38.9% whereas the new motor has an efficiency of 43.9%. The maximum efficiency of the motor was observed to be 54.5% at a speed of 1350rpm. From the table above it can be inferred that the modified motor performs well in the high speed region. In low speed and medium speed region the efficiencies of both the motors are very similar.

TABLE VII
COMPARISON OF TORQUE AT DIFFERENT SPEEDS (CONVENTIONAL VS MODIFIED)

S.no	Rotor speed	Torque in conventional motor	Torque in modified motor	Slip
1	200	21.8	22.7	86.7
2	400	25.1	25.2	73.3
3	600	29.3	29.3	60
4	800	34.7	35.1	46.7
5	1000	40.9	41.2	33.3
6	1200	43.4	44.2	20
7	1300	38.2	41.9	13.4
8	1400	23.9	28.1	6.71
9	1440	15.2	18.1	4.02

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Fig. 10. Torque curve of altered motor.

From Table VII it can be observed that the modified motor has a higher torque value compared to conventional motor when operating in high slip region for the same speed as that of conventional motor. The maximum torque was observed to be 44.3Nm at rotor speed of 1222rpm. The motor is suitable for high speed region applications that require good torque and efficiency.

Motion analysis is done for final design verification by performing a full time-stepping non-linear finite element analysis simulation for all types of operating conditions of the two motors using loss, energy and coenergy as result parameters was carried out and the following results were obtained.

TABLE VIII
COMPARISON OF LOSS, ENERGY AND COENERGY OF THE CONVENTIONAL AND MODIFIED MOTOR

		CONVENTIONAL			MODIFIED		
Source phase angle(˚)	Rotor angle(˚)	Loss	Energy(J)	Coenergy(J)	Loss	Energy(J)	Coenergy(J)
60	202	6.88	76	98.2	6.44	76.3	101
120	231	7.17	79.4	103	6.72	79.7	106
180	260	7.14	81.5	106	6.52	81.6	109
240	288	6.65	79.6	104	6.18	79.9	107
300	317	6.72	76.9	99.5	6.39	77.4	103
360	346	6.91	75.8	96.1	6.41	76.4	98.5
420	374	6.67	76	96.7	6.33	76.4	99.4
480	404	6.75	77.1	99	6.17	77	102
540	435	6.78	77.9	100	6.48	77.5	106
600	461	7.01	77.4	98.4	6.61	77.6	101
660	490	6.64	75.9	96.5	6.15	76.1	99.3
720	518	6.25	74.5	95.4	5.73	74.9	97.6

As coenergy and energy both relate to the electromagnetic torque of the motor, it is desirable to have higher values of the same. In the modified motor, coenergy is high for the same outer dimensions, which indicates higher power density of the machine and lower losses. This has been successfully obtained from the modified motor as per tabulated results.

TABLE IX
TEMPERATURES AT DIFFERENT POINTS IN THE MOTOR (UNIT ˚C)

Part	Conventional motor	Modified motor
Bar	109	110
Rotor back iron	109	110
Rotor tooth	109	110
Stator back iron	110	112
Stator coil side	122	128
Stator coil side slotmate	124	129
Stator tooth	113	115

From Table IX it can be observed that the altered motor is capable of operating at higher temperatures as compared to the conventional motor which accounts for its versatile use.

V. CONCLUSION

In this paper performance of a conventional induction motor was improved using by altering the structure of the motor using Aluminum as material for casing and rotor bar and end ring material, Silicon steel as stator back iron material and Nomex 430 as stator slot liner material. Although the initial costs of the motor are increased, it is compensated by low maintenance costs. The modified motor is light in weight and has better efficiency in high speed regions. The overall efficiency of the motor was increased by 5% which is significant in an induction motor. Efficiency and performance of motor can be further increased by intricate design of the casing. The modified motor is suitable for crashing plants, locomotives, large capacity exhaust fans etc.

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