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Characteristic Analysis Method of Irreversible Demagnetization in Single-phase LSPM Motor

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This paper presents the effective analysis method of irreversible demagnetization for line-start permanent magnet (LSPM) motor considering magnetic field produced by secondary conductor bars. The magnetic field by the secondary conductor bars opposes the variation of magnetic field by primary part, and this result in the reduced magnetic field acting on permanent magnet. By using Finite Element Analysis (FEA) in transient magnetic field, currents in primary and secondary conductors are estimated and used for demagnetization analysis in magneto-static field. Therefore, closer condition to actual situation can be achieved. General demagnetization analysis using primary currents only and presented analysis methods are compared and verified by experiments. General demagnetization analysis leads to the over estimation of magnetic field acting on permanent magnet, and results in excessive permanent magnet usage.

Index Terms — Permanent magnets, irreversible demagnetization, line-start permanent magnet (LSPM) motor, finite element analysis (FEA)

I. INTRODUCTION

A single-phase induction motor (IM) operating with commercial electricity without power electronic switching devices and position sensor is more economical and has higher maintenance than other inverter fed electrical motor [1]. So, it is becoming more generalized as direct operation by supplying the commercial single-phase voltage source of household appliance. However, the motor has problems such as the vibration caused due to unbalanced rotating field of main and subsidiary windings and the difficulty in improving efficiency because of the conductor bar loss [2].

On the other hand line-start permanent magnet (LSPM) motors have both conductor bars and permanent magnet (PM) in the rotor. Accordingly, line-start of IM is possible and operation in synchronous speed is possible at steady state by magnetic torque and reluctance torque. Therefore position sensor of general permanent magnet motor for starting and operation is not necessary, and conductor loss of general induction motor is small since LSPM motor operates at synchronous speed in steady state. Consequently, LSPM motor provides lower production cost than general permanent magnet motors and higher efficiency than general induction motors [3] [4]. The application of LSPM motor is suitable for home appliances which require low cost and high efficiency.

However, the large current at starting causes irreversible demagnetization of PM [5]. Generally the irreversible demagnetization of PM is decided by the operating point in B-H or M-H curve of PM when only primary part is excited. However, LSPM motor is operated as IM at starting and magnetic field by secondary conductors produced. This results in the reduced magnetic field acting on PM to be reduced. Therefore, general demagnetization analysis leads to the overall estimation of magnetic field acting on PM, and results in excessive PM usage.

This paper deals with demagnetization of LSPM motor by considering magnetic field by secondary conductor bars. By using FEA in transient magnetic field, currents in primary and secondary conductors are estimated and used for demagnetization analysis in magneto-static field. Therefore closer condition to actual situation can be achieved. General demagnetization analysis using primary currents only and presented analysis methods are compared and verified by experiments. This paper presents the effective analysis method of irreversible demagnetization for LSPM motor considering magnetic field produced by secondary conductor bars. By using Finite Element Analysis (FEA) in transient magnetic field, currents in primary and secondary conductors are estimated and used for demagnetization analysis in magneto-static field. Therefore closer condition to actual situation can be achieved. General demagnetization analysis using primary currents only and presented analysis methods are compared and verified by experiments.

II. STRUCTURE OF SINGLE-PHASE LSPM MOTOR

The configuration and winding connection of a single-phase LSPM motor with rare-earth PM and conductor bars are shown in Fig. 1(a) and (b), respectively. As shown in Fig. 1, both consist of main and auxiliary windings in the stator and conductor bars to produce the starting torque in the rotor. Starting capacitance Cs, running capacitance Cr, and positive temperature coefficient (PTC) are connected with the auxiliary windings to increase the starting torque and power factor [6]. Accordingly, it could be considered as a two-phase motor. The motor has 2-pole rotor with 28-slot stator for household appliance. Fig. 2 shows the fabricated LSPM motor.

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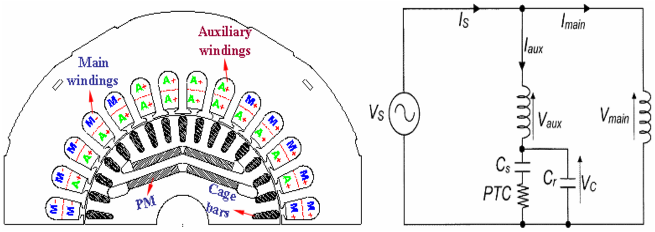


(a) Rotor of LSPM motor (b) Stator of LSPM motor

Fig. 1. Structure of single-phase LSPM motor and its stator winding circuit

(a) Rotor of LSPM motor (b) Stator of LSPM motor

Fig. 2. Fabricated single-phase LSPM motor

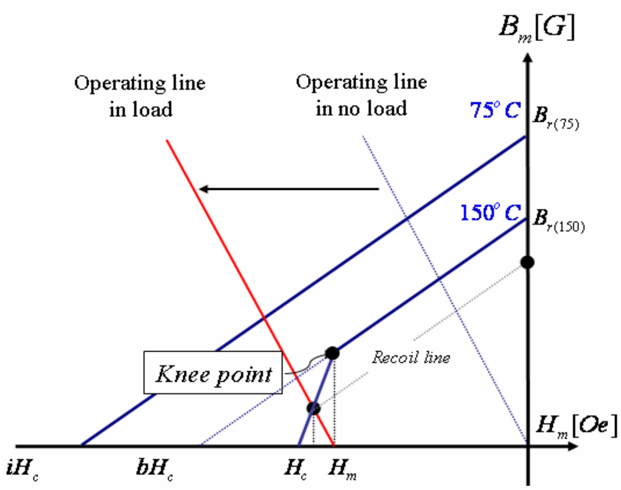


Fig. 3. Characteristic curve of permanent magnet

III. Demagnetization of PM

A. Non-linear analysis of PM

The demagnetization analysis considers not only nonlinear characteristics of the core but also that of the PM on the B-H curve. Fig.3 shows an irreversible demagnetization curve of rare earth PM magnet each temperature. The equation (1) is approximate equation for Magnetization *M* [7], [8].

$$M = B - \mu_0 f(B) = h(B) \tag{1}$$

where *h* is *f (B)* and μ_0 is permeability.

B. Calculation of demagnetizing current

In determining the thickness of PM in motor design stage, we can utilize equation (2). It is defined by the relation between external magnetomotive force(MMF) and MMF by PM.

From the equation (3), as the PM thickness and coercive force of PM increased, irreversible demagnetization current increased. TABLE I shows the demagnetization current according to temperature, and used in the initial design stage. It can be observed that irreversible demagnetization current decreases as temperature increase.

$$F = NI = h_M H_C \tag{2}$$

$$I \le h_M \frac{2}{m} \cdot \frac{\pi}{4} \cdot \frac{2pH_C}{\sqrt{2}Nk_w} \tag{3}$$

where H_c is coercive force, m is phase number, h_M is PM thickness, p is pole-pair, k_w is a winding factor and N is turn number.

TABLE I
Magnetizing Current According to PM Temperature

Temperature [℃]	Magnetizing current [A]
120	60
150	28
165	15

IV. Analysis Method

This paper deals with analysis methods of demagnetization of LSPM motor. Method 1 is general demagnetization analysis method using primary currents only. On the other hand method 2 considers currents in primary and secondary conductors for LSPM motor. Analysis process of Method 1 and Method 2 are compared.

A. Analysis process of Method1

Method 1 is general demagnetization analysis method and process of Method 1 is as Fig. 4. Method1 can be summarized as follows.

Initially, no-load back EMF is estimated. Then, magnetostatic field analysis is conducted with maximum current in primary conductor. At this point, the maximum current can be obtained in the worst case of operation according to slip variation. Induced current in the secondary conductor is ignored. When the operating point of PM is below its knee point, the residual flux density of the PM is renewed. Finally, with renewed flux density of the PM elements, no-load back-EMF is calculated. By comparing no-load back-EMF before and after demagnetization field, irreversible demagnetization of PM is determined.

B. Analysis process of Method2

General irreversible demagnetization analysis method (Method 1) using primary currents only and presented analysis method (Method 2) for LSPM motor are compared.

Initially, irreversible demagnetization current of Method1 is calculated using equation (3) at the TABLE I, and then identical current is used to Method2 in order to consider the effect of secondary conductor bars current on the irreversible demagnetization of PM using transient field voltage source analysis.

As shown in fig. 5, the analysis process of demagnetization for LSPM motor is as following. Firstly, using transient analysis, currents in primary and secondary conductor bars are estimated. Fig. 6 shows current density of the conductor bars. Then calculated currents by transient analysis are applied to irreversible demagnetization analysis in every rotor position considering not only nonlinear characteristic of the core but also that of the PM on the B-H curve. In the next, determination whether PM is irreversibly demagnetized or not can be made with identical process of Method 1.

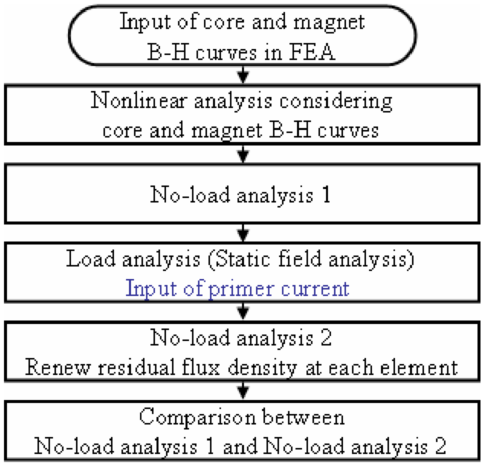


Fig. 4. The process of Method 1

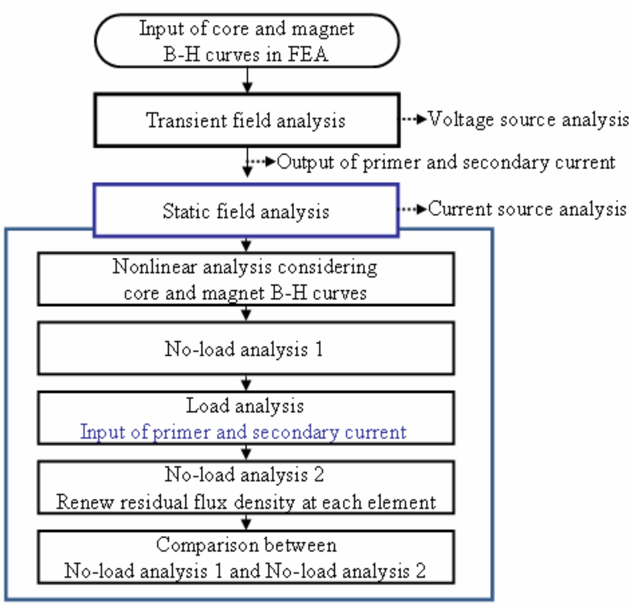


Fig. 5. The process of Method 2

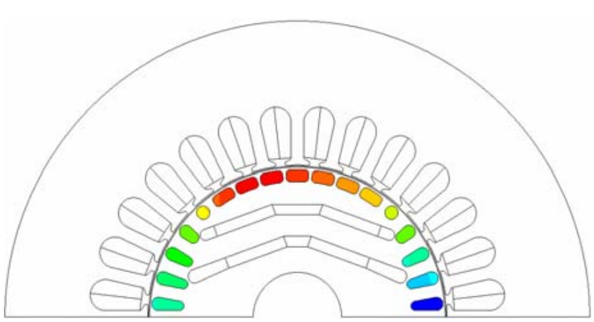


Fig. 6. Current density of the conductor bars

V. Result and Discussion

Fig. 7 shows comparison of magnetic flux density from Method1 and Method2 when external demagnetization field is applied. The flux density at A point is 2.36 [T] and 0.83 [T] using method 1 and method 2 respectively. And the flux density at B point is 1.18 [T] and 0.46 [T] using method 1 and method 2 respectively. Using Method2, magnetic field by primary current reduced by secondary conductor current can be observed.

Analysis results show that there is no difference of no-load back-EMF from Method2 and decrease of no-load back-EMF from 81.99V to 74.77V from Method1, as shown in Fig. 10(a). To verify results according to analysis method by the test, DC current is excited in Method1 and AC current is excited in Method 2.

In the Method1, current in the secondary conductor is not considered. Therefore primary conductor is supplied by DC current. Meanwhile, in order to induce currents in the secondary conductor, AC current is supplied in the Method2.

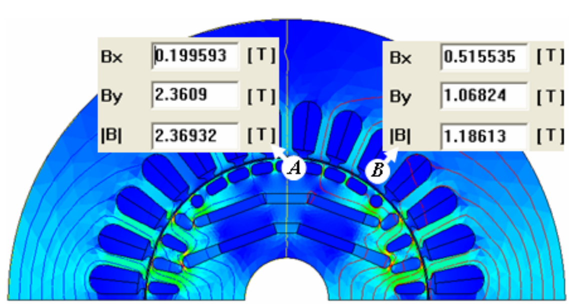
Experiments are conducted under identical current and temperature conditions. Fig. 8 and Fig. 9 show the input current and temperature of conductor bars and PM at experiments respectively.

In order to obtain high temperature in PM, rotor is fixed and AC current is supplied in the primary conductor. Then, 155^{o}C of secondary conductor temperature and 165^{o}C of PM temperature are obtained. Demagnetization analysis is conducted considering 165^{o}C of PM temperature.

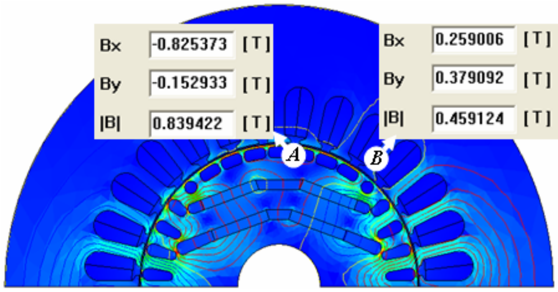
As shown in Fig. 10 (b) and TABLE II, 8.8% of PM is irreversibly demagnetized by using Method1. Meanwhile, no irreversible demagnetization occurs with Method2. In the Fig. 10, waveforms from FEA and experimental results are different because FEA is conducted in magnetostatic, i.e., effects of secondary conductor are not considered.

VI. Conclusion

In this paper, an effective analysis method of irreversible demagnetization for LSPM motor considering magnetic field produced by secondary conductor bars is presented. FEA and experimental results show effectiveness of reduced primary field by secondary conductor field clearly and Method2 is closer to actual situation. By using Method 2, effective estimation of irreversible demagnetization of PM and reasonable cost reduction of LSPM motor can be achieved.



(a) Current density by Method1



(b) Current density by Method2

Fig. 7. Current density by Method1 and Method 2

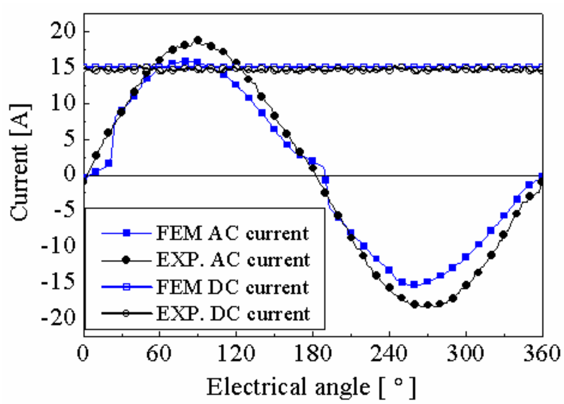


Fig. 8. Input current and temperature of PM and conductor bar

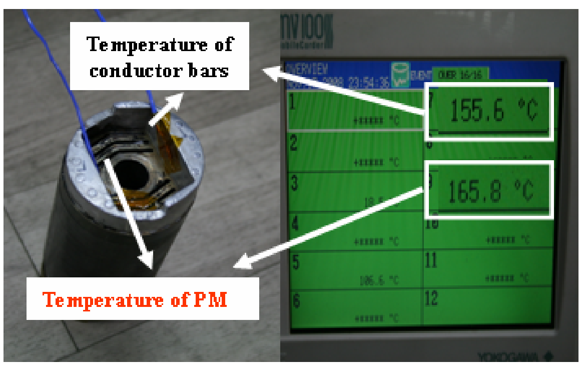
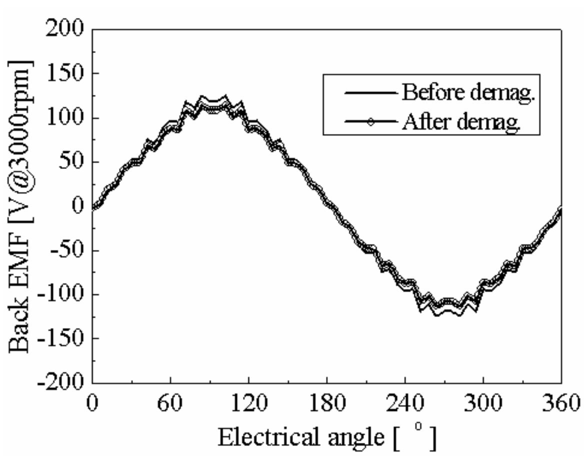
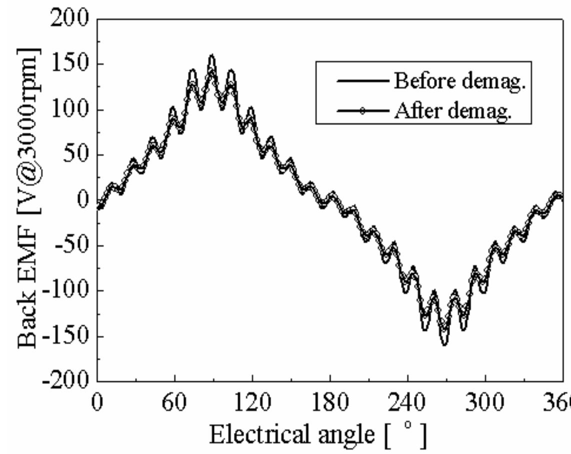


Fig. 9. Temperature of PM and conductor bar



(a) Result of FEM



(b) Result of experiments

Fig. 10. Back EMF comparison

TABLE II
MAGNETIZING CURRENT ACCORDING TO PM TEMPERATURE

	FEM result		Experiments result	
	Method 1	Method 2	Method 1	Method 2
Back EMF before demagnetization [Vrms]	81.99	81.99	78.42	78.42
Back EMF after demagnetization [Vrms]	74.77	81.99	72.35	78.41
Demagnetization ratio [%]	8.80	0.00	7.74	0.00

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