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SWITCHED RELUCTANCE MOTOR DESIGN: A BETTER AND UNIFIED APPROACH

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ABSTRACT Switched Reluctance Motors (SRMs) are one of the most useful special electrical machines. Due to characteristics such as rare-earth free material-based construction, good starting torque, speed range and fault tolerance. Nowadays this machine type is used widely in the electric vehicle industries. Design is done based on the calculations of the physical dimensions. Here a step by step process of design is done by using the principles of electromagnetics. In this paper, the design process is completely described, with the help of an example, of a specified motor. After the calculation of entire dimensions, the feasibility of the machine is verified using the finite element analysis results of the designed machine and the concluded whether design is correct.

KEYWORDS : Electric Vehicle, Finite Element Analysis, SRM.

1. INTRODUCTION

In 1838 using switched reluctance motor a locomotive was propelled, shows that the concept of motor very old [1]. 1970s contributed several concepts in the development of motors working on the principle of variable reluctance [2]. Day by day the control concepts of above-mentioned machine and the strategies of control are developing on the various aspects of requirements. The applications of switched reluctance motor are increasing in the automobile field, in the sense electric vehicles. The advantages of motor such as the rugged structure helps it to operate at harsh environments for long time, along with that the materials used for the construction the motor parts are free from rare earth metals.

SRM is efficient and economic, based on several factors. Numerous papers are existing on the design of SRM, but those are much depending on finite element analysis-based design procedures, in this work a systematic calculation of the design limits are explained. After that a model is designed in the ANSYS Maxwell software to simulate the entire machine, finite element analysis is also done to conclude whether the design aspects were correct or not.

Design of the SRM based on FEA is described in step by step in [3]. Here the process of design is based on the principles of electromagnetics. In this paper, the design process is completely described, with the help of an example of a specified motor. Design starts from the selection of outer frame size, after that the calculations of further dimensions were done. After the calculation's physical dimensions, a method for determining the aligned inductance were applied which was initially done by [4].

The design process which are illustrated here are starting from the basic equations, thus the designer can use this process for other configurations of the machine. After the calculation of the entire dimensions the feasibility of the machine is verified by using the simulation results of the designed machine. The design sheet of the simulation gives the efficiency of the machine too. By comparing the theoretical and simulation result the work is verified.

2. DESIGN OF SRM

Based on an example the design is framed. The procedure for the normal design has been explored in [5] and [6]. After the design in paper is completed the second step in design process is chosen by means of the simulation tool and compare it with the theoretical values.

2.1. SPECIFICATION OF MACHINE

Output Power	= 3730W
Supply voltage, V	= 420V
Initial Rated current, Ip	= 12A
Rated speed, N	= 1450rpm

The torque required can be calculated from the basic equation as,

$$T_{req} = \frac{\text{Output Power}}{2 \times \pi \times N/60} = \frac{3730}{2 \times \pi \times 1450/60} = 24.577\text{Nm} \quad (1)$$

2.2. FRAME SELECTION

Generally, in the case of motor design we start from the outer diameter usually in case of the induction-based machines, so we select the equation for outer diameter as,

$D_o = (\text{Frame Size} - 3)*2$ (2)

Where 3mm is used to account for the foot of the machine for the purpose of mounting. But the frame size is selected according to the IEC71 standards as 100mm [7].

$D_o = (100 - 3)*2 = 194\text{mm}$

2.3. SELECTION OF POLE

Normally the designer fixes the stator and rotor poles initially based on the application and the requirement of the control circuits based on the way in which the motor is designed to be**.** Many combinations are possible for the number of the poles, but the selection only based on the advantages it had. In this work a combination of 8 stator poles and 6 rotor poles are selected, also known as 8/6 machine. The main advantages of this type of machine is that it has only smaller percent of ripples in torque compared to lower combinations of the poles. But as the poles increases the control drive devices number for the motor also increases which may lead to the complexity also to the switching losses too.

2.4. LENGTH, POLE ANGLE, AND SHAFT DIAMETER SELECTION

The crucial part of design is the selection of the stator and rotor pole angles. The constraints for the selection of the above mentioned are detailed on the paper [1] and [8] and can be concluded as three points listed below.

1. The rotor pole arc angle is greater than the stator pole arc angle, i.e., $\beta r > \beta s$.
2. The effective torque zone must be greater than the stroke angle ε but less than the stator pole angle. The step angle can be defined as,

$$\varepsilon = \frac{2\pi}{\frac{N_s}{2}N_r} = 15^\circ \quad (3)$$

The profile of inductance repeats for every (2π/Nr) rad/sec, consider Figure 1.

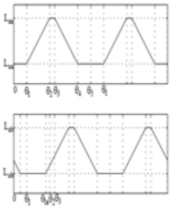


Figure 1. Inductance profiles vs. rotor position of two successive phases

3. The stator pole arc must be less than the corner angle between the adjacent rotor poles else there will be an overlap between the poles in the unaligned position. Based on the guidelines above mentioned, $\beta s = 22°$ and $\beta r = 23°$ are selected and according to IEC the stack length L for this combination is also selected as l80mm. D is primarily presumed to be same to the frame size. Hence D = 100 mm. At this juncture the shaft diameter, D_{sh} of the machine is chosen according to IEC71 as 28mm.

2.5. B-H CHARACTERISTICS

The B-H characteristics of the material, which will be used in the stator and rotor stampings, has to be examined (Figure 2). Materials analysed for the manufacture are: M19_24G Steel, Steel1008, Steel1010 these are available in the simulation tool. There is no much change in design based on the Bmax considering the three materials available, usually select M19_24G steel. Select the M19_24G Steel for the manufacturing purpose of the SRM as mentioned earlier. From the B-H characteristic the" knee" point is noted down. From Figure the "knee" value of M19_Steel is noted as Bmax = 1.74 T. Assuming flux density, Bs = Bmax

Figure 2. BH curves of materials from simulation

The schematic of 8/6 SRM describing its parameters is shown in Figure 3.

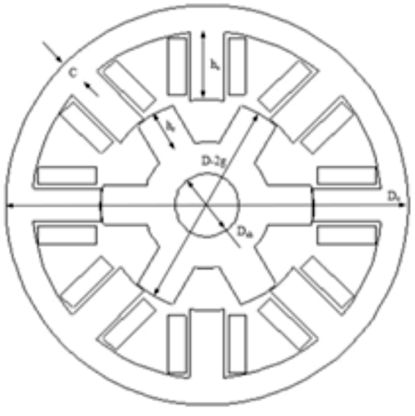


Figure 3. 8/6 SRM structure

2.6. DESIGN PARAMETER CALCULATIONS

Neglecting leakage and stacking factor, the stator pole area As can be written as,

$$A_s = \frac{D}{2} * L * \beta_s = 0.0035m^2 \quad (4)$$

Stator pole flux density Bs,

$$B_s = \frac{\emptyset}{A_s} \quad (5)$$

The flux in the stator pole is given by,

$$\emptyset = B_s * A_s = 5.7024mWb \quad (6)$$

The flux in the yoke is given by,

$$\emptyset_y = \frac{\emptyset}{2} = 2.8512mWb \quad (7)$$

Assuming that the yoke flux density is half the stator flux density, the yoke flux can be written as,

$$\emptyset_y = A_y * B_y = \frac{B_s}{2} * A_y \quad (8)$$

Area of the yoke is given by $A_y = A_s$. Then, the flux density in the yoke is given by,

$$B_y = \frac{\emptyset_y}{A_y} = 0.825T \quad (9)$$

The stator back iron thickness is given by,

$$C = \frac{A_y}{L} = 19.2mm \quad (10)$$

The height of the stator pole is given by,

$$h_s = \frac{D_o}{2} - C - \frac{D}{2} = 27.7mm \quad (11)$$

Area of the rotor pole is given by,

$$A_r = \left(\frac{D}{2} - g\right) * L * \beta_r = 0.00358m^2 \quad (12)$$

The flux density in the rotor pole is given by,

$$B_r = \frac{B_s A_s}{A_r} = 1.593T \quad (13)$$

Area of the rotor core is given by,

$$A_{rc} = L\left[\frac{D}{2} - g - h_r - \frac{D_{sh}}{2}\right] \quad (14)$$

The rotor core carries half the flux and is limited to a flux density of approximately 80% of max value, hence,

$$\emptyset_{rc} = \frac{B_s A_s}{2} \quad (15)$$

$$\emptyset_{rc} = B_{rc} A_{rc} \quad (16)$$

The rotor core flux density is,

$$B_{rc} = 0.8B_s = 1.32\ Wb/m^2 \quad (17)$$

$$\emptyset_{rc} = 0.8B_s A_{rc} \quad (18)$$

Comparing (15) and (18),

$$\text{Then, } A_{rc} = \frac{A_s}{1.6} = 0.0022m^2 \quad (19)$$

Height of the rotor pole is given by,

$$h_r = \frac{D}{2} - g - \frac{D_{sh}}{2} - \frac{A_{rc}}{2} = 23.5mm \quad (20)$$

Neglecting leakage and fringing the air gap area can be written as,

$$A_g = \frac{A_s + A_r}{2} = 0.00352m^2 \quad (21)$$

The flux density in the air gap is given by,

$$B_g = \frac{A_s * B_s}{A_g} = 1.621T \quad (22)$$

The magnetic field intensity of the air gap is given by,

$$H_g = \frac{B_g}{4\pi * 10^{-7}} = 1289950AT/m \quad (23)$$

Similarly, the magnetic field intensities of other parts are also calculated as,

$H_s = 6179.17AT/m$, $H_y = 238.54AT/m$,

$H_r = 4445.4AT/m$, $H_{rc} = 960.34AT/m$

Mean path length of the stator pole,

$$l_s = h_s + \frac{C}{2} = 37.4mm \quad (24)$$

Mean path length of the air gap, $l_g = 0.5mm$

Mean path length of the rotor pole,

$$l_r = \frac{D}{4} - \frac{g}{2} + \frac{h_r}{2} - \frac{D_{sh}}{4} = 29.5mm \quad (25)$$

Mean path length of the rotor core is given as,

$$l_{rc} = \pi\left[\frac{D}{4} - \frac{g}{2} - \frac{h_r}{2} + \frac{D_{sh}}{4}\right] = 62.83mm \quad (26)$$

Mean path length of the yoke,

$$l_y = \pi\left[\frac{D_o}{2} - \frac{C}{2}\right] = 274.58mm \quad (27)$$

MMF $J_{aligned}$ is calculated as,

Number of turns per phase Tph is given as,

$$J_{aligned} = 2\left[H_s l_s + H_g l_g + H_r l_r + \frac{H_{rc} l_{rc}}{2} + \frac{H_y l_y}{2}\right] = 2077.34AT \quad (29)$$

2.7. DESIGN OF WINDINGS

Assume wedge thickness h_{wedge} = 4 mm, and current density J = 6 A/mm2 the stator pole arc length is given as,

$$P_s = \left[\frac{D}{2} + h_{wedge}\right]\beta_s = 20.73mm \quad (30)$$

The stator pole pitch is given by,

$$\lambda_s = \frac{\pi D}{N_s} + \frac{\pi(2 * h_{wedge})}{N_s} = 42.41mm \quad (30)$$

Minimum area of the conductor is given by,

$$a_c = \frac{i}{2J} = 1.007mm^2 \quad (31)$$

The wire diameter including insulation is given by,

$$d_w = \sqrt{\frac{4a_c}{\pi}} + 0.1 = 1.319mm \quad (32)$$

According to the standard size sheet we are selecting a wire diameter of about $1.167mm^2$.

The maximum height of the winding to hold the windings is given by,

$$h_w = h_s - h_{wedge} = 23.8mm \quad (33)$$

The number of vertical layers is given by,

$$N_v = \frac{h_{wff}}{d_w} = 17.14 = 17 \quad (34)$$

Where f_f field factor, which is equal to 0.95 (app.). The value of N_v is rounded to nearest lower integer. The number of horizontal layers is given by,

$$N_h = \frac{Tph}{2N_r} + 1 = 6.04 = 7 \quad (35)$$

Width of the winding is given by,

$$W_t = \frac{d_w N_h}{f_f} \quad (36)$$

The space between two stator pole tips is given by,

$$Z = \lambda_s - t_s = 21.68\text{mm} \quad (37)$$

Clearance between the windings is given by,

$$C_l = Z - 2W_t = 2.242\text{mm} \quad (38)$$

The aligned inductance can be calculated as,

$$L_{aligned} = \frac{Tph*\emptyset}{i} = \frac{J*B_g*A_s}{i_p^2} = 81.2\text{mH} \quad (39)$$

C_l has to be positive and preferably greater than 3 mm [13], or else a different size conductor can be chosen and clearance can be checked again. Select D from 100 mm to 98 mm, and increasing L from 180mm to 200mm then recalculate the other design parameters. The recalculated values are tabulated in below table 1.

Table No. 1 New Parameter

As = 3.763*10^{3}m^2	Hs = 6179.17AT/m	$L_{aligned}$ = 79.3mH
ϕ = 6.208mWb	Hy = 238.54AT/m	t_s = 20.35mm
ϕ_y = 3.104mWb	H_r = 4453.5AT/m	λ_s = 41.626mm
C = 18.8mm	H_{rc}=960.34AT/m	A_C= 1.167mm
h_s = 29.2mm	ls = 38.59mm	d_w = 1.319mm
A_r = 0.00389m^2	lg = 0.5mm	h_w = 25.2mm
Br = 1.595T	l_r = 28.62mm	N_v = 18
A_{rc} = 0.00235m^2	l_{rc} = 62.45mm	N_h = 6
h_r = 22.74mm	l_y = 275.18mm	W_t = 8.3mm
Ag = 0.003829m^2	ℑ = 2085.12AT	Z = 21.28mm
B_g = 1.6216T	Tph = 172	Cl = 4.62mm
H_g = 1290433AT/m	I_p = 12.12A	

3. DESIGN OF MACHINE

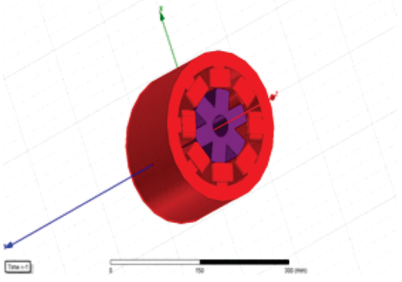


Figure 4. 3D model of the SRM designed

Maxwell gives reliable results when compared to other tools so we use that tool for the drawings. The whole structure of the SRM are shown in the figures 4. Finite element analysis is done for determining the flux path. By exciting one phase the analysis was done and the path obtained is shown in the figure.5.

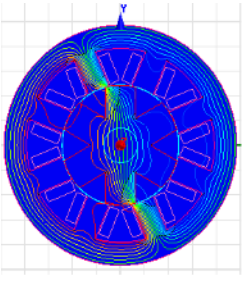


Figure 5. Flux distribution

3. RESULTS

The results obtained during simulation is given in this section, from the graphs it is clear that values obtained theoretically are nearly equal to the simulation results. The aligned inductance calculated theoretically was about 82.1mh, the value of inductance obtained during finite element analysis is about 78.2mH, which is approximately equal and can say that the design is correct. The figure 6 shows the Flux Linkage V/s Current at various position, Figure 7. shows the efficiency curve, figure 8 shows the inductance variations with the rotor position.

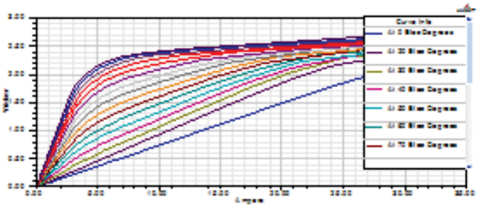


Figure 6. Flux Linkage V/s Current

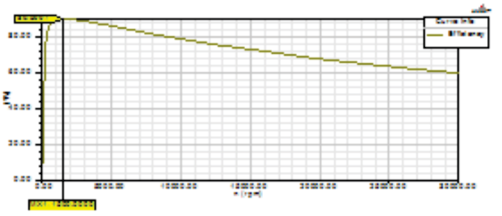


Figure 7. Efficiency V/s Speed

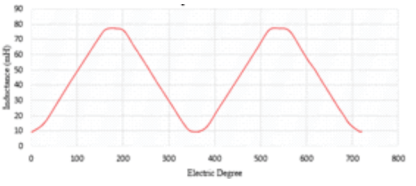


Figure. 8. Air Gap Inductance V/s Rotor Position

4. CONCLUSION

Designed and simulated a 5hp SRM motor theoretically and by simulation. While comparing with the theoretical values obtained during calculation with the simulation results, it was found that the design can be verified. The motor design done is correct, when compared with the simulation results, using various curves. Performance characteristics are plotted.

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