Effect of Variable Recoil Permeability on Demagnetization Characteristics of Permanent Magnet Assisted Synchronous Reluctance Motor with Bonded Magnets

Marika Kobayashi* a) Student Member, Shigeo Morimoto* Senior Member, Masayuki Sanada* Senior Member, Yukinori Inoue* Member

(Manuscript received Jan. 00, 20XX, revised May 00, 20XX)

Irreversible demagnetization analysis is complicated in motors with bonded magnets that have unique $B$-$H$ curves and do not exhibit distinct knee points. We have proposed a permanent magnet assisted synchronous motor (PMASynRM) with bonded magnets and examined its demagnetization characteristics by assuming the relative recoil permeability ($\mu_{rec}$) as constant to simplify the analysis. However, the present recoil loop measurements of bonded magnets show that $\mu_{rec}$ has different characteristics depending on the magnitude of the reverse magnetic field intensity at the working point of the magnet and temperature. Therefore, this study presents a demagnetization analysis method based on these measurement results and investigates the demagnetization characteristics of a PMASynRM considering the variation in $\mu_{rec}$ for bonded magnets. The results of the demagnetization analysis considering the variation in $\mu_{rec}$ are compared with those where $\mu_{rec}$ is assumed to be constant. The comparison results indicate that there is no problem with assuming a constant $\mu_{rec}$ of 1.15 in the demagnetization analysis of a motor with bonded magnets.

Keywords: bonded magnet, dysprosium-free, irreversible demagnetization, permanent magnet assisted synchronous reluctance motor, relative recoil permeability

1. Introduction

Interior permanent magnet (PM) synchronous motors (IPMSMs), which contain sintered rare-earth magnets (i.e., NdFeB magnets) inside their rotor, have been used for industrial, household and automotive applications. However, sintered magnets have the problems of high cost and instability of the supply of dysprosium (Dy). It is therefore necessary to develop Dy-free motors having high power and high efficiency, equivalent to those of conventional IPMSMs with sintered rare-earth magnets. IPMSMs containing Dy-free bonded magnets have been proposed by several researchers in recent years. Bonded magnets are significantly less costly than sintered rare-earth magnets because bonded magnets do not contain Dy. In addition, they have high design flexibility, which allows the motors to obtain a high reluctance torque. However, these studies did not examine the irreversible demagnetization analysis method for motors with bonded magnets.

In order to apply bonded magnets to motors driven at high current and high temperature, detailed demagnetization evaluation is essential.

When the external magnetic field produced by the stator is strong, the PMs undergo irreversible demagnetization, which causes degradation of the motor performance. The $B$-$H$ curves for sintered magnets and ferrite magnets have knee points where demagnetization occurs. Thus, the demagnetization of IPMSMs with such magnets are judged based on whether or not the flux density of the PMs becomes lower than that at the knee points. However, a demagnetization analysis of motors with bonded magnets is more complicated because the $B$-$H$ curves are not straight lines and do not have distinct knee points. Therefore, demagnetization will occur whenever the external magnetic field is applied to bonded magnets, even during normal operation. A method for demagnetization analysis considering the nonlinearity of bonded magnets has been proposed, and has been applied to IPMSMs with different rotor designs. We have also proposed a demagnetization analysis method for a Permanent magnet synchronous reluctance motor (PMASynRM) with bonded magnets. In these methods, however, the relative recoil permeability ($\mu_{rec}$) of the PMs was assumed to be a constant governed by the bonded magnets in order to simplify the analysis. In fact, $\mu_{rec}$ depends on the reverse magnetic field intensity at the working point of the magnet. Thus, the analysis results may differ from the experimental results.

Therefore, this study analyzes the demagnetization of a PMASynRM under the two conditions listed in Table 1. In condition A, $\mu_{rec}$ is set to a constant value, and Section 3 presents the analysis method and its results. In condition B, $\mu_{rec}$ is calculated from the measurements of the recoil loops of the bonded magnets. Section 4 presents the analysis method and its results.

In addition, Section 5 describes the effect of $\mu_{rec}$ on the demagnetization characteristics by comparing the results of both the conditions indicated in Table 1.
Table 1. Conditions for setting the value for relative recoil permeability $\mu_{rec}$ for demagnetization analysis.

| Condition A                                      | Condition B                                      |
|-------------------------------------------------|-------------------------------------------------|
| Set $\mu_{rec}$ to a constant value (Section 3) | Calculate $\mu_{rec}$ from measured recoil loops (Section 4) |

2. Analysis Model

Fig. 1 shows the cross-section of a PMASynRM with bonded magnets and Table 2 lists its specifications. This motor is designed for automotive applications. The maximum current is set to 180 A and the maximum terminal voltage is set to 468 V. The stator has eight poles and distributed windings with 48 slots. The rotor has Dy-Free Nd-Fe-B anisotropic bonded magnets (MAGFINE) developed by Aichi Steel Corporation (RNI-5610V). The remanence $B_r$ is 0.61 T and coercivity $H_{cb}$ is 390 kA/m at 100°C. The magnets have a double-layered reverse-arc shape and are magnetized in the radial direction as shown in Fig. 1.

Table 2. Motor specification.

| Item (Units)                 | Value               |
|------------------------------|---------------------|
| Number of poles/slots        | 8/48                |
| Stator diameter (mm)         | 215                 |
| Rotor diameter (mm)          | 140.4               |
| Number of armature winding (turns/phase) | 64                 |
| Stacks length (mm)           | 59                  |
| Winding resistance (Ω)       | 0.070               |
| Maximum phase current (A)    | 180                 |
| Maximum terminal voltage (V) | 468                 |
| Electrical steel sheet       | 20JNEH1200          |
| Bonded magnet                |                     |
| Product number               | RNI-5610V           |
| Remanence (T)*               | 0.61                |
| Coercivity (kA/m)*           | 390                 |

*At 100°C.

3. Demagnetization Analysis Method and Analysis Results Under Condition A

3.1 Analysis Method

Fig. 2 shows the $B$-$H$ curves of the sintered magnet and bonded magnet. The $B$-$H$ curve of the bonded magnet is not a straight line unlike that of sintered rare-earth magnets; thus, the demagnetization analysis is not as simple as in the case of sintered magnets.

This study investigated the irreversible demagnetization caused by an external magnetic field in the direction opposite to the magnetization of the PMs. Fig. 3 illustrates the demagnetization analysis method for bonded magnets. First, the working point of the PMs under no-load condition is set to point “a.” Next, when the external magnetic field due to the armature current is applied to the PMs, the working point shifts from “a” to “b.” $H_{rec1}$ is the reverse magnetic field intensity at point “b.” When the current is stopped, the working point shifts from “b” to “a1” along the recoil line with slope $\mu_{rec1}$. At this point, the flux density at no load decreases from $B_0$ to $B_1$. Subsequently, when a greater external magnetic field is once again applied to the PMs, the point shifts from “a1” to “b” and “c.” $H_{rec2}$ is the reverse magnetic field intensity at point “c.” When the current is stopped, the point shifts from “c” to “a2” and the flux density decreases further to $B_2$. For condition A, $\mu_{rec}$ is set to a
Effect of Recoil Permeability on Demagnetization of PMASynRM (Marika Kobayashi et al.)

Fig. 4. Input current waveform for demagnetization analysis.

Fig. 5. Distribution maps of PM flux density at no load after demagnetization ($\theta_0 = 720-1080^\circ$) for condition A.

The flux density differs depending on the values of $H_{rev}$ and temperature as shown in the following equation:

$$\mu_{rec1} = \mu_{rec2}$$ (1)

This procedure is performed for each element of the PMs using the 2D finite-element software JMAG-Designer 19.1.

Fig. 4 shows the input phase current for this analysis. The demagnetizing current flows in the armature windings of the stator for the 2nd cycle of the electrical angle. It is set to a maximum phase current $I_e$ of 180 A and the current phase angle $\beta$ is set to 90°, which is the worst condition and does not occur during normal operation.

3.2 Analysis Results

Fig. 5 shows the distribution maps of the PM flux density at no load after demagnetization, where $\theta_0$ is varied from $720^\circ$ to $1080^\circ$. $\mu_{rev}$ is set to 1.1 and 1.2, which are the upper and lower limits of the catalog value of RNI-5610V.

The flux density differs depending on $\mu_{rev}$; for example,

the flux density of an element X at the outer edge of the 1st layered magnets is 0.14 T when $\mu_{rev}$ is 1.1 and 0.23 T when $\mu_{rev}$ is 1.2 as shown in Fig. 5. The difference in flux density is approximately 0.1 T at the maximum.

Fig. 6 shows the working points of element X at the outer edge of the 1st layered magnets. The working points are calculated for each electrical angle $\theta_e$ of 4° (i.e., each mechanical angle of 1°).

When $\theta_e$ is 380°, the maximum reverse magnetic field intensity $H_{rev}$ of -688 kA/m is applied to the outer edge of the 1st layered magnets and the flux density is -0.8 T. $H_{rev}$ is the minimum value of the magnetic field $H$ at all steps. While the demagnetizing current continues to flow ($\theta_e$ is varied from $360^\circ$ to $716^\circ$), the working point makes a round trip along the recoil line for the number of times the edge of the PM faces the stator teeth.

When the energization is stopped ($\theta_e$ is varied from $720^\circ$ to $1080^\circ$), the flux density after demagnetization is obtained as shown in Fig. 5.

Fig. 7 shows the decrease rate of no-load PM flux linkage $\psi_e$ due to demagnetization at 100 and 150°C when $\mu_{rev}$ is set from 1.1 to 1.2. $\psi_e$ is proportional to $\mu_{rev}$ at both temperature conditions. When $\mu_{rev}$ varies from 1.1 to 1.2, the decrease rate of $\psi_e$ varies by about 9% at 100°C and 11% at 150°C. This means that the analysis results will differ depending on the set value of $\mu_{rev}$.
4. Recoil Loop Measurements and Demagnetization Analysis Under Condition B

4.1 Measured recoil loops In this study, we used a recoil loop of the bonded magnet (RNI-5610V). We visited a bonded magnet manufacturer and conducted the demagnetization test of a single magnet to obtain the magnet data for demagnetization analysis. The reverse magnetic field on the single magnet was determined by considering the maximum value applied to the magnet injection molded into the motor. Fig. 8 shows the results of the B-H curve and recoil loop measurements of a bonded magnet (RNI-5610V). Fig. 9 shows a schematic view of a measured recoil loop and recoil line with slope $\mu_{rec}$. The formula for calculating $\mu_{rec}$ is as follows:

$$\mu_{rec} = \frac{1}{\mu_0} \frac{B_{max} - B_{min}}{H_{max} - H_{min}} \tag{2}$$

Fig. 10 shows the recoil permeability $\mu_{rec}$ versus the reverse magnetic field intensity $H_{rev}$ at the working points of the magnets. As shown in Fig. 10, $\mu_{rec}$ depends on $H_{rev}$ and the temperature. The magnets exhibit a significant variation in $\mu_{rec}$ at 150°C, and the maximum points differ with temperature.

4.2 Analysis method and result

The demagnetization analysis method in condition B is basically the same as that described in Fig. 3; however, the conditions for setting the value of $\mu_{rec}$ are different as shown in Table 1. In condition B, the subroutines defined in the $\mu_{rec}$ vs. $H_{rev}$ characteristics in Fig. 10 were used to analyze the working points of each element in the PM.

Fig. 11 and 12 show the distribution maps for $H_{rev}$ and $\mu_{rec}$, respectively. $H_{rev}$ increases at the outer edge of the magnets and near the iron ribs. In this study, the subroutine calculates $\mu_{rec}$ and the magnetic field intensity using the magnetic flux density for each element and then determines the working points for the magnets.

Effect of Recoil Permeability on Demagnetization of PMASynRM (Marika Kobayashi et al.)
Therefore, $\mu_{rec}$ varies with the position of the magnets and can be calculated as shown in Fig. 12.

At 100°C in Fig. 11 and 12, $\mu_{rec}$ becomes largest at the outer edge of the magnets, where $H_{rec}$ is the smallest. On the other hand, at 150°C, $\mu_{rec}$ at the outer edge becomes the smallest because $\mu_{rec}$ decreases again below a $H_{rec}$ of -400 A/m, as shown in Fig. 10.

The decrease rate of no-load PM flux linkage $\psi_a$ due to demagnetization under condition B is 12.9% at 100°C and 43.3% at 150°C.

5. Comparison Analysis Results between Condition A and Condition B

This section compares the demagnetization analysis results for conditions A and B. For condition A, $\mu_{rec}$ is constant at 1.15, which is the average of 1.1 and 1.2.

5.1 PM flux linkage Table 3 compares the decrease rate of no load PM flux linkage $\psi_a$ due to demagnetization. The decrease rate of $\psi_a$ in condition B is 3.4% smaller at 100°C and 1.7% larger at 150°C than that in condition A. Here, it is obvious from Fig. 9 that the rate of decrease in condition B is smaller at 100°C because $\mu_{rec}$ is less than 1.15. However, this was examined to clarify the quantitative difference between the two conditions.

Only the comparison at 100°C will be presented from the next subsection because the difference between the two conditions is larger at 100°C.

5.2 Air-gap flux density waveform Fig. 13 shows the no load gap flux density before and after demagnetization, and Fig. 14 shows its harmonic components. The decrease rate of the fundamental amplitude due to demagnetization was 17.5% in condition A and 21.6% in condition B with a difference of 3.1%. The harmonic components also showed a maximum difference of approximately 3% between conditions A and B.

5.3 Maximum torque characteristics under maximum torque per ampere (MTPA) control Fig. 15 plots the torque versus the phase current $I_e$ under maximum torque per ampere (MTPA) control. As $I_e$ increases, the ratio of reluctance torque to the total torque ($T_r/T$) increases. Fig. 16 shows the rate of decrease of $T$ due to demagnetization with $T_r/T$ in the horizontal axis. The difference between the two conditions increases as $T_r/T$ decreases; however, the difference is approximately 2% even when $T_r/T$ is 32%. Therefore, it is clarified that the difference is small regardless of the variation in $T_r/T$.

5.4 Efficiency map Fig. 17 compares the efficiency maps before and after demagnetization. The difference in efficiency between the two conditions A and B is small in almost the entire area. In the middle and high-speed regions above 6000 min⁻¹, the high-efficiency regions under condition B are in the higher-speed regions. This is because, $\psi_a$ is lower under condition B leading to lower iron loss and a lower current for flux-weakening control, thus resulting in a lower copper loss.

Therefore, the efficiency is unaffected by the analysis conditions.
6. Conclusion

This study examined the demagnetization analysis method for a PMASynRM with Dy-free bonded magnets. The demagnetization characteristics were analyzed under two conditions: A and B. In condition A, the relative recoil permeability $\mu_{rec}$ is assumed to be constant and in condition B, it varies with the reverse magnetic field intensity and temperature. The results are summarized below.

1. Demagnetization analysis under the condition A showed that the PM flux linkage after demagnetization changed by 9.1% at 100°C and by 11% at 150°C depending on the set value of $\mu_{rec}$. Therefore, it is necessary to set $\mu_{rec}$ to an appropriate value within the range of catalog values.

2. Comparing the analytical results of conditions A ($\mu_{rec} = 1.15$) and B, the difference between the two conditions is particularly small regardless of the ratio of reluctance torque to total torque. The efficiencies after demagnetization were almost the same in all the operating regions.

Therefore, if $\mu_{rec}$ is set to 1.15, which is the average of 1.1 and 1.2, there is no problem using condition A in the demagnetization analysis of a motor with bonded magnets.

In this study, demagnetization analysis was performed using the measurement data of the recoil curve of a single magnet sample. In the future, we would like to build a prototype of a PMASynRM and compare the measurement results of the demagnetization distribution with the analytical results.

Acknowledgement

We are grateful to Aichi Steel Corporation for allowing us to witness the magnetic measurements of the magnet and for providing us with the measurement data to carry out our research. This work was supported by JSPS KAKENHI Grant Number JP19J22906.

References

(1) M. Kobayashi, S. Morimoto, M. Sanada, and Y. Inoue : “Influence of Variation of Recoil Permeability of Bonded Magnets on Demagnetization Characteristics of Permanent Magnet Assisted Synchronous Reluctance Motor”, International Conference on Electrical Machines and Systems (ICEMS), pp. 1568-1573 (2020)
(2) K. T. Chau, C. C. Chan, and C. Liu : “Overview of Permanent-Magnet Brushless Drives for Electric and Hybrid Electric Vehicles”, IEEE Trans. Ind. Electron., Vol. 55, No. 6, pp. 2246-2257 (2008)
(3) K. Yamazaki, M. Kumagai, T. Ikemi, and S. Ohki : “A Novel Rotor Design of Interior Permanent-Magnet Synchronous Motors to Cope with Both Maximum Torque and Iron-Loss Reduction”, IEEE Trans. Ind. Appl., Vol. 49, No. 6, pp. 2478-2486 (2013)
(4) S. Morimoto, Y. Asano, T. Kosaka, and Y. Enomoto : “Recent Technical Trends in IPMSM”, The 2014 International Power Electronics Conference, pp.1997-2003 (2014)
(5) X. Liu, H. Chen, J. Zhao, and A. Belahcen : “Research on the Performances and Parameters of Interior PMSM Used for Electric Vehicles”, IEEE Trans. Ind. Electron., Vol. 63, No. 6, pp. 3533-3545 (2016)
(6) Katsumi Yamazaki, Hiroshi Narushima : “Procedure for Optimization of Interior Permanent Magnet Synchronous Motors with Concentrated Windings by Considering End-Leakage Flux”, IEEJ J. Industry Applications, Vol. 8, No. 5, pp. 820-826 (2019).
(7) Akihiro Ura, Masayuki Sanada, Shigeo Morimoto, and Yukinori Inoue, "Influence of Structural Differences on Motor Characteristics of Concentrated Winding IPMSMs Obtained by Automatic Design", IEEJ J. Industry Applications, Vol. 8, No. 3, pp. 458-464 (2019).
(8) Takashi Kato, Kensuke Sasaki, Diego Fernandez Labordara, Daniel Fernandez Alonso, David Diaz Reigosa : “Magnet Temperature Estimation Methodology Using Magnet Flux Linkage Observer for Variable Leakage Flux IPMSM”, IEEJ J. Industry Applications, Vol.9, No.6, pp.723-730 (2020).
(9) M. Barcaro, and N. Bianchi : "Interior PM Machines Using Ferrite to Re-place Rare-Earth Surface PM Machines", IEEE Trans. Ind. Appl., Vol. 50, No. 2, pp. 979-985 (2014)
(10) Critical Raw Materials for the EU 2017, European Commission, Brussels, Belgium (2017)
(11) C. Mishima, K. Noguchi, M. Yamazaki, H. Matsuoka, H. Miturai, and Y. Honkura : “Development of Dy-Free Nd-Fe-B Anisotropic Bonded Magnet and Application to the Small Motors”, J. Japan Inst. Metals, Vol. 76, No. 1, pp. 89-95 (2012) (in Japanese)
(12) S. Karuhiro, R. Hosoya, and S. Shimomura : “Design of NdFeB Bond Magnets for In-Wheel Permanent Magnet Vernier Machine”, The 15th In-ternational Conference on Electrical Machines and Systems (2012)
(13) M. Miyamasu, Y. Nakamura, K. Akatsu, and M. Masuzawa : “A Study of Improvement in Permanent Magnet Synchronous Motor with High Permeability Magnet”, IEEE Trans. Ind. Appl., Vol. 133, No. 9, pp. 943-951 (2013) (in Japanese)
(14) H. Nishihara, S. Morimoto, and M. Sanada : “Structure and Characteristics of Interior Permanent Magnet Synchronous Motor with Bonded Rare-Earth Magnets”, IEEE Trans. Ind. Appl., Vol. 134, No. 10, pp. 863-869 (2014) (in Japanese)
(15) Y. Yoshikawa, T. Ogawa, Y. Okada, S. Tsutsumi, H. Murakami, and S. Morimoto : “Some Considerations on the Optimum Design of an IPMSM using a Bonded Rare-Earth Magnet”, IEEE Trans. Ind. Appl., Vol. 136, No. 12, pp. 1000-1004 (2016) (in Japanese)
(16) A. K. Jha, L. Gabuio, A. Kedous-Lebouc, J.-P. Younet, and J.-M. Dubus : “Design and Comparison of Outer Rotor Bonded Magnets Halbach Motor With Different Topologies”, IEEE ELMA Conf., Sofia, Bulgaria, pp. 6-10 (2017)
(17) R. Tsunata, M. Takemoto, S. Ogawara, A. Watanabe, T. Ueno, K. Yamada : “Development and Evaluation of an Axial Gap Motor Using Neodymium Bonded Magnet”, IEEE Trans. Ind. Appl., Vol. 54, No. 1, pp. 254-262 (2018)
(18) K. Kim, K. Kim, H. J. Kim, and J. Lee : “Demagnetization Analysis of Permanent Magnets According to Rotor Types of Interior Permanent Magnet Synchronous Motor”, IEEE Trans. Magn., Vol. 45, No. 6, pp. 2799-2802 (2009)
Effect of Recoil Permeability on Demagnetization of PMASynRM (Marika Kobayashi et al.)

Marika Kobayashi (Student Member) received the B.E. degree from Doshisha University, Kyotanabe, Japan, in 2017. She received a M.E. degree from Osaka Prefecture University, Sakai, Japan, in 2019. She is currently a Ph.D. student in the Department of Electrical and Information Systems, Osaka Prefecture University. Her research interests include permanent magnet synchronous machine designs. Ms. Kobayashi is a student member of the IEEE and a Research Fellow of the Japan Society for the Promotion of Science (JSPS).

Shigeo Morimoto (Senior Member) received the B.E., M.E., and Ph.D. degrees from Osaka Prefecture University, Sakai, Japan, in 1982, 1984, and 1990, respectively. In 1984, he joined Mitsubishi Electric Corporation, Tokyo, Japan. Since 1988, he has been with the Graduate School of Engineering, Osaka Prefecture University, where he is currently a Professor. His main areas of research interest are permanent magnet synchronous machines, reluctance machines and their control systems. Dr. Morimoto is a member of the IEEE, the Society of Instrument and Control Engineers of Japan, the Institute of Systems, Control and Information Engineers, the Japan Institute of Power Electronics, and Society of Automotive Engineers of Japan.

Masayuki Sanada (Senior Member) received the B.E., M.E., and Ph.D. degrees from Osaka Prefecture University, Sakai, Japan, in 1989, 1991, and 1994, respectively. Since 1994, he has been with the Graduate School of Engineering, Osaka Prefecture University, where he is currently an Associate Professor. His main areas of research interest are permanent-magnet synchronous motors, magnet field analysis. Dr. Sanada is a member of the IEEE, the Japan Institute of Power Electronics, and the Japan Society of Applied Electromagnetics and Mechanics.

Yukinori Inoue (Member) received the B.E., M.E., and Ph.D. degrees from Osaka Prefecture University, Sakai, Japan, in 2005, 2007, and 2010, respectively. Since 2010, he has been with the Graduate School of Engineering, Osaka Prefecture University, where he is currently an Associate Professor. His research interests include control of electrical drives, in particular, the direct torque control of permanent magnet synchronous motors and position sensorless control of these motors. Dr. Inoue is a member of the IEEE and the Japan Institute of Power Electronics.