Investigation of Direct & Quadrature Current Effects on Demagnetization of Flux Switching Permanent Magnet Motors

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Abstract. In recent years flux-switching permanent magnet machines have become popular for industrial applications and research, due to advantages such as robustness, high torque, and power density. However, as permanent magnet motors, their performance is affected by demagnetization. It is known, for example, that armature reactions and temperature increases cause permanent magnet demagnetization that leads to power and torque density reduction in motors. In this paper, partially irreversible demagnetization in an flux-switching permanent magnet motor will be investigated using the time stepping finite element method. In addition, the effects of the d and q-axis currents on this type of demagnetization are evaluated by considering several points on the magnets and comparing the flux density of these points with the flux density of the knee point. It is shown that an increase of the q-axis current component increases the machine’s demagnetization tolerance.

1. Introduction
In recent years, permanent magnet machines have been widely used for their high-performance characteristics such as high efficiency, high reliability, and high power and torque density [1],[2]. One of the major problems with these motors, however, which reduces the power density and the ability of the PM motors, is the demagnetization phenomenon. Factors affecting the demagnetization of PM machines can be divided into three categories: armature reaction, self-demagnetization and temperature [3], [4]. In an FSPM motor, the stator windings and magnets are all located on the stator, leading to sinusoidal flux, roughness, and high speed and torque [5],[6]. FSPM motors are suitable for high-speed applications and electric vehicles. In FSPM motors, the armature reaction field is perpendicular to the magnetization direction of the magnet. Therefore, the FSPM motor is in good demagnetization condition. However, when the rotor pole is aligned with the magnet, the magnet will be locally demagnetized [7]. On the other hand, adjacent magnets will demagnetize each other because their direction of magnetization is opposed [7], [8]. The temperature factor also greatly affects demagnetization of such magnets [9].

A great deal of attention has been devoted to demagnetization in PM motors; however, so far, little effort has been made to investigate demagnetization of FSPM motors and the factors affecting the demagnetization of these structures.

McFarland [10] examined the effects of d and q axis currents on the demagnetization of an Interior Permanent Magnet motor, and found that an increase in the q-axis current component increased the machine’s demagnetization tolerance.

In this paper, an investigation of demagnetization in an FSPM motor is thus carried out using the TSFEM. The effect of direct and quadrature currents on the FSPM motor is also examined to determine whether this effect exists in all permanent magnet machines. This article consists of five sections. In Section 2, the basis of demagnetization is presented. In Section 3, the method of demagnetization modelling on the FSPM motor is presented, and the simulation results are evaluated. In Section 4, the effect of the d-and q-axis currents is examined, and, finally, the conclusion is given in Section 5.
2. Fundamentals of demagnetization

As shown in figure 1, in absence of an external magnetic field, the operation point of the magnet is P1. When the magnet is exposed to an external demagnetization field, the magnet line is shifted to the left. If the working point of the magnet is P2, which is above the knee point, when the external magnetic field is removed, the magnet will recover its residual flux density. This condition is called reversible demagnetization. If the load line shifting causes the working point of the magnet to become P3, which is below the knee point, then the magnet will no longer be able to recover its residual magnetic flux density. When the external field is removed, the magnet will thus return to a new path, known as the recoil line. This line has a similar slope to the demagnetization curve above the knee point. Thus, the magnet will return to a smaller residual magnetic flux density and irreversible demagnetization will occur [11] to [13].

Another important factor in demagnetization is the influence of temperature conditions. The demagnetization characteristics of the NdFeB Neorem 593A are shown in figure 2. In NdFeB magnets, due to the negative thermal coefficient coercive force, as the temperature increases, the probability of demagnetization is increased. At temperatures below 150 °C, the knee point is not in the second quadrant of the B-H characteristic, which indicates that there is no demagnetization risk. As the temperature increases, the knee point appears on the demagnetization characteristic and the possibility of demagnetization increases.

![Figure 1. Fundamentals of demagnetization.](image1)

![Figure 2. NdFeB 593A demagnetization curve.](image2)

3. Demagnetization analysis of FSPM motor

TSFEM is used to investigate demagnetization in an FSPM motor. In figure 3, the FEM model of the motor is shown, and the motor specifications are given in Table (1).

To increase the accuracy of the calculations at each step of the calculation, demagnetization will be considered. In order to do this, at each step, the magnitude of the magnetic flux density of the working point is compared with the knee point. If the flux density of the working point is lower than that of the knee point, the new residual flux density obtained from the recoil line will be used in the next step of the calculations. Otherwise, the initial value of the residual flux density will be used. Simulation considering demagnetization is performed using Flux 12.0 2D finite element software in a transient state. Two temperature conditions are considered. First, the simulation is carried out at a temperature of 120 °C which is the normal working temperature of the motor. As shown in figure 2, there is no knee point in the demagnetization curve at a temperature of 120 °C, indicating that there is no risk of demagnetization. After simulation, the results shown in figure 4 are obtained for motor torque before and after demagnetization.

The results indicate that there is a partial demagnetization in the motor at 120 °C, and the average torque is reduced by about 4.77%. Additionally, in abnormal conditions, the motor temperature can rise to 180 °C, making it necessary to study demagnetization at this temperature. In this condition, the magnetic flux density of the knee point increases to 0.32 Tesla, and the possibility of demagnetization
increases. Per figure 5, six points on the surface of the magnet should be considered, four points in the corners of the magnet and two points in the middle of the magnet.

### Table 1. Machine parameters.

| Quantity                | Value          |
|-------------------------|----------------|
| Stator pole             | 12             |
| Rotor pole              | 14             |
| Inner diameter of stator| 49.4 (mm)      |
| Outer diameter of state | 90 (mm)        |
| Air gap                 | 0.65 (mm)      |
| Permanent magnet width  | 1.2389 (mm)    |
| Motor length            | 2 (m)          |
| Rotor tooth width       | 3.996 (mm)     |
| Stator tooth width      | 3.375 (mm)     |
| Rotor yoke              | 3.6029 (mm)    |
| Stator yoke             | 3.264 (mm)     |
| Winding turn number     | 46             |
| Nominal current         | 12 (A)         |

**Figure 3.** FSPM motor characteristics.  
**Figure 4.** Comparison of electromagnetic torque with (WD) and without consideration of demagnetization (WOD) at 120 °C.

In figure 6, the distribution of the flux density is shown on the surface of the magnet, at the temperature of 180 °C. This 3D image provides a better view of the magnitude and level of demagnetization of the magnet. The flux density of all points of the magnet is lower than the knee. The electromagnetic torque of the motor, both taking into account the demagnetization and disregarding it, is shown in figure 7. As is obvious, the electromagnetic torque of the motor is reduced severely due to the general demagnetization of the magnet. The electromagnetic torque declines from 139.76 Nm to 30.73 Nm. These results indicate that an FSPM motor at high temperatures is severely vulnerable to demagnetization, and that such motors should thus not be used in high temperature conditions unless magnetic materials with a high magnetic field strength are used to reduce the risk of demagnetization.
4. Influence of d and q axis currents on demagnetization

4.1. The effect of d-axis current of demagnetization

In this section, a temperature of 150 °C is considered in order to determine the effect of the d and q axes on demagnetization. At this temperature, the magnetic flux density of the knee point is about 0.11 Tesla. Applying currents with varying amplitudes and polarities thus produces results for the magnetic flux density of the working point as shown in figure 8.

Clearly, increasing the current of the d-axis in both polarities reduces the flux density of the working point and increases the probability of demagnetization.
Figure 8. Effect of d-axis current on demagnetization. Figure 9. Electromagnetic torque variation versus d-axis current.

Figure 9 shows that by increasing the d-axis current component in both positive and negative polarities, the electromagnetic torque of the motor is increased. It can be seen that as the d-axis current component increases, the increase in the torque of the motor output is not linear, tending slightly toward saturation. This can be attributed to PM demagnetization and the saturation of other parts of the motor.

4.2. The effect of q-axis current on demagnetization

To investigate the effects of q-axis current, two conditions are considered: 1. Fixed motor input current (12 A), and 2. Fixed d-axis current (12 A). In the first case, the simulation results are shown in figure 10. For constant input current, an increase of the q-axis current component increases the magnetic flux density and reduces the probability of demagnetizing in the machine. Also, as shown in figure 11, increasing the q-axis current component reduces the torque density of the motor.

In the second case, the d-axis current component is held constant at 12 A. The results are shown in figure 12, and they indicate that increasing the q-axis current in the both positive and negative polarities of the d-axis current reduces the magnetic flux density and increases the demagnetization probability of the magnet.

It is clear that increasing the current of the q-axis in the positive polarization direction will have a greater effect on the demagnetization of the machine than increases towards the negative polarization.

In [10], the effects of d-q axis currents on demagnetization of the IPM motor were investigated; it was found that increasing the q-axis current increased the motor demagnetization tolerance. In this
paper, it was found that in FSPM motor only in the case of constant input current mode does the increase in q-axis current increase the demagnetization tolerance. Otherwise, this factor has a non-significant effect.

Figure 12. Variation of magnetic flux density versus q-axis current.

5. Conclusion

In this paper, simulated demagnetization was performed on an FSPM motor using the Time Stepping Finite Element Method (TFSFM). The simulation was carried out at two temperatures of 120 and 180 degrees. This showed that, at high temperatures, the performance of the FSPM motor is severely affected and its torque density decreases. Therefore, these motors either should not be used at high temperatures or should be used with magnetic materials with high magnetic field strength to reduce the risk of demagnetization. In addition, the effects of direct and quadrature currents were studied, showing that an increase of the d-axis current increases the probability of demagnetization. Increasing the q-axis current under a constant input current condition of the machine will increase demagnetization tolerance and reduce motor torque density. This shows that, with the implementation of a proper control strategy, the risk of demagnetization can be reduced.

6. References

[1] Patel V I, Wang J and Nair S. S 2015 Demagnetization Assessment of Fractional-Slot and Distributed Wound 6-Phase Permanent Magnet Machines IEEE Transactions on Magnetics 51 pp 1-11.
[2] Xiong H, Zhang J, Degner M W, Rong C, Liang F and Li W 2016 Permanent-Magnet Demagnetization Design and Validation IEEE Transactions on Industry Applications 52 pp 2961-2970.
[3] Choi G and Jahns T.M 2014 Demagnetization characteristics of permanent magnet synchronous machines IECON 40th Annual Conference of the IEEE Industrial Electronics Society Dallas TX pp 469 - 475.
[4] Guo K et al 2016 Irreversible Demagnetization Analysis of Permanent Magnet Materials in a Novel Flux Reversal Linear-Rotary Permanent Magnet Actuator IEEE Transactions on Magnetics 52 pp 1-4.
[5] Shao L, Hua W, Zhu Z Q, Zhu X, Cheng M and Wu Z 2017 A novel flux-switching permanent magnet machine with overlapping windings IEEE Trans. Energy Convers. 32 pp. 172-183.
[6] Du Y et al 2016 Comparison of Flux-Switching PM Motors with Different Winding Configurations Using Magnetic Gearing Principle IEEE Transactions on Magnetics 52 pp 1-8.
[7] Li S, Li Y and Sarlioglu B 2015 Partial Irreversible Demagnetization Assessment of Flux-Switching Permanent Magnet Machine Using Ferrite Permanent Magnet Material *IEEE Transactions on Magnetics* **51** pp 1-9.

[8] Li G J, Taras P, Zhu Z Q, Ojeda J and Gabsi M 2017 Investigation of irreversible demagnetization in switched flux permanent magnet machines under short-circuit conditions *IET Electric Power Applications* **11** pp 595-602.

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

[10] McFarland J D and Jahns T M 2013 Influence of d- and q-axis currents on demagnetization in PM synchronous machines *IEEE Energy Conversion Congress and Exposition Denver CO* pp 4380 - 4387.

[11] Essam S 1994 Design of Small Electrical Machines *New York NY USA: John Wiley & Sons.*

[12] Kang D.W 2017 Analysis of Vibration and Performance Considering Demagnetization Phenomenon of the Interior Permanent Magnet Motor *IEEE Transactions on Magnetics* **53** pp 1-7.

[13] Choi G and Jahns T 2017 Analysis and Design Recommendations to Mitigate Demagnetization Vulnerability in Surface PM Synchronous Machines *IEEE Transactions on Industry Applications* **54** pp 1292 - 1301.