Magnet Temperature Estimation Methodology by Using Magnet Flux Linkage Observer for Variable Leakage Flux IPMSM

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This paper presents a novel methodology of magnet temperature estimation using a magnet flux linkage observer for a Variable Leakage Flux Interior Permanent Magnet Synchronous Motor (VLF-IPMSM), whose parameters vary depending on load current conditions. The magnet temperature estimation algorithm consists of a Gopinath-Style flux observer, magnet flux linkage observer, and magnet temperature estimator based on the look-up table. The estimation accuracy is evaluated on d-q current plane by using both a behavior model of JMAG-RT and a control model of MATLAB Simulink. Then it is shown that the proposed methodology can be applied to a VLF-IPMSM for magnet temperature estimation.

Keywords: magnetic flux linkage observer, magnet temperature estimation, variable leakage flux motor, IPMSM

1. Introduction

In recent years, battery electric vehicles (BEV) and hybrid electric vehicles (HEV) are becoming more widespread from the viewpoint of soaring crude oil prices and the reduction of CO₂ emissions. In these electric vehicles powered by the driving force of motors, there is a need for downsizing the motors to be installed in a limited vehicle layout space. Additionally, it is also necessary to convert the limited onboard energy into power with high efficiency. For these reasons, permanent magnet synchronous motors (PMSM), which are characterized by high power density and high efficiency, are often used. Further downsizing PMSM and improving the power density are in progress with the improvement in characteristics of rare earth magnets such as neodymium magnets. Because neodymium magnets have relatively large remanence and change in coercivity (temperature coefficient) with temperature change, the coercivity is typically improved by adding heavy rare earth elements such as dysprosium (Dy) and terbium (Tb) in order to prevent demagnetization during high-temperature use.

These heavy rare earth elements are rare raw materials with the supply risk due to factors such as uneven distribution of production areas. It is therefore desirable to use the minimum amount required according to magnet temperature and strength of the reverse magnetic field. However, due to the difficulty in accurately measuring the temperature of the magnet embedded in the rotating rotor, it is common to design materials with a certain temperature margin, preventing permanent demagnetization under the assumed usage conditions. Optimization of magnet amount and composition would become possible if the exact magnet temperature during an operation can be obtained, but in order to monitor in real time the temperature of the permanent magnet embedded in the rotor using a thermocouple, additional components such as a slip ring or a telemeter for temperature signal transmission are required.

Against this background, various magnet temperature estimation methods have been proposed for high-temperature applications of permanent magnets. In Reference (1), a magnet temperature estimation method was proposed for interior permanent magnet synchronous generators in hybrid electric vehicles, using a thermal circuit network composed of thermal resistances and heat capacities obtained by prior experiments and simulations. In this method, carrier harmonics are obtained first for three control methods: the sine wave PWM in the low-speed range, the 6-step voltage phase control in the high-speed range and the PWM over modulation in the middle range. Based on these current waveforms, temperature rise per unit time was then calculated from the heat value distribution under each operating condition, using a loss analysis model by 3-D FEA. Thermal resistance applied to the thermal network was determined by the temperature difference calculated from temperatures measured at multiple points using a specimen with embedded thermocouples. In addition, this study was performed for the direct coil cooling system by Automatic Transmission Fluid (ATF). The accuracy with the estimation error of approximately 10% was achieved by experimentally obtaining the correlation between ATF temperature and magnet temperature.

A proposed technology in Reference (2) aimed to improve
the estimation accuracy by constructing an observer to compare the measured and estimated temperatures of the fixed winding, in addition to the estimation by the thermal network. In this method, if an accurate thermal network model is constructed, a desirable temperature estimation accuracy can be obtained. On the other hand, however, it is necessary to construct an optimal lumped constant model according to the distributed parameter systems, which include actual motor structure, material properties and cooling methods such as oil cooling and air cooling. Strictly speaking, these circuit constants are expected to be affected by temperature distribution due to the operating point history and also by modeling errors.

In Reference (3), a method without a thermal circuit model was proposed to estimate temperature, based on the change in physical signals due to changing magnet temperature. Seen from the power supply side, PMSM can be viewed equivalently as a transformer model when the stator winding is considered as a primary coil and the eddy current path generated inside the rotor magnet through the air gap as a secondary coil. Here, electric resistance $R_m$ and inductance $L_m$ of the eddy current path in the magnet, which are both circuit constants on the secondary side, are functions of magnet temperature. Based on this, a harmonic current for magnet temperature estimation is superposed separately from the drive current, and the resulting change in the harmonic impedance $Z_{HF}$ can be used to estimate the magnet temperature. In the case of interior permanent magnet motors (IPM motors) that have an iron core on the magnet surface, the estimation accuracy of this method may be affected by the change in magnetic saturation of the iron core depending on load conditions and also the path of the harmonic flux based on the magnet arrangement. In particular, this must be taken into consideration for motors whose parameters such as magnet flux linkage and inductance vary significantly depending on load conditions.

In this paper, we examine a novel methodology of magnet temperature estimation for a Variable Leakage Flux Interior Permanent Magnet Synchronous Motor (VLF-IPMSM) \(^{(1)(3)}\), whose magnetic flux linkage varies significantly in response to load current conditions and thereby expands the high-efficiency range. While it is possible to apply the previously proposed methods to VLF-IPMSM, their drawbacks are as follows: the method in Reference (1) cannot directly be applied to a system that is not based on ATF; the method in Reference (2) contains thermal network modeling errors; and the method in Reference (3) will increase the non-linearity of the correlation between impedance and magnet temperature when applied for VLF-IPMSM whose motor parameters vary significantly. Therefore, in this paper, we propose a novel magnet temperature estimation method using a magnet flux linkage observer, which does not require a thermal network and is robust against parameter fluctuations. The magnet flux linkage observer consists of a Gopinath-Style flux observer for $d$-axis magnet flux estimation \(^{(6)(7)}\) and a calculator, which approximates the magnetic flux linkage $\lambda_{pm}$ from the change in the $d$-axis interlinkage magnetic flux $\lambda_d$ when the $d$-axis current is changed by a minute amount of $\Delta i_d$, by assuming the constant $d$-axis inductance during this minute change in the $d$-axis current.

The magnetic flux linkage in VLF-IPMSM greatly varies depending on current load states and is thereby expressed as $\lambda_{pm}(i_q, i_d)$. Magnetic temperature estimation is possible by obtaining the $\lambda_{pm}(i_q, i_d)$ characteristics at different temperatures in advance and comparing them with the magnetic flux linkage estimated by the magnet flux linkage observer $\lambda_{pm,est}$.

In this paper, we first describe the validity of using magnetic flux linkage for magnet temperature estimation from physical considerations, and propose a method to approximate the magnetic flux linkage from the $d$-axis magnetic flux. Next, we construct a magnetic flux linkage observer by combining a Gopinath-Style flux linkage observer and a magnetic flux linkage calculator, implement a JMAG-RT-based VLF-IPMSM behavior model and perform the estimation of magnetic flux linkage for each load current. We then compare the estimated $\lambda_{pm,est}$ and $\lambda_{pm,RT}$ calculated by JMAG-RT, which is defined as the true value in this study, with the relationship between the $\lambda_{pm}$ and magnet temperature analyzed by FEA in advance, and estimate magnet temperature at each operating point in order to demonstrate the validity of the proposed method.

2. Basic Principles of Magnetic Temperature Estimation in PMSM

We suppose magnet temperature estimation in PMSM without using any temperature sensors such as thermocouples by detecting changes in a physical quantity due to the change in magnet temperature. When magnet temperature changes, the remanence $B_r$ changes in response (in the case of neodymium magnets, the temperature coefficient of remanence is around $-0.1 -- -0.15\%/(K)$, and consequently the magnetic flux linkage $\lambda_{pm}$ and the relative magnetic permeability in the iron core $\mu_r$ also change due to magnetic saturation. Responding to the change of the relative magnetic permeability $\mu_r$, the inductance $L$ also changes. On the other hand, when the magnet volume resistivity $\rho$ changes, the electrical resistance $R_m$ of the eddy current path in the magnet changes, also resulting in change in the impedance $Z_m$ seen from the power supply side. The real part of the impedance $Z_{m,real}$ is related to the electrical resistance $R_m$, and the imaginary part is to the inductance $L$. Because these tendencies are attributed to the temperature dependence of permanent magnet remanence and resistivity as well as the magnetic saturation characteristics of the iron core material, they are commonly valid in PMSM including VLF-IPMSM, which is the subject of our paper.

In a general vehicle drive motor system, detectable physical quantities are current value from a current sensor, voltage command value from a motor controller, and rotation angle signal from a resolver. Using these values, it is necessary to estimate magnetic flux linkage and impedance containing magnetic temperature information. For highly accurate magnet temperature estimation, physical quantities with larger temperature coefficients are desired. For example, Fig. 1 presents the magnet flux linkage $\lambda_{pm}$ and the $d$-axis inductance $L_d$ as functions of the magnet temperature $T_{mag}$, which are the result of FEA analysis using VLF-IPMSM, the subject of this study (details of the model are described in Section 4). While the magnet flux linkage $\lambda_{pm}$ have the sensitivity of ap-
proximately −0.15%/K according to the temperature coefficient of the permanent magnet, the temperature sensitivity of d-axis inductance $L_d$ is minute. This is because, in the range where the interlinkage magnetic flux and the current is in a linear correlation, the change in $d/di$ is small even when the magnetic flux density in the iron core slightly changes in response to the magnet temperature change. On the other hand, in the magnetic saturation region where the load current is large, the magnetic flux component $\lambda_{pm}$ for the armature magnetic flux $L_d i_d$ becomes relatively small, the inductance fluctuation in response to magnet temperature change still becomes small. Therefore, in our study, we focus on the magnet flux linkage $\lambda_{pm}$, which directly changes in response to the magnet temperature change, and propose a novel temperature estimation method.

3. Magnet Temperature Estimation Using a Magnetic Flux Linkage Observer

3.1 Estimation of d-axis Interlinkage Magnetic Flux $\lambda_d$ Since the magnetic flux linkage $\lambda_{pm}$ is included in the d-axis interlinkage magnetic flux $\lambda_d$, it is necessary to obtain the d-axis interlinkage magnetic flux value first for the estimation of $\lambda_{pm}$. In this paper, we use a Gopinath-Style flux linkage observer\(^{10,17}\) to perform the estimation of the d-axis magnetic flux. This magnetic flux observer is composed of a current model and a voltage model. The structure of the observer is shown in Fig. 2.

In the current model, the d-axis magnetic flux component $\lambda_d$ is expressed as the sum of the magnetic flux $\lambda_{pm}$ and the inductance term $L_d i_d$ as shown in Eq. (1). The phase current value is detected by a current sensor, and d-q coordinate conversion is performed to obtain the d-q axis current. This is then multiplied by the inductance value and added to the magnetic flux $\lambda_{pm}$ to estimate the interlinkage magnetic flux component.

$$\begin{bmatrix} \lambda_d \\ \lambda_q \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \lambda_{pm} \\ 0 \end{bmatrix} \tag{1}$$

Because this model does not include the back electromotive force term and requires only the measured current value and the motor parameters acquired in advance for calculation, the magnetic flux estimation is possible even in a low-speed region where the back electromotive forces are small. However, in the case where the motor parameters fluctuate depending on the current load or temperature conditions, the estimation solely based on this current model will possibly increase error.

On the other hand, in the voltage model, the interlinkage magnetic flux estimated by the current model is used as the input value for a PI controller, and the voltage command value $v_{a_d}$, the current value, and the winding resistance in the fixed coordinate system are obtained. Substituting them in Eq. (2), the calculated voltage value is integrated to obtain the magnetic flux $\lambda_{a_d}$ in the fixed coordinate system, and the d-axis interlinkage magnetic flux $\lambda_d$ is calculated by the d-q coordinate transformation.

$$\lambda_{a_d} = \int (v_{a_d} - R_i i_d) dt \tag{2}$$

The voltage model here can be seen as a feedback controller system that combines the plant part, a simple integrator, and the PI controller. The cutoff frequency, which is set from the proportional gain and the integral gain in the voltage model, corresponds to the frequency characteristics with respect to the input of the voltage model (i.e., the output of the current model). In the region above the cutoff frequency, the magnetic flux due to the current model gradually attenuates and transitions to the estimated value by the voltage model\(^{10}\). In this paper, an observer that combines the current model and the voltage model is applied and we assume magnet temperature estimation in the region for the rotational speed where the output of the voltage model is dominant. For this reason, we performed our study with constant values for motor parameters in the current model despite a larger error due to parameter fluctuations.

3.2 Extraction of the Magnetic Flux Linkage $\lambda_{pm}$ Component from the d-axis Interlinkage Magnetic Flux $\lambda_d$ In general, for PMSM, the magnetic flux linkage $\lambda_{pm}$ and the d-axis inductance $L_d$ are assumed to be constant, and the d-axis interlinkage magnetic flux $\lambda_d$ is expressed using Eq. (1). However, exceptions are when it is not trivial to ignore the change in remanence in response to magnet

Fig. 1. Temperature dependency of $\lambda_{pm}$ and $L_d$

![Fig. 1. Temperature dependency of $\lambda_{pm}$ and $L_d$](image)

Fig. 2. Gopinath-style flux linkage observer for Magnet Flux Linkage Estimation

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temperature change or the influence of magnetic saturation due to the current load, as well as for the case of motors whose parameters significantly vary depending on the current load such as VLF-IPMSM, the subject of this paper. In such a case, the first and the second terms in Eq. (1) must be expressed as functions of the $d$-$q$ axis current and magnet temperature as shown in Eq. (3).

$$\lambda_d = \lambda_{pm}(T_{mag}, i_d, i_q) + L_d(T_{mag}, i_d, i_q)i_d \cdots \cdots \cdots \cdots (3)$$

However, only the total magnetic flux $\lambda_d$ is detectable by the actual motor, and it is difficult to estimate the magnet temperature $T_{mag}$ directly from the sum of the first and the second terms that are both functions of $T_{mag}$. We therefore consider a method to extract only the magnetic flux linkage $\lambda_{pm}$ by approximation.

Figure 3 illustrates the scheme of the relationship between $d$-axis current and $d$-axis magnetic flux. We suppose superposing a minute $d$-axis current $\Delta i_d$ on arbitrary current load state $i_d$ and $i_q$. Assuming the changes in $\lambda_{pm}$ and $L_d$ caused by the superposition are negligible, the change in the $d$-axis magnetic flux $\Delta \lambda_d$ can be approximated to depend only on $i_d$ on the change in the second term of Eq. (3). On the other hand, with the superposition of $\Delta i_d$, the $d$-axis magnetic flux $\lambda_d'$ is expressed as shown in Eq. (4).

$$\lambda_d' = \lambda_{pm}(T_{mag}, i_d, i_q) + L_d(T_{mag}, i_d, i_q)(i_d + \Delta i_d) \cdots \cdots \cdots \cdots (4)$$

Rearranging Eq. (3) and Eq. (4) leads to Eq. (5).

$$\frac{\lambda_d'}{\lambda_d} = 1 + \frac{1}{i_d + \Delta i_d} \left[ \frac{\lambda_{pm}(T_{mag}, i_d, i_q)}{L_d(T_{mag}, i_d, i_q)} \right] \cdots \cdots \cdots \cdots (5)$$

By further rearranging Eq. (5) for $\lambda_{pm}$, Eq. (6) is obtained.

$$\lambda_{pm} = \frac{\lambda_d - i_d \lambda_d'}{i_d - i_d'} \cdots \cdots \cdots \cdots (6)$$

In FEA, by substituting the $d$-axis interlinkage magnetic flux $\lambda_d$ calculated from the winding flux linkage, and the $d$-axis current $i_d$ in Eq. (6), the magnetic flux linkage $\lambda_{pm}$ can be obtained at any magnetic temperature $T_{mag}$ and $d$-$q$ axis currents $i_d$ and $i_q$. In addition, for control simulation and in actual environment, the magnetic flux linkage $\lambda_{pm}$ can be calculated by estimating $\lambda_{d, est}$ and $i_d$ using the magnetic flux observer introduced in Section 3.1 and substituting them in Eq. (6).

### 3.3 Magnet Temperature Estimation by the Magnetic Flux Linkage Observer

As discussed in the previous section, the approximation of the magnetic flux linkage $\lambda_{pm}$ at the current $i_{dq}$, using the $d$-axis interlinkage magnetic flux $\lambda_d$ and $\lambda_d'$ under the current condition that differs by a minute amount $\Delta i_d$, would enable the magnet temperature estimation through the comparison with previously obtained $\lambda_{pm}(T_{mag}, i_d, i_q)$. A block diagram of the magnet temperature estimation algorithm is presented in Fig. 4. For the feedback control system consisting of the plant motor model and the PI controller, a superposing device that generates a minute $d$-axis current $\Delta i_d$ is placed so that it will add $\Delta i_d$ to the current command value according to the trigger signal. The voltage controller, a superposing device that generates a minute system consisting of the plant motor model and the PI control algorithm is presented in Fig. 4. For the feedback control system consisting of the plant motor model and the PI controller, a superposing device that generates a minute $d$-axis current $\Delta i_d$ is placed so that it will add $\Delta i_d$ to the current command value according to the trigger signal. The voltage controller, a superposing device that generates a minute $d$-axis current $\Delta i_d$ is placed so that it will add $\Delta i_d$ to the current command value according to the trigger signal.

![Fig. 3. Definition of d-axis flux approximation](image)

![Fig. 4. Block diagram of magnet temperature estimation using magnet flux linkage observer](image)

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magnetic flux linkage calculator, the magnetic flux linkage $\lambda_{pm}$ is calculated according to Eq. (6).

Next, this calculated $\lambda_{pm}$ is input to the magnet temperature estimator. The magnet temperature estimator has previously obtained $\lambda_{pm}(i_d, i_q)$ at different magnet temperatures, which are stored as temperature coefficient mapping information. Once the voltage command value is determined, the relationship between the magnetic flux $\lambda$ and the magnet temperature $T_{mag}$ is determined as shown in Fig. 5, enabling the estimation of $T_{mag}$ from $\lambda_{pm,est}$ obtained by the magnetic flux linkage calculator.

4. Principle Validation by Simulation

4.1 Understanding the Relationship between Magnet Temperature and Magnet Flux $\lambda_{pm}$ by FEA

We perform analysis using VLF-IPMSM*8, which has variable leakage flux characteristics, as a model for principle validation. Schematic drawings and main specifications of VLF-IPMSM are presented in Fig. 6 and Table 1, respectively. As shown in Fig. 6, VLF-IPMSM has a magnetic flux bypass structure between the magnetic poles, and consequently the magnetic flux linkage $\lambda$ varies substantially depending on current amplitude and phase. We use $d$-$q$ axis current $i_{dp}$ and magnet temperature $T_{mag}$ as parameters to calculate the interlinkage magnetic flux $\lambda$ under each analysis condition by magnetic field analysis. By using this obtained $\lambda$ and Eq. (6), the magnetic flux linkage $\lambda_{pm}$ is calculated, and relationships between $\lambda_{pm}$ and each parameter are examined.

Analysis condition:
Rotation speed: $3000 \text{ min}^{-1}$
$d$-$q$ axis current: 0 to 600 A (increment by 100 A; 7 levels)
Magnet temperature: 20 to 140$^\circ$C (increment by 30$^\circ$C; 5 levels)

The magnetic flux linkage $\lambda_{pm}$ under each current and temperature condition is plotted in Fig. 7. Under the zero-load condition when $i_{dq} = 0$, the magnetic flux linkage $\lambda_{pm}$ is suppressed due to the short circuit of magnetic flux via the magnetic flux bypass sections. In contrast, $\lambda_{pm}$ increases as the $q$-axis current increases. This trend is consistent among different magnet temperature conditions, and the $\lambda_{pm}$ maps at different temperature conditions do not cross each other throughout the entire current conditions within the operating range. For permanent magnets and magnetic steel sheets typically used in PMSM, the sign of remanence and magnetic permeability gradients in response to temperature change does not reverse within the operating temperature range and under operating point conditions. It is therefore safe to assume that $\lambda_{pm}$ maps at different temperature conditions for general PMSM systems other than this paper will not cross each other either. This suggests that the estimation of magnet temperature is possible by comparing $\lambda_{pm,est}$, which is estimated from the $d$-$q$ axis current values and the magnetic flux observer, with the mapping data in Fig. 7.

A minute $d$-axis current $\Delta i_d$ was set at 1% of the command value current in the prior FEA analysis for obtaining $\lambda_{pm}$ characteristics in this study. In the actual machine, $\Delta i_d$ is set at an appropriate value in consideration of factors such as noise levels and errors in the current sensor. In order to reduce analysis errors, $\lambda_{pm}$ was obtained by averaging values obtained from Eq. (6) for each of $\lambda_d$ at the reference $d$-axis current $i_d$ and two $d$-axis interlinkage magnetic flux $\lambda_{pm}'_{id+\Delta id}$ and $\lambda_{pm}'_{id-\Delta id}$ at $i_d \pm \Delta i_d$. Based on these results in Fig. 7, the distribution of temperature coefficient at 20$^\circ$C under any current condition was calculated, and it showed almost uniform characteristics as seen in Fig. 8.

![Fig. 5. Magnet temperature estimation scheme](image)

![Fig. 6. Schematic drawings of VLF-IPMSM](image)

| Motor | Maximum torque | 265 | Nm |
|-------|----------------|-----|-----|
|       | Maximum power  | 120 | kW |
|       | DC link voltage| 280 | V  |
|       | Phase current  | 450 | $A_{pm}$ |
|       | Stacking length| 140 | mm |
| Stator| Outer diameter | 200 | mm |
|       | Number of slots| 48  |     |
|       | Winding connection| 2 series 4 parallel | - |
| Rotor | Outer diameter | 130 | mm |
|       | Number of poles | 8  |     |
|       | Magnet type     | Ne-Fe-B | - |
|       | Mag. direction  | Radial | - |

![Fig. 7. Magnet flux linkage on d-q plane by FEA](image)
4.2 Operation Validation of the Magnetic Flux Observer using the VLF-IPMSM Model

In order to validate the operation of the magnetic flux observer, we build a behavior model using a JMAG-RT spatial harmonic model (JSOL Corporation) for the VLF-IPMSM shown in Fig. 6. This model is based on a FEA model and made into an LUT by calculating in advance the interlinkage magnetic flux under each condition with parameters of current amplitude and phase. It is configured to enable the output of the magnetic flux information in response to the voltage command value generated by the circuit simulator. The model is incorporated into the magnetic flux observer in Fig. 4 to estimate \( \lambda_{d,q} \) under an arbitrary current condition \( i_{d,q} \). The estimated \( \lambda_d(i_d, i_q) \) is then input to the magnetic flux linkage calculator for estimating \( \lambda_{pm} \).

In the JMAG-RT model used in this study, we set magnet temperature at 20°C and the \( d,q \) current values in the range between 0–600 A. To simplify the gain setting described in Section 3.1, we focus on the open-loop transfer function in the current model and the gain is set to have the cutoff frequency of 5 Hz (with rotation speed below 100 min\(^{-1}\)). As mentioned earlier, as we keep the motor parameters in the current model constant in this study, the error due to magnetic flux in the current model is expected to increase in the low-speed region below the cutoff frequency. However, it should not be an issue in practice because, in the vehicle drive motors studied in this paper, the main reason for magnet temperature increase is considered to be eddy current loss in magnet due to slot harmonics in the medium- to high-speed region where the voltage model output becomes dominant.

For the current command value, with \( i_{d,q} \) as the reference, the waveform superposed with \( \pm \Delta_i \) for estimation of magnetic flux linkage as shown in Fig. 9 is applied to the \( d \)-axis current. We set \( \Delta_i \) as 5% of the reference current \( i_d \). The currents of \( i_d, i_d - \Delta_i \) and \( i_d + \Delta_i \) are applied stepwise in this order at 100 ms intervals starting at \( t = 300 \) ms. The average value in each section is calculated as estimate \( d \)-axis magnetic flux \( \lambda_{d,est} \).

As an example of the analysis results, Fig. 10 shows the estimated \( d-q \) axis magnetic flux \( \lambda_{d,q,est} \) by the magnetic flux observer and the magnetic flux output \( \lambda_{d,q,RT} \) from the behavior model JMAG-RT at \( i_d = 200 \) A and \( i_q = -200 \) A. The estimated magnetic flux responsively follows the stepwise changes of \( d-q \) current command value. In this simulation for principle validation, when the JMAG-RT output of \( d-q \) axis magnetic flux; 45.09 mWb is regarded as the true value and compared with the estimated value by the magnetic flux observer; 45.05 mWb, the result demonstrates that the estimation with an error below 1% is achieved under this current condition. Using \( \lambda_{d}, \lambda_{d,est}, \lambda_{d,RT} \) and \( \lambda_{d,est} \) under this condition, the estimated magnetic flux \( \lambda_{pm} \) from Eq (6) is 71.92 mWb. Comparing it with the true value of 73.56 mWb, the estimation was achieved with an error of approximately \(-2.2\% \). We next examine the influence of the estimation error of magnetic flux on the accuracy of magnet temperature estimation. Figure 11 presents the relationship between magnet temperature and magnetic flux linkage under the current condition in Fig. 10. The magnet temperature estimated from the magnetic flux linkage \( \lambda_{d,est} \) calculated by the observer is compared with the magnet temperature setting of 20°C in the JMAG-RT model as the true value, and the estimation was with an error of approximately 11.7°C.

Similarly, for the input conditions at \( i_{d,q} = 0–600 \) A, \( \lambda_{pm,est}(T_{mag}, i_d, i_q) \) was calculated for each condition, and the obtained result of magnet temperature estimation error mapping is shown in Fig. 12. These results show that the magnet temperature estimation was achieved with an error ranging about \(-3–23^\circ C \) within the current limit circle, although the estimation error varies depending on the current condition. Based on this, for the VLF-IPMSM, where the motor parameters significantly fluctuate depending on the current load state, we confirmed the validity of the magnet temperature estimation method by the
magnet flux linkage observer proposed in this paper.

5. Conclusion

In this paper, we showed from our theoretical consideration that magnetic flux linkage is an effective physical quantity to evaluate for magnet temperature estimation, and proposed a novel methodology of magnet temperature estimation using a magnet flux linkage observer.

For the VLF-IPMSM in which the motor parameters fluctuate significantly depending on the current load, the proposed method was examined with a high-precision motor model and control simulation by magnetic field analysis. As a result, we showed good temperature estimation accuracy in the range of \( i_{dq} \) operation conditions, demonstrating the validity of this method.

References

(1) M. Kamiya, H. Awata, T. Miura, Y. Yagyu, T. Kosaka, and N. Matsui: “Permanent Magnet Temperature Analysis Considering PWM Carrier Harmonics for Interior Permanent Magnet Synchronous Generator in Hybrid Vehicles”, IEEJ Trans. on IA, Vol.127, No.12, pp.1238–1244 (2007) (in Japanese)

(2) Y. Imanishi and S. Nishiguchi: “Development of Temperature Estimation for Magnet of Electric Vehicle”, SAE J Trans., Vol.45, No.5, pp.841–845 (2014)

(3) D. Reigosa, D. Fernandez, H. Yoshida, T. Kato, and F. Briz: “Permanent-Magnet Temperature Estimation in PMSMs Using Pulsating High-Frequency Current Injection”, IEEE Trans. on Industry Applications, Vol.51, No.4, pp.3159–3168 (2015)

(4) T. Kato, H. Hijiwata, M. Minowa, K. Akatsu, and R.D. Lorenz: "Design Methodology for Variable Leakage Flux IPM for Automobile Traction Drives", IEEE Trans. on Industry Applications, Vol.51, No.5, pp.3811–3821 (2015)

(5) T. Kato, K. Sasaki, T. Matsuru, and T. Tanimoto: “Principle of Variable Leakage Flux IPM Using Arc-shaped Magnet Considering Variable Motor Parameter Characteristics Depending on Load Current”, IEEE Energy Conversion Congress and Exposition (2017)

(6) J.S. Lee, C.-H. Choi, J.-K. Seok, and R.D. Lorenz: “Deadbeat-Direct Torque and Flux Control of Interior Permanent Magnet Synchronous Machines With Discrete Time Stator Current and Stator Flux Linkage Observers”, IEEE Trans. on Industry Applications, Vol.47, No.4, pp.1749–1758 (2011)

(7) P.L. Jansen and R.D. Lorenz: “A physically insightful approach to the design and accuracy assessment of flux observers for field-oriented induction motor drives”, IEEE Trans. on Industry Applications, Vol.38, No.5, pp.1334–1343 (2002)

(8) A. Shinohara and K. Yamamoto: “Estimation error analysis of stator flux observer for DTC-based PMSM drives”. Proceedings of International Power Electronics Conference 2018 (IPEC-Nagoya 2018), pp.1308–1314 (2018)

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Magnet Temperature Estimation Methodology by Using Magnet Flux Linkage Observer (Takashi Kato et al.)

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