Third International Conference on
Advances in Control and Optimization of Dynamical Systems
March 13-15, 2014. Kanpur, India

Design of a Three Phase Squirrel Cage Induction Motor for Electric Propulsion System

Ravi Prakash*,Mohammad JunaidAkhtar,**
R. K.Behera, S. K.Parida****

*Department of Electrical Engineering
National Institute of Technology, Silchar ,Assam, India (e-mail: ravipr955@gmail.com).
**Department of Electrical Engineering
Indian Institute of Technology, Patna, India (e-mail:junaid,rkb,skparida@iitp.ac.in)

Abstract: This paper presents the design of three-phase induction motor (IM) for high speed with torque speed curve suitable for vehicle propulsion applications. First, analysis of induction motor with the classical approach to machine design is presented and this method is verified by a commentary on contemporary design using RMxprt and design optimization techniques. This paper will describe how RMxprt analysis can be utilized to design and model the performance of rotary electrical machines. Maxwell2D Design software is used as finite element analysis tool to design and model the performance of 5 hp, 4-pole, 2400 rpm induction motor.

*Keywords:*Induction motor, locked rotor torque, power factor, efficiency, genetic algorithm

1. INTRODUCTION

Cage rotor induction motor (IM) is widely accepted as the most potential candidate for electric propulsion owing, to their reliability, robustness, less maintenance and ability to work in hostile environments. These induction motors require special attention during its design process (Boldeo and Nasar (2002)). A primary consideration for induction motor designer is the design of motor with high starting torque, better efficiency and power factor. There are many design components like stator core diameter, core length, air gap length, stator and rotor slot shape and many others parameters which are considered during design process to achieve the desired performance (Parasiliti and Bertoldi (2003)).

Induction motors used for electric propulsion are principally similar to that for industrial applications. Nevertheless, these induction motors need to be especially designed according to Indian road transportation standards. Laminated thin silicon cores should be used for the rotor and stator to reduce the iron loss, while copper bars should be adopted for squirrel cage to reduce winding loss. All housings should be made of cast aluminum to reduce the total motor weight. Low stray reactance is also necessary to work under flux weakening operation as addressed by Rama et al. (1997). Concerning on motor performances for Electric Vehicle (EV) operation, high torque at low speeds, low torque at high speeds and instantaneous overloading capability are desired for hill climbing, highway cruising and vehicle overtaking, respectively.

In order to optimize motor geometries and parameters, Computer Aided Designing (CAD) techniques are employed by Wirasinghaet al. (2008), Wang et al. (2005) and Finken et al. (2008). In general, the two-dimensional finite element method (FEM) is used to carry out both steady state and dynamic electromagnetic field analysis. Moreover, it is becoming interested in three-dimensional FEM-based thermal field analysis of induction motors. The reason is due to the fact that the skin effect of the motor generally causes a considerable variation of the loss density distribution with respect to time during starting, hence resulting in a serious transient thermal stress on both rotor bars and end-rings.

2. THREE PHASE INDUCTION MOTOR AND PERFORMANCE TARGETS

The basic considerations for an induction motor design includes magnetic loading, the peak of fundamental component of radial flux density in the air-gap of the motor, core length, air-gap length, number of poles, number of stator and rotor slots, stator tooth width and slot depth, thermal resistance at each part of the thermal circuit, speed, torque and efficiency, torque per unit weight and weight of copper and magnetic iron core etc. are used. Along with these requirements, the key challenges are better utilization of steel, magnet and copper, better electromagnetic coupling, better geometry and topology, better thermal design,cooling and understanding the limits of motor performance. Achieve higher power per unit weight, higher torque per unit weight and better performance etc. A suitable specification is needed for a battery operated IM under lower voltage.The specifications are given in Table 1.

Table 1.IM specification

Power rating	5 hp
Type	3-phase
Base frequency	80 Hz
Line-to-line voltage	110V
No. of poles	4
Ambient temperature	50 deg. C
Insulation Class	Class B
Degrees of Protection	IP55
Cooling type	TEFC
Efficiency	84%
Power Factor	0.86
Duty Cycle	70% duty
Bearing	Insulated type

3.Design Methodology

The design process of induction motor is an iterative process. The machine designer first assumes the efficiency and power factor at the rated condition. The below mentioned design process is done as per (Say (2002) and Pyrhonen et al. (2011)). Then KVA input is calculated using (1)

$$Q = \frac{h.p. \times 0.746}{\eta \cos\phi}. \tag{1}$$

where, η =Efficiency and $\cos\phi$ = power factor

The main dimension of the motor is calculated using (2)

$$D^2 L = \frac{Q}{C_o n_s} \tag{2}$$

where,

$C_o = 1.1 k_w B_{av} ac \times 10^{-3}$

D is stator bore diamter

L is core length

n_s is synchronou s speed in r.p.s.

Once the diameter of the stator and length of the core is determined then winding part is calculated using (3)

$$T_s = \frac{E_s}{4.44 f \phi_m k_{ws}} \tag{3}$$

where,

E_s is stator tur n per phase.

f is supply frequency

ϕ_m is flux density

k_{ws} is winding factor

After the winding part is done, then the conductor and slot dimensions are calculated.

Finally the stator outer diameter is given by

$$D_o = D + 2d_{ss} + 2d_{cs} \tag{4}$$

where,

D_o is stator outer diameter

d_{ss} is depth of slot

d_{cs} is depth of stator core

Once the stator design is completed, and then comes the rotor part.

Air gap length is a major part of induction motor design. The air gap length is given by

$$l_g = 1.6\sqrt{D} - 0.25\, mm. \tag{5}$$

where,

l_g is air - gap length

Then the no. of rotor slots are selected such that the difference between no. of stator slots and rotor slots should not be equal to 0,±*p*, ±2*p*, ±3*p*, ±(*p*±1), ±(*p*±2) where *p* is no. of poles.

Now the dimensions of rotor slots are calculated. Then the end ring dimensions are calculated using (6).

$$A_e = \frac{S_r I_b}{\pi p \delta_e}. \tag{6}$$

where,

S_r is no. of rotor slots

I_b is rotor bar current

A_e is end ring area

δ_e is current density in end rings

Finally, rotor diameter is given by

$$D_r = D - 2l_g \tag{7}$$

where,

D_r is rotor outer diameter

The inner diameter of rotor lamination is calculated using

$$D_i = D_r - 2d_{sr} - 2d_{cr}. \tag{8}$$

D_i is rotor inner diameter

d_{sr} is depth of rotor slot

d_{cr} is depth of rotor core

The leakage inductance of a machine can be calculated as the sum of different leakage inductances is given as per (Pyrhonen et al. (2011)). The leakage inductance can be divided into the following partial leakage inductances:

(i) air gap leakage inductance
(ii) slot leakage inductance
(iii) tooth tip leakage inductance
(iv) end winding leakage inductance
(v) skew leakage inductance.

Here, only slot leakage inductance is considered.

Slot leakage inductance is an inductance created by real leakage flux. The slot leakage inductance is given by

$$L_u = \frac{4m}{S}\mu_o l^{'} N^2 \lambda_u \tag{9}$$

$$N = \frac{S}{2am} z_S$$

where,

S is no. of slots

m is no. of phase

$l^{'}$ is equivalent core length

λ_u is slot permeance factor

N is no. of series turns

a is no. of parallel paths

z_S is no. of conductors in a slot

Once the design is completed then we can calculate the performance parameters like efficiency, power factor and torque of the machine using circle diagram or equivalent circuit. The efficiency is given by (10)

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + \sum losses}. \tag{10}$$

where,

$$\sum losses = p_{Co} + p_{Al} + p_{iron} + p_{mv} + p_{stray}$$

p_{Co} is stator winding loss

p_{Al} is rotor cage loss

p_{iron} is core loss

p_{mv} is mechanical loss

p_{stray} is stray loss

The power factor can be calculated by equation (11)

$$\cos\varphi = \frac{P}{3U_{ph,s} I_s \eta}. \tag{11}$$

where,

$U_{ph,s}$ is stator voltage

I_s is stator current

The electromagnetic torque is given by

$$T_{em} = \frac{3[U_s(1 - \frac{L_{s\sigma}}{L_m})]^2 \frac{R_r^{'}}{s}}{\omega_s / p[(R_s + R_r^{'}/s)^2 + (\omega_s L_{s\sigma} + \omega_s L_{r\sigma}^{'})^2]} \tag{12}$$

where,

$L_{s\sigma}$ is leakage inductance of stator

L_m is magnetizing inductance

$R_r^{'}$ is rotor resistance referred to stator

R_s is stator resistance

$L_{r\sigma}^{'}$ is leakage inductance of rotor referred to stator

4. CASE STUDY

4.1 Theoretical Calculations

The induction motor is designed using the conventional method as per the specification given in Table 1.All the dimensions are calculated and its performance is also evaluated. The efficiency of the machine is found to be 86%.

4.2 Calculations using machine designing software

The induction motor is designed using the RMxprt software as per the specification given in Table 1. RMxprt software speeds the design and optimization process of rotating electric machines. RMxprt software is electric machine specific user friendly template based designing software. It has the features of optimization, parametric, sensitivity and many other analyses. It can create Maxwell 2D and 3D model for electromagnetic analysis.

Critical performance data, such as torque versus speed, power loss, flux in the air gap, power factor and efficiency can be quickly calculated.

The performance parameter obtained from RMxprt software are given in Table 2

Table 2.Performance parameter obtained from software

Mechanical Shaft Torque (Nm)	15.3114
Efficiency (%)	88.9732
Power Factor	0.862243
Rated Slip	0.0307328
Rated Shaft Speed (rpm)	2326.24
Locked-Rotor Torque (Nm)	37.6459

It has been observed that the efficiency obtained by theoretical calculation is 86% and that from software is 88.97% which is very close to the theoretical result. The power v/s speed curve is plotted in Fig. 1. It is observed that that maximum power is delivered at 1900 rpm.

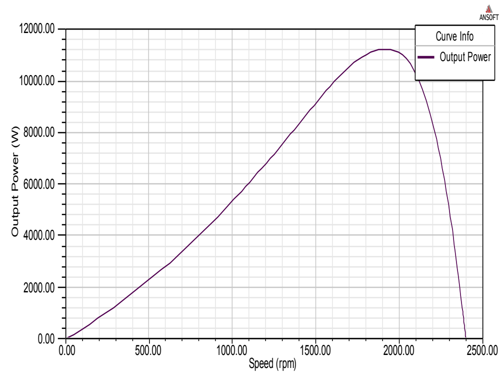

Fig. 1. Output power vs speed

The Torque vs speed curve is plotted in Fig. 2. The locked rotor torque is around 38 N-m, twice as that of rated loadtorque.While breakdown torque is around 4 times that of rated value. These are decent figure for an electric vehicle.

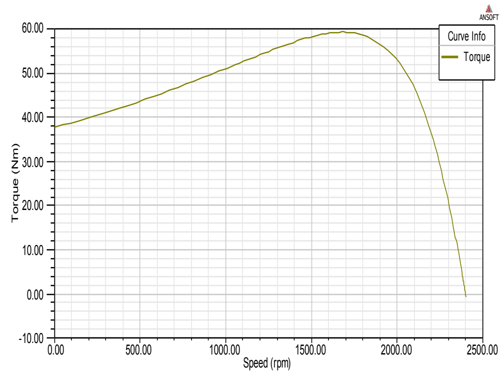

Fig. 2. Torque vs speed curve

The efficiency vs speed curve is plotted in Fig. 3. The maximum efficiency is at around 3.72kW.

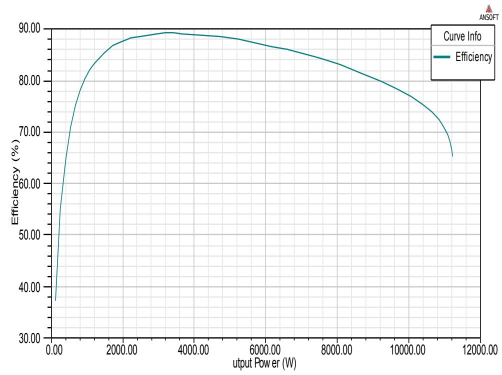

Fig. 3. Efficiency vs Output Power curve

Flux lines plot at rated speed is shown in Fig. 4. It is observed that the lines are not so dense.

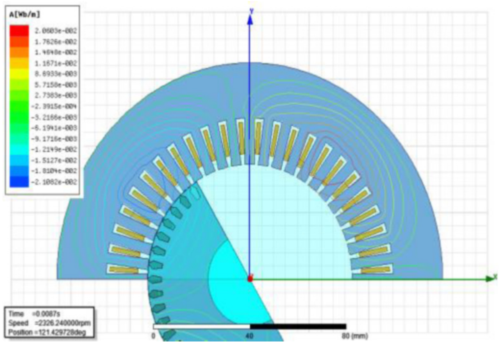

Fig. 4. Flux line plot

In Fig. 5 Flux density plot at rated speed is shown. It can be observed that the stator yoke flux density is around 1.5T which is in the desired limit.

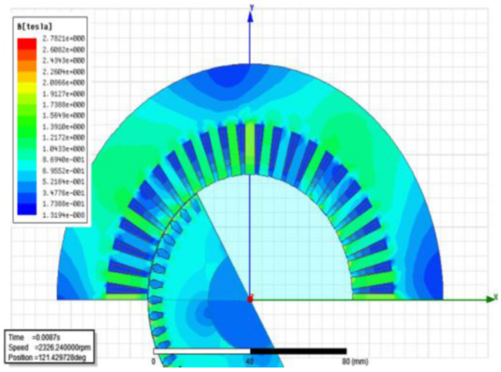

Fig. 5. Flux density plot

In Fig. 6, transient torque curve is plotted. It is found that the maximum peak transient torque is -80Nm and the torque becomes stable at 30 ms.Since the air gap flux density takes time to attain its maximum and constant value, hence till that time due to inertia there is demagnetization of flux. Therefore negative transients torque is present.

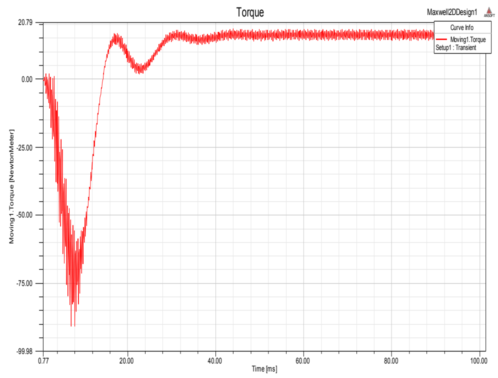

Fig. 6. Transient torque curve

4.3Slot opening is kept constant and slot width is varied

A rectangular slot has been taken as shown Fig. 7. Its dimension is as given below. The slot width (bs1) is varied from 1.5 mm to 4 mm keeping the slot opening (bs0) fixed at

1 mm. The torque vs speed curve is shown in Fig. 8. Different parameters are shown in Table 3.

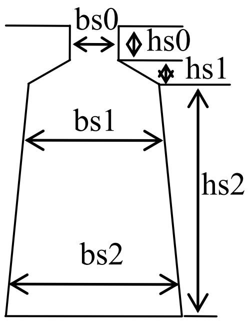

Fig. 7.Stator and rotor slot dimensions

Table 3. Different observation of variable slot width

Slot Opening (mm)	Slot Width (mm)	Locked Rotor Torque (Nm)	Stator Leakage Reactance (ohm)
1	1.5	24.179	0.278639
1	2.0	34.567	0.243259
1	2.5	40.647	0.224525
1	3.0	41.091	0.210076
1	3.5	48.206	0.194967
1	4.0	56.367	0.174367

It is observed that as the slot width (bs1) is increased the slot leakage permeance decreases and from equation (9) the stator leakage inductance decreases as seen in Table 3. And hence from equation (12) we can say that with less leakage inductance, less leakage reactance will be there, so the electromagnetic torque will be higher and therefore will have higher starting torque and break down torque as it is seen in Table 3 and Fig. 8.

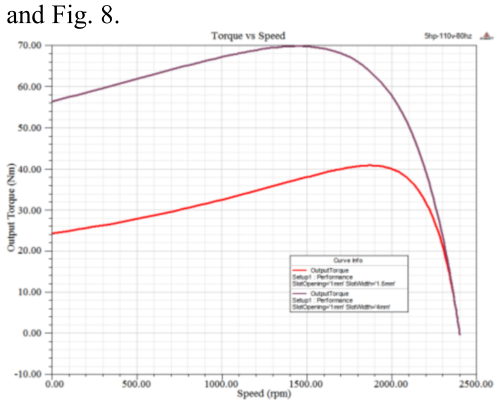

Fig. 8. Torque vs speed curve

4.4 Optimization using Genetic Algorithm of conventional design of induction motor

Optimization is the process of selecting the best solution for a certain problem from the various possible solutions. The solution is chosen in such a way that the design in regard to a particular feature is the best, and at the same time it should satisfy all the constraints imposed on its performance. Here, in the optimization process of three phase induction motor the Genetic algorithm method is implemented. Two different types of cases are considered. In the first case, objective function taken are efficiency, power factor and locked rotor torque and each are optimized individually. In the second case, a goal is set up to get the desired performance in which all the three objective functions are given a desired goal and optimized simultaneously.The optimization is done using RMxprtsoftware .

First objective function: Maximum efficiency

The rated efficiency is maximized and the objective function is given by (10).

Second objective function: Maximum locked rotor torque

The locked rotor torque is maximized and the objective function is given by (12).

Third objective function: Maximum power factor

The power factor is maximized and the objective function is given by (11).

In fourth case a goal setup is done. In this case, a desired goal is given for efficiency, locked rotor torque and power factor.

Table 4 gives the designed parameter used for optimization.The designed parameters need to be bound between upper and lower bound. The design parameters are shown in Fig. 7. The design constraints are given in Table 5.

A comparison is shown between Conventional design and optimized design in Table 6. It is observed that optimized design gives better result than conventional design.

Table 4.Design parameters and their limits

Design parameter	Description	Lower limit (mm)	Upper limit (mm)
h_{s2}	Stator slot height	5.25	15.75
b_{s0}	Stator slot opening	0.35	1.05
b_{s1}	Stator slot width	2.1	6.3
b_{s2}	Stator slot width bottom	1.85	5.55
h_{s2}	Rotor slot height	3	9
b_{s0}	Rotor slot opening	0.525	0.825
b_{s1}	Rotor slot width	0.35	3.3
b_{s2}	Rotor slot width bottom	0.8	2.1

Table 6 gives the comparison of the results of conventional design and optimized design.

Table 5.Design constraints

Air	0.7-0.90 T
Stator yoke flux density	1.4-1.7 T
Tooth flux density (stator)	1.4-2.1 T
Tooth flux density (rotor)	1.5-2.2 T
Rotor yoke	1-1.6T
Stator winding current density	3-8 A/mm^2
Rotor bar current density	3-8 A/mm^2

5. CONCLUSION

A basic design has been introduced here towards the requirement for a propulsion motor. First theoretical design was done using conventional method and then RMxprt software is used for the design. It is found that the theoretical result obtained matches the simulated result. It is observed that as the slot width is increased the torque increases.

The optimization of the conventional designed motor is done using Genetic algorithm. It is observed that the efficiency, power factor and locked rotor torque are improved.

More analysis and development can be done in future regarding parametric variations and optimization of some critical parameters as torque to weight ratio, efficiency etc. to achieve high performance propulsion motor

6. REFERENCES

Boldea, I. and Nasar, N. A. (2002).*The induction machine handbook.*CRC Press.

Finken, T., Felden, M., Hameyer, K. (2008).Comparison and design of different electrical machine types regarding their applicability in hybrid electrical vehicles.In *ICEM-2008, September6-9*.

Parasiliti, F. and Bertoldi, P. (2003).*Energy efficiency in motor driven systems*.Springer.

Pyrhonen, J., Jokinen, T. and Hrabovocova, V. (2011).*Desing of Rotating Electrical Machines.*Wiley.

Rama, J. C. and Gieseche, A. (1997). High-Speed Electric Drives: Technology and Opportunity. *IEEE IAS Annual Meeting,* 3(5), 48-55.

Say, M. G. (2002). *Performance and design of AC machines.*CRC Press.

Wirasingha, S. G., Schofield, N. and Emadi, E. (2008).Plug-in Hybrid electric vehicle developments in the US trends, barriers, and economic feasibility. In *IEEE Vehicle Power and Prop.*, *VPPC-2008*, *September 3-5*.

Wang, T., Zheng, P., Zhang, Q. and Cheng, S. (2005). Design Characteristics of Induction Motor Used for Hybrid Electric Vehicle. *IEEE Trans. Magnetics*, 41(1), 505-508.

Table 6.Comparisons with conventional design and optimized design

	Conventional design	Maximum efficiency	Maximum power factor	Maximum locked rotor torque	Goal: Efficiency > 86% Power factor >0.86 Locked rotor torque > 45Nm
Stator slot					
hs2 (mm)	10.5	15.08	9.68	10.11	8.92
bs0 (mm)	0.7	1.01	0.55	0.35	0.91
bs1 (mm)	4.2	5.61	2.95	5.80	2.53
bs2 (mm)	3.7	3.88	3.58	4.75	4.18
Rotor slot					
hs2 (mm)	6	7.92	7.72	7.81	5.49
bs0 (mm)	0.55	0.45	0.30	0.79	0.50
bs1 (mm)	2.2	2.44	2.39	3.15	2.49
bs2 (mm)	1.28	1.50	0.96	1.28	1.78
Efficiency (%)	88.97	92.90	91.55	91.3	91.15
Power Factor	0.86	0.67	0.86	0.60	0.87
Locked-Rotor Torque (Nm)	37.64	122.10	57.84	132.3	64.16