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Analysis of Permanent Magnet Demagnetization Effect Outer-rotor Hybrid Excitation Flux Switching Motor

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ABSTRACT

This paper addresses the irreversible permanent magnet (PM) demagnetization analysis of hybrid excitation flux switching motor (HEFSM) with outer-rotor configuration. PM demagnetization cause the PM strength used in the motor significantly reduces and hence contributes less torque performance. The study is focused on thermal analysis and conducted at various temperature up to as high as 180 degrees Celsius which has a tendency to be demagnetized. Therefore, PM demagnetization is among a critical issue and influences the choice of the applied motor. The analysis is carried out based on finite element method (FEM) and percentage of PM demagnetization is then calculated. Finally, based on simulated and calculated results the final design outer-rotor HEFSM has only 0.85 percent PM demagnetization at very high temperature and obviously the is no PM demagnetization at normal operating conditions.

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1. INTRODUCTION

Recently, research and development of electric vehicles (EVs) have rapidly increased in achieving green vehicle as an alternative transportation besides conventional internal combustion engine vehicle (ICE). The main reason looking for alternative vehicles are to reduce emission that contributes for greenhouse effect and global warming. An EV promises air quality benefits of a battery-powered and convenience of a conventional ICE [1]-[3]. A lot of automobile companies such as GM Chevrolet Volt, Nissan Leaf, Mitsubishi i-MiEV, Honda Fit etc. have already sell their EV worldwide [4]-[5]. In conjunction, PM machines either surface or interior mounted PM synchronous motor (PMSM) are the most widely used in EV drives due to their advantages of high torque density, wide speed range and high efficiency [6]-[7].

More recently, PM flux switching motor (PMFSM) that applied a “flux switching” concept has attractive research topic due to their extreme advantages of robust rotor structure and high torque density [8],[9]. The active components such as PM and armature coil of the motor are housed at the stator, while rotor is only consist a stack of iron core similar to switched reluctance motor (SRM). This configuration offer great advantages of easy cooling of all active components and suitable to be used for high speed applications. In addition, with high performance of torque and power density, the motor seem like a combination features of SRM and permanent magnet synchronous motor (PMSM) [10].

Nevertheless, conventional PMFSMs are only have a constant magnetic flux source of PM resulting poor flux weakening performance especially at flux weakening region. On the other hand, they are necessary to have armature winding current control to be counteracted with PM flux on reducing the magnetic flux. Consequently, it might increase in cooper loss hence reducing the motor efficiency and also contributes in

PM demagnetization effect. Therefore, a new PMFSM with outer-rotor configuration has been proposed by the authors in which the optimized design has been described previously [11]. The proposed motor also has additional field excitation coil (FEC) as a secondary flux source and illustrated in Figure 1 which has similar concept with several previous design of PMFSMs with FEC, hence called as hybrid excitation flux switching motor (HEFSM) [12]-[13].

Magnetic flux linkage of PM motor is proportional to strengths of the PMs, therefore it is required to analyse PM demagnetization effect on a new design motor. In harsh working condition, high temperature operation especially at high speed region, high armature reaction and high density PM of the motor may cause the performance of the motor decline [5],[14],[15]. Therefore, this paper presents the PM demagnetization analysis on a new design of outer-rotor HEFSM with 12-slot 14-pole configuration. The analysis is carried out using 2D-FEA of JMAG-Designer software package. The parameters and performances of the proposed design is tabulated in Table 1.

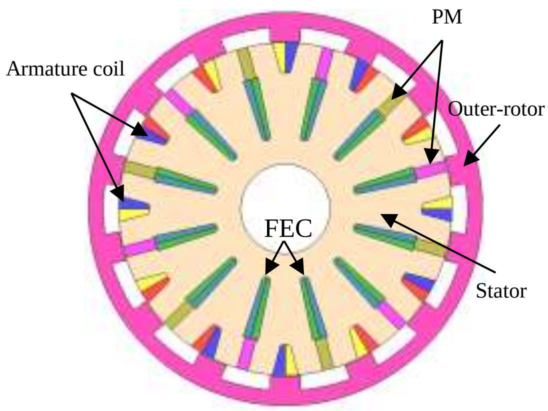

Figure 1. Cross sectional view of final design outer-rotor HEFSM

Table 1. The Specifications and Performances of Outer-Rotor HEFSM

Descriptions	Unit	Outer-rotor HEFSM
PM weight	kg	1.0kg
Motor outer-diameter	mm	264
Motor stack length	mm	70
Shaft radius	mm	30
Maximum speed	r/min	12,400
Maximum torque	Nm	335.08
Maximum power	kW	160.2
Rotor mechanical stress at max. speed	Mpa	377
Machine weight	kg	27.08
Maximum torque density	Nm/kg	12.4
Maximum power density	kW/kg	5.93
Motor efficiency over most of operating point	%	88

2. DEMAGNETIZATION EFFECT OF PERMANENT MAGNET

In general, mechanism of each PM demagnetization is dissimilar which depends on the chemical constitution and crystal structure of their material. In normal situation of designing machine where volume of PM is required to be reduced, high energy PM will be used. In most of applications especially in electric vehicle, the Neodymium magnet is widely used because of high energy production. Several demagnetization factors may encounter in irreversible demagnetization that corresponding to the applied areas and conditions. In the field of electric vehicle, the temperature and the external magnetic field of PM is the most contributes in irreversible demagnetization of PM, while chemical, vibration and aging demagnetization are not prominent to PM demagnetization. When subjected to external magnetic fields and/or temperature changes, the magnetic properties of PMs may change, leading to demagnetization, which may affect the performance of such machines. It is therefore very important to take this phenomenon into account when designing such machines.

In other circumstances, if the magnet produces fluxes which in turn resulting for irreversible losses then the efficiency of the motor is become less. Furthermore, due to the demagnetization fault, it may cause unbalanced magnetic pull and produces vibration that lead to increase noise. PM demagnetization may occur especially in high loads or due to armature reaction during rapid change to static condition. Therefore, selection of PM used in motor design is essential to prevent the PM from demagnetization effect. In this analysis, the demagnetization effect is investigated at various temperature conditions in which implemented at maximum current density and maximum speed conditions flux density applied to the machine, then the flux characteristic is closer to the knee point.

3. B-H CURVE OF NEOMAX-35AH CHARACTERISTICS

The B-H curve of NEOMAX-35AH PM used in this research is illustrated in Figure 2. It is clearly shown that the B-H curve can be saperated into three region with their own characteristic. Region 1 is in between of normal operating point and the knee point, while Region 2 is the narrow region when the flux behavior suddenly change due to some any fault occur on PM and Region 3 is happen when much negative current injected into the motor that cause the flux characteristic transform in parallel with Region 1.

Normal operating points are the point when there is no magnetic density, while the flux density is measured on y-axis which intersect at zero magnetic density. Moreover, knee point is a point where flux start to change its behavior into a new flux characteristics. This circumstances occurs when more negative magnetic flux density applied to the machine, then the flux characteristic is closer to the knee point.

Temperature also influences to PM’s parameters which described through the temperature coefficients. The PM will demagnetized irreversibly when the value of external demagnetization field strength is higher than that of the magnetic field strength at the knee point. Therefore, the value of magnet field strength at a certain working temperature is usually regarded to proof the PM demagnetization condition. For NEOMAX-35AH material, the demagnetization curve of the PM at various temperature conditions are demonstrated in Figure 3. The line characteristic with purple, blue, green, red and black color shows demagnetization curve of PM at 180°C, 140°C, 100°C, 60°C and 20°C, respectively. Hereafter, based on B-H characteristic graph, PM flux performance which less than their knee point at the particular temperature is considered demagnetized.

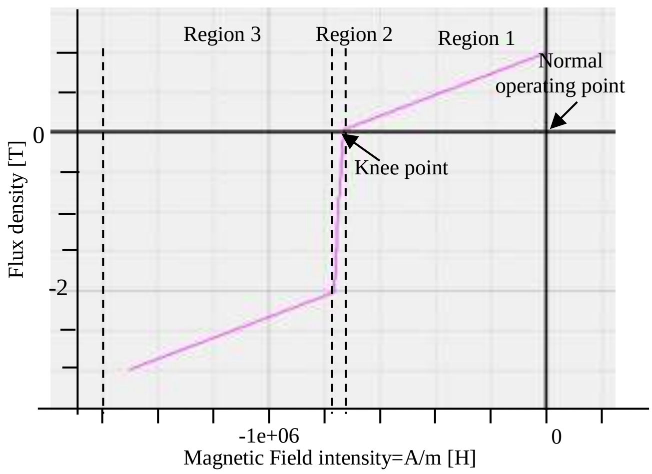

Figure 2. B-H curve

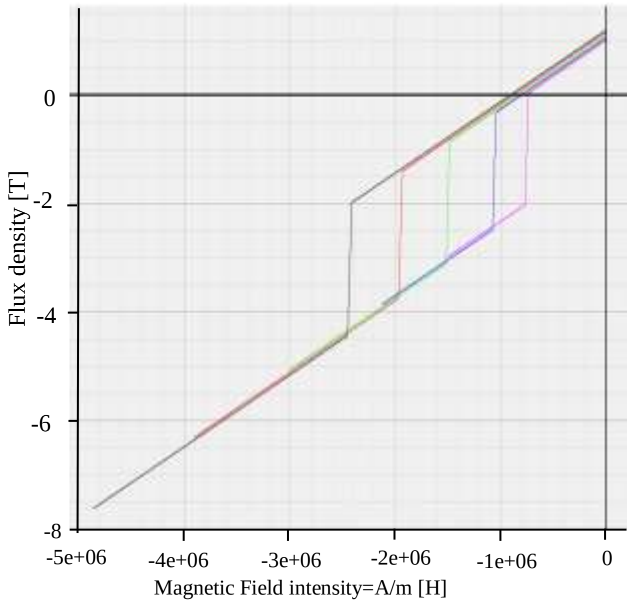

Figure 3. B-H curve of NEOMAX-35AH at various temperature

4. PM DEMAGNETIZATION INVESTIGATION

The effects of demagnetization on the PM must be avoided to keep the performance of the machine at the optimal level, especially when operating at high temperature conditions. Therefore, the selection of materials for the PM is essential and careful consideration must be taken. The demagnetization of PM is calculated using equation (1).

$$\%D = \sum_{\substack{i=1 \\ (B_i<B_{DP})}}^{n} \frac{A_i}{A_T} \tag{1}$$

where the A_i and A_T is the PM demagnetised area and total area of the PM, respectively (mm^2), the B's are the magnetic flux densities (T), n is the number of elements, and DP is the demagnetisation point of the permanent magnets, as per their BH curve.

Initially, the motor is simulated at maximum current density of 30(rms)/mm2 and 30A/mm2 for both armature and FEC windings, respectively. The simulation procedures are simplified and illustrated in Figure 4. On the other hand, the temperature is set at various conditions. The knee point of each temperature condition has been used as a reference to identify the demagnetization effect. It is expected that demagnetization might occurs at high temperature operating condition.

Figure 5 shows simulation results of PM demagnetization investigation at the temperature of 180ºC in seven steps. From the diagram, it is clearly shown that for every step there is a small area on the upper right edge of PM has demagnetized, while the percentage ratio of PM demagnetized and torque performance at each step is depicted in Table 2. Through the calculation, the demagnetization of PM at 180ºC is only 0.85% on each step of analysis has been demonstrated. Therefore, the final design outer-rotor HEFSM is considerably has low PM demagnetization even operated at high temperature condition. The norminal operating temperature for motor employed in either hybrid electric vehicle or electric vehicle is within 120ºC-150ºC, thus the PM is in the safe condition. At high temperature condition, the maximum average torque produced by the motor is only 307.77Nm, which approximately reduced by 8.2% from its maximum torque. Finally, the details of PM demagnetization at various temperature conditions are depicted in Table 3 and it is obvious that there is no PM demagnetization for the temperature less than 180 ºC. Therefore, the proposed motor has very high PM reliability at normal operating conditions.

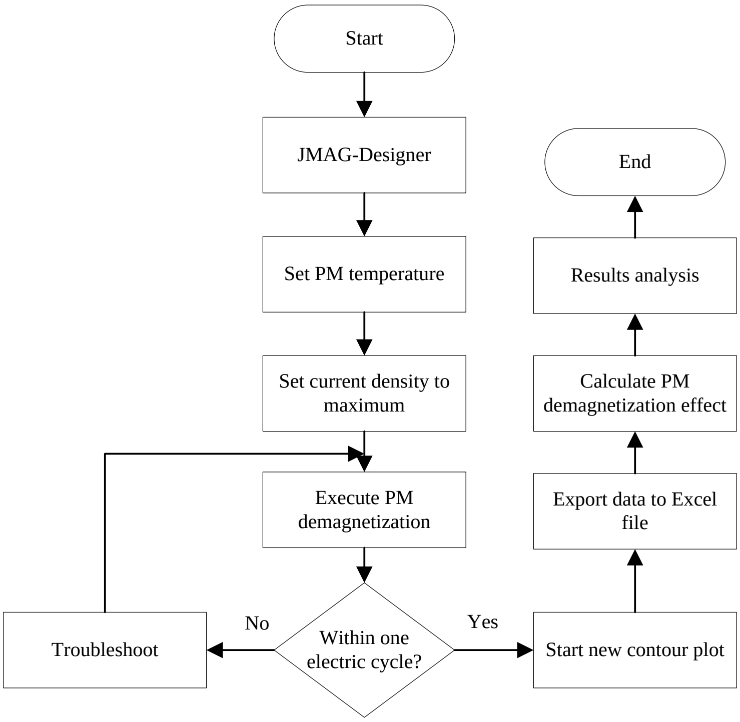

Figure 4. Simulation proceedures of PM demagnetization analysis

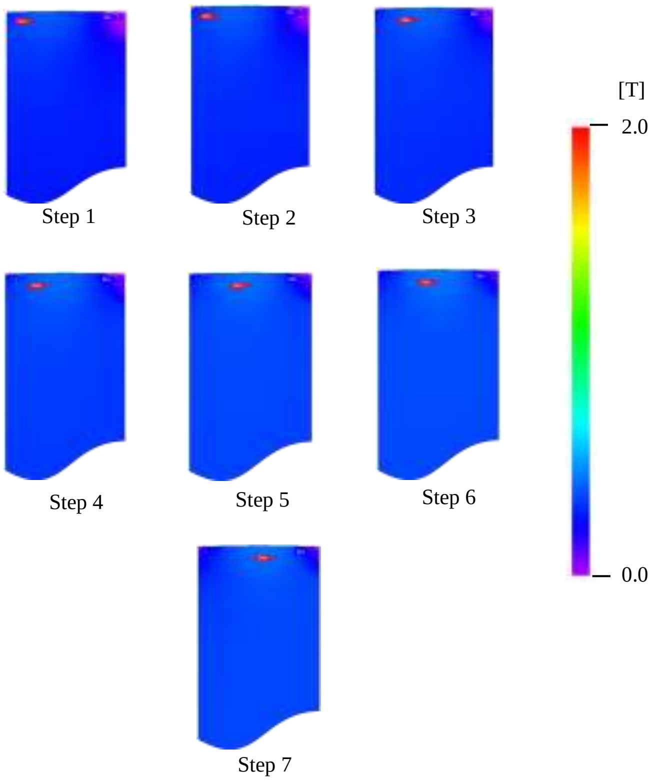

Figure 5. PM demagnetization of outer-rotor HEFSM at at 180ºC

Table 2. PM Demagnetization of Final Design Outer-Rotor HEFSM at 180℃

Total PM Area (mm^2) : 157.77			
Step	Area D (mm^2)	D[%]	T(Nm)
1	1.34	0.85	300.26
2	1.34	0.85	306.27
3	1.34	0.85	313.97
4	1.34	0.85	319.02
5	1.34	0.85	315.60
6	1.34	0.85	302.09
7	1.34	0.85	297.16
		T_{ave}	307.77

Table 3. PM Demagnetization at Various Temperature Conditions

Temperature (°C)	Max. area demagnetization (mm^2)	Percentage of PM demagnetization (%)
180	1.34	0.85
140	0.00	0.00
100	0.00	0.00
60	0.00	0.00
20	0.00	0.00

5. CONCLUSION

This paper presents PM demagnetization analysis based on 2D-FEA and calculation techniques. The analyses are implemented at maximum current density of armature and FEC windings, while the temperature has been set at various conditions. The results obtained show that the PM (NEOMAX-35AH) used in this design machine has no demagnetization at most normal operating conditions and only 0.85% demagnetization when the machine operated at high temperature as high as 180 °C. Thus, it is concluded that the proposed motor is suitable to be applied for in-wheel drive EV.

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