ISSN (e): 2250 – 3005 || Volume, 06 || Issue, 7|| July – 2016 ||
International Journal of Computational Engineering Research (IJCER)

Three Phase SquirrelCage Induction Motor design RMxpert analysis

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Abstract: *Thispaperpresentsthedesignofthree-phaseinductionmotor(IM)forhighspeedwithtorque speedcurvesuitableforvehiclepropulsionapplications. First,analysisofinductionmotorwiththe classicalapproachtomachinedesignispresentedandthismethodisverifiedbyacommentary on contemporary designusingRMxprtanddesignoptimizationtechniques. Thispaperwilldescribehow RMxprtanalysiscanbeutilizedtodesignandmodeltheperformance ofrotaryelectricalmachines. Maxwell2DDesignsoftwareisusedasfiniteelementanalysistooltodesignandmodeltheperformance of5 hp,4-pole,2400rpminductionmotor*.
Keywords:*Inductionmotor,lockedrotortorque,powerfactor,efficiency,geneticalgorithm*

I. INTRODUCTION

In order to optimize motor geometries and parameters,Cagerotorinduction motor(IM)iswidely acceptedasthe mostpotentialcandidatefor electricpropulsionowing, to theirreliability,robustness,lessmaintenance andabilityto workin hostileenvironments.Theseinduction motorsrequire specialattention duringitsdesignprocess (BoldeoandNasar(2002)). A primary consideration for induction motor designeristhedesign ofmotorwithhighstarting torque, betterefficiency andpowerfactor.Therearemanydesign components likestatorcorediameter,corelength,airgap length, stator and rotor slot shape and many others parameters whichareconsidered during design processto achievethedesiredperformance(ParasilitiandBertoldi(2003)).

Inductionmotorsusedforelectricpropulsion areprincipally similartothatforindustrial applications.Nevertheless, these inductionmotorsneedtobeespeciallydesignedaccordingto Indianroadtransportation standards.Laminatedthinsilicon coresshouldbeusedfortherotorandstatortoreducethe ironloss,whilecopperbars shouldbeadoptedforsquirrel cagetoreducewindingloss.Allhousings shouldbemadeof castaluminum toreducethetotalmotorweight.Lowstray reactanceisalsonecessary toworkunderfluxweakening operationasaddressedbyRamaetal.(1997).Concerning on motorperformancesforElectricVehicle(EV)operation,high torqueatlow speeds,lowtorqueathighspeedsand instantaneous overloading capability aredesiredforhill climbing,highway cruising andvehicle overtaking, respectively.

ComputerAidedDesigning (CAD)techniquesareemployed byWirasinghaetal. (2008), Wangetal. (2005)andFinkenet al. (2008).In general,the two-dimensionalfinite element method(FEM)isusedtocarry outbothsteady stateand dynamicelectromagnetic fieldanalysis.Moreover,itis becominginterestedinthree-dimensionalFEM-basedthermal fieldanalysisofinductionmotors. Thereasonisduetothe fact that the skin effect of the motor generallycauses a considerable variation ofthelossdensitydistributionwith respecttotimeduringstarting,henceresulting inaserious transientthermalstressonbothrotorbarsandend-rings.

II. THREEPHASEINDUCTIONMOTORAND PERFORMANCETARGETS

Thebasicconsiderations foraninductionmotordesign includesmagnetic loading,thepeakoffundamental component ofradialfluxdensity intheair-gapofthemotor, core length,air-gaplength, numberofpoles,numberofstator androtorslots,stator toothwidth andslotdepth, thermal resistanceateachpartofthethermalcircuit,speed,torque andefficiency, torqueperunitweightandweightofcopper andmagnetic ironcoreetc.areused.Alongwiththese requirements, thekey challenges are better utilization of steel,magnetandcopper,betterelectromagnetic coupling, bettergeometry andtopology,betterthermaldesign,cooling andunderstanding thelimitsofmotorperformance.Achieve higherpowerperunitweight, highertorque perunitweight andbetter performanceetc.Asuitable specificationisneeded 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

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. [illegible]

$$O = \frac{h.p.\times 0.746}{\eta \cos\phi}. \qquad (1)$$

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

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

$$D^2 L = \frac{\hat{}}{C_o n_s} \qquad (2)$$

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)

$$T_s = \frac{E_s}{4.44 f \phi_m k_{ws}} \qquad (3)$$

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

$$D_o = D + 2d_{ss} + 2d_{cs} \qquad (4)$$

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

$$l_g = 1.6\sqrt{D} - 0.25\, mm. \qquad (5)$$

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,$\pm p$, $\pm 2p$, $\pm 3p$, $\pm(p\pm 1)$, $\pm(p\pm 2)$ where p is no. of poles.

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

$$A_e = \frac{}{\pi p \delta_e}. \qquad (6)$$

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

$$D_r = D - 2l_g \qquad (7)$$

where,

D_r is rotor outer diameter

The inner diameter of rotor lamination is calculated using

$$D_i = D_r - 2d_{sr} - 2d_{cr}. \qquad (8)$$

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

$$L_u = \frac{4}{S}\mu_0 l N \lambda_u \tag{9}$$

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

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,

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

p_{Cu} 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)

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

where,

$U_{ph,s}$ is stator voltage

I_s is stator current

The electromagnetic torque is given by

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

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.

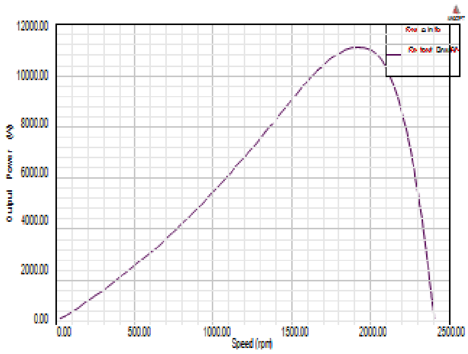


Fig. 1. Output power vs speed

TheTorque vsspeedcurveisplottedinFig.2.Thelocked rotortorque isaround 38N-m,twiceasthatofrated loadtorque.Whilebreakdowntorqueisaround4timesthatof ratedvalue.Thesearedecentfigure foranelectricvehicle.

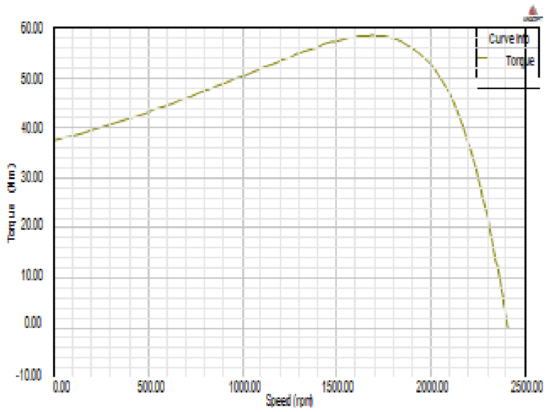


Fig. 2. Torque vs speed curve

The efficiencyvsspeed curve is plotted in Fig. 3. The maximumefficiencyisataround3.72kW.

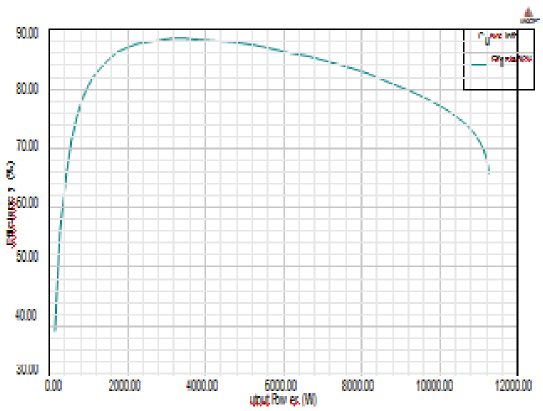
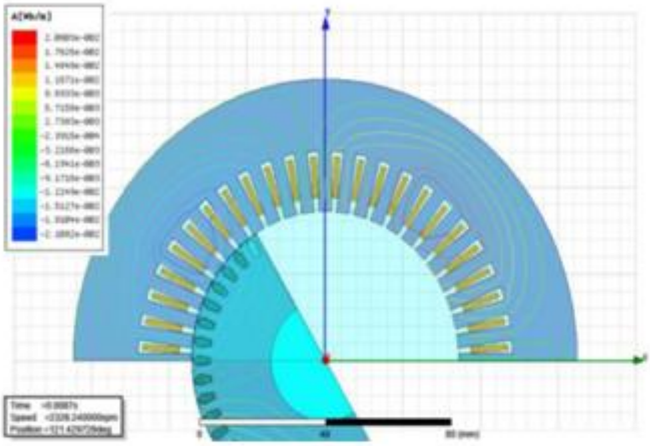


Fig. 3. Efficiency vs Output Power curve

Flux linesplot at rated speed is shown in Fig. 4. It isobservedthatthelinesare notsodense.

Fig.4. Fluxlineplot



InFig.5Fluxdensity plotatratedspeedisshown.Itcanbe observedthatthestatoryokefluxdensity isaround1.5T whichisinthedesiredlimit.

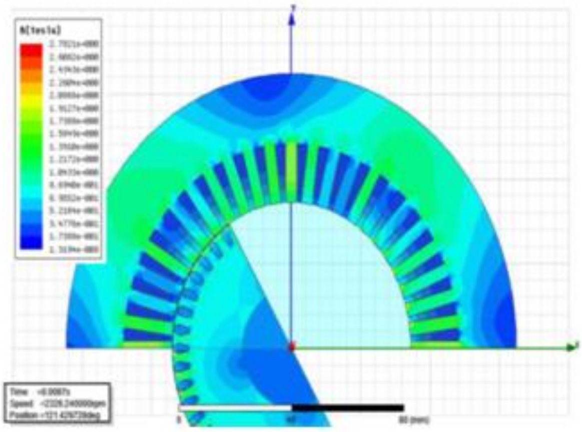


Fig. 5. Flux density plot

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.

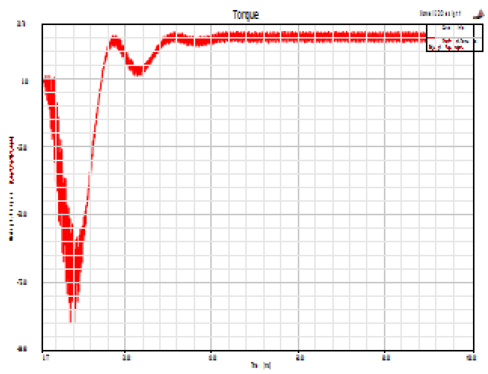


Fig. 6. Transient torque curve

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 at1 mm. The torquevs speed curve is shown in Fig. 8. Different parameters are shown in Table 3.

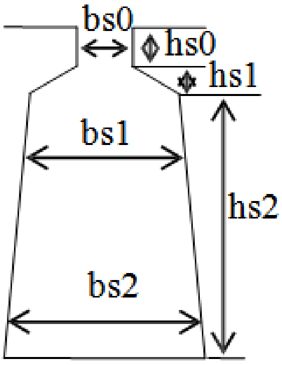


Fig. 7.Stator and rotor slot dimensions

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

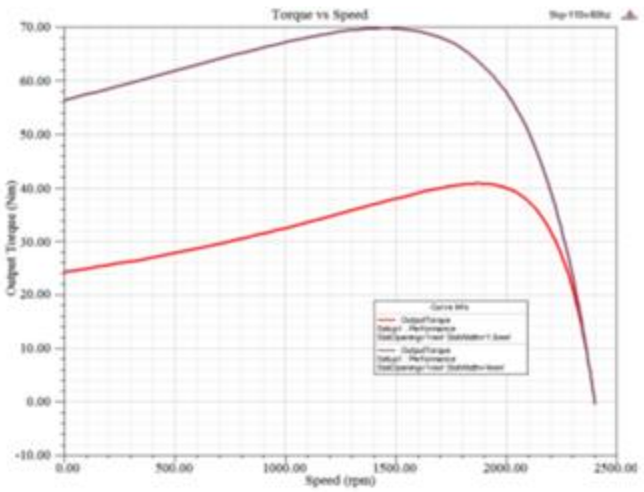


Fig. 8. Torque vs speed curve

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. Herein 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 .

Theratedefficiency ismaximizedandtheobjectivefunction isgivenby(10).

Secondobjectivefunction:Maximumlockedrotortorque

Thelockedrotortorqueismaximized andtheobjective functionisgivenby(12).

Thirdobjectivefunction:Maximumpowerfactor

Thepowerfactorismaximized andtheobjectivefunctionis givenby(11).

Infourthcase agoal setup is done.Inthiscase,adesiredgoal isgivenforefficiency,lockedrotortorqueandpowerfactor.

Table 4givesthedesigned parameterusedfor optimization.Thedesignedparametersneedtobebound betweenupperandlowerbound.Thedesignparameters are showninFig.7. Thedesignconstraintsare giveninTable 5.

AcomparisonisshownbetweenConventional designand optimized design inTable6.Itisobservedthatoptimized designgivesbetterresultthanconventionaldesign.

Table4.Designparametersandtheirlimits

Design parameter	Description	Lower limit (mm)	Upper limit (mm)
h_{s2}	Statorslotheight	5.25	15.75
b_{s0}	Statorslotopening	0.35	1.05
b_{s1}	Statorslotwidth	2.1	6.3
b_{s2}	Statorslotwidthbottom	1.85	5.55
h_{s2}	Rotorslotheight	3	9
b_{s0}	Rotorslotopening	0.525	0.825
b_{s1}	Rotorslotwidth	0.35	3.3
b_{s2}	Rotorslotwidthbottom	0.8	2.1

Table6givesthecomparison oftheresults ofconventional designandoptimizeddesign.

Table5.Designconstraints

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

V. 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

Table6.Comparisonswithconventionaldesignandoptimizeddesign

	Conventional design	Maximum efficiency	Maximum powerfactor	Maximum lockedrotor torque	Goal:Efficiency > 86%Powerfactor >0.86 Lockedrotortorque>45Nm
			S		
hs2(mm)	10. 5	15.08	9.68	10.11	8
bs0(mm)	0.	1.01	0.55	0.35	0
bs1(mm)	4.	5.61	2.95	5.80	2
bs2(mm)	3.	3.88	3.58	4.75	4
			R		
hs2(mm)	6	7.92	7.72	7.81	5
bs0(mm)	0.5	0.45	0.30	0.79	0
bs1(mm)	2.	2.44	2.39	3.15	2
bs2(mm)	1.2	1.50	0.96	1.28	1
Efficiency(%)	88.97	92.90	91.55	91.3	9 1
PowerFactor	0.8	0.67	0.86	0.60	0
Locked-Rotor Torque(Nm)	37.64	122.10	57.84	132.3	6 4

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