RESEARCH PAPER

Irreversible Demagnetization analysis of the Line Start Permanent Magnet Motor Using Time Stepping Finite Element Method

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ABSTRACT:
In recent years Line Start Permanent Magnet (LSPM) motor has attracted a lot of attention thanks to many advantages, such as high efficiency, high power factor, and high power density. In this motor, at the start, the risk of irreversible demagnetization in Permanent Magnet (PM) is essential due to the large inrush current. So in this paper using Finite Element Method (FEM) the effective factors on demagnetization of this motor structure at various temperatures will be investigated. In addition, the sensitivity analysis will be carried out. Finally, the electromagnetic torque of this motor using a modified FEM algorithm will be calculated and compared to the conventional FEM algorithm.

KEY WORDS: Demagnetization; Line Start PM Motor; Finite Element Method; and Permanent Magnet.
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INTRODUCTION:
Line start permanent-magnet motor (LSPM) is an alternative to increase the efficiency and power factor of the induction motors, due to the high efficiency, high power factor, and high power density (McElveen et al., 2014; Aliabad and Ghoroghchian, 2016). However, there are some drawbacks that limit the use of them. One of these drawbacks is the irreversible demagnetization of the permanent magnets due to the large inrush current in the starting (Faiz and Tehrani, 2017; Zhu et al., 2015).

A common problem in all PM structure motor is their vulnerability to irreversible demagnetization at abnormal working conditions. The irreversible demagnetization occurred due to the high temperatures, external magnetic field, self-demagnetization, and a combination of the mentioned factors (Mahmouditabar et al., 2018; Xiong et al., 2016). Irreversible demagnetization leads to a reduction in the motor performances and reduces power and torque density of the motor (Choi and Jahns, 2018). So the accurate model for investigating the demagnetization characteristics of the PM motors are essential in the evaluation process of the initial design of the PM motor.

There is a different method for modelling of demagnetization in the PM motor which are FEM, Magnetic Equivalent Circuit (MEC), Laplace-Poisson, Field Reconstruction Method (FRM), and Experimental analysis (Fan et al.,
2018; Wang et al., 2018; Mahmouditabar et al., 2018). The experimental analysis due to the destructive nature of the demagnetization test is rarely used and not conventional. The FE Method due to the highest accuracy in the analysis is the more favourable approach to investigate demagnetization (Lee et al., 2018; Kang et al., 2003). So in this paper, we used the Altair Flux 2018 FEM Software for demagnetization analysis of LSPM motor.

This paper consists of five sections. In section (2) the demagnetization principles and the FEM model are discussed. In section (3) the effect of different factors on demagnetization are investigated. In section (4) the time stepping finite element method is presented and with this method, the electromagnetic torque of the motor is calculated. Finally is a section (5), the conclusion is given.

1. Demagnetization Principles and FEM Model of LSPM Motor

1.1 Demagnetization Principles

As shown in Fig.1 (a), with applying demagnetization field of H1 on the magnet, the working point moves along the normal curve above the knee point and reversible demagnetization occurs. But when a larger demagnetization field (H2) is applied on the magnet, the working point of the magnet is located below the knee point and irreversible demagnetization occurs so magnet loses some of its magnetic characteristics.

In Fig.1 (b) the B-H curve of SmCo26H at difference temperature is shown. As visible in Fig.1 (b), with raising the temperature, the residual flux density and intrinsic field of the SmCo are reduced and the knee point appears on the second quarter of the B-H curve which increases the risk of irreversible demagnetization.

1.2 FEM Model of Line Start PM Motor

The FEM model of LSPM motor, based on design specification presented in Tab.1, is shown in Fig.2. In accordance with the periodicity, only ¼ of the motor structure is simulated and after simulation, the obtained results can be extended to the whole motor. The face elements considered on the surface of the magnet have a different size due to the complexity of the magnetic field in the corresponding area. This different mesh leads to a compromise between accuracy and computation time. Small mesh increased both the accuracy and computation time. So in the air gap, we have the smallest mesh and in the outer surface of the stator, the mesh is larger. The distribution of magnetic flux density and the Back-EMF waveform of the LSPM motor is shown in Fig.3. The average magnetic flux density on the surface of the magnet when the magnet considered linear is about 0.9 T and only the reversible demagnetization occurs. So with removing the external field, the magnet can recover its initial residual flux density.

2. Influenced factors on demagnetization of LSPM

First of all, by running the FEM model in a condition that the magnet region is considered as air, the direction of the external magnetic field on the surface of the magnet is investigated. The results are shown in Fig.4 (a) indicates that only the small surface of the magnet is exposed to demagnetization field of the stator windings (the right corner of the magnet and the small surface of the left corner) and irreversible demagnetization can occur in this two parts due to the armature reaction. In the nominal working condition of the LSPM motor, with 180 mechanical degrees changing in rotor positions, the minimum working point of the magnet elements at each step stored and the final conditions of the magnet are shown in Fig.4 (b). The results verifying the previously mentioned quotes about the possible locations exposed to the demagnetization field of armature current.

The effect of magnet thickness on demagnetization of LSPM is shown in Fig.4 (c). As we expected the rate of demagnetization is decreased with an increase in magnet thickness. With a thickness of 5 mm demagnetization doesn’t occur and magnet can restore its initial residual flux density. But there is something important in the design procedure of PM motors and that is the cost of PMs. PMs are the most expensive parts of the machine so it needs to minimize the volume of the PM and we don’t allow to over design the PMs. In Fig.4 (d) the effect of air gap variation on demagnetization rate is investigated. The results are shown that by increasing the air gap length, the demagnetization rate is reduced but we know that increasing the air gap leads to increasing magnetizing current and
the associated electrical loss so there is a restriction in the selection of air gap.

3. Time-Stepping Finite Element Method

In this section, the tolerant of the LSPM motor for working in the hot-temperature environment in the case of irreversible demagnetization is carried out. As shown in Fig.1 (b), the worst temperature case for SmCo26H is 300°C, so using Time Stepping Finite Element Method (TSFEM) the demagnetization tolerant of this structure is modelling. The principles of TSFEM are shown in the following:

1. Implementation of the FEM model of the LSPM motor.
2. Import properties of the material used in the motor.
3. Run magnetic transient of Altair Flux Software and obtaining the working points of the magnet elements.
4. Comparing the magnetic flux density of the working point with the knee point
5. If the irreversible demagnetization occurred, we should renew the residual flux density in the elements and recalculate the working point.
6. But if the irreversible demagnetization doesn’t occur, the electromagnetic torque of the motor is calculated for this rotor positions.
7. All the mentioned steps are carried out for the other rotor positions.

The electromagnetic torque of the LSPM motor at the temperatures of 150°C and 300°C with and without considering demagnetization are shown in Fig.5. At high temperatures due to the severe irreversible demagnetization on the surface of the magnet, the electromagnetic torque evaluated by TSFEM is severely reduced and over time, this reduction in torque will increase. The average value of electromagnetic torque is reduced from 20.42 to 14.68 N.m at a temperature of 300°C, whereas a temperature of 150°C only local demagnetization occurs and the electromagnetic torque is reduced about 0.89 %. The demagnetization rate of this motor is calculated from the following relation:

$$\text{Demagnetization Rate} = \left(1 - \frac{B_r}{B_{r^*}}\right) \times 100$$

Where $B_r$ is the initial residual flux density of the magnet and $\left(\frac{B_r}{B_{r^*}}\right)$ is the residual flux density after demagnetization. Using Eq. (1) the calculated rate of demagnetization is 21.3% temperature of 300°C and 2.06% at temperature of 150°C for SmCo26H material. The demagnetization results shown that the LSPM motor can be a good choice for replacement of induction motors in industries because its demagnetization rate for conventional working condition in the industries is low and acceptable.

4. CONCLUSIONS

In this paper first, the principles of demagnetization phenomenon are presented, then using the finite element method, irreversible demagnetization in line start permanent magnet motor is carried out. Also, the influence of magnet thickness and airgap length is investigated. In addition, using TSFEM which is the modified FEM algorithm, the modelling of demagnetization at highest temperature condition is done. The results showed that the LSPM motor has good potential for application in hot temperatures and rough working conditions.

| Table (1). Design specification of the LSPM motor |
|-----------------------------------------------|
| Item                          | Value  | Item                          | Value  |
| Phase                         | 3      | Rotor Outer Diameter [mm]     | 39.5   |
| Pole Number                   | 4      | Rotor Inner Diameter [mm]     | 30     |

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**Table**

| Parameter                          | Value     |
|------------------------------------|-----------|
| Rated Speed [rpm]                  | 1000      |
| Frequency [Hz]                     | 33.3      |
| Rotor Bar Number                   | 36        |
| Stator Outer Diameter [mm]         | 130       |
| Material of Magnet                 | SmCo26    |
| Magnet Thickness [mm]              | 3.5       |
| Stator Inner Diameter [mm]         | 80        |
| Core Material                      | M270      |
| Stack Length [mm]                  | 90        |
| Rotor bar Material                 | Copper    |

**Figure 1.** (a) Influence of temperature and external magnetic field on demagnetization (b) The B-H curve of SmCo26H at different temperatures.

**Figure 2.** (a) Finite Element Model of LSPM Motor (b) Face elements on the surface of the motor (MESH).
Figure 3. (a) Distribution of magnetic flux density (b) Back-EMF waveform of LSPM motor

Figure 4. (a) Direction of the external magnetic field, (b) Back-EMF waveform of LSPM motor, (c) The effect of magnet thickness variation on demagnetization rate, (d) The effect of air-gap variation on demagnetization rate.
Figure 5. The electromagnetic torque of the LSPM motor with and without considering demagnetization, (a) 150°C and (b) 300°C

REFERENCES

A D Aliabad and F Ghoroghchian (2016), Design and Analysis of a Two-Speed Line Start Synchronous Motor: Scheme One, IEEE Transactions on Energy Conversion, 31, 1, pp. 366-372.

B Lee, J Jung and J Hong (2018), An Improved Analysis Method of Irreversible Demagnetization for a Single-Phase Line-Start Permanent Magnet Motor, IEEE Transactions on Magnetics, 54, 11, pp. 1-5.

D Fan, X Zhu, L Quan and Z Xiang (2018), Dynamic demagnetisation investigation for less-rare-earth flux switching permanent magnet motors considering three-phase short-circuit fault, IET Electric Power Applications, 12, 8, pp. 1176-1182.

F Mahmouditabar, A Vahedi and M Bafghi. (2018). Investigation of Direct & Quadrature Current Effects on Demagnetization of Flux Switching Permanent Magnet Motors. IOP Conference Series: Materials Science and Engineering, 433, p.012092.

F Mahmouditabar, A Vahedi, P Ojahlu (2018). Investigation of Demagnetization Effect in an Interior V-Shaped Magnet Synchronous Motor at Dynamic and Static Conditions. IEEE, 14, 1, pp. 22-27.

G Choi and T M Jahns (2018), Analysis and Design Recommendations to Mitigate Demagnetization Vulnerability in Surface PM Synchronous Machines. IEEE Transactions on Industry Applications, 54, 2, pp. 1292-1301.

G H Kang, J Hur, H Nam, J P Hong and G T Kim (2003), Analysis of irreversible magnet demagnetization in line-start motors based on the finite-element method, IEEE Transactions on Magnetics, 39, 3, pp. 1488-1491.

H Xiong, J Zhang, M W Degner, C Rong, F Liang and W Li (2016), Permanent-Magnet Demagnetization Design and Validation, IEEE Transactions on Industry Applications, 52, 4, pp. 2961-2970.

J Faiz and E M Tehrani (2017), Demagnetization Modeling and Fault Diagnosing Techniques in Permanent Magnet Machines Under Stationary and Nonstationary Conditions: An Overview, IEEE Transactions on Industry Applications, 53, 3, pp. 2772-2785.

R McElveen, M Melfi and R Daugherty (2014), Line start permanent magnet motors - Starting, standards and application guidelines, 2014 IEEE Petroleum and Chemical Industry Technical Conference (PCIC), San Francisco, pp. 129-139.

S Zhu, M Cheng, W Hua, X Cai and M Tong (2015), Finite Element Analysis of Flux-Switching PM Machine Considering Oversaturation and Irreversible Demagnetization, IEEE Transactions on Magnetics, 51, 11, pp. 1-4.

W Wang, P Zheng, M Wang, Y Liu, Z Fu and Y Sui (2018), Demagnetization and Permanent-Magnet Minimization Analyses of Less-Rare-Earth Interior Permanent-Magnet Synchronous Machines Used for Electric Vehicles, IEEE Transactions on Magnetics, 54, 11, pp. 1-5.