RESEARCH ARTICLE OPEN ACCESS

Analysis of the Effect of Electric and Magnetic Loadings on the Design Parameters of an Induction Motor and Its Performance Using Matlab/Simulink

Folorunso Oladipo*, Olowu Temitayo O**, Orizu Eziafa F***.
*(Department of Electrical/Electronic & Computer Engineering, Afe Babalola University, Ado Ekiti, Nigeria)
**(Department of Electronic & Electrical Engineering, Obafemi Awolowo University, Ile-Ife, Nigeria)
***(National Engineering Design Development Institute, Nnewi, Nigeria)

Abstract
This paper looks at the effect of magnetic loading and electric loading on the design parameters of an induction motor and its performance. The study involves the use of MATLAB to simulate 50kW, 3-phase, 415V, 50Hz, 6 poles induction machine. Based on the variation of the magnetic and electric loading of the machine, the various design values of the rotor and stator of the machine are specified. The performance index which includes stator loss, rotor loss, cost, power factor, efficiency, and torque are also specified for squirrel cage induction motor (SCIM)
Keyword: MATLAB, stator, rotor, magnetic loading, electric loading, SCIM.

I. INTRODUCTION

Generally, all rotating electrical machines work by the interaction of the magnetic field set up in stator and rotor windings of the machines to convert mechanical energy into electrical energy and vice versa. These machines include induction motors, direct current motors, synchronous motors and other rotating electrical machines. The commonly used of all these machines is the induction motor; reason for this is its ruggedness, and lower cost [1]. One major feature that differentiates induction motor from synchronous motor is the slip between the rotational speed of the stator field and somewhat slower speed of the rotorfield. The synchronous machines run at the speed that equals the synchronous speed of the stator field. [2]
The performance analysis of a 50KW, 3-phase 6-poles induction motor is the central focus of this paper. This is based on effect of the electromagnetic loading of the machine.
This gives an insight to how this motor can be adapted to various drives purposes.

II. ELECTRIC AND MAGNETIC LOADING IN INDUCTION MOTORS:

There are two parameters that guide the design of electric motors which are, the specific electric loading, and the specific magnetic loading. These parameters have a direct bearing on the output of the motor.

The specific electric loading (B) is the average radial flux density over the cylindrical surface of the rotor, while the specific electric loading (q) is the axial current per meter of circumference of the rotor [3].

Advantages of higher value of B include lower size of the machine, decrease in cost of the machine, increase in machine overload capacity [4].
Advantages of higher value of q include reduced size, reduced cost of machine.

Disadvantages of higher value of q include, higher amount of copper, more copper losses, increased temperature rise, lower overload capacity [4]

III. METHODOLOGY

3.1 DEVELOPMENT OF SIMULATION GUI USING MATLAB

MATLAB is built around a programming language, and as such it’s really designed with tool-building in mind. Guide extends MATLAB’s support for rapid coding into the realm of building GUIs. Guide is a set of MATLAB tools designed to make building GUIs easier and faster. Just as writing math in MATLAB is much like writing it on paper, building a GUI with Guide is much like drawing one on paper. As a result, you can lay out a complex graphical tool in minutes. Once your buttons and plots are in place, the Guide Callback Editor lets you set up the MATLAB code that gets executed when a particular button is pressed [5]. The full meaning of GUI is Graphics User Interface.

3.2. MODELING EQUATIONS

In design of electrical machines, the requirement is to design the stator core, tooth and windings. Similarly, rotor core, tooth and rotor windings.

3.2.1 POWER OUTPUT EQUATION OF ELECTRICAL MACHINES

This gives a relationship between length, diameter (physical dimension) and electrical rating of the machine. For a single phase machine, power is expressed in the form

$$p = ivcos\emptyset \quad \dots\dots\dots.1$$

Considering efficiency of device, then output power is given in equation 2:

$$p_o = ivcos\emptyset * \eta \quad \dots\dots\dots 2$$

For multi-phase machine,

$$p_o = mivcos\phi * \eta * 10^{-3}$$

where m = number of phase
v = input voltage (phase)
i = input phase current
cos∅ = input power factor
η = efficiency of motor

By considering the RMS of voltage ($v = 4.44F\varphi Nk_w$, substituting the magnetic loading ($\varphi = \frac{\pi B_g DL}{P}$) and the electric loading ($Q\pi D = 2mNi$), the power output is expressed as given in equation 3.

$$p_o = c_o D^2 Ln \quad \dots\dots.3$$

c_o is the output coefficient of the machine which is given as $1.11\pi^2 B_g k_w Q * 10^{-3}$; n is speed in rps.

From equation 3, conclusion it can be concluded that output power of a machine is a function of its main dimension, specific magnetic loading and electric loading.

3.2.2 STATOR DESIGN EQUATIONS

The following equations are few of part equations considered:

$$volume\ of\ machine = \frac{p_{in}}{c_o * n} \dots\dots 4$$

$$Axial\ lenght, L = \sqrt{\frac{volume}{0.018225 * P^2}} \dots.5$$

where P is the number of poles.

$$Bore\ diameter, D = \sqrt[3]{\frac{p_{in} * P}{c_o \pi n}} \dots\dots 6$$

$$Velocity = \frac{\pi D}{P} \quad \dots\dots\dots.7$$

$$N = \frac{v}{4.44 * F * \varphi * k_w} \dots\dots 8$$

$$\frac{conductor}{phase} = 2mN \quad \dots\dots.9$$

$$lenght\ of\ air\ gap, l_g = \frac{0.2 + \sqrt{DL}}{1000} \dots\dots.10$$

$$stator\ slot, Ss = 3mP \dots\dots.11$$

$$cross\ sectional\ area, As = \frac{i}{Js} \dots\dots 12$$

where Js is the stator current density

$$depth\ of\ the\ stator\ core, dsc = \frac{\pi B_g D}{B_{sc} P} \quad \dots\dots\dots 13$$

$$width\ of\ the\ stator\ slot, wst = \frac{\pi B_g D}{B_{st} Ss} \quad \dots\dots.14$$

$$lenght\ of\ mean\ turn, lmt = 2L + 2.3\left(\frac{\pi D}{P}\right) + 0.24 \dots\dots\dots.15$$

$$resistance\ of\ the\ stator\ winding, Rs = \frac{0.021 * 10^{-6} * lmt * N}{As} \dots\dots.16$$

$$copper\ loss, Culoss = 3i^2 Rs \quad \dots 17$$

$$outer\ diameter, Do \cong \frac{D}{0.55} \dots.18$$

$$depth\ of\ stator\ slot, dss = \frac{Do - D + 2dsc}{2} \dots.19$$

3.2.3 ROTOR DESIGN EQUATIONS

The various rotor parts considered in this study include the following.

$$rotor\ slot, rslot \cong 1.5 + (Ss - 1) + ((Ss - 2) + (Ss - P - 1) + (Ss - P - 2))/4 \ ..20$$

$$the\ rotor\ conductor = \frac{2mN}{0.55} \dots\dots.21$$

$$the\ rotor\ diameter, Dr = D - 2\lg \quad \dots\dots.22$$

$$the\ width\ of\ the\ rotor, wrt = \frac{\pi B_g Dr}{B_{rt} * rslot} \dots.23$$

$$depth\ of\ rotor\ core, drc = \frac{\pi B_g D}{B_{rc} P} \dots 24$$

$$the\ rotor\ bar\ , ir = 0.85i \quad \dots..25$$

$$the\ rotor\ bar\ current, ib = ir * k_w * Ss * \frac{Zs}{rslot} \dots 26$$

$$the\ lenght\ of\ rotor\ bar, lb = L + 0.046 \quad \dots..27$$

$$rotor\ bar\ cross\ sectional\ area, Ab = \frac{ib}{Jr} \dots\dots.28$$

where Jr is the rotor bar current density;

$$rotor\ resistance, rb = 0.021 * 10^{-6} * \frac{lb}{Ab} \dots..29$$

$$copper\ loss, curotor = ib^2 rb * rslot \dots 30$$

$$end\ ring\ current, ie = rslot * \frac{ib}{\pi P} \dots.31$$

$$length\ due\ to\ end\ ri, lme \cong \pi(D - 0.48) \dots 32$$

$$end\ ring\ area, ae = \frac{ie}{Je} \dots..33$$

$$resistance\ due\ to\ end\ ring, Re = 0.021 * 10^{-6} * \frac{lme}{ae} \dots..34$$

$$end\ ring\ loss = 2ie^2 Re \quad \dots\dots 35$$

IV. SIMULATION INPUT AND OUTPUT

Table 1: Variation of Electrical Loading with all other parameter remain constant

MODELING INPUT PARAMETERS						
	UNIT	1	2	3	4	5
ELECT. LOADING	**ac/m**	11000	15000	18000	22000	26000
MAGNETIC LOADING	**Tesla**	0.48	0.48	0.48	0.48	0.48
WINDING FACTOR		0.955	0.955	0.955	0.955	0.955
STATOR TOOTH FLUX DENSITY	**Tesla**	2.1	2.1	2.1	2.1	2.1
STATOR CURRENT DENSITY	**A/m2**	6	6	6	6	6
ROTOR BAR CURRENT DENSITY	**A/m2**	6.5	6.5	6.5	6.5	6.5
STATOR CORE FLUX DENSITY	**Tesla**	1.7	1.7	1.7	1.7	1.7
END RING CURRENT DENSITY	**A/m2**	5.5	5.5	5.5	5.5	5.5
POLES		6	6	6	6	6
FREQUENCY	**Hz**	50	50	50	50	50
ROTOR TOOTH FLUX DENSITY	**Tesla**	1.5	1.5	1.5	1.5	1.5
ROTOR CORE FLUX DENSITY	**Tesla**	1.2	1.2	1.2	1.2	1.2
VOLTAGE	**Volts**	240	240	240	240	240
POWER OUTPUT	**kW**	50	50	50	50	50
EFFICIENCY		0.89	0.89	0.89	0.89	0.89
POWER FACTOR		0.86	0.86	0.86	0.86	0.86
PHASE		3	3	3	3	3

Table 2: Variation of Magnetic Loading with all other parameter remain constant

MODELING INPUT PARAMETERS						
	UNIT	1	2	3	4	5
ELECT. LOADING	**ac/m**	11000	11000	11000	11000	11000
MAGNETIC LOADING	**Tesla**	0.48	0.5	0.62	0.72	0.82
WINDING FACTOR		0.955	0.955	0.955	0.955	0.955
STATOR TOOTH FLUX DENSITY	**Tesla**	2.1	2.1	2.1	2.1	2.1
STATOR CURRENT DENSITY	**A/m2**	6	6	6	6	6
ROTOR BAR CURRENT DENSITY	**A/m2**	6.5	6.5	6.5	6.5	6.5
STATOR CORE FLUX DENSITY	**Tesla**	1.7	1.7	1.7	1.7	1.7
END RING CURRENT DENSITY	**A/m2**	5.5	5.5	5.5	5.5	5.5
POLES		6	6	6	6	6
FREQUENCY	**Hz**	50	50	50	50	50
ROTOR TOOTH FLUX DENSITY	**Tesla**	1.5	1.5	1.5	1.5	1.5
ROTOR CORE FLUX DENSITY	**Tesla**	1.2	1.2	1.2	1.2	1.2
VOLTAGE	**Volts**	240	240	240	240	240
POWER OUTPUT	**kW**	50	50	50	50	50
EFFICIENCY		0.89	0.89	0.89	0.89	0.89
POWER FACTOR		0.86	0.86	0.86	0.86	0.86
PHASE		3	3	3	3	3

Table 3: Output of the Machine Design with respect to Electrical loading

STATOR DESIGN		Iteration				
Parameter	Unit	1	2	3	4	5
Stator Slot		54	54	54	54	54
Total Conductor Per Slot		3.27653	4.13464	4.74049	5.51044	6.24596
Per Phase Stator Current	Amp	90.7296	90.7296	90.7296	90.7296	90.7296
Sectional Area of Stator Conductor	m^2	15.1216	15.1216	15.1216	15.1216	15.1216
Depth of Stator Slot	m	0.127046	0.117567	0.112328	0.106832	0.102462
Width of Stator Tooth	m	0.006177	0.005716	0.005462	0.005194	0.004982
Length of Mean Turn	m	1.45704	1.32084	1.2487	1.17542	1.11892
Resistance of Stator Winding	Ohm	5.97E-08	6.83E-08	7.40E-08	8.10E-08	8.73E-08
Total Copper Losses	kW	0.001474	0.001686	0.001827	0.001999	0.002157
Depth of the Stator Core	kW	0.034338	0.031776	0.03036	0.028875	0.027694
Outer Diameter	m	0.787237	0.728502	0.696042	0.661985	0.634907

ROTOR DESIGN		Iteration				
Parameter	Unit	1	2	3	4	5
Rotor Slot		51	51	51	51	51
Number of Turns		53.6159	67.6577	77.5717	90.1708	102.207
Total Rotor Conductor		321.695	405.946	465.43	541.025	613.24
Rotor Diameter	m	0.463288	0.428721	0.409615	0.389568	0.373629
Width of Rotor Tooth	m	0.009134	0.008452	0.008075	0.00768	0.007366
Depth of Rotor Core	m	0.048522	0.044901	0.0429	0.040801	0.039131
Rotor Current	Amp	77.1202	77.1202	77.1202	77.1202	77.1202
Rotor Bar Current	Amp	255.51	322.428	369.674	429.716	487.073
Length of Rotor Bar	m	0.37881	0.331576	0.307043	0.282504	0.263872
Cross Sectional Area	m	39.3093	49.6043	56.8729	66.1101	74.9343
Rotor Resistance	Ohms	1.93E-10	1.34E-10	1.08E-10	8.55E-11	7.04E-11
Rotor Copper Loss	kW	0.000642	0.000709	0.000753	0.000805	0.000852
End Ring Loss	kW	0.000209	0.000242	0.000263	2.89E-04	0.000312

Output Design Value		Iteration				
Parameter	Unit	1	2	3	4	5
The Input Power	KVA	65.3253	65.3253	65.3253	65.3253	65.3253
The output Coefficient		55.2551	75.3479	90.4175	110.51	130.603
Bore Diameter	m	0.46447	0.429816	0.410665	0.390571	0.374595
The Axial Length	m	0.32881	0.281576	0.257043	0.232504	0.213872
Peripheral Velocity	m/s	24.3227	22.508	21.5052	20.4529	19.6163
Pole Pitch		0.243227	0.22508	0.215052	0.204529	0.196163
Total Stator Conductors		176.932	223.27	255.987	297.564	337.282
Machine Volume	m3	0.070935	0.052019	0.043349	0.035468	0.030011
Number of Turns		29.4887	37.2117	42.6644	49.5939	56.2136
Length of Air-gap	m	0.000591	0.000548	0.000525	0.000501	0.000483

Table 4: Output the Machine Design with Magnetic Loading

STATOR DESIGN		Iteration				
Parameter	Unit	1	2	3	4	5
Stator Slot		54	54	54	54	54
Total Conductor Per Slot		3.24326	3.16689	3.07345	2.96068	2.86596
Per Phase Stator Current	Amp	90.7296	90.7296	90.7296	90.7296	90.7296
Sectional Area of Stator Conductor	m^2	15.1216	15.1216	15.1216	15.1216	15.1216
Depth of Stator Slot	m^2	0.124339	0.117955	0.109777	0.099285	0.089851
Width of Stator Tooth	m^2	0.006369	0.006841	0.007484	0.008373	0.00923
Length of Mean Turn	m	1.43808	1.39505	1.34338	1.28244	1.23246
Resistance of Stator Winding	ohm	5.83E-08	5.52E-08	5.16E-08	4.75E-08	4.41E-08
Total Copper Losses	kW	0.00144	0.001364	0.001274	0.001172	0.00109
Depth of the Stator Core	kW	0.035406	0.038029	0.041604	0.046542	0.05131
Outer Diameter	m	0.779244	0.760896	0.738445	0.711349	0.688593

ROTOR DESIGN		Iteration				
Parameter	Unit	1	2	3	4	5
Rotor Slot		51	51	51	51	51
Number of Turns		53.0715	51.8219	50.2928	48.4474	46.8976
Total Rotor Conductor		318.429	310.931	301.757	290.684	281.385
Rotor Diameter	m	0.458584	0.447786	0.434572	0.418625	0.40523
Width of Rotor Tooth	m	0.009417	0.010115	0.011066	0.01238	0.013648
Depth of Rotor Core	m	0.05003	0.053737	0.058789	0.065766	0.072504
Rotor Current	Amp	77.1202	77.1202	77.1202	77.1202	77.1202
Rotor Bar Current	Amp	252.916	246.961	239.674	230.88	223.494
Length of Rotor Bar	m	0.372167	0.357174	0.339314	0.318472	0.30157
Cross Sectional Area	m	38.9102	37.994	36.8729	35.52	34.3837
Rotor Resistance	Ohms	1.91E-10	1.88E-10	1.84E-10	1.79E-10	1.75E-10
Rotor Copper Loss	kW	0.000624	0.000585	0.000539	0.000487	0.000447
End Ring Loss	kW	0.000204	0.000194	0.000182	1.69E-04	0.000157

Output Design Value		Iteration				
Parameter	Unit	1	2	3	4	5
The Input Power	KVA	65.3253	65.3253	65.3253	65.3253	65.3253
The output Coefficient		57.5574	63.3132	71.3712	82.8827	94.3942
Bore Diameter	m	0.459754	0.448929	0.435682	0.419696	0.40627
The Axial Length	m	0.322167	0.307174	0.289314	0.268472	0.25157
Peripheral Velocity	m/s	24.0758	23.5089	22.8152	21.9781	21.275
Pole Pitch		0.240758	0.235089	0.228152	0.219781	0.21275
Total Stator Conductors		175.136	171.012	165.966	159.876	154.762
Machine Volume	m^3	0.068098	0.061907	0.054917	0.04729	0.041523
Number of Turns		29.1893	28.502	27.661	26.6461	25.7937
Length of Air-gap	m	0.000585	0.000571	0.000555	0.000536	0.00052

V. CONCLUSION

The choice of magnetic and electrical loading in the design of domestic and industrial machine is very important as these defined the performance of the machine. From the observation of this study, it can be concluded that increase magnetic loading is a better choice for loss reduction, decrease in the outer diameter, decrease in the rotor number of turns, decrease in bore diameter, decrease in rotor diameter, decrease in length of air-gap, etc. The economy benefit of this is reduction in the cost of the machine.

REFERENCE

[1] Austin hughes, Bill Drury,"*Electric motor and drives; fundamentals, types and applications"* Published by Elsevier Ltd.Third edition 2006.

[2] Edward J. Thornton and J. Kirk Armintor " *the fundamental of AC electric induction motor design and application; proceedings of the twentieth international pump users* symppsium, 2003

[3] K. L . SHI, T . F. CHAN, Y. K. WONG and S. L . HO, "*Modelling And Simulation Of The Three-Phase Induction Motor Using Simulink*, Int. J. Elect. Enging. Educ., Vol. 36, pp. 163–172. Manchester U.P., 1999. Printed in Great Britain

[3] A.K Sawhney, "*A course in electrical machine design*" 5th edition.

[5] Building GUI with MATLAB (December, 1996), pg 1-4.