Rotor Design of a Novel Self-Start Type Permanent Magnet Synchronous Motor

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***Abstract*--Recently, permanent magnet type synchronous motor has been used widely for industry application. In the paper, we propose a novel self-start type permanent magnet synchronous motor with squirrel-cage and analyze the basic characteristics of the motor. We try to increase the efficiency by the rotor design with the finite element analysis.**

***Index Terms*--Induction motor, Permanent magnet, Self-start type, Synchronous motor**

I. INTRODUCTION

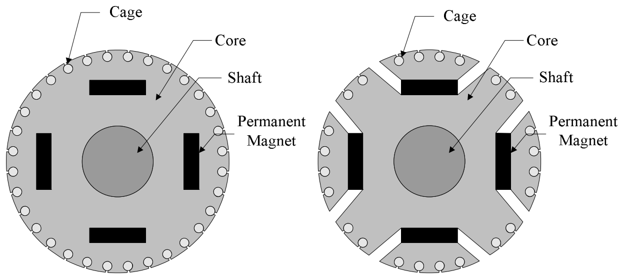
In this paper, we propose a hybrid type permanent magnet synchronous motor (PMSM) and call it a self-start type PMSM. It consists of a squirrel-cage induction motor and a permanent magnet synchronous motor. By its unique rotor structure, the motor is able to obtain starting torque as an induction motor (IM). The motor is not also required to detect the rotor position and can be driven with open-loop control. Additionally, at loss of synchronism, the motor can continue to drive as an IM. In the paper, we show the design and the results of characteristics analysis.

II. A NOVEL SELF-START TYPE PMSM

A. Rotor Design

First of all, the stator is the same structure as the general AC motor. By applying three-phase alternating current to the three-phase stator winding, a revolving magnetic field is generated. That is to say the structure of the motor is a rotating field mechanism.

Next, the important point is the structure of the rotor for a self-start type PMSM. This type of motor has been studied from the past. For example, Fig. 1 shows traditional rotor structures. Fig. 1(a) is a simple structure with permanent magnets embedded in the rotor core of the IM. The advantage is that high efficiency is achieved at asynchronous operation. However, the magnetic field of permanent magnets is not used effectively because most of flux is short-circuited at both ends of each permanent magnet. Fig. 1(b) shows a structure with flux barriers placed at both ends of the magnets. By providing flux barriers, the magnetic field of permanent magnets is used effectively and the efficiency is improved at synchronous speed. However, the efficiency reduces at asynchronous speed because flux barriers interfere with the revolving magnetic field while running as an IM. As described above, it is very difficult to design the rotor of a self-start type PMSM considering the balance of function as a synchronous motor and an asynchronous motor.



(a) Type 1. (b) Type 2.
Fig. 1. Rotor Structures of PMSM.

Fig. 2 shows the rotor structure of a self-start type PMSM proposed in this paper. An important feature is that two permanent magnets mounted on the surface of the rotor to operate as a 4-pole machine [1,2]. Two permanent magnets are magnetized in a radial direction with the same polarity. The two located permanent magnets induce hypothetical polarity opposite to the magnets, which makes 4-pole arrangement. This structure enables to effectively use the revolving magnetic field and the magnetic field of permanent magnets. To reduce the amount of permanent magnets corresponds to reducing the gap preventing the revolving magnetic field. In this way, the rotor structure attains high efficiency at asynchronous operation. It also maintains high efficiency at synchronous operation because the magnetic field of permanent magnets can be used effectively and can be less the gap by placing permanent magnets on the surface of rotor. In addition, to enlarge slots at both ends of each permanent magnet is effective to prevent flux leakage. Moreover, those windings ensure paths to flow secondary current because those are short circuited with other squirrel-cage winding.

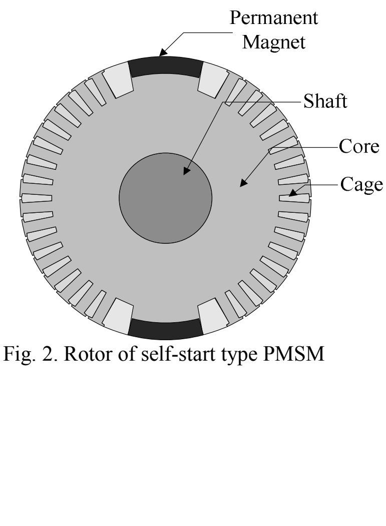


Fig. 2. Rotor of self-start type PMSM

B. Operating Principles

At starting process, the revolving magnetic field induced in the stator winding generates torque at the squirrel-cage winding of the rotor. Then the motor operates from start to around synchronous speed as an IM. The torque at asynchronous operation is given by

$$T=\frac{P}{4\pi f}3V_1^2\frac{r_2'/s}{(r_1+r_2'/s)^2+(x_1+x_2')^2} \tag{1}$$

P: Number of poles V_1: Input voltage
r_1: Primary resistance
r'_2: Secondary resistance seen from the primary side
x_1: Primary leakage reactance
x'_2: Secondary leakage reactance seen from the primary side

At around the synchronous speed, the rotor is synchronized by the pull-in torque and the motor operates as a synchronous motor. In this state, because the torque given by the equation (1) is lost, in accordance with the principles of a synchronous motor, the motor operates with magnet torque and reluctance torque. Then, the torque is given by

$$T=P_n\left\{\phi_a I_a\cos\beta+\frac{1}{2}\left(L_q-L_d\right)I_a^2\sin 2\beta\right\} \tag{2}$$

P_n: Number of pole pairs
φ_a: Armature flux linkage by PM
I_a: Amplitude of current
β: Phase angle of current

Even if the motor loses synchronization, the motor can continue to drive as a synchronous motor with damper windings.

III. Design and Analysis Specification of Motor

A. Design Parameter

Table I shows design parameters and Fig. 3 a 2-dimensional model of the proposed self-start type PMSM. The rated output power is 2.2kW, the rated voltage 200V, and the rated speed 1800rpm. For the stator, the number of slots is 36 and the number of slots per pole and per phase is 3. For the rotor, the number of slots of squirrel-cage is based on the design of an IM with 44 slots.

TABLE I
Design Parameter.

Output power	2.2 kW
Number of poles	4
Voltage	200 V
Frequency	60 Hz
Rated speed	1800 rpm
Stator diameter	157 mm
Rotor diameter	99.4 mm
Shaft diameter	32 mm
Motor length	90 mm
Air gap	0.3 mm
Number of slots / phase / pole	3
Number of slots	36
Coil pitch	7/9
Connection	Y

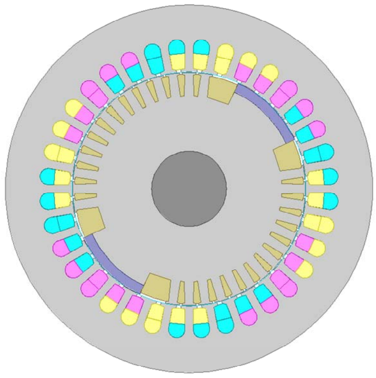


Fig. 3. 2-dimensional model of self-start type PMSM.

B. Analysis Specification

We analyze the basic characteristics of the motor using a 2-dimesional finite element method software. For the magnet materials, the permanent magnet is N42SH of neodymium magnets, the steel sheet is 50A250 of highlight cores and the squirrel-cage winding is aluminum. The temperature is assumed to be 20˚C.

IV. Basic Characteristics

A. Considering of magnet size in rating

In the design of a rotor for the proposed configuration, it is important to determine the magnet size mounted on it, namely the magnet angle shown in Fig. 4 and the magnet height. We clarify the magnet size adequate to produce the rated output at synchronous operation through the finite element analysis. The validity of the design is confirmed by comparing the proposed motor with a surface-mounted permanent magnet synchronous motor (SPMSM) with the same stator. Fig. 5(a) shows a 2-dimensional model for the SPMSM. Fig.6 and Table II summarize the magnet height required for the rated output at each of the magnet angle. In the analysis, the power angle is fixed for maximum output. It is shown that the self-start type PMSM requires magnets which are twice the height of those in SPMSM for the same output.

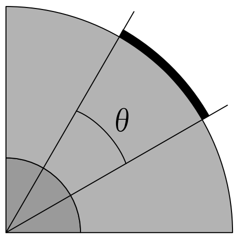
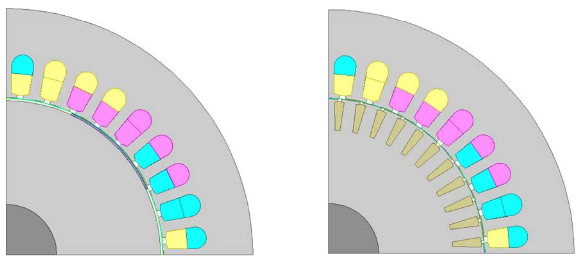


Fig. 4. Magnet angle.



(a) SPM. (b) IM.
Fig. 5. 2-dimensional model for FEM.

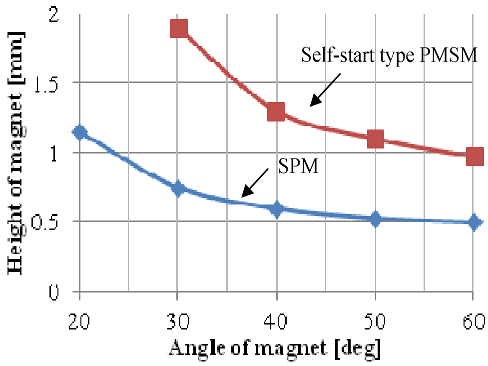


Fig. 6. Comparison of magnet size.

TABLE II
COMPARISON OF MAGNET SIZE.

	SPM	Self-start type PMSM
Magnet angle [deg]	Height of magnet [mm]	
30	0.75	1.9
40	0.60	1.3
50	0.53	1.1
60	0.50	0.97

B. Torque and efficiency characteristics

For the magnet design to produce the rated output, we analyze the torque and the efficiency of the self-start type PMSM based on the finite element method. The analysis is carried out for the slip to understand the characteristics of a starting process and the synchronous operation. As a reference of the starting process, we add the characteristics of an IM with the same stator. The 2-dimensional model for the IM is shown in Fig. 5(b). Figs. 7 and 8 show the torque and efficiency characteristics for the slip. The efficiency is given by

$$\eta = \frac{P}{P + P_c + P_i} \times 100\,[\%] \tag{3}$$

P: Output power P_c: Copper loss P_i: Iron loss

The detailed values of the characteristics at the synchronous speed are described in Table III. In Fig. 7, increasing the magnet angle corresponds to decreasing the torque. The best efficiency 85.8 % is achieved at the synchronous operation with 40 deg magnet angle and 1.3mm magnet height.

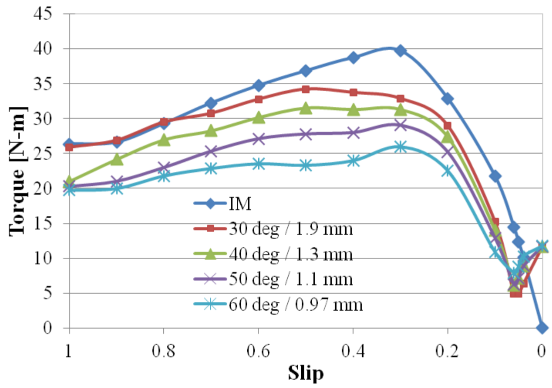


Fig. 7. Torque characteristics.

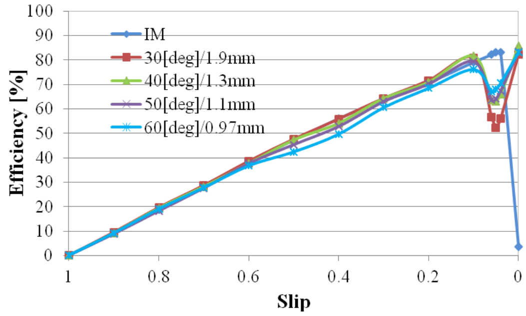


Fig. 8. Efficiency characteristics.

TABLE III
CHARACTERISTICS AT SYNCHRONOUS SPEED.

Magnet angle [deg]	Torque [N-m]	Current [A]	Efficiency [%]
30	11.70	14.1	82.6
40	11.68	12.0	85.8
50	11.74	13.4	83.4
60	11.76	13.5	83.2

C. Considering efficiency at synchronous speed

The characteristics are obtained at the minimum size of magnets required for the rated output at the synchronous operation without control. The efficiency can be improved by using i_d=0 control. We examine a practical design of magnets with high efficiency at the rated output. Tables IV-VII describes the induced torque, the armature current, and the efficiency for the magnet angle and height. The increment of the magnet angle decreases the armature current and improves the efficiency.

TABLE IV
30 DEGREES OF SELF-START TYPE PMSM.

Height of magnet [mm]	Torque [N-m]	Current [A]	Efficiency [%]
2	11.65	14.0	82.3
3	11.64	13.3	83.7
4	11.67	12.6	84.8
5	11.67	12.2	85.4

TABLE V
40 DEGREES OF SELF-START TYPE PMSM.

Height of magnet [mm]	Torque [N-m]	Current [A]	Efficiency [%]
2	11.67	10.9	87.6
3	11.71	9.87	88.8
4	11.70	9.43	89.6
5	11.74	9.21	89.8

TABLE VI
50 DEGREES OF SELF-START TYPE PMSM.

Height of magnet [mm]	Torque [N-m]	Current [A]	Efficiency [%]
2	11.74	8.86	90.6
3	11.74	8.11	91.6
4	11.74	7.79	91.7
5	11.63	7.53	91.9

TABLE VII
60 DEGREES OF SELF-START TYPE PMSM.

Height of magnet [mm]	Torque [N-m]	Current [A]	Efficiency [%]
1	11.72	11.6	86.4
2	11.66	7.62	91.7
3	11.70	6.99	92.5
4	11.69	6.70	92.5

V. Design of a Prototype

Based on the obtained basic characteristics, we design a prototype of the self-start type PMSM. The characteristic at starting process is important for the performance of the motor. However the motor should be designed for high efficiency at the synchronous speed because the motor is used as a synchronous motor at most operation time. The numerical results suggest that an adequate magnet angle is 40 deg or 50 deg because torque characteristics similar to those of IM are obtained for the magnet angle. Here we examine the torque characteristics for the height of magnets of each angle in detail. Fig. 9 shows the torque characteristics and Fig. 10 the efficiency characteristics. Table VIII describes the characteristics at 0.05 slip. In the starting process, the induced torque decreases as the magnet size is larger. Therefore we determine as the best design parameters 40 deg magnet angle and 3 mm height of magnet for the prototype.

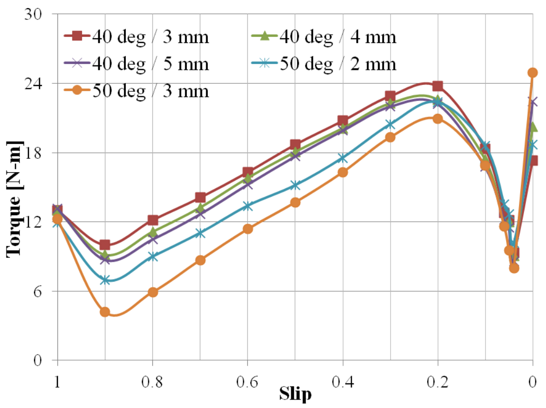


Fig. 9. Torque characteristics.

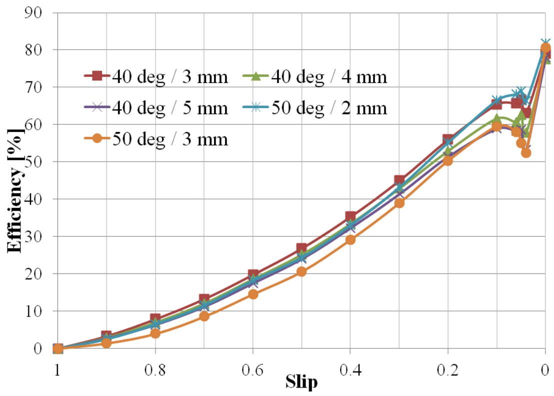


Fig. 10. Efficiency characteristics.

TABLE VII
Characteristics at 0.05 Slip.

Magnet angle / Height of magnet	Torque [N-m]	Primary current [A]	Efficiency [%]
40 deg / 3 mm	12.15	20.5	66.0
40 deg / 4 mm	11.98	22.8	61.9
40 deg / 5 mm	11.49	24.6	58.2
50 deg / 2 mm	12.68	20.2	68.2
50 deg / 3 mm	9.51	24.4	54.6

VI. Conclusions

Design analysis is carried out for a novel self-start type permanent magnet motor. In the future, we will confirm the actual operation of the prototype motor.

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