Fundamental Characteristics of a Novel Self-Starting Type Permanent Magnet Synchronous Motor

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***Abstract*—Wide use of permanent magnet synchronous motors produces a request for adding self-starting function to them. We propose a squirrel-cage rotor with permanent magnets for the self-starting synchronous motors. This paper shows the rotor configuration of a proposed motor and investigates the fundamental characteristics associated with the self-starting function.**

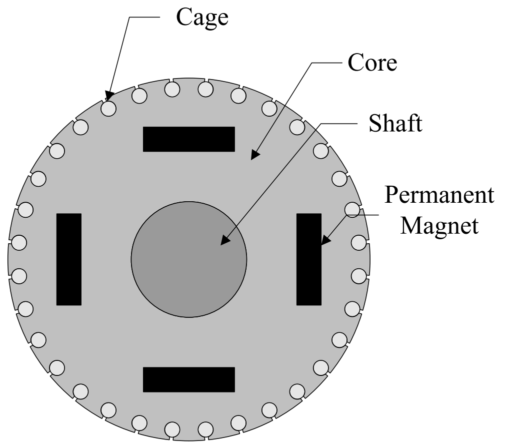
***Index Terms*—Induction motor, Line-start motor, Permanent magnet, Synchronous motor**

I. Introduction

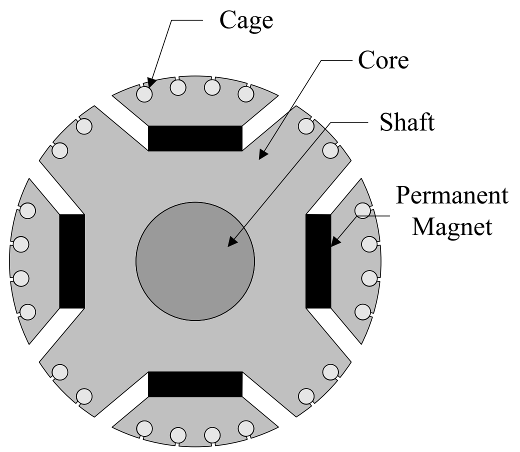
Line-start permanent magnet synchronous motors have been investigated as high efficiency constant-speed poly-phase motors [1-3]. The motors first were proposed to replace synchronous reluctance motors [2]. Then it was recognized that the motors have the potential to outperform induction motors which are used in the industrial, commercial, and consumer applications [1,2]. However the practical use of the motors are not realized today. The spread of the use of permanent magnet synchronous motors implies the importance and significance to improve the performance of the motors.

Permanent magnet synchronous motors, in general, produce no starting torque without variable frequency supplies. The starting performance of a line-start permanent magnet synchronous motor is due to a squirrel cage winding disposed in the rotor with permanent magnets. The stator of the motor is similar to that of a poly-phase synchronous motor or induction motor establishing the rotating magnetic field.

A variety of configurations have been proposed for the rotor [1]. Fig. 1 shows two basic configurations for four-pole arrangement with radially magnetized magnets [4]. Fig. 1(a) shows a rotor configuration without flux barriers per pole and (b) with flux barriers. The former contains the same disposition of a squirrel cage as the rotor of an induction motor. The disposition produces the performance in starting process and asynchronous operation equivalent to an induction motor. On the other hand, the configuration causes short-circuiting of the magnet flux which reduces the magnet flux through the air gap, that is, the performance in synchronous operation. In the latter, the performance in synchronous operation is improved due to flux barriers per pole. However the flux barriers interrupt the rotating magnetic field through the squirrel cage winding for some positions of the rotor. These rotor configurations specialize in one of the two performances. The performances as an induction motor and a synchronous motor exhibit incompatible characteristics in the rotor configurations.



(a) Without flux barriers.



(b) With flux barriers.

Fig. 1. Basic rotor configurations.

We propose a rotor configuration for a line-start permanent magnet synchronous motor to produce both the performances. The rotor contains the permanent magnets mounted on the surface and squirrel cage windings. This paper describes the detailed explanation of the proposed motor and shows the fundamental characteristics of the line-start permanent magnet synchronous motor with the rotor.

II. ROTOR CONFIGURATION

Before introducing a proposed rotor, we discuss the design configuration for the rotor of a line-start permanent magnet synchronous motor to produce both high performances as a synchronous motor and as an induction motor. The characteristics at synchronous operation such as torque depend on flux linkage of permanent magnets through the stator. To obtain the flux linkage effectively requires the designed construction of magnetic circuits with respect to the permanent magnets and the rotor core. The circuit construction is realized by locating flux barriers between the poles at both the sides of each magnet. The starting process and asynchronous operation as an induction motor are due to the electromagnetic interaction between the current in a squirrel cage winding and the rotating magnetic field established in the stator. The interaction can be enhanced by the disposition of the squirrel cage winding and the construction of the magnetic circuit with respect to the rotating magnetic field.

The flux barriers to prevent the short-circuiting of the magnet flux occupy a part of the surface domain of the rotor for cage bars and interrupt the rotating magnetic field through the rotor at some rotor positions as Fig. 1(b). Thus the flux barriers are obstacles for asynchronous operation. On the other hand, the flux barriers are necessary for synchronous operation. We explain how to locate flux barriers in the rotor for high-performance in starting process and asynchronous operation.

In a standard pole arrangement, the number of permanent magnets located in the rotor is the same as the pole number of design. The location of magnets is carried out symmetry or at equal pole pitch. For this arrangement, flux barriers have to be located at the middle position of each pair of the poles or symmetry against the middle position. The interval of neighboring flux barriers is shorter than the pole pitch. Thus the flux barriers interrupt the rotating magnetic field at an arbitrary rotor position because the field is induced at the pole pitch. Therefore the flux barriers have to be located asymmetry against the magnetic middle position not to interrupt the rotating magnetic field at arbitrary rotor position.

Figure 2 shows the cross section of the proposed rotor for a novel line-start permanent magnet synchronous motor based on the above design concept. The rotor is designed for a four-pole arrangement with two permanent magnets and a squirrel cage winding. The two permanent magnets are magnetized radially with the same polarity and mounted on the surface at double pole pitch, namely at interval of 180˚ for a four-pole machine. The magnetization induces the other polarity at the position at the distance of the pole pitch from the magnets, namely 90˚. Flux barriers are configured by four thicker squirrel cage bars located at both the sides of the magnets. The polarity distribution due to the two surface-mounted permanent magnets provides the distance between the flux barriers without a magnet that is wider than the pole pitch. Thus the rotating magnetic field is not always interrupted by the flux barriers. That is, the starting process and asynchronous operation as an induction motor is sustained regardless of the introduction of the flux barriers.

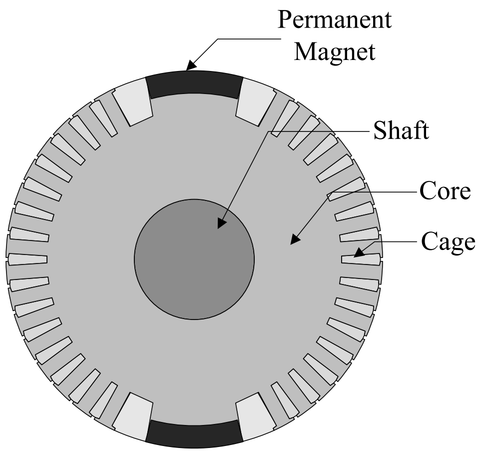


Fig. 2. Proposed rotor configuration.

III. FINITE ELEMENT ANALYSIS

This section is devoted to numerical analysis for the fundamental characteristics of the proposed line-start permanent magnet synchronous motors through the finite element method.

A. Model

Fig. 3 shows the 2-dimensional model for the proposed line-start permanent magnet synchronous motor. As mentioned above, the motor operates as a four-pole machine. Table I describes the specification of the model. In the stator slots, the two-layer short pitch winding is carried out. The short pitch factor is 7/9. The material of the permanent magnets is Nd-Fe-B (N42SH) and that of the steel plate for the stator and the rotor core is the non-oriented magnetic steel (50H250). Fig. 4 shows the B-H curve of the core material.

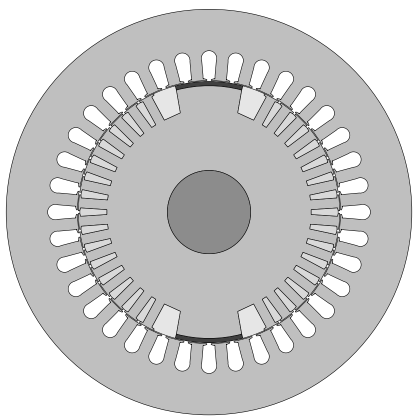


Fig. 3. Model for numerical analysis.

TABLE I
SPECIFICATIONS OF THE MODEL.

Output power	2.2 kW
Number of poles	4
Voltage	200 V
Current	8.11 A
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/phases/poles	3
Number of slots	36
Connection	Y

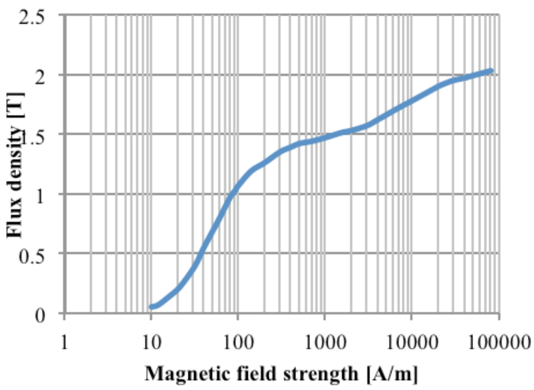
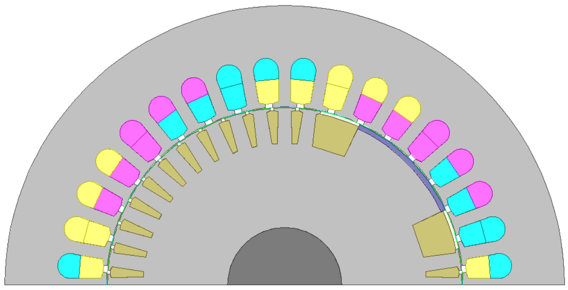


Fig. 4. B-H curve of the core material (50H250).

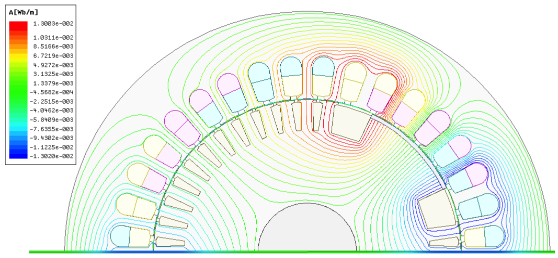
B. Magnetic Flux Distribution

The proposed rotor is designed for four-pole arrangement. First the polarity due to the location of the permanent magnets is confirmed by showing the magnetic flux distribution in the motor.

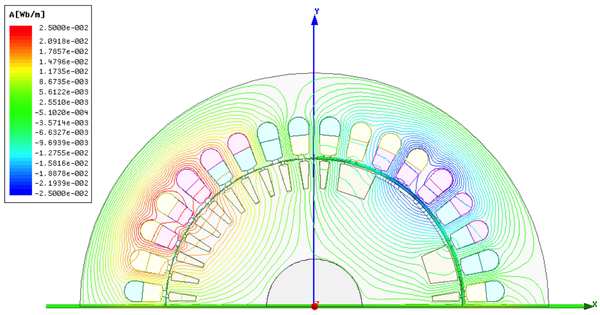
Fig. 5(a) shows the analyzed half model and (b) the corresponding magnetic flux distribution produced by the permanent magnets. There is magnetic flux through the surface domain of the rotor occupied for the squirrel cage winding. This implies that the opposite polarity is induced against that of the magnet at the surface domain as the design concept. It produces synchronous torque by interacting with the rotating magnetic field. Figs. 5(c)-(e) show the magnetic flux distribution produced by the 3-phase armature current at some phases. Since the air gap length is small, the rotating magnetic field gets into the rotor vertically. Therefore, asynchronous torque will be produced in the circumferential direction.



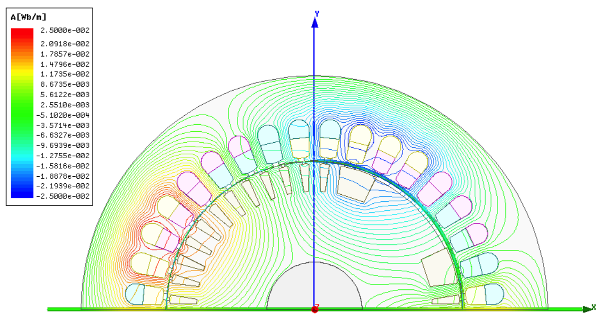
(a) Half model.



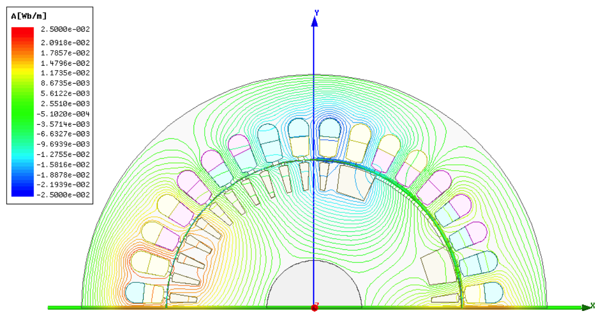
(b) Magnetic flux distribution produced by magnets.



(c) Magnetic flux distribution produced by armature current at ωt=0˚.



(d) Magnetic flux distribution produced by armature current at ωt=60˚.



(e) Magnetic flux distribution produced by armature current at ωt=120˚.

Fig. 5. Magnetic flux distribution of the half model.

C. *Static Characteristics*

In order to understand the starting process of the proposed line-start permanent magnet synchronous motor, we study the torque characteristics for the rotational speed or slip as an induction motor. Fig. 6 shows the torque-slip characteristics of the line-start motor and an induction motor with the similar specification. Each curve corresponds to the motor with the different design for the permanent magnet, namely the arc width and the thickness. The design of magnet is determined to produce the same output. The proposed motor exhibits the similar characteristics as the induction motor. The result suggests that the proposed rotor can sustain the performance as an induction motor with permanent magnets and flux barriers. At zero slip or synchronous operation, the proposed motor can supply torque as a synchronous motor.

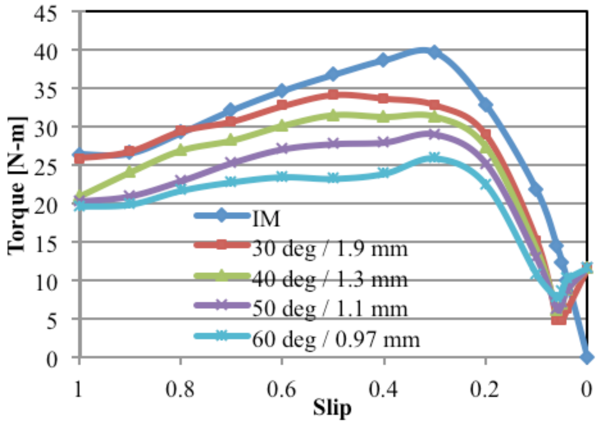


Fig. 6. Torque-slip characteristics.

IV. CONCLUSIONS

In the paper, we propose a novel rotor configuration for a self-starting type permanent magnet synchronous motor. The rotor is designed for both performances as an induction motor and a synchronous motor. The design concept is confirmed by analyzing the magnetic flux distribution and the fundamental characteristics of the static operation. In the future, we experimentally verify the validity of the design concept.

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