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Computer Aided Design and Analysis of Switched Reluctance Motor

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Abstract

This paper present method to designing a switched reluctance motor (SRM). Switched Reluctance Motor (SRM) is coming up as an alternative selection for variable speed drives in many automobile and industrial applications. Its construction is simple and rugged. Its higher efficiency, high torque to inertia ratio and thermal toughness are some of the salient advantages of SRM. It is used in centrifugal pumps, fans, plotter drives, and automotive application, under water marine drive, washing machine, electrical vehicle and medical application. However, the SRM has not gained prominent importance in many practical applications, because of its few disadvantages like large torque ripple, acoustic noise and proper design. This paper describes a step for design procedure of SRM. The design step verification of the motor winding inductance at different rotor positions from un-aligned to aligned position and the static flux linkage characteristics will be carried out. Design verification and performance calculation of switched reluctance motor (SRM) will be carried out using Finite elements method. The Computer Aided Design (CAD) of switched reluctance motor will be carried out. Minimization of the torque ripple is done by Changing stator and rotor pole arc, tapered angle of stator and rotor pole, changing turn-on and turn-off angle, changing pole tip shape design, reducing mutual inductance.

Keywords: SRM, computer aided design, torque ripple minimization.

Introduction
SRM consists of a stator with excitation windings and a winding less rotor. Rotor conductors are not required because the torque is produced by the tendency of the rotor to obtain position having minimum reluctance. Performance analysis of the

SRM requires the dimensions for stator and rotor laminations, winding details, pole numbers, and pole arcs. An approximate sizing of the SRM is obtainable using a power output equation. This paper contains the output equation and selection of various machine variables such as number of poles, rotor and stator pole arcs, core length, bore diameter, back iron thickness, number of turns in each phase, and air gap for rotary switched reluctance machines.

Design Procedure

The output equation for SRM is

$$P_d = k_e k_d k_1 k_2 B A_s D^2 L N_r \quad (1)$$

Where,

k_e = Efficiency of SRM

$k_d = \frac{\theta_i q P_r}{360}$ = Duty Cycle of SRM

θ_i = Current Conduction Angle for each rising induction profile

q = Number of stator phase

P_r = Number of rotor pole

$k_1 = \frac{\pi^2}{120}$

$k_2 = 1 - \frac{1}{\sigma_s \sigma_u}$ (0.5 to 0.75)

σ_s = Ratio of saturated aligned inductance to unsaturated aligned inductance

σ_u = Ratio of unsaturated aligned inductance to unaligned inductance

B = Flux density of stator pole at aligned position

A_s = Specific electric loading (25000 A/m to 90000 A/m)

D = Bore diameter

L = Axial length of stator pole

N_r = Rotor speed in rpm

$$L = kD \quad (2)$$

From above equation (1) & (2), D is evaluated if the rated speed and k are known. So from above equation, D and L are evaluated. For non servo applications k is 0.25 to 0.75 and for servo application k is 1 to 3. Number of turns per phase T_{ph} is calculated by below equation

$$A_s = \frac{2T_{ph} i}{\pi D} \quad (3)$$

$$_{sp} = D \sin\frac{\beta_s}{2} \quad (4)$$

$\boldsymbol{\beta}_s$ and $\boldsymbol{\beta}_r$ are stator pole arc and rotor pole arc respectively. Phase current is denoted by i.

Stator back iron thickness b_{sy} is selected between 0.5_{sp} to $_{sp}$. Stator coil dimensions like height of stator (h_c) coil and width of stator coil (w_c) are calculated from eq. (6). w_{cs} is width or gap to be left between the two adjacent coils in a slot at the bore including the slot liners. P_s is number of stator phase. a_c is area of cross section of the conductor.

$$\omega_c = \frac{\pi D - P_s\left[\beta_s \frac{D}{2} + \omega_{cs}\right]}{2P_s} \quad (5)$$

$$\text{Area of Stator coil} = h_c\omega_c = \frac{a_c T_{ph}}{2} \quad (6)$$

$$h_c = a_c T_{ph}\left[\frac{P_s}{\pi D - P_s\left\{\beta_s \frac{D}{2} + \omega_{cs}\right\}}\right] \quad (7)$$

Stator pole height (h_s) is selected between h_c to $1.4h_c$.

Outer diameter = $D_0 = D + 2b_{sy} + 2h_s$ (8)

Rotor back iron thickness (b_{ry}) is selected between 0.5_{sp} to 0.75_{sp}.

Rotor pole height = $h_r = \left[\frac{D - 2b_{ry} - 2l_g - D_{sh}}{2}\right]$ (9)

Where, D_{sh} is the rotor shaft diameter.

$$\text{Lenght of air gap} = l_g = \frac{\pi D}{P_r K_g} \quad (10)$$

The K_g is ratio of rotor pole pitch to air gap length in range of 50 to 120 [1].

Losses Calculation

Total core loss (P_{co}) is summation of stator and rotor core loss. ρ is density of magnetic material. C_{sp}, C_{sy}, C_{rp}, C_{ry} are core loss per kg in stator pole, stator yoke, rotor pole, and rotor yoke respectively [2].

Core loss in stator pole = $P_{csp} = V_{sp}\rho C_{sp}$ (11)

Volume of stator pole = $V_{sp} = \frac{P_s P_r D \beta_s L h_s}{2}$ (12)

Core loss in stator yoke = $P_{csy} = V_{sy}\rho C_{sy}$ (13)

Volume of stator yoke = $V_{sy} = 2P_r(0.5D_0 - b_{sy})\left(\frac{2\pi}{P_s}\right) b_{sy} L$ (14)

Core loss in rotor pole = $P_{crp} = V_{rp}\rho C_{rp}$ (15)

Volume of rotor pole = $V_{rp} = P_s P_r \beta_r h_r L\left[\frac{D}{2} - l_g\right]$ (16)

Core loss in rotor yoke = $P_{cry} = V_{ry}\rho C_{ry}$ (17)

Volume of rotor yoke = $V_{ry} = b_{ry} L\pi(D - 2l_g - 2h_r + D_{sh})$ (18)

$P_{co} = P_{csp} + P_{csy} + P_{crp} + P_{cry}$ (19)

Total copper loss = $P_{cu} = I^2 R_{eq}$ (20)

Equivalent resistance of winding = $R_{eq} = \frac{T_{ph}\rho_c l_m}{a_c}$ (21)

Mean length of turn = $l_m = 2L + 2D\sin\frac{\beta_s}{2} + 4\omega_c$ (22)

Where, ρ_c is resistivity of winding material. a_c is cross section area of conductor [3].

Total losses = Core loss (P_{co}) +Copper loss (P_{cu}) (23)

$$\text{Efficiency}(\eta) = \frac{\text{Output}}{\text{Output+Total losses}} \quad (24)$$

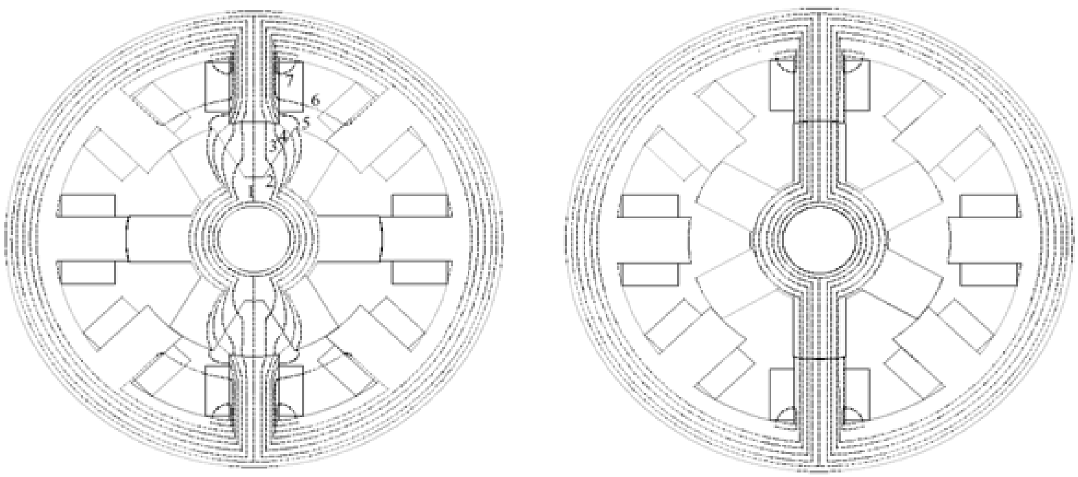
Inductance Calculation

$$\text{Total unaligned inductance} = L_u = \sum_{j=1}^{7} L_{uj} \quad (25)$$

The calculation of unaligned inductance is done by flux paths. One flux path calculation is given below. For all flux paths this procedure is repeated. B_{g1}, B_{sp1}, B_{sy1}, and $B_{ry1}$are flux density for flux path 1 in air gap, stator pole, stator yoke, rotor yoke respectively.

$$R = \frac{l}{\mu\mu_0 A} \quad (26)$$

From eq. (26) reluctance of stator pole (R_{sp1}), stator yoke (R_{sy1}), rotor yoke (R_{ry1}), and air gap (R_{g1}) for flux path 1 are calculated.



(a) (b)

Fig.2 Identification of seven flux paths for analytical calculation of (a) unaligned inductance (b) aligned inductance

Unaligned inductance of flux path

$$1 = L_{u1} = \frac{T_{ph}^2}{2R_{sp1} + 2R_{g1} + \frac{R_{sy1}}{2} + \frac{R_{ry1}}{2}} \quad (27)$$

All flux path unaligned inductance calculation is same as flux path 1.

The flux in the machine consists of flux path 1 and flux path 7, identified for the aligned position. Flux path 1 consists of the majority of the flux. Flux path 7 has leakage flux. For aligned inductance calculation, the reluctance and inductance of flux path 1 and flux path 7 is calculated same as unaligned calculation. Total aligned inductance is sum of both paths inductances [1].

Computer Aided Design of SRM

The CAD program is implemented of SRM and calculates main dimension, losses and efficiency.

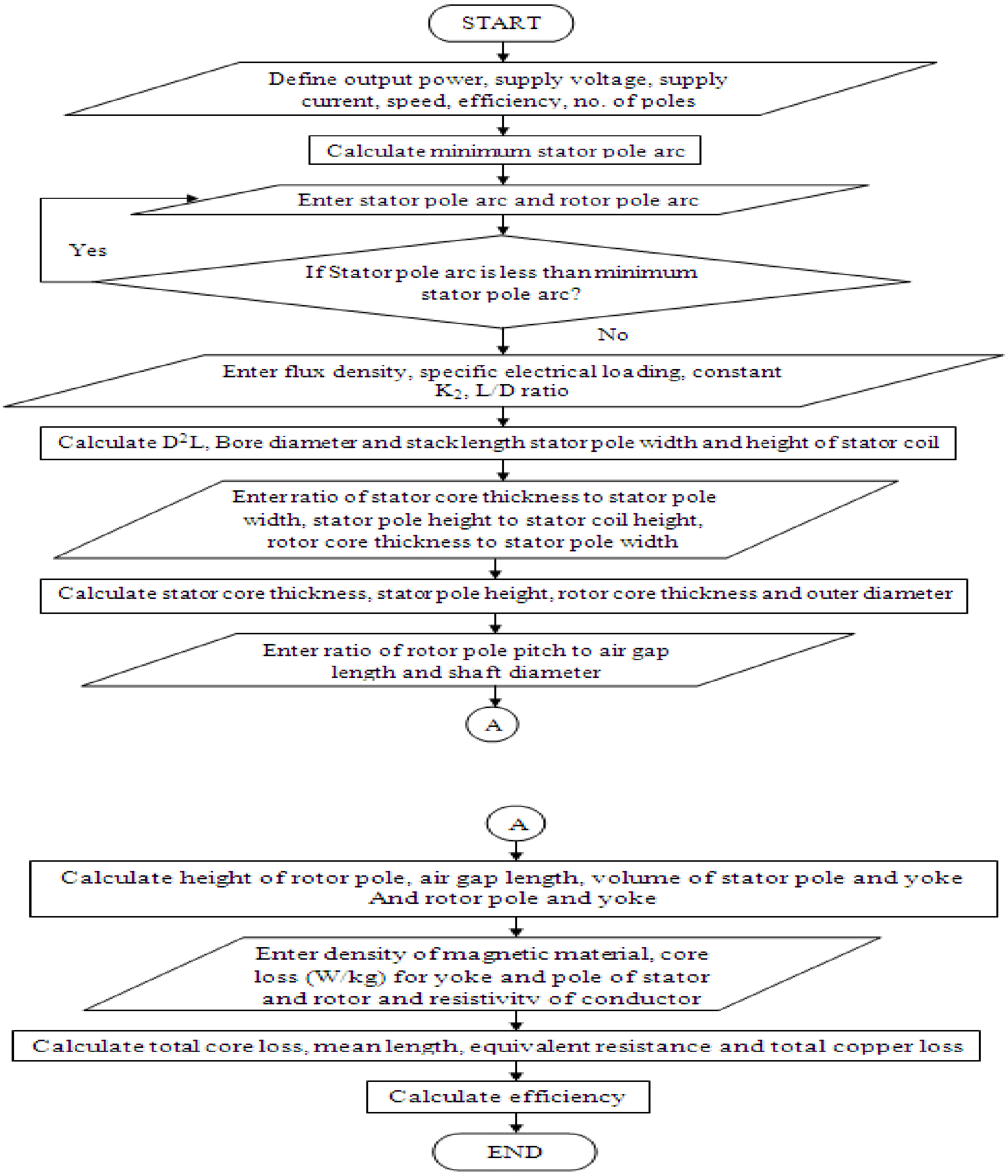


Fig. 3 Flowchart of CAD program

Comparison between CAD result and Speed software result

5 hp 8/6 655 V, 13 A, 1500 rpm servo type SRM, 55 kW 6/4 784 V, 93 A, 3500 rpm servo type SRM and 250 W 6/4 12.8 V, 39 A, 3600 rpm non servo type SRM are design by CAD program and main dimensions are shown in Table 1 [4,5,6].

Table 1 Main Dimension of SRM obtained from CAD program

Symbol	5 hp SRM	55 kW SRM	250 W SRM	Unit	Description
D	100.741	126.051	48.862	mm	Bore diameter
L	120.889	214.948	28.828	mm	Stack length
D_0	201.867	238.66	96.569	mm	Outer diameter
$\boldsymbol{\beta}_s$	22	30	30.13	deg	Stator pole arc
$\boldsymbol{\beta}_r$	26	32	32.4	deg	Rotor pole arc
l_g	0.7535	0.4	0.4	mm	Air gap
h_s	36.75	37.8	16.233	mm	Stator pole height
b_{sy}	13.8131	18.504	7.62	mm	Stator yoke thickness
h_r	20.8419	19.121	13.411	mm	Rotor pole height
b_{ry}	12.11	17.003	6.699	mm	Rotor yoke thickness
T_{ph}	608	206	54	mm	Number of turns/phase
w_c	6.61	6.61	3.868	mm	Stator coil width
h_c	29.1667	14	14.43	mm	Stator coil height
D_{sh}	33.33	36	7.84	mm	Shaft diameter

The model of this three SRM are made in speed software using main dimension which are obtained by CAD program and efficiency which is obtained in speed software is compared with CAD result.

Table 2 Comparison of efficiency between CAD result and speed software result

	5 hp SRM	55 kW SRM	250 W SRM
Efficiency by CAD program	89.29 %	95.35 %	84.09 %
Efficiency in Speed software	94.21 %	98.42 %	89.59 %

Torque ripple minimization

The torque ripple is defined as the difference between the maximum and minimum instantaneous torque expressed as a percentage of average torque during steady state operation.

Changing stator and rotor pole arc.

By changing stator and rotor pole arc, the inductance profile of SRM can be changed due to that the torque of SRM change [7].

$$\beta_s, \beta_r \geq \frac{2\pi}{\frac{P_s P_r}{2}} \quad (28)$$

$$\beta_s + \beta_r \leq \frac{2\pi}{P_r} \quad (29)$$

Tapered angle of pole.
Cross section of pole is increased by changing tapered angle of its. So inductance is increased and due to this average torque and torque ripple can minimized.

Changing turn-off and turn-on angle.
By advance turn-on and turn-off angle technique, rising edge of current is on the part of no change of inductance with respect to rotor position so current reach peak value at positive changing inductance. So average torque is increased and torque ripple can minimized.

Changing pole tip shape design.
Pole tip shape is changed and by this the flux linkage is increase. The inductance increase so average torque is increased and torque ripple is decreased.

Reducing mutual inductance.
When two phase currents are overlap at that time torque is given by below eq.30. so reducing mutual inductance torque ripple can minimized [8].

$$\text{Torque} = \frac{1}{2} I_A^2 \frac{dL_A}{d\theta} + \frac{1}{2} I_B^2 \frac{dL_B}{d\theta} + \frac{1}{2} I_C^2 \frac{dL_C}{d\theta} + I_A I_B \frac{dM_{AB}}{d\theta} + I_A I_C \frac{dM_{AC}}{d\theta} + I_B I_C \frac{dM_{BC}}{d\theta} \quad (30)$$

By changing stator and rotor pole arc, changing turn-on and turn-off angle and tapered stator and rotor pole in speed software's model torque ripple is changed. Torque ripple minimization is shown in Table 3.

Table 3 Torque ripple minimization using speed software

		Before changing design	After changing design
55 kW SRM	Maximum instantaneous torque	178 Nm	136 Nm
	Minimum instantaneous torque	44 Nm	38 Nm
	Average torque	155 Nm	138 Nm
	Torque ripple	86.45 %	71.01 %
250 W SRM	Maximum instantaneous torque	2.4 Nm	2.84 Nm
	Minimum instantaneous torque	0.3 Nm	1.84 Nm
	Average torque	1.37 Nm	2.38 Nm
	Torque ripple	153.28 %	42.01 %

Conclusion
A procedure for the design of a non-servo and servo switched reluctance motor has been described. The design is based on the output equation which is correlated bore

diameter and axial length of stator pole similar to that of conventional ac machines. The material which is used in yoke and poles of stator and rotor are chosen to get maximum efficiency. The calculation of inductance is done according to different flux paths for aligned and unaligned position of rotor. The CAD program is done as a design procedure of SRM. This obtain data is entered into speed software and analysis of SRM model is done. The torque ripple minimization is done by changing pole arc, changing turn off and turn on angle and tapered angle of stator and rotor pole. These techniques are applied on SRM model in speed software and torque ripple is calculated.

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