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Design Consideration of Permanent Magnet Synchronous Reluctance Motor by Finite Element Method

Zaw Htet Myint
Department of Electrical Power Engineering
Mandalay Technological University
Mandalay, Myanmar

Abstract: A synchronous reluctance motor (SynRM) which uses a sinusoidal wave to drive a rotor constructed with several flux barriers. The stator winding of this motor is the same specifications as that used in an induction motor or a brushless motor which utilizes permanent magnet. This paper presents the design of synchronous reluctance motor with assistant of permanent magnet for 8kg washing machine. At the beginning of the design, main dimension of stator and number of stator slots are calculated. Rotors design parameters such as flux barriers, different insulation, magnet position are considered after calculating the number of stator slot. The rotor design process is considered to determine the best value for maximum average torque and minimum torque ripple. Permanent magnets are placed inside the flux barriers and results are verified by using finite element method (FEM).

Keywords: synchronous reluctance motor, permanent magnet, NdFeB, magnetic flux distribution, finite element method (FEM), washing machine

1. INTRODUCTION

Washing machine is the electronic home appliance used to wash the various type of clothes without applying any physical efforts. With washing machine people don’t have to rub the clothes with hand or squeeze them to remove the water. The washing machine washes the clothes automatically without having to supervise its operation. The washing machine automatically takes the required amount of water and detergent. It also automatically sets the timer for washing, rinsing and drying as per the selected mode of operation. There are many types of washing machines varying in mechanical construction, motor type driving a drum, a control system of motor control part, human interface, semi-automatic type, level of energy efficiency, washing performance, drying performance and water consumption. Many types of washing machines are horizontal type and vertical type based on drum position, front loading and top loading washing machines based on drum loading, belt driven and direct drive based on drive construction.

Washing machine is mainly operated by a motor, which is connected to the agitator through a unit called a transmission. The motor and transmission are near the bottom of the machine, while the agitator extends up through the middle of the machine. The motor is coupled to the agitator or the disc and produces it rotator motion. These are multispeed motors, whose speed can be changed as per the requirement. In the fully automatic washing machine the speed of the motor i.e. the agitator changes automatically as per the load on the washing machine. In fact, it is the motor which accelerates the process of washing. Therefore, it is a very important component of a washing machine.

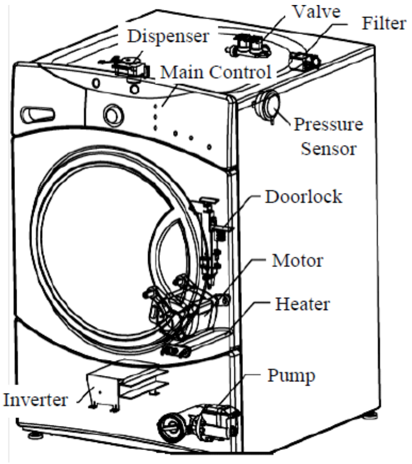


Figure 1. Inside a front-loading washing machine

Most of the Washing machine runs with the help of induction motor and universal motor. Moreover, modern motor construction such as synchronous motors are also used in washing machine. Nowadays, direct drive washing machines utilizing PM motor is increasing due to the mechanical simplicity, high performance and efficiency of the system. Induction motors are the wide used motors in industrial and civil applications, due to the simple realization, the robustness and the possibility to be supplied directly by the sinusoidal main without the necessity of a static power supply with related control system. If the application requires speed regulation, motor different from the induction motor type can be adopted. In the last years, among the electric motors available for variable speed drives, the synchronous reluctance motors (transvers rotor lamination type) have gained consistent market quotes. Synchronous reluctance motor has a higher rated torque compared with induction motor because of the absence of the rotor losses. The comparison between SynRM and IM at the same torque at the same frame size is the induction motor is hotter than the reluctance one. As a consequence, with the same power dissipation, (the same temperature of the stator windings), the reluctance motor is able to produce a higher torque than the induction motor. In this paper, synchronous reluctance motor is considered to use in washing machine. Some specifications of the washing machine for the research is as shown in Table 1.

Table 1. Specifications of washing machine

Voltage	220-240 V
Current	10 A
Frequency	50 Hz
Wash capacity	8 kg
Speed	1400 rpm
Power	400 W
Water consumption	64 liters

2. SYNCHRONOUS RELUCTANCE MOTOR

The Synchronous Reluctance machines were discovered many years ago, around the early 60’s, even if the theory of anisotropic filed structure go back to the 1923 where Doherty and Nickle published a paper. Kusko in 1926 shows a first design of synchronous reluctance motor with multi barriers structure. Honsinger in 1957 developed some of the first consistent theory on the design of multi barrier synchronous reluctance machines.

2.1 Types of Synchronous Reluctance Rotors

The major types of synchronous reluctance rotors are the simple salient pole rotor, the axially laminated rotor and the transverse laminated rotor. They are depicted in Figure 2. The salient pole rotor design has a simple and rigid structure but a low saliency ratio and consequently poor performance. However, the rigid structure creates the possibility of using the salient pole rotor design in high-speed and extremely high-speed machines. The axially laminated rotor design has a good saliency ratio and performance, but the eddy current losses as a result of the axial lamination are large. However, the mechanical design is extremely complex for industrial manufacturing, at least for four-pole machines, where the sheets have to be bent and connected with bolts. However, a two-pole axially laminated machine is easier to manufacture because the electrical sheets are straight. The transverse laminated rotor has similar sheets that can easily be punched and iron losses in the rotor are reduced compared to the axially laminated structure. Therefore, the transverse laminated structure is the best choice for industrial manufacturing.

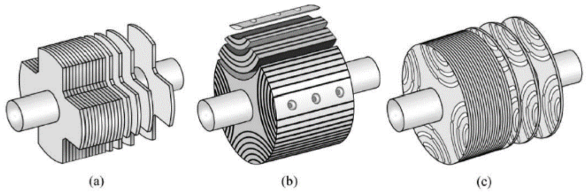
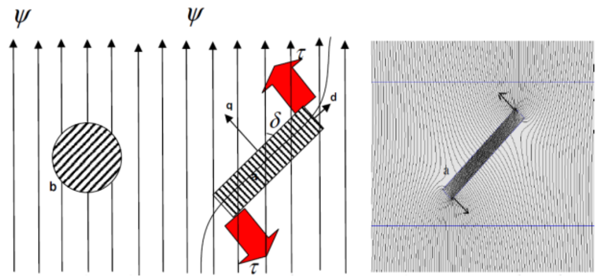


Figure 2. Schematics of (a) simple salient pole; (b)axially laminated; (c) transverse laminated rotors

The structure of reluctance motor is same as that of salient pole synchronous machine. The rotor does not have any field winding. The stator has three phase symmetrical winding, which creates sinusoidal rotating magnetic field in the air gap, and the reluctance torque is developed because the induced magnetic field in the rotor has a tendency to cause the rotor to align with the stator field at a minimum reluctance position. The rotor of the modern reluctance machine is designed with iron laminations in the axial direction separated by non-magnetic material. The performance of the reluctance motor may approach that of induction machine.

2.2 Basic Theory of synchronous reluctance motor

The synchronous reluctance machine (SynRM) utilizes the reluctance concept and rotating sinusoidal MMF, which can be produced by the traditional IM stator, for torque production. The main idea can be explained by Figure 3. A magnetic field (Ψ) which is applied to the anisotropic object is producing torque if there is an angle difference between the d-axis and the field. It is obvious that if the d-axis of object is not aligned with the field, it will introduce a field distortion in the main field. The main direction of this distortion filed is aligned along the q-axis of the object. In the SynRM (Ψ) is produced by a sinusoidally distributed winding in a slotted and it links the stator and rotor through a small air gap, exactly as in a slotted and it links the stator and rotor through a small air gap, exactly as in a traditional IM. The field is rotating at synchronous speed and can be assumed to have a sinusoidal distribution. In this situation there will always be a torque which acts to reduce the whole system potential energy by reducing the distortion filed in the q-axis. If load angle is kept constant, for example by control or applying a load torque, then electromagnetic energy will be continuously converted to mechanical energy. The stator current is responsible for both the magnetization and the torque production which is trying to reduce the field distortion, this can be done by controlling the current angle, which is the angle between the current vector to the stator winding the rotor d-axis in synchronous reference frame.



(a) (b)

Figure 3. An object with anisotropic geometry (a) and isotropic geometry (b) in a magnetic field Ψ and torque production mechanism

Synchronous reluctance motor has two rotor paths for the flux. One is a high permeability path, the flux lines flowing in rotor iron paths, parallel to the flux-barriers. It is commonly referred to as the d-axis path. The second is a low permeability path, the flux lines have to cross the rotor flux barriers. It is commonly referred to as the q-axis path. The final dq reference frame is obtained. The rotor is designed with several flux barriers, in order to obstacle the flux along the q-axis. And, to achieve a high saliency ratio, that is, a high reluctance torque component. The iron bridges (at the ends and sometimes in the middle of each barriers) sustain the rotor parts. A portion of q-axis flux flows through these bridges, with a consequence reduction of the torque. The diagrams of a SynRM geometry with their d- and q- axes flux lines are shown in Figure 4.

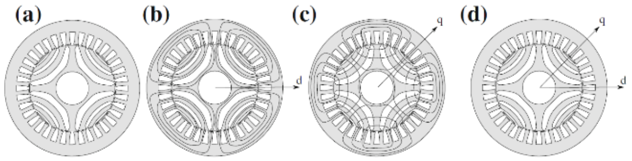


Figure 4. Sketch of a synchronous reluctance motor with (a) geometry, (b) d-axis flux lines, (c) q-axis flux lines, and (d) reference frame

3. DESIGN CONSIDERATION OF SYNCHRONOUS RELUCTANCE MOTOR

There are three main classes of parameter classification for SynRM.

- Design parameters of stator geometry
- Design variables or microscopic parameters
- Target variables

The first group includes the parameters of stator geometry such as number of slots, poles, outer diameter and inter diameter of stator, etc. the second group includes variables that are mainly based on the rotor geometry. The third group and rotor geometry (second) should be calculated from finite element method in order to obtain accurate results. The stator structure of transversally laminated type is essentially the same with other machines such as induction machines, so, the main performance difference comes from rotor structure. The SynRM can be built putting a reluctance rotor inside stators extracted from the induction production line.

3.1. Design Specifications of SynRM Rating

The specifications of the proposed synchronous reluctance motor is described in Table 2.

Table 2. Specifications of SynRM

Voltage	220V
Current	4.2A
Frequency	50Hz
Speed	1500rpm
Output Power	400W
Efficiency	68%
Power Factor	0.65
Number of poles	4

3.2. Design consideration for stator geometry

The output power equation is

$$KVA = VI \times 10^{-3} \tag{1}$$

where V=rated voltage

I=full load current

$$V = 4.44 k_w f \phi T_m \tag{2}$$

where Ø=flux per pole

K_w=winding factor

F=frequency

T_m=number of turns of main winding

$$\phi = B_{av} \frac{\pi D}{p} L \tag{3}$$

where B_{av}=average value of flux density in air gap

p=number of pole

D= stator bore diameter

L=stator core length

$$ac = \frac{2T_m I}{\pi D} \tag{4}$$

where ac=ampere conductor per meter pf arm periphery

$$KVA = 4.44 k_w f \phi T_m \times 10^{-3}$$

$$KVA = (1.11\pi^2 k_w B_{av} ac \times 10^{-3}) D^2 L n_s \tag{5}$$

$$C_0 = 1.11\pi^2 k_w B_{av} ac \times 10^{-3}$$

where, C_0=output coefficient

$$KVA = c_0 D^2 L n_s \tag{6}$$

If the rating is horse power, it can be changed in KVA.

$$KVA = \frac{hp \times 0.746}{\eta \times \cos\phi} \tag{7}$$

where, η=full load efficiency

cos Ø=full load power factor

Main dimension is

$$D^2 L = \frac{hp \times 0.746}{\eta \cos\phi C_0 n_s} \tag{8}$$

To separate D and L from D^2L

$$L \cong \tau_p \tag{9}$$

pole pitch, $\tau_p = \frac{\pi D}{p}$ (10)

Depth of stator core is

$$d_{c1} = \frac{B_t}{B_c} \times \frac{S_1 \times b_{t1}}{\pi p} \tag{11}$$

Width of the teeth is

$$b_{t1} = \frac{(1.27 + 0.035 D_i) D_i}{S_i} \tag{12}$$

Width of the slot at top section is

Assuming parallel sided teeth and trapezoidal slots with flat bottom, the width of the slot at the mouth is given by,

$$b_{11} = \frac{\pi(D_i + 2(h_{10} + h_{11})}{S_1} - b_{t1} \tag{13}$$

Depth of the slot below the mouth is

$$h_{14} = 0.5(D_0 - D_i) - (h_{10} + h_{11} + d_{c1}) \tag{14}$$

Width of the slot at bottom is

$$b_{13} = b_{11} + 2h_{14} \tan\alpha \tag{15}$$

Length of Air Gap is

$$l_g = 0.013 + \frac{0.0042 D_i}{\sqrt{p}} \tag{16}$$

Winding distribution factor

$$k_w = \frac{k_{p1}T_1 + k_{p2}T_2 + k_{p3}T_3 + \ldots}{T_1 + T_2 + T_3 + \ldots} \tag{17}$$

Current carried by main winding,

$$I = \frac{hp \times 0.746}{V.\eta.\cos\phi} \tag{18}$$

Area of cross section of conductor,

$$a_m = \frac{I}{\delta_m} \tag{19}$$

The useful slot height, teeth area per pole, depth of stator core, depth of slot below the mouth and width of tooth can be calculated from the above equations.

3.3. Design results for stator geometry

The calculated design results are shown in Table 3 and the geometrical diagram of the stator is depicted in Figure 5.

Table 3. Result data of stator geometry

Name	Symbol	Result
Outer diameter	D_0	18cm
Inner diameter	D_i	11cm
Core length	L	7cm
Number of stator slots	S_1	24
Slot opening	b_{10}	0.26cm
Depth of tip	h_{10}	0.07cm
Depth of mouth	h_{11}	0.09cm
Width of tooth	b_{t1}	0.76cm
Stator core depth	d_{c1}	1.74cm
Width of slot at the top section	b_{11}	0.72cm
Length of air gap	l_g	0.036cm
Depth of slot below the mouth	h_{14}	1.6cm
Width of the slot at the bottom	b_{13}	1.41cm

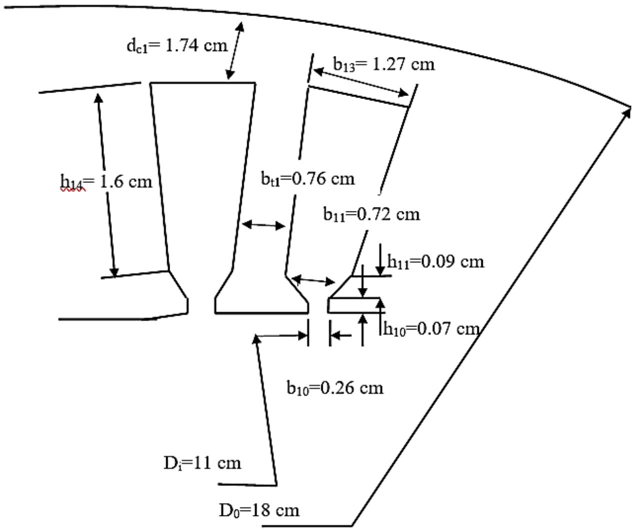


Figure 5. Stator Slot Geometry

4. PERFORMANCE ANALYSIS OF SYNCHRONOUS RELUCTANCE MOTOR

The finite element method (FEM) is an important tool for the design and analysis of electric machine. The rotor structure of synchronous reluctance motor is made of laminated iron. There are three flux barriers per pole in this design. Permanent magnets are inserted in them. The running condition by NdFeB32MGOe is depicted in Figure 6.

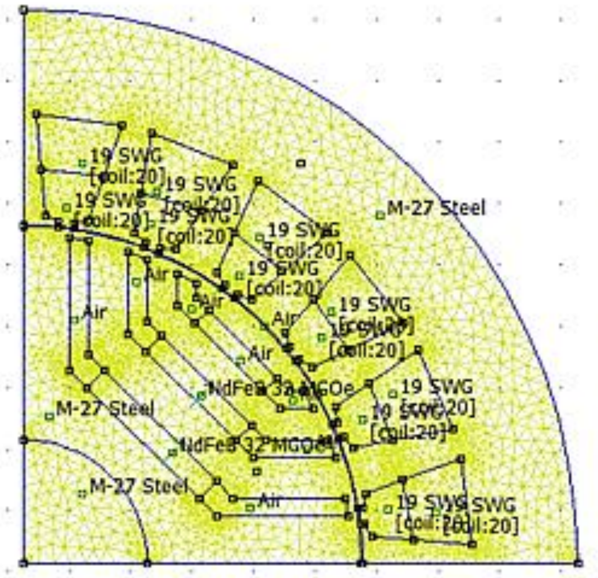


Figure 6. Running condition by NdFeB32MGOe

Figure 7 shows the magnetic flux density values for SynRM per pole result output, flux density which can be plotted as a colour density plot.

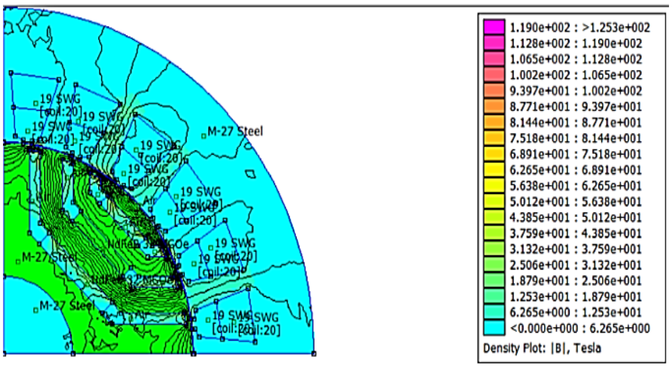


Figure 7. Magnetic flux density for SynRM per pole

Figure 8 shows the magnitude of magnetic flux density for one pole of SynRM by using finite element method (FEM) software.

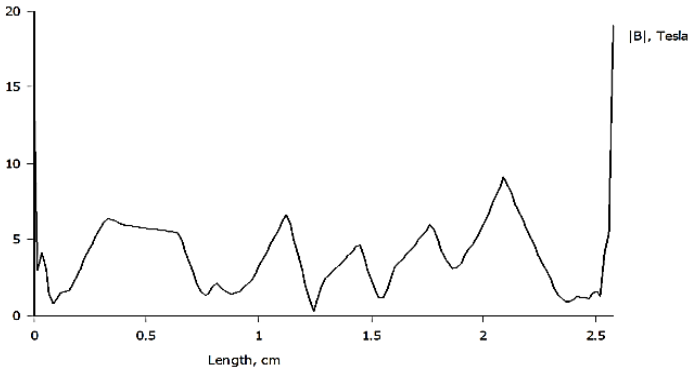


Figure 8. The magnitude of magnetic flux density for one pole

5. CONCLUSION

The simulation of stator slot number, rotor flux barriers number, insulation ratio and permanent magnet position of a synchronous reluctance motor is investigated. The design process has been carried out by using analytic calculation. Moreover, the finite element method was used to calculate the flux density in the motor components. In this design, stator slot dimensions are calculated by sizing equation and then rotor structure is analyzed with finite element method. In this paper, Synchronous reluctance motor is designed for 8kg washing machine which rated power 400W.

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