The Analysis of the Line-Start Single-Phase Permanent Magnet Motors

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Abstract

In this paper, modeling of line-start single-phase permanent magnet (LSSPPM) motor is investigated. Mathematical model and equivalent circuit of the motor are obtained. Afterwards, the effects of using different permanent magnet materials in the rotor are analyzed. The results of back EMF, motor torque and cogging torque are evaluated for each different material by using Finite Element Method (FEM).

1. Introduction

Permanent magnet synchronous motors are preferred in many areas such as home appliances, industrial robots, centrifuges, fans and toys because of having simple construction and low cost. Single phase permanent magnet (SPPM) motors provide much more efficiency and power factor compared to induction motors and their rate of watt per kilogram is higher than DC motors. Besides this, absence of excitation windings increase the efficiency and reactive power demand supplied by the magnet instead of power network increase the power factor [1].

On the other hand, these motors have some disadvantages. High stator current can demagnetize the magnet. Also every magnet has a Curie temperature, if this temperature exceed, the magnet will be demagnetized. Moreover, the turn direction of the motor is unpredictable and having an asymmetric air gap makes difficult to analyze the working behavior of the motor.

The reason of U-type shape of the stator is because the simple manufacturing. Laminated stator core has two coils as can be seen in Fig. 1 and rotor is completely made of permanent magnets. Most preferred permanent magnet type is ferrite due to low cost in the industrial applications; so, ferrite is chosen here for the motor analysis. The other commercial magnets are AlNiCo, SmCo and NdFeB. Choosing the right permanent magnet is very important since it directly affects the efficiency of the motor [3].

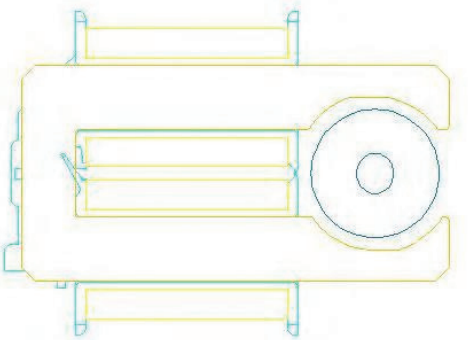

Fig. 1. Line-start single-phase permanent magnet motor

2. Analytical Motor Model

The equivalent circuit of the motor is given in Fig. 2 to predict motor performance with acceptable accuracy. If the core losses and saturation are neglected and voltage supply is assumed as sinusoidal, then the induced voltage in the stator windings written as:

$$e = N.\Phi_m.\dot{\theta}.\sin\theta \quad (1)$$

In (1), N is the number of turns of the stator windings, Φ_m is the maximum useful rotor flux, and $\dot{\theta}$ is derivative of position of the motor.

And the equivalent circuit equation for the motor:

$$V_s.\sin(\omega_{el}t-\varphi) = i.R_{cu} + L.\frac{di}{dt} + N.\Phi_m.\dot{\theta}.\sin\theta \quad (2)$$

In (2), V_s is the supply voltage, ω angular frequency, t and φ are the time and the phase angle, i is instantaneous value of the current, R_{cu} and L are resistance of the stator coil and the stator inductance [2].

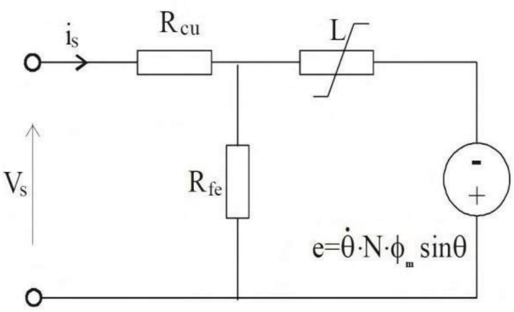

Fig. 2. Equivalent circuit of LSSPPM [2]

Table 1. PMSM ratings

Power [W]	30
Speed [min^{-1}]	3000
Voltage [V]	220-240
Current [mA]	300
Frequency	50
Phase	1
Frame	46
Type	S
L [mm]	25.5
Air gap [mm]	1.85 (min), 2.40 (max)

The torque equation of the motor is

$$N.i.\ \Phi_m.\sin\theta - M_{r,m}\sin[2(\theta - \theta_0)] - M_y = J\,\frac{d\omega}{dt} \qquad (3)$$

In (3), θ is the first position of the rotor and $M_{r,m}$ is the peak value of the reluctance torque.

The first expression in the equation is called electromagnetic moment. This torque can be calculated by the help of equivalent circuit and caused by interactions between stator magnetic field and permanent magnet.

Second expression on the formula represents reluctance torque caused by unsymmetrical air gap. This torque exists always whether the current is flowing into the stator windings or not.

3. Finite Element Model

Using numerical simulations are much more beneficial than experiments. Since experiments take too much time and increase the cost of the project. On the other hand, these numerical solutions bring complicated electromagnetic field calculations. To handle this obstacle it's necessary to use numerical methods. Some of most preferred methods in electromagnetic field applications are finite element method, finite difference method, Monte Carlo method and boundary element method [4].

The finite element method based on the building a complicated system, dividing a complicated object into small pieces. Fig. 3 shows that finite element mesh of the SPPM is composed of triangular and rectangular finite elements. The modeling of the motor is achieved by using the finite element program, Flux2D.

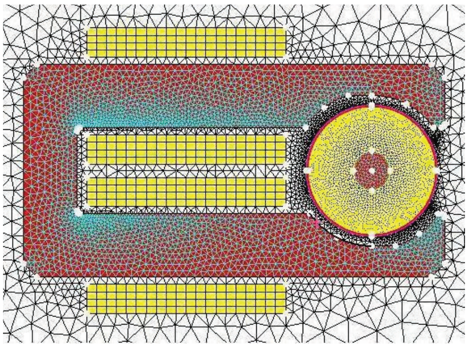

Fig. 3. Finite element mesh of the SPPM

It can be seen in Fig. 4, equi flux line of the motor goes to one pole to another, so figure shows the motor has 2 poles and the peak value of magnetic flux is obtained as 53e-6 Wb.

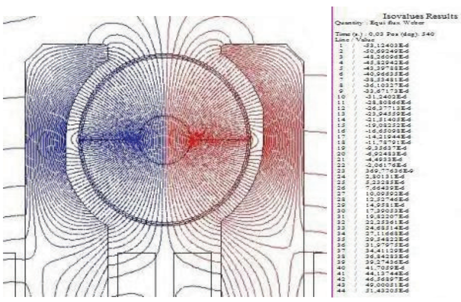

Fig. 4. Equi flux line of the motor at 30 ms.

In Fig. 5, the calculated value of magnetic vector potential is shown. The maximum magnetic flux density is found 706 mT.

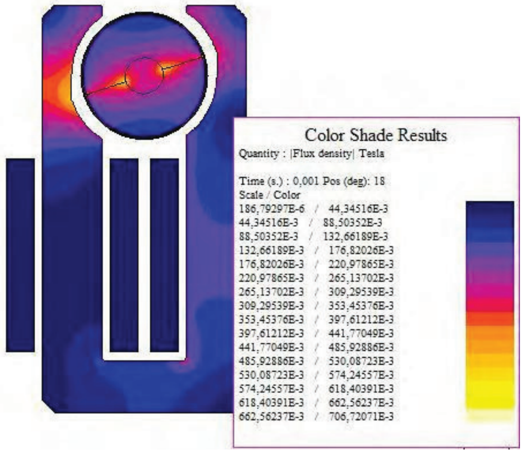

Fig. 5. Flux density distribution of the motor at 10ms.

Flux density in the airgap for one cycle is shown in the Fig. 6a and it's effective value is 350 mT and Fig. 6b shows flux density change in the airgap in time.

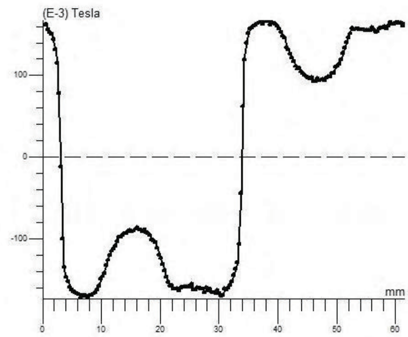

Fig. 6a

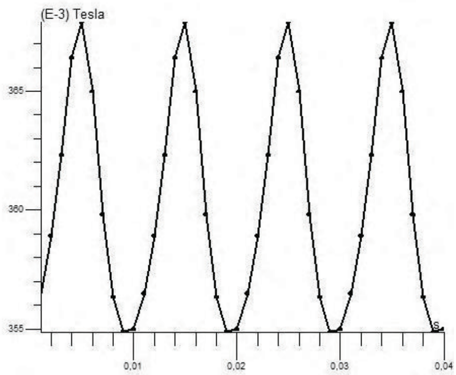

Fig. 6b

Fig. 6a, b. Flux density in the air gap

Rotor is rotated at rated speed to get back EMF, without any excitations of the stator windings. The changing of the magnetic field in the winding induced a voltage in the rotor. In this analysis its effective value is 79,456 V as shown in Fig. 7.

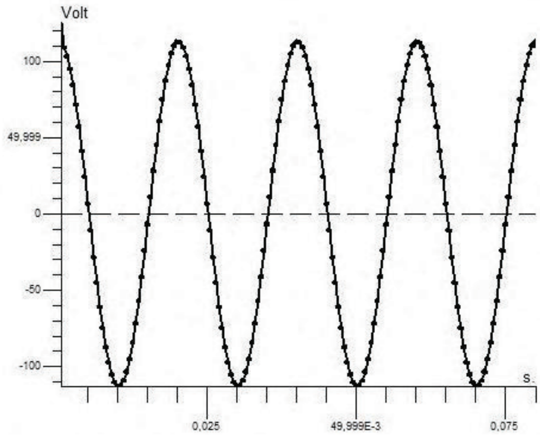

Fig. 7. Flux density in the air gap

The motor power output and torque is:

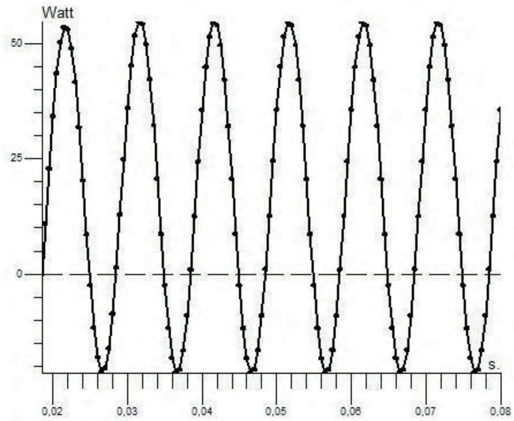

Fig. 8a. Output power

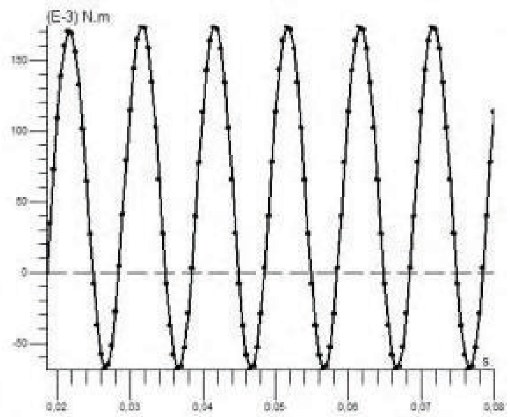

Fig. 8b. Output torque

Output power can be defined as:

$$M_m = \frac{P_{output}}{\omega} \qquad (4)$$

Iron losses are calculated as 0,275 W, this means 0,3% of the total power. It also means that iron losses can be neglected.

4. Cogging Torque

Cogging Torque can be seen in the motors which have unsymmetrical air gap. It affects motor performance and causes vibrations, acoustic noise and speed oscillations in the motor.

Cogging torque also causes moment oscillations. Motor shows difficulties at the first start because of cogging torque and demands much more current on the supply. The analyzed motor is rotated at 1/6 min^{-1} to observe cogging torque and calculated as 11e-5Nm.

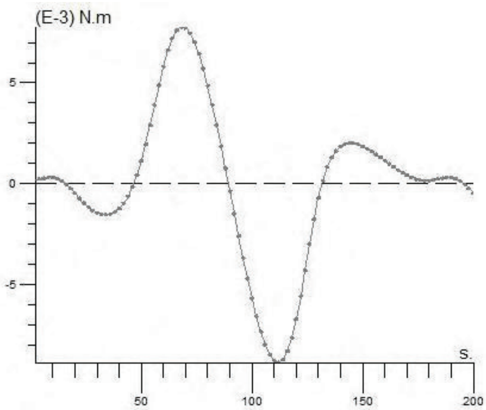

Fig. 9. Cogging torque

Table 2. The comparison of the Test and FEM results

	Test	FEM	Error [%]
BEMF [V]	83	79.456	4.3
Output Power [W]	30	31.5	5
Torque [N.m]	0.09549	0.1003	5

5. Usage of Other Permanent Magnets

To increase motor performance, motor material is chosen by other permanent magnets such as AlNiCo, SmCo and NdFeB. AlNiCo's have high remanence value and can be used in heavy duty applications like the ambient temperature exceeds 400^{0}C. On the other hand, coercivity of AlNiCo's is very low. Rare-earth permanent magnets (SmCo and NdFeB) have stronger fields and larger energy according to other PM materials. The biggest deficit of rare-earth materials is having a very low Curie temperature. Different kinds of permanent magnets are used in the analyzed model to observe how affect the behavior of the SPPM. Properties of magnets are given in Table 2.

Table 3. Permanent magnet properties

	Magnetic remanence [mT]	Relative Permeability
Ferrite (Test Motor)	340	1.071
AlNiCo	850	3

SmCo	920	1.05
NdFeB	1220	1.22

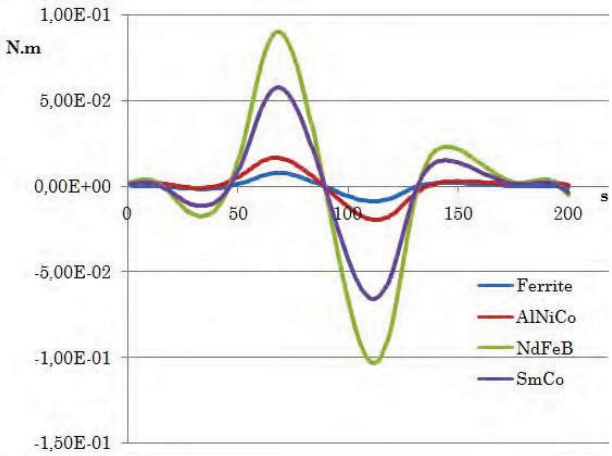

Fig. 10a. Cogging Torque for different types of permanent magnets

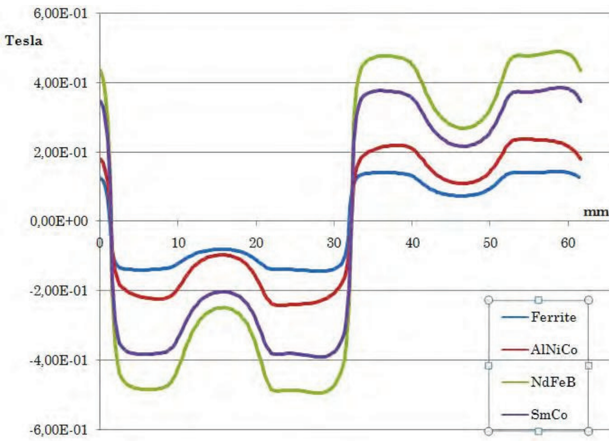

Fig. 10b. Magnetic flux densities for different types of permanent magnets

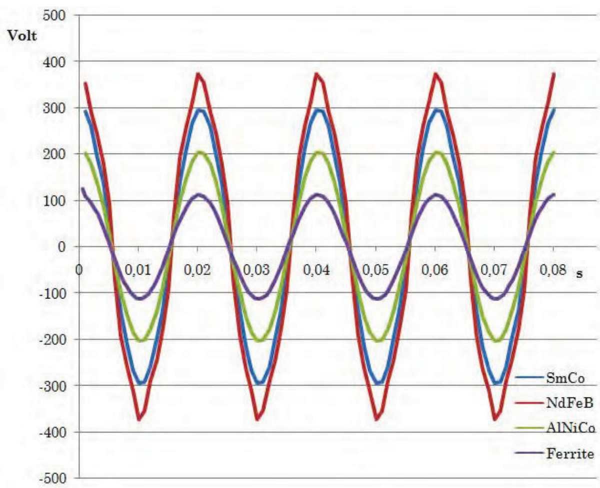

Fig. 10c. BEMF results for different types of permanent magnet materials

6. Conclusions

The behavior of LSSPPM motor is analyzed analytically and modeled by using finite element method. The motor characteristics such as torque, cogging torque and output power are searched. Other types of permanent magnets are investigated to see how affect the motor performance.

Using permanent magnets with higher remanence value increase the output torque but affect the machine performance in a bad way. AlNiCo has very inconvenient demagnetization curve and has to be protected from armature flux, due to its low coercivity. Rare-earth materials provide high power density with low volume.These materials such as SmCo and NdFeB increase motor efficiency but their costs are still too high.

Although Ferrite gives low efficiency, it offers low cost, higher remanence compared to AlNiCo and good withstand against corrosion and temperature.

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REFERENCES

[1] Gieras, J. F. and Wing, M., "Permanent Magnet Motor Technology" *2nd Edition*, Marcel Decker Publishing Company, New York, 2002.

[2] Ertan, H. B., Dağ, B. and Capolino G., "Monofaze Sabit Mıknatıslı Motorların Bazı Parametrelerinin Tasarım Amacıyla ile Hesaplanması", *Elektrik-Elektronik-Bilgisayar Mühendisliği 10. Ulusal Kongresi*, pp. 139-143, Istanbul, Turkey, 2003.

[3] Schemmann, H., "Theoretische und Experimentelle Untersuchungen über das Dynamische Verhalten eines Einphasen Synchronmotors mit Dauermagnetischem Läufer", A. W. Sijthoff International Publishing Company, Leyden, 1971.

[4] Kalenderli, Ö., "Elektrik Mühendisliğinde Sonlu Elemanlar Yöntemi", Lecture delivered at Istanbul Technical University, Istanbul, n.d.