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DESIGN AND FABRICATION OF HIGH EFFICIENCY SQUIRREL CAGE INDUCTION MOTOR USING FINITE ELEMENT METHOD

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ABSTRACT

This paper presents the design and analysis of a die- cast copper rotor cage, to improve the efficiency of three phase induction motor used in industrial applications and also it describes the various factors affecting the efficiency of motor. The proposed copper rotor motor has better efficiency and increase in torque with minimum losses. An incremental difference in the efficiency is also discussed with different values of loads. Simulation has been carried out using Finite element Analysis (FEA) and experimental results are shown. Simulation and experimental results presented here demonstrates the feasibility of the copper rotor motor.

Keywords: Finite element method (FEM), induction motor, copper cage Induction motor, cost analysis, die casting.

1. INTRODUCTION

Electric motors are almost importance in industrial agriculture and electric propeller sector. Energy conservation and efficiency are closely related to each other. Due to uncertainties in oil supply and fluctuating price of conventional fuels, efficiency and to increase in demand of energy. An electrical energy is consumed by an induction motor used for industrial and rural sector. In India industrial sector and agriculture is developing rapidly in the same way electrical energy consumption is increasing. The three-phase induction motors have some advantages in the machine efficiency, power factor, and torque ripples compared to their single-phase counterparts. Though the precise control of single phase induction motor is less complex in comparison to the three phase induction motor, but when the torque requirement is considered then three phase induction motor is the best choice. The applications for these motors cover almost every stage of manufacturing and processing. It is not surprising to find that among all types of electric motors, Induction motor is so popular, when one considers its simplicity, reliability, and low cost. One of these is a labeling program for motors under the Energy Conservation Act 2001. At the commencement of this Project, the Bureau of Indian Standards (BIS) approved the standard IS 12615-2004 for the performance requirements and efficiency of 3-phase squirrel-cage energy efficiency induction motors.

However, in some rural areas where only a single-phase utility is available, we should convert a single-phase to a three-phase supply. This paper proposes an alternative solution for phase conversion with very low overall cost, moderate motor performance during start up and high steady-state performance at line frequency. This system fits the requirements in rural areas where only a single-phase supply is available. To the improvement of the average efficiency of a motor with copper rotor over aluminium rotor motor is around 3-4%.

- Due to the required size of the motor which reduces the size of a copper rotor motor. A smaller motor should result in cost saving and flatter efficiency curve from 50% to full load gives the additional advantage.
- These motors are used in various manufacturing sectors as well as for pumping in the agricultural sector. Small motors (<100 HP or 75 kW) dominate the motor market in India In the industrial sector, most of these motors are loaded for more than 3,000 hrs annually (roughly 11 hrs for 333 days each year). Hence, a transformation of the small motors market will result in significant energy savings for India.

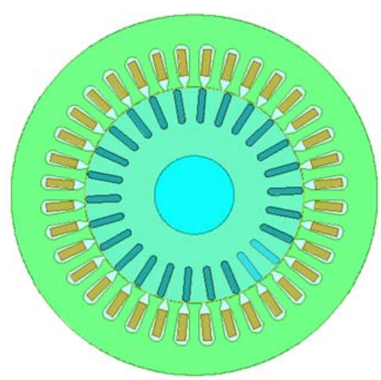

Figure-1. Squirrel Cage induction motor.

2. COPPER ROTOR

The metal chosen for the squirrel cage structure of the induction motor has substantial implications to both motor performance and motor manufacturability. Electrical grade copper is used in very large (>250 Hp, 200 kW) motors and in some smaller special purpose motors. These are manufactured by a costly and slow fabrication procedure not suitable for production of the millions of integral horsepower and kilowatt motors

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produced annually. Die casting of the copper would be preferable, but this process has not been economical because of short die life due to copper's high melting temperature.

Use of copper in the rotors in a broad range of sizes of induction motors represents a significant advance in motor technology. This is because the readily available and least expensive improvements to increase motor energy efficiency have been adopted in recent years.. In addition, analyses by motor manufacturers have shown that the copper rotor can be employed to reduce overall manufacturing costs at a given efficiency or to reduce motor weight, depending.

3. ELECTROMAGNETIC FIELD COMPUTATION

Today, the FEM is used to solve all kinds of engineering problems. FEM is one of the most power full methods and commonly used for field computation problems both electrostatic and electromagnetic. Variational and the Galerkin approach are commonly used methods for deriving the finite element equations are the being a special case of the method of weighted residuals. In two and three dimensional analysis, the field of interest is to divide a large and complex area problem into small and simple area problems than function calls it as discretised. The small problem area is defined as an element. The element shape may be triangular or rectangular for two dimensional and any shape simple volume elements are used for three dimensional problems with a number of simple triangular or rectangular elements, the finite elements with homogenous properties. The potential function is approximated in those finite elements by simple shape functions, mainly linear or quadratic. This results in a large linear system of equations. Saturation effects can be easily considered. Finite element method offers the compute accurate results with low computational costs than analytical method. Inherently non-linearity due to the characteristic of the ferromagnetic parts in the magnetic circuit is implemented. Non-linear ties caused by the relative displacement between moving parts are implemented as well. Finite element results are computed by simulations

The TDFEM of induction motor described in this paper, the theory of electromagnetic electrical machines modeling is described by the time-space Maxwell's equations

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

$$\nabla \times H = J \tag{2}$$

Both the magnetic and electric fields are related to the material property of electrical machines expressed by the following relations

$$H = \nu B \tag{3}$$

$$j = \sigma E \tag{4}$$

Here ν is the reluctivity and σ is the conductivity of the material. The electric scalar potential φ is obtained from Equ.1 and 3

$$\nabla \times \left(\nu \nabla \times A\right) + \frac{\partial A}{\partial t} = \frac{\sigma}{1} U e_z \tag{5}$$

The time dependent field equation with a nonlinear is needed, the field equation must be solved by a step- by step method evaluating in short time variation is Δt. in the crank- Nicholson method the vector potential at a time step k+1 is approximated

$$A_{k+1} = \frac{1}{2}\left\{\frac{\partial A}{\partial t}_{k+1} + \frac{\partial A}{\partial t}_{k}\right\}\Delta t + A_k \tag{6}$$

The potential difference between the ends of the conductor vector is obtained from Equation (5) potential is

$$\nabla \times \left(\nu_{k+1} \nabla \times A_{k+1}\right) + \nabla \times \left(\nu_k \nabla \times A_k\right) + \sigma\left\{\frac{\partial A}{\partial t}_{K+1} + \frac{\partial A}{\partial t_k}\right\} = \frac{\sigma}{1}\left\{U_{k+1} + U_k\right\} e_{\partial z} \tag{7}$$

When Equation (5) substituted in Equation (6) and the corresponding time step k are transferred to the right hand, the equation becomes

$$\nabla \times \left(\nu_{\partial k+1} \nabla \times A_{k+1}\right) + \frac{2\sigma}{\Delta t} A_{k+1} = \frac{\sigma}{1} U_{K+1} e_z - \left\{\nabla \times \left(\nu_K \nabla \times A_k\right) - \frac{2\sigma}{\Delta t} A_k - \frac{\sigma}{1} U_k e_z \right. \tag{8}$$

The all right side terms, the previous time step k of the vector potential and the source potential differences. The partial difference equation for the vector potential at time t =tk+1. i.e. the vector potential is evaluated step by step from the initial value and this procedure is very important to compute time because induction motor every period of line frequency must be divided into time intervals in order to get accurate results.

The initial and boundary value must be known in the field problem. In field analysis the outer surface of the machine is assumed to be zero, i.e. there is no flux at the outer surface

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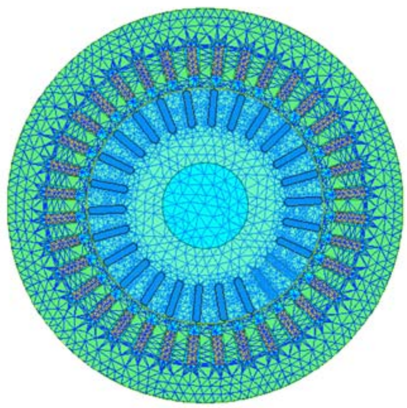

Figure-2. Squirrel Cage induction motor Mesh model.

4. EFFICIENCY COMPUTATION

A 3 phase ,50 Hz,4 pole 32 slot, totally enclosed, squirrel cage induction motors, rated at 5 hp, were used to investigate the annual energy saving. Energy saving usually calculated depending up the efficiency of the motor. The proposed motor is designed to improve efficiency levels EFF1 from EFF2 as per international standard such as CEMP – European Committee of Manufacturers of Electrical Machines & Power Electronics and other standard CSA – Canadian Standard Association / IEEMA- Indian Electrical and Electrical Machines Association / BIS – Bureau of Indian Standards.

Induction motor losses can be classified into four categories:

(i).Core losses

Core losses are due to the main flux and leakage fluxes of the motor if the input voltage is to be constant, the core loss can also be constant. The hysteresis and eddy current loss in the conductors increase the resistance, which can be reduced laminated sheet and high permeability material in the paper I chose M19-24G steel core for both stator and rotor. Mostly it should be 15 % – 25 % of motor rating

Iron-Core Loss (W): Pcore = 93.4121W

(ii) Copper losses

Another name of copper losses called as power losses which induce due to current losses in the active material like stator and rotor winding or rotor bar and end ring in squirrel cage induction motor, if can be minimized by high conductivity copper material and die casting copper rotor. in stator 25 % – 40 % and rotor 15 % – 25 % of motor rating

Stator copper losses: $P_{scu} = 3i_r^2 R_r$ W` (9)

$i_s^2 = 9.8$ A

$R_s = \frac{0.0177 * l_m T_{ph}}{a_c}\Omega = 0.7890$ (16)

$P_{scu} = 256.402$ W

Rotor copper losses: $P_{rcu} = 3i_r^2 R_r$ W (10)

$i_r^2 = 6.6$A

$R_r = \frac{0.0177 * l_m T_{ph}}{a_c}\Omega = 0.789099\ \Omega$ (11)

$P_{rcu} = 100.225$ W

$P_{cu} = P_{scu} + P_{rcu} = 356.627$W

(iii) Windage and friction losses

Windage and friction losses due to mechanical parts and friction in bearings, it should be 5 % – 15 % of motor rating

Wind age and friction losses: $P_f + P_w =$ 20. 5867W

(iv) Stray load losses

This is increasing with load and multitude of sources, such as surface and slot conditions, leakage flux, and another name is additional load losses, it should be 10 % – 20 % of motor rating

Stray load losses: $P_{stay} = 50$ W (12)

Table-1. Total Losses of Copper.

Losses of motor	SM (Watts)	SCRIM (Watts)
Copper Loss of Stator Winding(W)	260.675	256.402
Copper Loss of Rotor Winding (W)	129.932	100.225
Iron-Core Loss (W)	93.3603	93.4121
Frictional and Windage Loss (W)	20.4319	20.5867
Stray Loss (W)	50	50
Total Loss (W)	554.398	520.626

Efficiency (E) is a ratio of the motor shaft power output divided by the electrical power input and is calculated as follows:

(v) Total loss calculation

$P_{TL} = P_{core} + P_{cu} + P_f + P_w + P_{stay}$

$P_{TL} = 520.626$W

(vi) Output power calculation

Pout=Pin-PTL = 4.32051 -520.626= 3.7999KW

(vii) Efficiency calculation:

$$\eta = (1 - \frac{P_{TL}}{P_{in}})\ \text{X100} = 87.795\%$$

5. FEA SIMULATION RESULT

The 2D Electromagnetic Finite Element problem is solved by ANSOFT 2DMAXWELL FEM software package, by which the magnetic flux line path of squirrel cage induction motor and the chart for magnetic flux density are obtained. The magnetic flux density is nearer to the saturation level. The Figure-5 shows the magnetic flux distribution and the Figure-6 shows the magnetic flux density of the induction.

The comprehensiveness of the both rotor, SCRIM copper rotor has better efficiency, better torque with reduced losses. The efficiency is maintained constant and changing rotor configurations results high torque and reduced size with low weight, which is another factor which impels us to choose the all rotor configurations for industrial and hybrid vehicle applications.

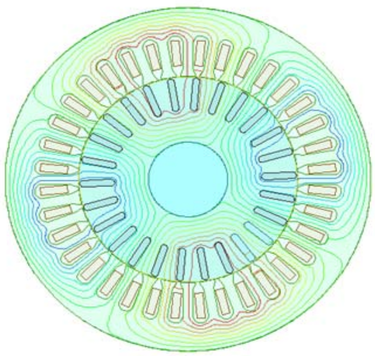

Figure-3. Magnetic flux distribution of SCRIM.

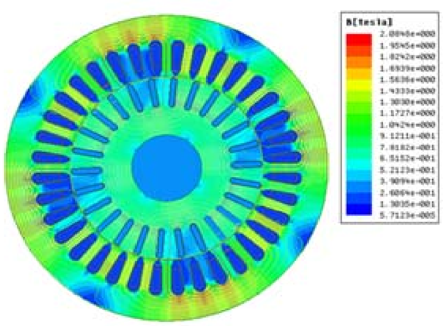

Figure-4. Magnetic flux density of SCRIM.

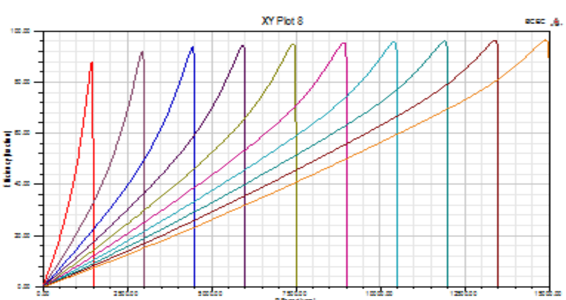

Figure-5. Efficiency Vs Speed.

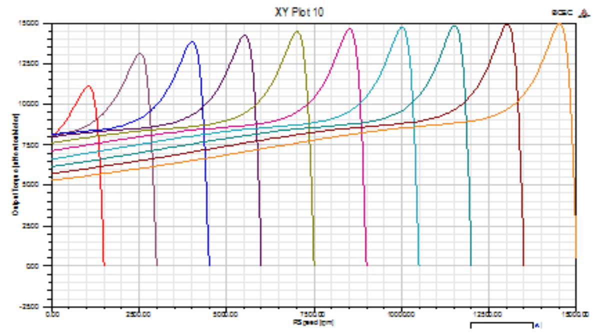

Figure-6. Torque Vs Speed.

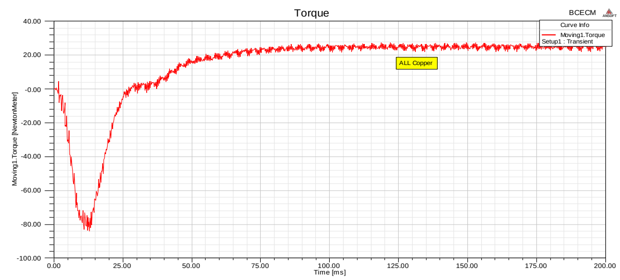

Figure-7. SCRIM running toque.

Table-2. Efficiency of SARIM.

Parameter	SCRIM	SM
Te(N-m)	25.539	25.254
η	87.79	85.586
P.F	0.670861	0.679388
Speed(rpm)	1461.44	1420.93
Plosses (W)	520.626	640.028

6. EXPERIMENTAL TESTS

Figure-8. Prototype SCRIM.

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A wide test campaign has been conducted on the three prototypes to characterize them and to deeply evaluate their behavior under different working conditions. First of all, the prototypes have been tested with sinusoidal supply. Load test and an evaluation of mechanical and core losses have been done. To perform a significant analysis on the different solutions adopted for the three rotors, a condition of uniformity has to be defined for the stator. Even if the three stators appear to be identical, possible differences in their realization can compromise the comparative analysis on the rotors. Hence, on the basis of the results coming from the no load and locked rotor tests, one stator has been selected to become "the stator" for the three rotors. In this way the tests have been conducted inserting any time a different rotor inside the same stator. The motors have been tested in the authors' laboratory. In particular, for each machine the following standard tests have been performed.

* No-load test;
* Variable load test.

In the load tests the motors are loaded with testing equipment (constant torque controlled) with regenerative inverter and the braking torque is measured with a torque/speed transducer mounted on the motor shaft The electrical quantities have been measured using a power meter (Infratek 305A), with 800 kHz bandwidth. Variable load tests and the no load tests have been conducted under sinusoidal supply, according to the methodology prescribed by the IEEE Std. 112-B.

Figure-9. Variable load test of SCRIM.

The testing setup shown in Figure-8. The overall performances of the SCRIM of various ratings/heads are shown in Figure-8. Due to high rotational speed of SCRIM, The low voltage performances of all ratings were tested.

The comparison of No load test result values of various ratings of SCRIM motors are shows in Figure-8 with a rated voltage, almost irrespective of the ratings of motor, the efficiency values are found high in DCR motor. Due to lower slip, the full no load speed of a SCRIM motor is high during rated voltage and a reduced voltage. The starting Torque value is increased. The comparison of No load test result values of various ratings of SCRIM motors are shows in Figure-10 with a rated voltage, almost irrespective of the ratings of motor, the efficiency values are found high in DCR motor. Due to lower slip, the full no load speed of a SCRIM motor is high during rated voltage and a reduced voltage. The starting Torque value is increased.

Table-3. No Load Test Data of SCRI.

Voltage	Current	Power	Freq	PF	Torque	output	Speed	Eff	Load %
Volt	Amps	kW	Hz		kgm	Kw	Rpm	%	%
416	4.64	0.64	49.93	0.19	0.13	0.2	1494	31.17	5.39
414	4.64	0.9	49.88	0.27	0.35	0.54	1491	59.56	14.49
419	4.96	1.28	49.86	0.36	0.61	0.93	1487	72.79	25.18
416	5.13	1.73	49.86	0.47	0.97	1.48	1483	85.41	39.93
415	6.19	3.02	49.86	0.67	1.86	2.81	1473	93.18	76.06
414	6.54	3.34	49.9	0.71	2.13	3.22	1471	96.35	86.98
417	7.71	4.34	49.88	0.78	2.82	4.24	1463	97.64	114.53
417	8.15	4.7	49.92	0.8	3.06	4.59	1461	97.7	124.11
417	8.8	5.22	49.93	0.82	3.4	5.09	1457	97.47	137.52
416	9.23	5.54	49.94	0.83	3.6	5.54	1454	97.05	145.31

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Table-4. Load Test Data of SCRI.

Voltage	Current	Power	Freq	PF	slip	Torque	Total losses	Speed	Eff	Load %
Volt	Amps	kW	Hz			kgm	W	rpm	%	%
416	4.64	0.64	49.93	0.19	0.00	0.13	305.09	1494	51.86	0.19
414	4.64	0.9	49.88	0.27	0.01	0.35	305.09	1491	65.38	0.27
419	4.96	1.28	49.86	0.36	0.01	0.61	320.27	1487	73.96	0.36
416	5.13	1.73	49.86	0.47	0.01	0.97	328.75	1483	79.68	0.47
415	6.19	3.02	49.86	0.67	0.02	1.86	388.07	1473	85.15	0.68
414	6.54	3.34	49.9	0.71	0.02	2.13	410.09	1471	85.6	0.71
417	7.71	4.34	49.88	0.78	0.02	2.82	492.50	1463	85.03	0.78
417	8.15	4.7	49.92	0.8	0.03	3.06	527.00	1461	86.05	0.8
417	8.8	5.22	49.93	0.82	0.03	3.4	581.46	1457	85.88	0.83
416	9.23	5.54	49.94	0.83	0.03	3.6	619.78	1454	85.66	0.84

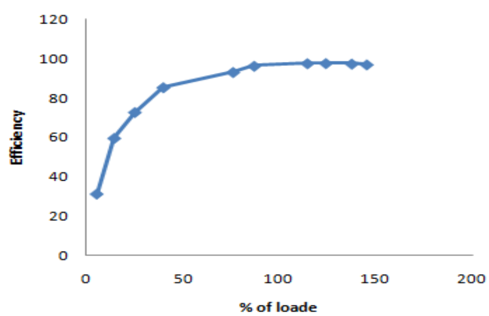

Figure-10. Effiency Vs % load.

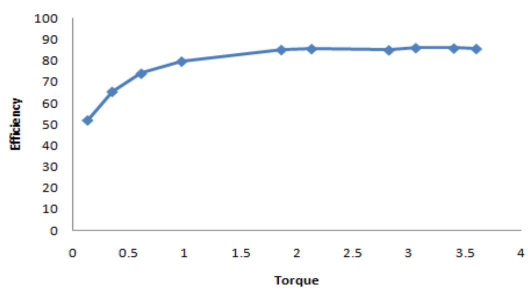

Figure-11. Effiency Vs Torque.

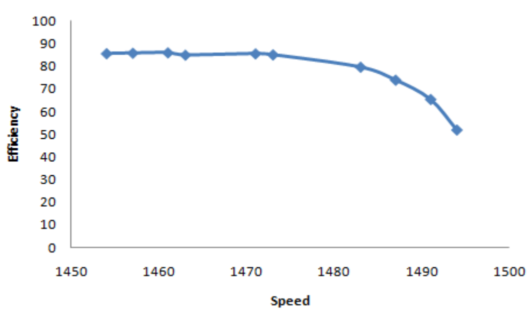

Figure-12. Effiency Vs Speed.

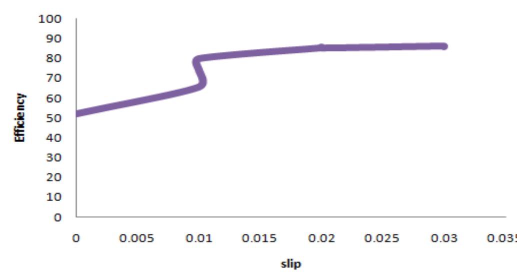

Figure-13. Effiency Vs Slip.

Table-3. .All Motor Performance Comparison.

Parameter	SM	SCRIM (simulation)	SCRIM (testing)
Te (N-m)	25.254	25.539	27.65
η	85.586	87.79	86.03
P.F	0.679388	0.670861	0.78
Speed (rpm)	1420.93	1461.44	1463.0
Plosses (W)	640.028	520.626	527.00

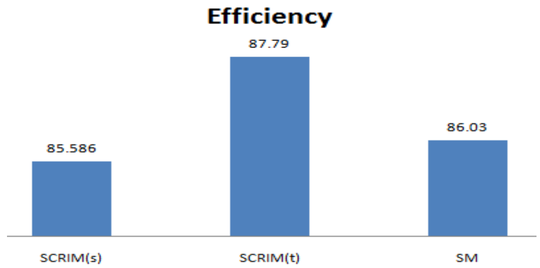

Figure-14. All Motor Efficiency Comparison.

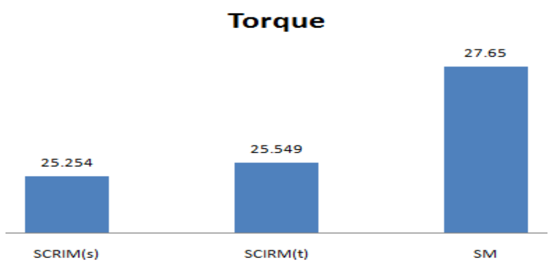

Figure-15. All Motor Torque Comparison.

7. CONCLUSIONS

A design for 3-phase 50Hz 5hp squirrel copper rotor cage induction motor using Time Domain Finite Element Method TDFEA has been proposed. Simulation and experimental results on prototype has been compared and observed that proposed copper rotor motor has higher efficiency, lower losses and good torque makes suitable application on both industrial as well as agricultural sectors.

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