

Influence of Stator/Rotor Poles Switched Reluctance Motor Performances

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Abstract

The stator and rotor pole structure and power inverters have significant influence on electromagnetic torque performances and efficiency performances. Many papers have investigated on those design parameters on motor result [1][2][3][4]. Inductance and flux linkage will be influenced by rotor and stator pole combination and magnetic circuit. In this paper, The SRM 12/10 and 8/6 will be modified from 12/8 with the same outer diameter stator and stack length. The paper figures out some stator and rotor pole arc to get maximum average torque and torque ripple reduction. For commercial switched reluctance motor, control method is single voltage or current pulse in higher speed not chopping current. The DC link voltage of power converter of SRM is limited, it is difficult to achieve constant torque in wider range of speed because the magnetic circuit is saturated condition, and the phase current cannot rise reference value. To improving average torque at high speed, increasing voltage or rotor poles or winding phases are possible for E-bike application.

Keywords

Switched Reluctance Motor - SRM, Novel Rotor Pole, Finite Element Method - FEM.

1. Introduction

This paper will improve torque and efficiency of the conventional design of SRM 12/8 with the same outer rotor and length. The design proposal will be SRM 8/4 or 12/10. The power and torque density have compared each other and novel rotor pole in detail design. This paper did not mention power electronic of IGBT or Diode cost.



Fig 1. Conventional SRM 12/8

In SRM, the number of stators, rotors and winding phases must be followed a regular. The number of phases m is calculated with the number of stator poles N_s and rotor poles N_r [11]

$$m = \frac{N_s}{|N_s - N_r|} \quad (1)$$

Table 1. Geometry parameters of SRM 12/8 and 12/10

Parameter	Unit	SRM 12/8	SRM 12/10	SRM 8/6
Stator Poles		12	12	8
Stator Pole Angle	degree	15	15	22.5
Stator Lam Dia	mm	140	140	140
Stator Bore	mm	90	90	90
Stator Pole Depth	mm	15	15	15
Stator Pole Radius	mm	2	2	2
Pole Number		8	10	6
Rotor Pole Angle	degree	16	14	16
Rotor Slot Depth	mm	11	11	11
Pole Taper Angle	degree	0	5	5
Airgap	mm	0.3	0.3	0.3
Number of phase		3	6	4
Shaft Dia	mm	25	25	25

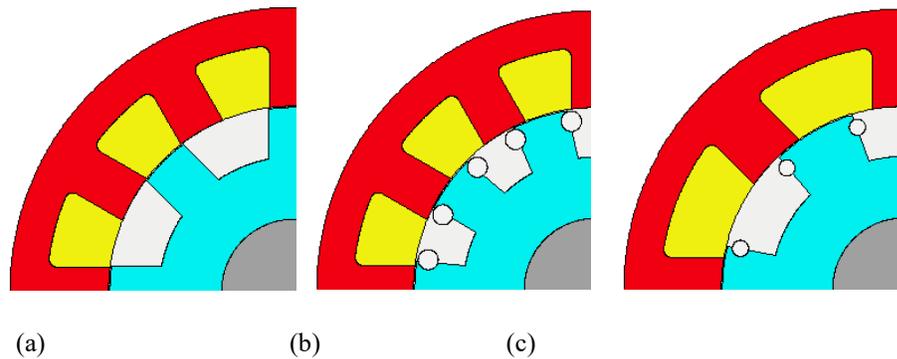


Fig 2. Stator and rotor SRM 12/8; 12/10 and 8/6

These SRMs have the same outer diameter and different phase but the total material weights are kept the same or changed very little less than 5%. Number of stator poles N_s and the number of rotor poles N_r are determined by special applications and power converter topology. There are many possible combinations for the number of poles for SRM 8/6, 12/10 and 12/8. This paper focuses on the popular combination of 10-12 stator poles and 6-8-10 rotor poles to improve torque performances in wide rangel speed. The stator and rotor pole angle selection form a crucial part of the design process. The standard design normally has the stator pole arc angle β_s smaller than the rotor pole angle β_r . The constraints on the values of pole arc angles are as follows: Rotor pole arc (β_r) is selected to be equal or greater than stator pole arc (β_s), since the number of rotor pole is less than number of stator pole ($\beta_s \leq \beta_r$). β_s should be equal or greater than step angle to generate required torque. When β_s is selected as smaller than step angle ($\beta_s < \varepsilon$), none of the phases may not have rising inductance slope, there may be some positions in the machine from where the machine may not start[13]. Step angle is shown by

$$\varepsilon = \frac{2\pi}{\frac{N_s}{2} \cdot N_r} \quad (2)$$

Where ε is step angle.

Rotor pole angle should be greater than sum of stator and rotor pole arc as follows:

$$\beta_r \geq \beta_s; \beta_r + \beta_s < \frac{2\pi}{N_r}; \min(\beta_r, \beta_s) \geq \frac{2\pi}{m \cdot N_r}$$

There are three constraints in determining the poles arc angle. These constraints are shown in the form of a triangle named Feasible Triangle. According to these restrictions, the ranges can be specified as $15^\circ \leq \beta_s$, $\beta_s + \beta_r < 45^\circ$, and $15^\circ \leq \beta_r \leq 30^\circ$ for SRM 12/8. Pole embrace of SRM is an important factor to have a good performance of the motor. Therefore, it should be considered in the motor design. Pole embrace is defined as the ratio of pole arc to pole pitch. Embrace coefficient of SRM generally affects the rotor and stator tooth widths. It also influences the torque ripple and average torque. Hence, the selection of pole embrace has a significant importance for the performance of SRM.

Table 2. Geometry parameters of SRM 12/8; 12/10 and 8/6

Parameters	SRM 12/8	SRM 12/10	SRM 8/6
Stator Lam (Back Iron)	2.246	2.246	2.246
Stator Lam (Tooth)	1.322	1.322	1.172
Stator Lamination [Total]	3.568	3.568	3.418
Armature Winding [Active]	1.002	1.002	1.001
Armature EWdg [Front]	0.1911	0.1873	0.2523
Armature EWdg [Rear]	0.1911	0.1873	0.2523
Armature Winding [Total]	1.384	1.376	1.506
Wire Ins. [Active]	0.0222	0.0222	0.02229
Rotor Lam (Back Iron)	1.476	1.322	1.384
Rot Inter Lam (Back Iron)	6.73E-06	6.02E-06	6.30E-06
Rotor Lam (Tooth)	0.7389	0.9606	0.8413
Rotor Inter Lam (Tooth)	3.37E-06	4.38E-06	3.83E-06
Rotor Lamination [Total]	2.215	2.282	2.225
Shaft [Active]	0.6229	0.6229	0.6229
Flange Mounted Plate	7.158	7.158	7.158
Total	7.932	7.992	7.913

3. Analytical and FEM Simulation Program

Since FEMM was first introduced, this program has been spread widely due to several reasons, particularly due to opensource code and free license. Unlike other finite element analysis program, FEMM allows the user can edit its code by themselves, to optimize and improve the calculation accuracy and speed in each problem. By coupling with MATLAB, it has a strong calculation ability with easy to use in structure and programming. Furthermore, the design model in Simulink automatically with using several circuit topologies is also considered in future work. The program was developed for the purpose of combining all design process into one program. It allows to exchange the data between design process and simulation process. This is done by monitoring and active collecting results from both process when they were executed. Design program is developed in MATLAB environment. The analytical calculation can be used and stored by MATLAB programming language; the program interface was developed by MATLAB GUI. After calculation, the system can present on screen as well as export drawings in dxf type. All drawings can be development works involve the integrated environment linking analytical calculation to simulation environment of FEMM.

This program also has ability to moving part of the motor which allow us to deal with many transient problems. To do that, it must have a code for the geometrical changes of boundary and the material assignment. Furthermore, there are many geometrical and magnetic relationships and combination of number of rotor and stator poles to achieve some electrical parameters This program has functions of sizing, overlapped the rotor slot, changing the size and worse performance report. The program must find the best choice for both, using regression. Collecting and responding data concept is also quite simple. There are only some special parameters of the motor to be verified, for example, output torque or the air gap flux density. The output torque is taken by a block integral of the shaft and the air gap flux density similarly can be collected by function. All result will be stored in database and used for further comparison. In addition, results which belonged to calculation progress and resulted in simulation progress are saved separately in 2 files. The

program is divided into three main parts: analytical calculation, exporting drawing and magnetic simulation. There are also some supporting parts including material library which also associate with FEMM library.

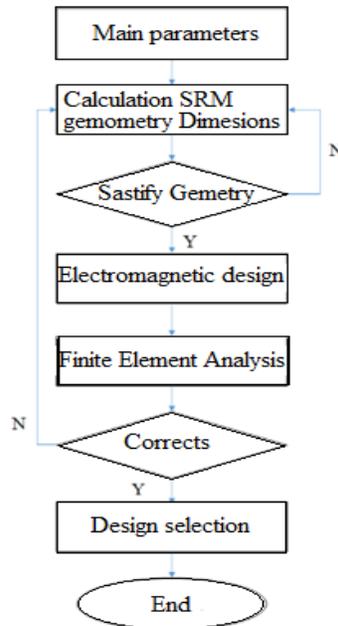


Fig 3. Program Structure

The program interface is well defined set of MATLAB function to parse, manage and interpolate data. There is some information which was provided in the program, but only some important results will be displayed and to be divided into tabs. The interface is written by MATLAB GUIDE. There is menu, button, box, and pop-up menu to manipulate, main parameters and material library must be selected first. The calculation progress is not activated without these parameters, e.g., power, torque, pole numbers..., however, there are default materials for each part of the motor. The interface links to database, material library as well as calculation results. When the system receives main parameters for motors, calculations will be executed. The results will be stored in database in file. Mat format. Main dimensions are shown, and the drawing is also plotted. Electrical steel material will be defined by specific parameters. The wire library includes the diameter, electrical conductivity. Electrical steel parameters consist of B-H curve and electrical conductivity. In motor core materials of industrial applications, low iron loss is required for high motor efficiency [3-8], and high magnetic flux density is required for motor downsizing and high torque. To reduce the iron loss of electrical steel sheets, Si addition is effective from the viewpoints of increasing resistivity and decreasing magnetic anisotropy, and approximately 3% Si is added to high grade electrical steel sheets

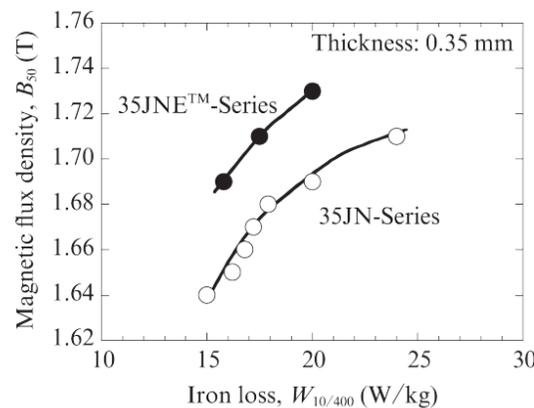


Fig 5. Silicon steel B-Iron loss curves

The analyzing process will be started by choosing motor length, diameter and height based on motor standard. During the process, there are some experience coefficients must be defined. All dimensions of motor will be calculated, including stator slot, rotor slot, airgap. This process is quite like induction motor design. In details, stator slot size is calculated mainly based on stator winding which depended on power, current and experience coefficients. After analytical results are achieved, all the dimensions of motor are saved in database in matrix form. When the export command is generated, the drawing process will be executed. The program was developed by MATLAB DXF library. Their coordinates must be calculated. The algorithm must satisfy both requirement: ensure the shape of these lines like desired curve and using least points as much as possible. Using minimum number of lines will help the system does not have to store a lot of data, which will result slowing down speed and difficulties when exporting the drawings to another software. In the other hand, rotating and mirror is also a difficult task in programming. The strategy, using loop function to redraw several times and using trigonometric function with angle steps, is applied and returns good results. The system will export 3 drawings: motor, rotor, and stator separately. These drawings can be used in several simulation program and design and manufacturing progress.

3. SRM 12/8; 12/10 and 8/6 Comparison

In this study, a SRM 8 and 10 rotor poles 1.2 kW- 1500rpm are carried out and the Electromagnetic analyses are performed for the reference motor and then two different SRM rotor designs are realized. The SRM 10 rotor poles alternatives are investigated in detail using FEA and several parametric optimizations are also performed before finalizing the design.

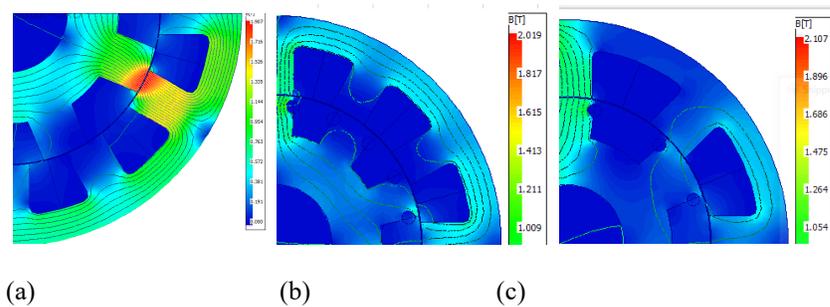


Fig 2. Stator and rotor SRM 12/8; 12/10 and 8/6

The Analytical Program and FEM analysis is realized to investigate the efficiency and output torque. The Electromagnetic design results have been summarized in below table 3. The best combination of stator and rotor pole SRM 8/6 is be selected for optimum analysis.

Table 3. Efficiency comparison of SRM 12/8; 12/10 and 8/6

Parameters	SRM 12/8	SRM 12/10	SRM 8/6	Unit
Maximum Torque Possible	8.5519	9.4214	10.251	Nm
Average torque (virtual work)	7.8803	8.265	8.7094	Nm
Average torque (loop torque)	7.61	8.1104	9.2362	Nm
Torque Ripple (MsVw)	5.0008	5.5833	7.1258	Nm
Torque Ripple (MsVw) [%]	63.801	68.667	80.653	%
Electromagnetic Power	1149.1	1192.1	1295.3	Watts
Input Power	1321	1366.2	1480.7	Watts
Output Power	1108	1115.5	1250.2	Watts
Total Losses (on load)	212.94	250.75	230.47	Watts
System Efficiency	83.88	81.646	84.435	%

Radial force results on the effect of pole side by side circle holes are given in table 4. The combination SRM 8/6 has lowest radial force. Therefore, acoustic noise and vibration are reduced significantly.

Table 4. Radial Force Comparison of SRM 12/8; 12/10 and 8/6

Parameters	SRM 12/8	SRM 12/10	SMR 8/6	Unit
Unbalanced Magnetic Pull (On Load)	5.35E-07	1.84E-06	8.70E-08	kN
Unbalanced Magnetic Pull Angle (On Load)	79.069	64.711	22.931	MDeg
Tangential Force (On Load)	0.0286743	0.0159136	0.140357	kN
Radial Force (On Load)	-2.5701	-1.87471	-1.63473	kN
X Force (On Load)	1.02E-07	7.88E-07	8.02E-08	kN
Y Force (On Load)	5.26E-07	1.67E-06	3.39E-08	kN

4. Conclusion

The article has analyzed number stator and rotor poles influenced on efficiency average torque and torque ripples by FEM simulation method. Radial forces of different stator/rotor poles with circle holes have been investigated. So the SRM 8/6 design is improved torque, efficiency and radial forces. It is better than the convention SRM 12/8 design.

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