Design of Single-Phase Line-Start Permanent Magnet Motor Using Equivalent Circuit Method

Sun-Hyo Kwon*, Chul-Kyu Lee† and Byung-Il Kwon**

Abstract - In this research, the design procedure and the design method of a single-phase line-start permanent magnet motor (LSPM) are proposed. In the design procedure, the permanent magnet is designed first and the windings and capacitors are designed later. As well, the points of design of each design parameter are explained. In the design of the single-phase LSPM, the equivalent circuit method is combined with the finite element method (FEM) because it has a shorter analysis time than FEM. The 400 watts single-phase LSPM is designed and manufactured. The characteristics of the manufactured single-phase LSPM are analyzed and experimented. From the analysis result and the experiment result, it is verified that the design procedure and the design method of the single-phase LSPM is valid.

Keywords: Design method, Design procedure, Equivalent circuit method, Single-phase line-start permanent magnet motor (LSPM)

1. Introduction

It is widely known that a single-phase line-start permanent magnet motor (LSPM) has many advantages over a single phase induction motor. The single phase LSPM has a high energy density and runs at synchronous speed in the steady state. It provides higher efficiency than the single-phase induction motor and is competitive from a cost standpoint because the driving device is not used [1, 2].

The drawbacks of the single-phase LSPM are the difficulty of start-up and the longer start-up time. Currently, there is a paucity of research concerning the design of the single-phase LSPM. The difficulty of start-up and the longer start-up time result from the overlapping of the torque produced by permanent magnets and the torque produced by electromagnetic induction in the rotor bars. In particular, the torque produced by permanent magnet decreases the start-up torque, resulting in difficulty of start-up and longer start-up time [3, 4].

In this research, a design procedure and a design method of the single-phase LSPM are proposed. The design procedure and the design method are concentrated on the permanent magnet, the windings and the capacitors. The permanent magnet greatly affects the start-up and the synchronization. And the windings and capacitors should be designed considering the output power and the symmetrization conditions [5].

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The design of the single-phase LSPM is executed by the equivalent circuit method combined with FEM in order to reduce the analysis time. The circuit parameters of the motor are calculated by the finite element method, which is able to consider the nonlinearity of the core's permeability.

In order to verify that the proposed design procedure and the proposed design method are valid, a 400 watt single-phase LSPM is designed and manufactured.

2. Design and analysis

2.1 Design Procedure

In this research, the authors use the stator core and the rotor core of a 400 watt single-phase induction motor that was developed commercially already. Therefore, the design of the slot of the stator and rotor is omitted. In designing the single-phase LSPM using the single-phase induction motor, the cost of developing the single-phase LSPM can be reduced.

Fig. 1 shows the shape of a single-phase LSPM motor. The 1/4 model is shown because the single-phase LSPM has 4 poles. The stator of the single-phase LSPM is the same as the single-phase induction motor and the rotor has rotor bars, a permanent magnet and a barrier.

Fig. 2 shows the design procedure of the single-phase LSPM. The design of the single-phase LSPM can be divided into two parts. The first part is the design of the permanent magnet in the rotor and the second part is the design of windings and capacitors. When the air gap magnetic flux density by the permanent magnet is high, the braking torque produced by the permanent magnet disturbs the start-up seriously. However, high air gap magnetic flux density provides the motor with improved capability for synchronization. On the other hand, if the air gap magnetic flux density by the permanent magnet is low, the braking torque by the permanent magnet upon start-up is low, thus providing a smooth start-up. However, the weak force at synchronous speed decreases synchronization capability and the synchronous speed may not be maintained even by a slight load change. Therefore, these two properties have to be adequately considered in the design of the permanent magnet.

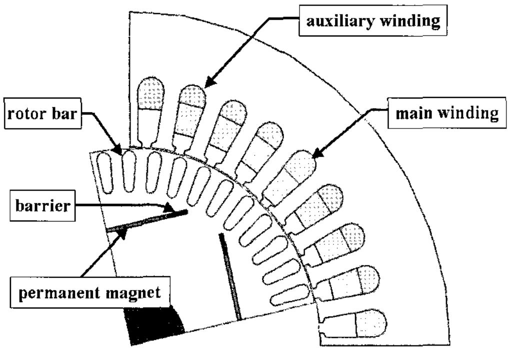


Fig. 1: The shape of a single-phase LSPM motor

The second part is the design of the windings and capacitors. The windings consist of the main winding and the auxiliary winding. And the capacitors consist of the starting capacitor and the running capacitor. The main winding should be designed to produce the necessary 3~4 times rated torque in order to maintain synchronous speed even at load torque greater than rated torque. The number of turns of auxiliary winding and the running capacitor should be adequately designed to provide the symmetryzation conditions [5]. The starting capacitor should be designed to provide the motor with large starting torque. The diameters and specifications of the windings are selected in consideration of the slot size and fill factor of the selected single-phase induction motor.

The permanent magnet is designed based on the air gap magnetic flux density, and the windings and the capacitors are designed using the equivalent circuit method combined with FEM. In the equivalent circuit method combined with FEM the circuit parameters are calculated using FEM in order to consider the nonlinearity of permeability of the core.

2.2 Design of a Permanent Magnet

The NdFeB magnet is used in the single-phase LSPM. The NdFeB magnet has anisotropic property. Therefore, the direction of magnetization of the magnet is in unity and the NdFeB magnet has high remanent magnetization and high coercive force. Therefore, it can provide higher air gap magnetic flux density than other magnets. The NdFeB magnet is designed as follows.

The cross section (A_m) of the NdFeB magnet is calculated by equation (1).

$$A_m = \frac{K_l B_g A_g}{B_m} \tag{1}$$

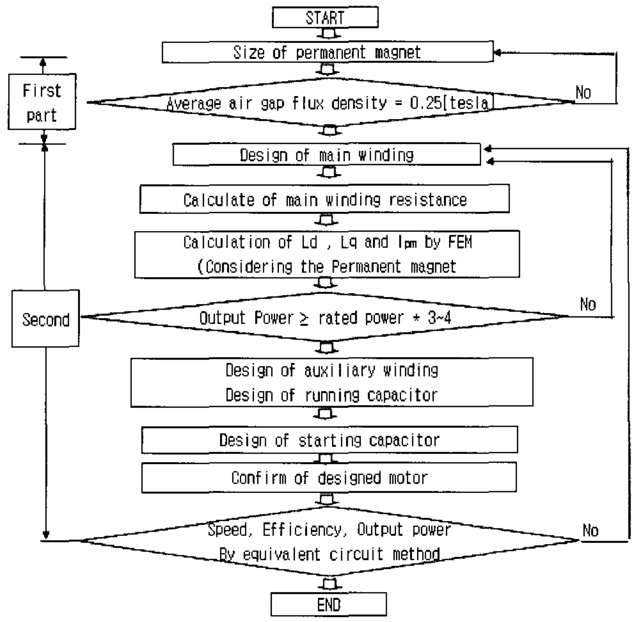


Fig. 2. Design procedure

Where, B_m is the flux density in the magnet, A_m the area of the magnet, B_g the average flux density in the air gap, A_g the area of air gap and k_l the leakage factor.

The average air gap magnetic flux density of the synchronous motor is 0.7[T] ~ 0.9[T] generally [6]. But in the single-phase LSPM the rotor bar also produces the magnetic flux. Therefore, the average air gap magnetic flux density produced by the NdFeB magnet is determined as 0.25[T]. The thickness of a permanent magnet is calculated by equation (2).

$$l_m = \frac{K_r H_g l_g}{H_m} \tag{2}$$

Where, H_g is the air gap magnetic field intensity, l_g the air gap length, H_m the magnetic field intensity in the permanent magnet and K_r the reluctance factor.

Table 1 shows the specifications of the designed NdFeB magnet. The irreversible demagnetization characteristic is analyzed by the method proposed in [7]. By the analysis, it is verified that the designed NdFeB magnet is not demagnetized irreversibly. Fig. 3 shows the air gap magnetic flux density produced by the designed NdFeB magnet. The magnetic flux density is large at the center and small at the edge because the flux barrier is installed at both ends of the magnet.

Table 1. Spec. of designed NdFeB magnet

Item	Size
Area	1600 [mm^2]
thickness	1 [mm]

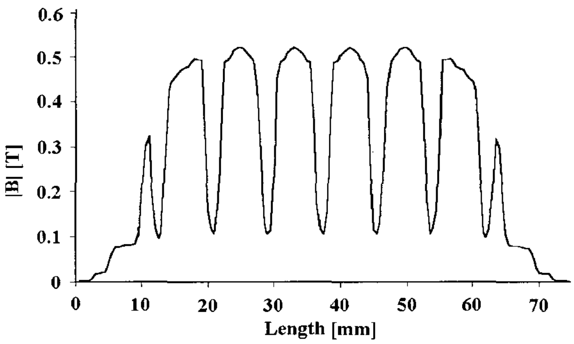


Fig. 3. Magnetic flux density in air gap by the designed NdFeB magnet

2.3 Design of Windings and Capacitors

The design of windings consists of two parts. One part is the design of the main winding and the other part is the design of the auxiliary winding. The main winding should be designed prior to the design of the auxiliary winding. The design of the main winding is done in consideration of the maximum output power in the steady state. The LSPM runs at synchronous speed. However, if the single-phase LSPM is not designed properly, the synchronous speed may be lost even by a slight load change. To prevent this, the output power should be enough to maintain the synchronous speed at higher load than rated load.

For the design of the main winding, the motor is assumed as an ideal 2-phase motor. Therefore, the number of turns of the main winding is assumed to be equal to the number of turns of the auxiliary winding and the current of the main winding is assumed to be equal to the current of the auxiliary winding. The phase angle difference between the current of the main winding and the current of the auxiliary winding is assumed to be 90 electrical degrees. After the number of turns of the main winding is determined arbitrarily, the value of d-axis inductance (L_d), q-axis inductance (L_q) and equivalent magnetization current (I_{pm}) produced by the permanent magnet are calculated by the FEM. Then L_d, L_q and I_{pm} are applied to an equivalent circuit method to analyze the maximum output power.

Fig. 4 shows the analysis result of output power in steady state according to load angle for the designed main winding. The number of turns of the designed main winding is 752[turn]. The maximum value of the graph becomes the maximum power that can be produced by the motor. Fig. 4 shows that the maximum output of 1800 watts is achieved at the load angle of 100 degrees. The maximum power by permanent magnet is achieved at the load angle of 90 degrees. However, the LSPM also has a reluctance torque because the d-axis reluctance and the q-axis reluctance are not equal. The LSPM has maximum reluctance power at the load angle of 135 degrees while the electromagnet synchronous motor has maximum reluctance power at the load angle of 45 degrees. Total power is the sum of the permanent magnet power and the reluctance power. Hence the maximum total power is achieved at nearly 100 degrees of load angle.

The rated output of the single-phase induction motor to be designed is 400 watts. Therefore, the number of turns of the designed main winding is proper.

After determining the number of turns of winding, the specification for winding is calculated in consideration of the stator slot size and a fill factor. The current of the main winding at the steady state is calculated approximately using (3).

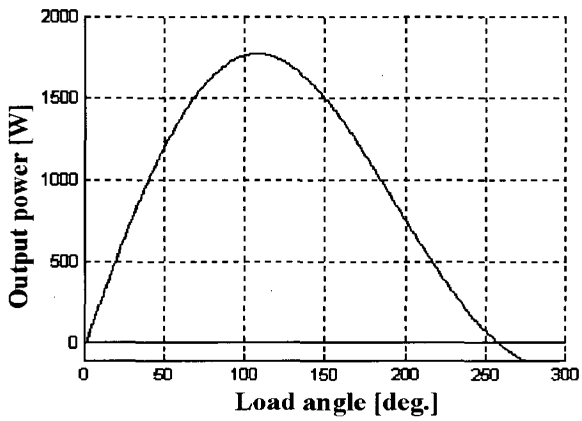


Fig. 4. Output power according to load angle

$$I_s = \frac{P_{out} \times 10^3}{2 \times V_{ph} \times \cos\phi \times \eta} \tag{3}$$

Where, I_s is the main winding current, P_{out} the rated output power, V_{ph} the phase voltage, $\cos\phi$ the power factor and η the efficiency. The diameter of the main winding of a stator is calculated by (4).

$$a_s = \frac{I_s}{\delta_s}[mm^2] \quad (4)$$

Where, a_s is the cross section of a winding, and δ the current density of the conductor, which is about 3~6 A/mm^2. The resistance of the winding is calculated by (5).

$$R = \frac{L_{mts} \times N}{\sigma \times a_s} \quad (5)$$

Where, L_{mts} is the length of winding for 1 turn, N the number of turns of winding, σ the conductivity of conductor and a_s the cross section of conductor of winding. The length of winding for 1 turn is determined using (6).

$$L_{mts} = 2L + 2.3\tau \quad (6)$$

Where, L_{mts} is the length of winding for 1 turn, L the core length and τ the pole pitch.

The number of turns of auxiliary winding and the running capacitor are designed for the single-phase LSPM to be near the symmetrization conditions at steady state. The running capacitor is determined in consideration of the phase angle between the main winding current and auxiliary winding current. For the single-phase LSPM to be the symmetrization conditions, the phase angle between the main winding current and auxiliary winding current should be about 90 degrees, and the magnitudes of magnetomotive forces produced by the main winding and by the auxiliary winding should be identical to what is shown in (7). The auxiliary winding and the running capacitor is designed by trial and error using the equivalent circuit method.

$$I_{main} \times N_{main} = I_{aux} \times N_{aux} \quad (7)$$

Where, I_{main} is the current of main winding, N_{main} the number of turns of main winding, I_{aux} the current of auxiliary winding and N_{aux} the number of turns of auxiliary winding.

Starting capacitor has to be designed in consideration of the starting torque. Generally, the starting capacitor design method follows the method used for the general single-phase induction motor [5]. The specification of an auxiliary winding is also calculated using the same methods used for the specification of the main winding, i.e. equations (3) and (4). Table 2 presents the specifications of the designed winding of the single-phase LSPM.

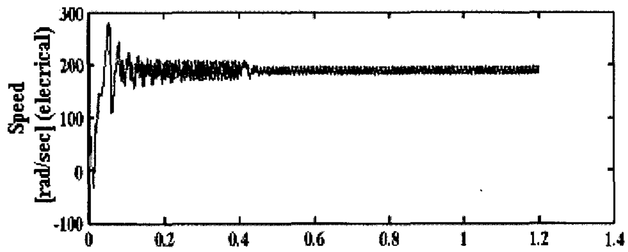
Table 2. Spec. of the winding of single-phase LSPM

Item	Specification
main winding	752 [turns]
auxiliary winding	920 [turns]
starting capacitor	30 [μF]
running capacitor	10 [μF]

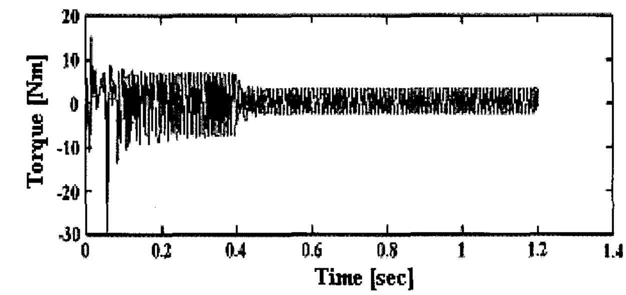
2.4 Analysis and Experiment Result

The circuit parameters of the designed single-phase LSPM are calculated by FEM and the characteristics of the designed single-phase LSPM are analyzed. Fig. 5 shows the results of analyses. Fig. 5 (a) indicates the speed characteristic and Fig. 5 (b) presents the torque characteristic. The starting capacitor is disconnected from the auxiliary winding and the running capacitor is connected with the auxiliary winding at 0.4 seconds after starting using PTC (positive temperature coefficient). As shown in Fig. 5, starting is enabled, and it is running at synchronous speed of 1800 rpm at no load.

The rated torque of the manufactured single-phase LSPM is at 2.2[Nm] at synchronous speed. Fig. 7 shows the analysis result and the experiment result of speed characteristic according to time increasing the load torque. The analysis result concurs with the experiment result. The single-phase LSPM is able to keep the synchronous speed until 3.2[Nm] and break down point occurs at 3.3[Nm]. Therefore, it is verified that the design procedure used in this research is suitable for the design of the single-phase LSPM.



(a) Speed characteristic (at no-load)



(b) Torque characteristic (at no-load)

Fig. 5. Results of analyses

The designed single-phase LSPM was manufactured. Fig. 6 shows the manufactured single-phase LSPM.

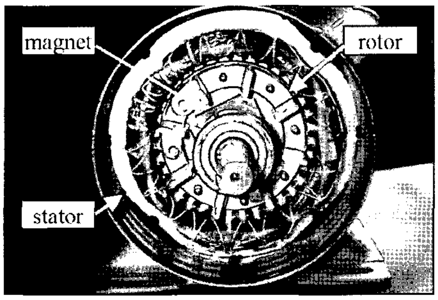


Fig. 6. Shape of manufactured single-phase LSPM

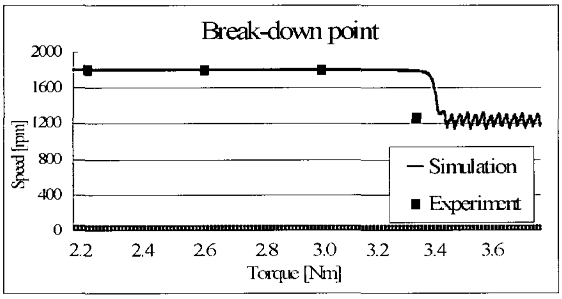


Fig. 7. Break-down point of the manufactured single-phase LSPM

3. Conclusion

In this research, the design procedure and the design method of the single-phase LSPM are proposed. The design procedure is that the permanent magnet is designed first and the windings and the capacitors are designed later. The points of the design of the each design parameter are as follows.

(1) Permanent magnet: The air gap magnetic flux density produced by the permanent magnet should be properly designed. If the air gap magnetic flux density is too high, the single phase LSPM is disturbed in start-up. On the other hand, if the air gap magnetic flux density is too low, the single-phase LSPM is disturbed in synchronization. In addition, the average air gap flux density of the single-phase LSPM produced by permanent magnet should be much smaller than the air gap magnetic flux density of the synchronous motor because the rotor bars currently produce magnetic flux in the single-phase LSPM in addition.

(2) Main winding: In the design of main winding, the single-phase LSPM is assumed to be ideal as a 2-phase induction motor. Therefore, the auxiliary winding is assumed to be equal to the main winding. The number of turns of the main winding should be designed for the single-phase LSPM to produce 3~4 times the rated torque.

(3) Auxiliary winding: The auxiliary winding and running capacitor are designed for the single-phase LSPM to be near the symmetrization conditions.

(4) Starting capacitor: The starting capacitor should be designed to produce a large starting torque.

The single-phase LSPM is designed according to the proposed design procedure and the proposed design method. The equivalent circuit method combined with FEM is used in the design of the windings and capacitors. The designed single-phase LSPM is manufactured and experimented. From the experiment result, it is verified that the proposed design procedure and the proposed design method is valid.

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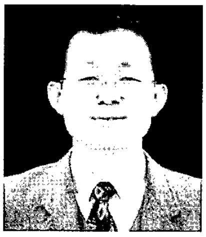

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