Magnet Operating Point Estimation Using Flux Linkage Observer and Magnetic and Thermal Equivalent Circuit in PMSM

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In this study, an effective combination of methods to estimate the magnet operating points in a permanent magnet synchronous motor (PMSM) is proposed. First, the magnet temperature estimation is compensated with the initial temperature and magnet loss based on the error between the estimated temperature obtained using the thermal equivalent circuit and the estimated temperature obtained using the flux observer. In addition, stator loss is compensated based on the error between the measured temperature and estimated temperature obtained using the thermal equivalent circuit. Then, the flux linkage observer is compensated with the d/q inductance value using the magnetic equivalent circuit. A method of estimating the magnetic flux density of a permanent magnet is designed to estimate the magnetic flux density of the motor using a magnetic equivalent circuit reflecting the value of the measured magnet temperature and magnetic flux density in the permanent magnet's B-H curve. Unlike the rotor temperature, the stator temperature can be easily measured, and the magnet operating point estimation can be designed as a more accurate and error-resistant estimation method. Furthermore, simulation and experimental verification demonstrate the effectiveness of the proposed method.

Keywords: flux linkage observer, magnetic equivalent circuit, magnetic flux density, magnet operating point, magnet temperature, thermal equivalent circuit

1. Introduction

Electric vehicles (EV), which are currently being studied and interested in various cases as eco-friendly vehicles, are heavily applied with electric machines along with batteries (1). In particular, many automakers adopt an interior permanent magnet synchronous motor (IPMSM) as an electric machine for EV, as it is easy to realize, higher-power density, and higher-efficiency than induction motors (IM) or synchronous reluctance motors (Syn. RM). In addition, a variable flux interior permanent magnet synchronous motor (VF-IPMSM) with low coercive force magnet have been studied to achieve a wide speed region (2). The characteristics of this motor are that it can achieve an operation of a wide speed region by changing the magnet magnetization state using either a negative d-axis current or a positive d-axis current. In order to identify and control the magnetization status of the permanent magnet, a study to estimate the magnet operating point representing the current magnetization state is required.

As shown in Fig. 1, the magnet operating point represents the current state in the B-H demagnetization curve, it consists of magnetic fields and flux density that is changed by the temperature of the magnet body and by the external magnetic field. The magnet operating point estimation is simplified by estimating two factors: the temperature and magnetic flux density of the magnet. Since IPMSM applied to EVs has many high-speed and high-power operating points, these operations increase motor loss and the magnetic flux density often changes rapidly due to the high motor temperature. In the case of using a neodymium magnet, NdFeB, high temperature of magnet reduces the magnetic flux density which leads to decrease the overall efficiency of EV, and the risk of irreversible demagnetization due to the decrease of the permanent magnetic flux density by excessive temperature exists (3)-(6).

Against this background, there are three main methods to indirectly estimate the magnet temperature. The first is to estimate the temperature using heat transfer theory, such as the thermal equivalent circuit (7)-(10). This method can easily estimate the temperature of the entire components of the motor. However, it requires different calculations depending on the shape or structure of the motor, and the estimated temperature error also increases with errors under initial temperature, motor loss, and convection.
conditions. The second method is to observe the magnetic flux linkage of permanent magnet with temperature-varying properties to estimate the temperature of the magnet (11)-(13). It has an advantage in estimating the initial temperature and instantaneous temperature in medium to high-speed regions, without being affected by motor geometry or loss and convection conditions. However, the use of voltage equations requires precision in voltage and current information, and it effects on parameter errors such as motor resistance and inductance, as well as temperature estimation errors in low-speed region with low voltages. The third method is to estimate the temperature of the magnet using a high-frequency signal injection method (14)-(15). It uses a method of converting high frequency impedance values that change linearly with the magnet temperature. However, there is also a limitation that must be used in a limited manner due to the additional loss caused by high frequency injection and the acoustic noise is not negligible.

Therefore, an effective combination of these methods is proposed in this paper, the temperature estimation method based on a combination of the thermal equivalent circuit and the magnetic flux observer is proposed. This proposed combination can reduce the estimated temperature error under individual initial temperature, motor losses, convection conditions. It also has the advantage of reducing the impact on the voltage error and motor parameter error at low-speed region, which are weaknesses in the flux observer method. While the temperature of the permanent magnet inserted in the rotor is not easy to measure, the fixed windings temperature can be easily measured, which is widely applied throughout the industry in the form of temperature checks and insulation protection (16). In this paper, using this measured winding temperature, the magnet operation point estimation can be designed as a more accurate and error-resistant estimation method.

Meanwhile, various methods have been studied to estimate the magnetic flux density of permanent magnet, which is an important second factor in estimating magnet operating point. It can be divided into two main methods: finite element analysis (FEA) base and magnetic equivalent circuits base. The FEA is often used in the initial design of motors and in the interpretation of static motor characteristics, as they have the advantage of obtaining magnetic flux relatively accurately due to their high computational capacities. On the other hand, analysis based on the magnetic equivalent circuit has the advantage of being able to estimate magnetic flux in real time because it is easy to operate magnetic flux and has a small amount of computation compared to the FEA (17). The proposed magnetic equivalent circuit reflected changes in the residual flux density according to the magnet temperature, using the temperature estimated by the thermal equivalent circuit, in order to consider the effect on the magnet temperature.

Fig. 2 shows the ideation for the magnet operating point estimation. As shown in this figure, the magnetic flux linkage of magnet, \( \lambda_m \), is the most important parameter that is affected by electrical, magnetic, and thermal phenomenon. Thus, the flux linkage observer is firstly used to identify the magnetic flux linkage of magnet. In addition, the motor inductance, \( L_s \), resistance, \( R_s \), and residual magnetic flux density, \( B_r \), are selected as parameters that combine magnetic and thermal equivalent circuits with flux linkage observer. Consequently, the magnet operating point is estimated by the magnetic flux density, \( B_m \), estimated by the magnetic equivalent circuit and the magnet temperature, \( \theta_m \), estimated by the thermal equivalent circuit.

In this paper, section 2 describes the estimation of magnetic flux density of magnet, and section 3 describes the proposed magnet temperature estimation and combination method for magnet operating point estimation. Finally, the experimental results of the estimation of the operating point of the magnet according to each motor temperature condition is verified in section 4. The simulation and experimental verification have been provided to demonstrate...
2. Estimation of the Magnetic Flux Density

2.1 Magnetic Equivalent Circuit To estimate the magnet operating point, the magnetic flux density of permanent magnet must be calculated. In this paper, the magnetic equivalent circuit, MEC, which allows the calculation of magnetic flux in real-time, is used thanks to the advantage of less computation than the finite elements analysis, FEA. The magnetic equivalent circuit consists of the magnetic resistances and the magneto-motive forces, MMF. IPMSM has been selected for verifying the proposed method analysis.

![Magnetic Equivalent Circuit](image)

Fig. 6. Magnetic flux density Estimation using MEC

In this equation, using Gaussian elimination method, the inverse operation of the permeance matrix allows the magnetic potential value of each node, and the magnetic flux and magnetic flux density of each branch are obtained by the following equation.

\[
\Phi_{ij} = P_i \times (F_j - F_i) + \Phi_j
\]

where \( \Phi_{ij} \) is the magnetic flux and \( B_{ij} \) is the magnetic flux density between nodes \( i \) and \( j \).

The block diagram of magnetic flux density Estimation using MEC is shown in Fig. 6. It is important to note here that the magnetic permeability of the core, \( \mu \), is not a fixed value, but rather a nonlinear value that varies with the magnetic flux density value on the B-H curve of iron. Therefore, it is calculated repeatedly to satisfy the reference residual error, \( \varepsilon \), that set the magnetic flux density and permeability of the core.

\[
\left| \frac{\mu^k - \mu^{k-1}}{\mu^{k-1}} \right| \leq \varepsilon
\]
Finally, the magnetic flux density of a permanent magnet, a component of the operating point of a permanent magnet, is obtained as follows,

\[ B_m = \frac{\phi_m}{A_m} \]  

where \( B_m \) is the magnetic flux density of magnet, \( \phi_m \) is the magnetic flux of magnet and \( A_m \) is the area of magnet. To validate the proposed magnetic equivalent circuit for IPMSM, the comparison between the FEA and MEC results of the 3-phase magnetic flux linkages are shown in Fig. 7.

### 2.3 Calculation of Motor Inductances

In addition, the motor inductance reflecting the saturation of iron cores can be obtained using the superposition of MMF in permanent magnets and windings. As shown in Fig. 8, the MMF of the magnet is removed from the magnetic flux source vector and the d-q axis inductances are obtained from following equation.

\[ L_{dq} = \frac{N\lambda_{dq}}{i_{dq}} = \frac{\lambda_{dq}}{i_{dq}} \]  

where \( L_{dq} \) is the d-q axis inductances, \( \phi_{dq} \) is the d-q axis magnetic flux, \( \lambda_{dq} \) is the d-q axis flux linkage and \( i_{dq} \) is the d-q axis current.

Fig. 9 show the comparison of d-q axis inductances estimation results between FEA and MEC. As shown in this figure, the magnetic flux saturation of the iron core decreases the q-axis inductance as the current increases. The higher current and the higher speed, the greater the impact on inductances, so it is important to reflect the exact inductance value in the estimation of the magnetic flux density of magnet.

### Table 1. Temperature Coefficient of Magnet

| Magnet type | Grade | \( \alpha_{cm} \) [%] | \( \beta_{cm} \) [%] |
|-------------|-------|----------------------|----------------------|
| Alnico, cast | 5     | -0.02                | -0.01                |
| Sm<sub>2</sub>Co<sub>17</sub> | 27MG0e | -0.035               | -0.20                |
| NdFeB, bonded | MOP-A, -O | -0.13               | -0.40                |
| NdFeB, bonded | MOP-B  | -0.11                | -0.40                |
| NdFeB, sintered | L-38UHT | -0.10                | -0.50                |
| NdFeB, sintered | N38UJ  | -0.12                | -0.55                |
| NdFeB, sintered | N48M   | -0.12                | -0.65                |
| Ferrite, sintered | C-5, -8 | -0.20                | 0.27                 |

### Fig. 10. Magnet temperature estimation using flux linkage observer.

### Fig. 11. The simulation of the flux linkage, Current 1 to 9[A], Current angle 5/15/25/45[deg], Magnet temperature 20/100[degC] at 1500[min<sup>–1</sup>]

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### 3. Estimation of Magnet Operating Point

#### 3.1 Flux linkage Observer

Usually, the flux linkage observer is widely used for high-performance control such as flux weakening, rotor position sensor-less control and MPPT. Furthermore, additional advantage is that the magnet temperature can be estimated through this flux linkage observer (13). As shown in Table 1, the permanent magnet shows that the residual magnetic flux density varies according to its characteristic temperature (18). Especially for the widely used a neodymium magnet, NdFeB, the residual magnetic flux density decreases as the temperature increases.

\[ B_r = B_{rm}(1 + \alpha_{RM}(\theta_m - \theta_i)) \]  

\[ H_i = H_{im}(1 + \beta_{RM}(\theta_m - \theta_i)) \]  

where \( \alpha_{RM} \) is the temperature coefficient of residual magnetic flux density, \( \beta_{RM} \) is the temperature coefficient of coercive force, \( H_{im} \) is the intrinsic coercive force, \( \theta_m \) is the magnet temperature and \( \theta_i \) is the initial temperature. This change due to temperature increase also reduces the flux linkage of permanent magnets during operation. Using this, the magnet temperature can be estimated by the flux linkage observer. It is derived from the motor voltage equation. The voltage equation in IPMSM is as follows,

\[ \begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_i + L_d p & -L_d \omega_s \\ L_d \omega_s & R_q + L_q p \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \lambda_m \omega_s \end{bmatrix} \]  

where \( v_d, v_q, i_d \) and \( i_q \) are the voltage and current of the d-q axis and \( \omega_s \) is the angular velocity of the rotor, \( R_q \) is the resistance of the coil, \( L_d \) and \( L_q \) are the inductance of the d-q axis, \( \lambda_m \) is the magnetic flux linkage by the magnet and \( p \) is \( d/dt \).

The model reference adaptive system, MRAS, method uses the difference between actual and estimated current to estimate motor parameters. As shown in Fig. 10, the d-q axis inductance uses the values obtained using the previously described the magnetic equivalent circuit, and the motor resistance uses the values measured at the temperature of the winding as follows.

\[ R_{dq} = R_{dq0}(1 + \alpha_{cm}(\theta_m - \theta_i)) \]  

where \( \alpha_{cm} \) is the temperature coefficient of copper and \( \theta_m \) is the stator winding temperature.

The voltage equation is expressed in the current equation in the form of discrete time, as follows. 

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The block diagram of the proposed flux linkage observer is shown in Fig. 10. The voltage is compensated using dead-time compensation and resistance is calculated by measured winding temperature. In addition, the d-q axis inductances use values extracted from the magnetic equivalent circuit. Therefore, the magnet temperature can be estimated as follows:

\[ \dot{\lambda}_m = \lambda_{mo} \left(1 + \alpha_m \left(\dot{\lambda}_m - \dot{\lambda}\right)\right) \] ........................................ (21)

\[ \dot{\lambda}_{m-FO} = \frac{1}{\alpha_m} \left(\dot{\lambda}_{m-FO} - \dot{\lambda}_m\right) + \dot{\theta}_0 \] ........................................ (22)

where \( \lambda_{mo} \) is the initial flux linkage of magnet at 20 degC, \( \alpha_m \) is the temperature coefficient of flux linkage of magnet. Fig.11 shows the magnetic flux linkage of permanent magnets according to load current and temperature using the FEA Tool. As the magnet temperature increases, the flux linkage decreases in the form of the slope as shown above, and the initial flux linkage of magnet is a value that varies with current and speed, so it is stored and used in the look-up table.

3.3 Thermal Equivalent Circuit

In the PMSM, electric losses such as copper loss and iron loss are the heat generation sources. Temperature rising occurs due to conduct heat energy from the sources. Firstly, the proposed method calculates electric losses of each part using FEA, copper loss, iron loss and eddy current loss. Electric losses of each part are calculated each driving conditions such as the rotational speed and the current. Secondly, the magnet temperature is calculated using thermal equivalent circuit by heat generations and initial temperature. As shown in Fig. 12, Each value is calculated as following equations.
\[ C_{th} = \rho Vc \] ................................. (23)
\[ R_{cond} = \frac{l}{kA} \] .................................. (24)
\[ R_{conv} = \frac{1}{kA} \] .................................. (25)
\[ \frac{d\theta}{dt} = C_{th} \times (Q_{th} - G_{th} \times \theta) \] .......................... (26)

where, \( C_{th} \) is thermal capacitance, \( \rho \) is density, \( V \) is volume, \( c \) is specific heat. \( R_{cond} \) is thermal resistance of conduction, \( k \) is thermal conductivity, \( l \) is length and \( A \) is area. \( R_{conv} \) is thermal resistance of convection, \( h \) is heat transfer coefficient. \( \theta \) is temperature vector, \( C_{th} \) is thermal capacitance matrix, \( Q_{th} \) is motor loss vector and \( G_{th} \) is thermal permeance matrix.

Convection is a heat transfer that occurs between a solid plane and a fluid or gas flowing in it, with a combination of conduction and fluid flow. The flow between the solid surface and the fluid enhances the heat transfer, but the heat transfer coefficient varies depending on the flow rate of the fluid, making it difficult to calculate the heat transfer rate. The points at which convection occurs in the motor are the outside of the frame, the airgap, the air inside the end cap, etc. In the above three points, natural convection occurs outside the frame and inside the endcap, and in the airgap, the rotor rotates and forced convection occurs. Various methods have been studied on the heat transfer coefficient calculation for rotating cylindrical motors (19)-(21). In this paper, simple method was used for the heat transfer coefficient calculation (19). First, the natural convection heat transfer coefficients outside the frame and inside the endcap are calculated as follows,

\[ h = 15.5 \cdot (0.29V_{air} + 1) \] .................................. (27)

where \( V_{air} \) is the velocity of airflow.

On the other hand, in the airgap, convection heat transfer is caused by the relative rotational motion of the stator and the rotor. The convective heat transfer coefficient in the airgap \( h_{airgap} \) is expressed as Nusselt Number \( N_{Nu} \), the length of the airgap \( l_g \), and the thermal conductivity of the air \( k_{air} \), as shown as follows.

\[ h_{airgap} = \frac{N_{Nu} k_{air}}{l_g} \] .................................. (28)

\[ N_{Nu} = \begin{cases} 2.2 & \left( N_{Ta} \leq 41.1 \right) \\ 0.23N_{Ta}^{0.63} N_{Pr}^{0.25} & \left( N_{Ta} \geq 41.1 \right) \end{cases} \] .................................. (29)

\[ N_{Pr} = \frac{\rho c_p V_c}{\kappa_{air}} \] .................................. (30)

where, \( N_{Ta} \) is Taylor Number and \( N_{Pr} \) is Prandtl Number. \( V_{rotor} \) is the velocity of rotor, \( c_a \) is the dynamic viscosity of air and \( c_p \) is the specific heat of air. Thus, the convection heat transfer coefficient in the air gap can be calculated based on the above equations.

However, it is hard to obtain iron losses accurately in studies that use the magnetic circuit method or rules of thumb. One needs to find the distribution and time variations of the magnetic flux density in each part of motor after accounting for a fine geometry and the material’s nonlinear magnetic properties. Iron losses are greatly changed in stator with large changes in magnetic flux density. The iron loss density is the largest at the end of the rotor core and the teeth of the stator, which are located close to the air gap. Unlike coil losses, iron loss has a small difference even if the current changes from 3 to 7[A] as shown in Fig. 13, matrix.

In this paper, the magnet loss and stator iron loss estimation is proposed as shown in Fig. 14. Since the computation of motor loss is difficult in real time, it has been proposed to estimate the losses by comparing the estimated magnet temperature by the flux linkage observer and the measured windings temperature with the estimate values of the thermal equivalent circuit.

### 3.3 Proposed Magnet Operating Point Estimation

The combination of three methods to estimate the operating points of permanent magnet is proposed as shown Fig. 15. First, the magnet temperature estimation is compensated for the initial temperature and magnet loss by using the error between the estimated temperature by thermal equivalent circuit and the estimated temperature by flux observer. In addition, stator loss is also compensated using the error between the measured temperature the estimated temperature by thermal equivalent circuit. Then, the flux linkage observer is compensated for the d/q inductance value by the magnetic equivalent circuit. The method of estimating the magnetic flux density of a permanent magnet is designed to estimate the magnetic flux density of the motor using a magnetic equivalent circuit reflecting the value of the measured magnet temperature and magnetic flux density on the permanent magnet’s B-H curve.

![Fig. 16. Experimental Set of Proposed method](image-url)
4. Experimental Verification

In this section, the effectiveness of the proposed method is verified by experimental result. An interior permanent magnet synchronous motor (IPMSM) with 24 slots / 4 poles and distributed windings is used for evaluation, and the specification and test condition are shown in Table 2 and 3. The temperature was measured by a k-type thermocouple and the non-contact measurement data transmission device using RF communication was used to measure the temperature of rotating rotor as shown Fig. 16. The motor speed conditions are 1500 / 2000 / 2500 [min⁻¹] and the control current is 7[A] and current angle is 25[deg].

4.1 Magnetic Flux Linkage Estimation Result
As shown in Fig. 17, as expected, the magnetic flux linkage can be seen to decrease proportionally with increasing magnet temperature. The magnet loss can be also estimated by comparing the temperature estimated by flux observer with the temperature estimated by the thermal equivalent circuit. Through these results, the temperature coefficient of flux linkage $\alpha_m$ is determined to be $-0.09125 \cdot 10^{-2}$.

4.2 Loss Estimation Result
An additional advantage of the proposed method is that it is possible to estimate the loss of magnets and iron cores that are not easy to obtain accurately. Fig. 17 show the result of the loss estimation. It is confirmed that the estimated stator loss oscillates in a particular frequency form in the transient response state and the steady-state response confirms that the estimated loss differs from the value computed by FEA.

Despite its many advantages, thermal models are highly dependent on the geometry of the motor and cooling system and operating speed. Therefore, specific design and calibration are often required to increase the accuracy of temperature estimates (22). Especially in transient state, thermal capacitances are important because of the large amount of change in temperature. This vibration can occur because of the error in the thermal capacitance of thermal equivalent circuit. On the other hand, the change in temperature is small in steady-state responses and the thermal resistance is important. Therefore, it is necessary to identify exact
thermal capacitance $C_m$ for transient response and exact heat transfer coefficient $h$ for steady-state response.

4.3 Magnet Temperature Estimation Result
The estimated temperature and the measured temperature of magnet, $\theta_m$, and loss estimation results are shown in Fig. 17. As the speed increases, the temperature of the stator and magnet can be seen to increase. The error of temperature is $|\Delta \theta_m| < 2.0$ [deg] or below and appears to be following the trend of slope. This result means that the magnetic flux linkage $\lambda_m$ estimation is equivalent to indirectly measuring the magnet temperature using look-up table of initial flux linkage of magnet and it demonstrates the effectiveness of magnet and stator loss estimation.

4.4 Magnet Operating Point Estimation Result
Finally, the estimation result of the magnet operating points is shown in Fig. 18. The operating point of the measured temperature were compared with the estimated result to determine the performance of the operating point estimation. Using the proposed method, the magnetic flux density of magnet $B_m$ and magnet temperature $\theta_m$ are estimated in real time, and the validity of the estimated values was verified through theses experiment results.

5. Conclusion
For the stable and efficient operation of PMSM, a new method of the magnet operating point estimation has been proposed in this paper. An effective combination of the methods to estimate the magnet operating points was introduced for more accurate estimation performance. The special features are that all of three methods, which are magnetic equivalent circuit, thermal equivalent circuit, and flux linkage observer, are compensated each other and they are connected with magnetic flux linkage of magnet $\lambda_m$. In addition, unlike the rotor temperature, the stator temperature can be easily measured, the magnet operation point estimation can be designed as a more accurate and error-resistant estimation method. The simulation and experimental verification have been provided to demonstrate the effectiveness of the proposed method. The effectiveness of the proposed method may require more verification of other conditions, such as various load or temperature conditions.

References
(1) Y. Shimizu, S. Morimoto, M. Sanada, Y. Inoue, “Influence of Permanent Magnet Properties and Arrangement on Performance of IPMSMs for Automotive Applications”, IEEJ Transactions on Industry Applications, Vol. 6, No. 6, pp. 401-408 (2017)
(2) Chen-Yen Yu, Takashi Fukushige, Natee Limsuwan, Takashi Kato, David Díaz Reigosa, Robert D. Lorenz, “Variable-flux machine torque estimation and pulsating torque mitigation during magnetization state manipulation”, IEEE Trans. Ind. Appl., Vol. 50, No. 5, pp. 3414-3422 (2014)
(3) P. Zhou, D. Lin, Y. Xiao, N. Lambert, M. A. Rahman, “Temperature-dependent demagnetization model of permanent magnets for finite element analysis”, IEEE Trans. on Magnetics, Vol. 48, No. 2, pp. 1031-1034 (2012)
(4) Howard C. Lovatt, Peter A. Watterson, “Energy stored in permanent magnets”, IEEE Trans. on Magnetics, Vol. 35, No. 1, pp. 505-507 (1999)
(5) S. Ruoho, J. Kolehmainen, J. Ikaheimo, A. Arkkio, “Interdependence of demagnetization, loading, and temperature rise in a permanent-magnet synchronous motor”, IEEE Trans. on Magnetics, Vol. 46, No. 3, pp. 949–953 (2010)
(6) M.-D. Calin and E. Helerea, “Temperature Influence on Magnetic Characteristics of NdFeB Permanent Magnets”, in International Symposium on Advanced Topics in Electrical Engineering (ATEE) (2011)
(7) G. D. Demetriades, H. Z. D. L. Parra, E. Andersson, and H. Olsson, “A Real-Time Thermal Model of a Permanent-Magnet Synchronous Motor”, IEEE Transactions on Power Electronics, Vol. 25, No. 2, pp. 463-474 (2010)
(8) S. Nategh, O. Wallmark, M. Leksell, and S. Zhao, “Thermal Analysis of a PMaSRM Using Partial FEA and lumped Parameter Modeling,” IEEE Transactions on Energy Conversion, Vol. 27, No. 2, pp. 477–488 (2012)
(9) T. Huber, W. Peters and J. Böcker, “A Low-Order Thermal Model for Monitoring Critical Temperatures in Permanent Magnet Synchronous Motors”, in International Conference on Power Electronics, Machines and Drives (PEMD) (2014)
(10) W. Wang, Y. Zhou, Y. Chen, “Investigation of lumped-parameter thermal model and thermal parameters test for IPMSM”, International Conference on Electrical Machine and Systems (ICEMS) (2014)
(11) A. Specht and J. Böcker, “Observer for the rotor temperature of IPMSM”, in Proc. IEEE Power Electron. Motion Control Conf., pp. T4-12–T4-15, 2010.
(12) A. Specht, O. Wallischd, and J. Böcker, “Determination of rotor temperature for an interior permanent magnet synchronous machine using a precise flux observer”, in Proc. Int. Power Electron. Conf., pp. 1501–1507 (2014)
(13) O. Wallischd, A. Specht, J. Böcker, “Observing the Permanent-Magnet Temperature of Synchronous Motors Based on Electrical Fundamental Wave Model Quantities”, IEEE Transactions on Industrial Electronics, Vol. 64, No. 5, pp. 3921-3929 (2017)
(14) D. D. Reigosa, F. Briz, P. Garcia, J. M. Guerrero, and M.W. Degner, “Magnet temperature estimation in surface PM machines using high-frequency signal injection,” IEEE Trans. Ind. Appl., Vol. 46, No. 4, pp. 1468-1475 (2010)
(15) D. Reigosa, D. Fernandez, H. Yoshida, T. Kato, and F. Briz, “Permanent magnet temperature estimation in PMSM using pulsating high frequency current injection,” IEEE Trans. Ind. Appl., Vol. 51, No. 4, pp. 3159–3168 (2015)
(16) R. Mocanu, A. Onea, “Determination of stator temperature for thermal protection in a Permanent Magnet Synchronous Machine”, Mediterranean Conference on Control and Automation (MED) (2017)
(17) D. J. Gómez, A. L. Rodríguez, I. Villar, A. López-de-Heredia, I. Etxeberria-Otadui, Z. Q. Zhu, “Improved permeance network model for embedded magnet synchronous machines”, 2014 International Conference on Electrical Machines (ICEM), Vol., No., pp.1231-1237 (2014)
(18) M. Calin and E. Helerea, “Temperature influence on magnetic characteristics of NdFeB permanent magnets,” INTERNATIONAL SYMPOSIUM ON ADVANCED TOPICS IN ELECTRICAL ENGINEERING (ATEE), Bucharest, pp. 1-6 (2011)
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(19) S.K. Chowdhury, P.K Baski, “A Simple Lumped Parameter Thermal Model for Electrical Machine of TEFC design”, Power Electronics, Drives and Energy Systems (PEDES) & 2010 Power India, 2010 Joint International Conference on, pp. 1–7 (2010)

(20) S. Hirano, H. Ogasawara, M. Ejiri, T. Yuasa, A. Kaneko and Y. Abe, “Estimation of heat transfer property among parts on EV motor using thermal network method,” Transactions of the JSME (in Japanese), 2015, vol. 81, no. 822 (2015)

(21) M. Hettegger, B. Streibl, O. Biro, and H. Neudorfer, “Measurements and Simulations of the Convective Heat Transfer Coefficients on the End Windings of an Electrical Machine,” IEEE Transactions on Industrial Electronics, vol. 59, no. 5, pp. 2299–2308 (2012)

(22) Z. J. Liu, K. J. Binns, and T. S. Low, “Analysis of eddy current and thermal problems in permanent magnet machines with radial-field topologies,” IEEE Trans. on Magnetics, vol. 31, no. 3, pp. 1912–1915 (1995)

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