Design of Flux Observer Robust to Interior Permanent-Magnet Synchronous Motor Flux Variation

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***Abstract*—This paper presents a modified flux observer which is robust to the variation of the permanent-magnet flux linkage of an interior permanent-magnet synchronous motor (IPMSM). The IPMSM is driven by a current-regulated inverter, where the d–q axis currents are controlled by two proportional and integral controllers with feedforward cross-coupling decoupling terms. The integrator outputs of the current regulator reflecting flux errors are used to compensate the flux variation according to the operating temperature and manufacturing tolerance. The proposed flux observer shows satisfactory performance not only in maximum torque per ampere operating region but also in flux weakening region. The experimental results reveal the effectiveness of the proposed observer.**

***Index Terms*—Current regulator, flux observer, flux weakening, interior permanent-magnet motor, maximum torque per ampere (MTPA).**

I. Introduction

An interior permanent-magnet synchronous motor (IPMSM) has many attractive features such as high efficiency, high power density, mechanical robustness of rotor construction, and a wide flux-weakening region [1]. Therefore, it is widely used particularly for hybrid electric vehicle applications such as traction motors or integrated starter and generators (ISGs). In these applications, inductance difference between d- and q-axis generates a reluctance torque, which plays an important role in enhancing the power density.

In the maximum torque per ampere (MTPA) region, references for d–q axis current controllers can be determined by the d-axis and the q-axis inductances considering the reluctance torque previously mentioned. Likewise, in the maximum torque per volt region, the d-axis inductance and the permanent-magnet flux linkage determine the center of the voltage limit ellipse [2]. Unfortunately, however, these values vary according to magnetic saturation, operating temperature variation, and manufacturing tolerance. To make matters worse, these variations are nonlinear. Hence, the nominal values of these inductances and the magnet flux linkage are not appropriate for high-performance operation of an IPMSM in the entire operating region. Instead of using the nominal values of these parameters, two 2-D lookup tables, which produce d–q axis current references by taking the torque reference and flux linkage as inputs, are generally used for high-performance operation of IPMSM [3], [4]. Then, the control performance depends closely on the accuracy of d- and q-axis flux linkage values and torque data in the 2-D lookup table. Therefore, these inductances or flux linkage values should be accurate enough to achieve high performance from a control perspective. However, there is a problem that the flux data cannot be gained directly while the torque information can be obtained easily with an accurate sensor. Thus, it should be calculated indirectly from the voltage equations or estimated by a state observer.

Additionally, in the case of the permanent-magnet synchronous motor (PMSM), the rotor reference frame machine model contains cross-coupling terms consisting of the electrical rotor speed and the flux linkage. The cross-coupling terms can generally be decoupled by a feedforward scheme, which is an industry standard for achieving high-performance current control. The electrical rotor speed can be obtained with position sensors such as an encoder or a resolver. On the other hand, as the flux data cannot be calculated directly, the nominal value is usually used in the current controller instead of the actual value. Under these conditions, the overall control bandwidth of the current regulator cannot be maximized.

As shown above, the mismatched flux data degrade the control performance of the PMSM. There have been several studies on how to estimate motor parameters accurately [5]–[8]. In [5], the authors proposed an online adaptive estimator to enhance the current regulation performance. This method, however, uses not only inaccurate magnet flux linkage values but also a low-pass filter, causing a time delay. In [6], an adaptive flux observer with inductance estimation was proposed. In this method, the dynamics of the flux observer depend on how accurate the inductance estimation is. However, it is very difficult to estimate the dynamic inductance to reasonable accuracy. In [7] and [8], a novel estimation method for the stator resistance was proposed in which the inductance value is constant in the case of an induction machine drive system. In the PMSM drive system, however, the stator resistance does not vary as much as the

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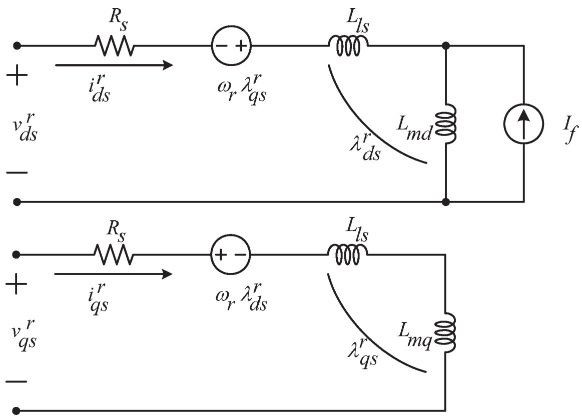

Fig. 1. Equivalent circuit of IPMSM.

stator inductance. Even if that is the case, the stator resistance of an IPMSM can be easily obtained by simple 1-D table according to temperature variation.

This paper conducts an analysis of a flux observer linked to the current regulator of the IPMSM in various cases of parameter errors. An existing flux observer, based on the voltage model and the current model of the IPMSM, is presented, and a modified flux observer, which is robust to the inductance variation as well as the magnet flux linkage variation, is proposed. The modified flux observer complements the existing flux observer by using the information of the current regulator with a feedforward decoupling strategy. The experimental results with an IPMSM are shown to verify the effectiveness of the proposed method.

II. Modeling IPMSM and Current Regulator With a Feedforward Decoupling Strategy

In this section, the mathematical modeling of an IPMSM and the current regulator with feedforward decoupling terms are discussed for the understanding of the flux observer.

A. Modeling IPMSM

The stator flux linkage information can be calculated by current information. In Fig. 1, an equivalent circuit of an IPMSM is shown. It can be seen that the flux linkages induced by the permanent magnet and stator current can be expressed as

$$\begin{bmatrix} \lambda_{ds}^r \\ \lambda_{qs}^r \end{bmatrix} = \begin{bmatrix} L_{ls}+L_{md} & 0 \\ 0 & L_{ls}+L_{mq} \end{bmatrix} \begin{bmatrix} i_{ds}^r \\ i_{qs}^r \end{bmatrix} + \begin{bmatrix} \lambda_f \\ 0 \end{bmatrix} \quad (1)$$

where λ_{ds}^r and λ_{qs}^r are d- and q-axis stator flux linkages, respectively, i_{ds}^r and i_{qs}^r denote d- and q-axis stator currents in rotor reference frame, respectively, L_{md} and L_{mq} are d- and q-axis magnetizing inductance, respectively, L_{ls} is leakage inductance, and λ_f is magnet flux linkage ($\lambda_f = L_{md} I_f$).

In (1), d- and q-axis stator inductances are defined as

$$L_{ds} = L_{ls} + L_{md}$$
$$L_{qs} = L_{ls} + L_{mq}. \quad (2)$$

Even though (1) and (2) are given, it is not an easy task to acquire the exact flux values since the inductances vary according to the load condition, particularly in case of an IPMSM.

Another way to calculate the stator flux is to exploit the stator voltage equation. The voltage equation of an IPMSM in the stationary reference frame can be derived as

$$\begin{bmatrix} v_{ds}^s \\ v_{qs}^s \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} + \begin{bmatrix} s & 0 \\ 0 & s \end{bmatrix} \begin{bmatrix} \lambda_{ds}^s \\ \lambda_{qs}^s \end{bmatrix} \quad (3)$$

where λ_{ds}^s and λ_{qs}^s are d- and q-axis stator flux linkages, respectively, v_{ds}^s and v_{qs}^s are d- and q-axis stator voltages, respectively, i_{ds}^s and i_{qs}^s denote d- and q-axis stator currents in the stationary reference frame, respectively, R_s is stator resistance, and s is Laplace operator.

From (3), the d- and q-axis stator flux linkage can be deduced as

$$\begin{bmatrix} \lambda_{ds}^s \\ \lambda_{qs}^s \end{bmatrix} = \begin{bmatrix} \frac{1}{s} & 0 \\ 0 & \frac{1}{s} \end{bmatrix} \left(\begin{bmatrix} v_{ds}^s \\ v_{qs}^s \end{bmatrix} - \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} \right). \quad (4)$$

In (4), the d- and q-axis stator flux is obtained from the integral calculation. However, if there is an offset in the measured voltage or current information, the deduced flux linkage would diverge. To settle this situation, a low-pass filter can be used instead of the pure integrator in (4). However, the low-pass filter cannot fix the offset problem perfectly, and therefore it still degrades the calculation performance in the transient [9].

B. Current Regulator With Decoupling Strategy

The rotor reference frame proportional and integral (PI) regulator is widely used as the current regulator, owing to its robustness to parameter variations. The output voltages of the current regulator are given by

$$\begin{bmatrix} v_{ds\_fb}^r \\ v_{qs\_fb}^r \end{bmatrix} = \begin{bmatrix} k_{p\_d} + \frac{k_{i\_d}}{s} & 0 \\ 0 & k_{p\_q} + \frac{k_{i\_q}}{s} \end{bmatrix} \begin{bmatrix} i_{ds}^{r*} - i_{ds}^r \\ i_{qs}^{r*} - i_{qs}^r \end{bmatrix} \quad (5)$$

where k_{p_d}, k_{p_q}, k_{i_d}, and k_{i_q} are d- and q-axis PI gains, i_{ds}^{r*}, i_{qs}^{r*}, i_{ds}^r, and i_{qs}^r are d- and q-axis current references and feedback currents, and $v_{ds\_fb}^r$ and $v_{qs\_fb}^r$ are d- and q-axis output voltages of PI regulator in rotor reference frame, respectively.

To regulate the current precisely and accurately, decoupling of the cross-coupling terms should be considered. From Fig. 1, the voltage equation of an IPMSM in the rotor reference frame can be expressed as

$$\begin{bmatrix} v_{ds}^r \\ v_{qs}^r \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} i_{ds}^r \\ i_{qs}^r \end{bmatrix} + \begin{bmatrix} s & 0 \\ 0 & s \end{bmatrix} \begin{bmatrix} \lambda_{ds}^r \\ \lambda_{qs}^r \end{bmatrix} + \begin{bmatrix} 0 & -\omega_r \\ \omega_r & 0 \end{bmatrix} \begin{bmatrix} \lambda_{ds}^r \\ \lambda_{qs}^r \end{bmatrix} \quad (6)$$

where v_{ds}^r and v_{qs}^r are d- and q-axis stator voltages, respectively, and ω_r is the electrical rotor speed.

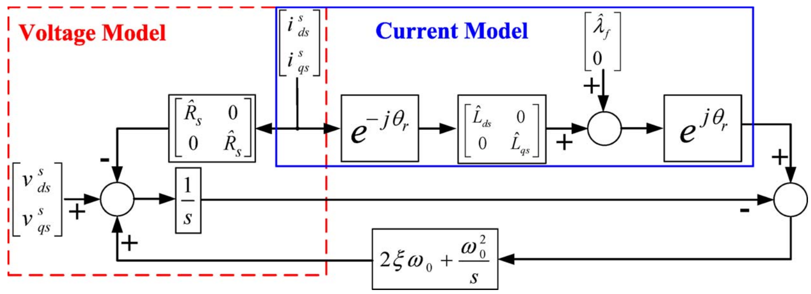

Fig. 2. Existing flux observer.

The last term on the right-hand side of (6), which is defined as the back EMF, can be cancelled out by the decoupling control if the obtained stator flux linkage information is accurate.

The output voltages of the decoupling control are shown in

$$\begin{bmatrix} v^r_{ds\_ff} \\ v^r_{qs\_ff} \end{bmatrix} = \begin{bmatrix} 0 & -\omega_r \\ \omega_r & 0 \end{bmatrix} \begin{bmatrix} \hat{\lambda}^r_{ds} \\ \hat{\lambda}^r_{qs} \end{bmatrix} \tag{7}$$

where $v^r_{ds\_ff}$ and $v^r_{qs\_ff}$ are d- and q-axis output voltages for decoupling control, respectively, $\hat{\lambda}^r_{ds}$ and $\hat{\lambda}^r_{qs}$ are the estimated stator flux linkage.

Lastly, the final outputs of the current regulator can be obtained as

$$\begin{bmatrix} v^{r*}_{ds} \\ v^{r*}_{qs} \end{bmatrix} = \begin{bmatrix} v^r_{ds\_fb} \\ v^r_{qs\_fb} \end{bmatrix} + \begin{bmatrix} v^r_{ds\_ff} \\ v^r_{qs\_ff} \end{bmatrix} \tag{8}$$

where v^{r*}_{ds} and v^{r*}_{qs} are the d- and q-axis output voltages of the current regulator, respectively.

If the actual currents track their references well in the steady state, the derivative terms in (6) can be neglected and the output of the current regulator would be equal to the stator voltages, which is described as

$$\begin{aligned} \begin{bmatrix} v^r_{ds} \\ v^r_{qs} \end{bmatrix} &= \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} i^r_{ds} \\ i^r_{qs} \end{bmatrix} + \begin{bmatrix} 0 & -\omega_r \\ \omega_r & 0 \end{bmatrix} \begin{bmatrix} \lambda^r_{ds} \\ \lambda^r_{qs} \end{bmatrix} \\ &= \begin{bmatrix} v^r_{ds\_fb} \\ v^r_{qs\_fb} \end{bmatrix} + \begin{bmatrix} 0 & -\omega_r \\ \omega_r & 0 \end{bmatrix} \begin{bmatrix} \hat{\lambda}^r_{ds} \\ \hat{\lambda}^r_{qs} \end{bmatrix}. \end{aligned} \tag{9}$$

It is clear from (9) that the PI regulator is in charge of both the voltage drop by the stator resistance and the flux information error. If the variation of the stator resistance is not too much or if the variation can be compensated, the flux information error can be calculated as an average from the integral term of PI regulator. Under the aforementioned assumptions and derivation, (10) can be formulated.

$$\begin{bmatrix} \Delta\lambda^r_{ds} \\ \Delta\lambda^r_{qs} \end{bmatrix} = \frac{1}{\omega_r} \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \left(\begin{bmatrix} v^r_{ds\_fb\_i} \\ v^r_{qs\_fb\_i} \end{bmatrix} - \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} i^r_{ds} \\ i^r_{qs} \end{bmatrix} \right) \tag{10}$$

where $v^r_{ds\_fb\_i}$ and $v^r_{qs\_fb\_i}$ are the d- and q-axis output voltages of the integral term in PI current regulator, respectively, and $\Delta\lambda^r_{ds}$ and $\Delta\lambda^r_{ds}$ are the calculated error between the actual stator flux linkage and the estimated one $(\Delta\lambda^r_{ds} = \lambda^r_{ds} - \hat{\lambda}^r_{ds}, \Delta\lambda^r_{qs} = \lambda^r_{qs} - \hat{\lambda}^r_{qs})$, respectively.

III. Flux Observer Design

In this section, an analysis of the existing flux observer is given first, and then the modified flux observer, which is robust to inductance variations and inaccuracy of the magnet flux linkage, is addressed.

A. *Existing Flux Observer*

Fig. 2 shows the block diagram of the existing flux observer for an IPMSM. The structure is similar to the closed loop Gopinath flux observer for an induction machine which is presented in [10]. As shown in Fig. 2, the existing flux observer consists of the voltage model and the current model. The dotted line stands for the voltage model, and the solid line the current model. Their mathematical descriptions are given in (11) and (12).

$$\begin{bmatrix} \lambda^s_{ds\_est\_v} \\ \lambda^s_{qs\_est\_v} \end{bmatrix} = \begin{bmatrix} \frac{1}{s}\left(v^s_{ds} - R_s i^s_{ds}\right) \\ \frac{1}{s}\left(v^s_{qs} - R_s i^s_{qs}\right) \end{bmatrix} \tag{11}$$

$$\begin{bmatrix} \lambda^s_{ds\_est\_i} \\ \lambda^s_{qs\_est\_i} \end{bmatrix} = \begin{bmatrix} \cos\theta_r & -\sin\theta_r \\ \sin\theta_r & \cos\theta_r \end{bmatrix} \begin{bmatrix} \hat{L}_{ds} i^r_{ds} + \hat{\lambda}_f \\ \hat{L}_{qs} i^r_{qs} \end{bmatrix} \tag{12}$$

where $\lambda^s_{ds\_est\_v}$, $\lambda^s_{qs\_est\_v}$, $\lambda^s_{ds\_est\_i}$, and $\lambda^s_{qs\_est\_i}$ are the d- and q-axis estimated stator flux linkage by the voltage and the current model, respectively, $\hat{L}_{ds}$ and $\hat{L}_{qs}$ are the estimated nominal d- and q-axis inductances, respectively, $\hat{\lambda}_f$ is the estimated nominal magnet flux linkage, and θ_r is the electrical rotor position.

The voltage model calculates the stator flux linkage from the difference between the voltage references in the stationary reference frame and the voltage drop by the stator resistance. The voltage model is reliable when the voltage references are large enough to ignore the voltage disturbance, which is due to the nonlinearity of the inverter, such as dead time and the voltage drop of the switching devices, and also to the error of the voltage drop by the stator resistance error. The current model, however, requires d- and q-axis inductances and the magnet flux linkage, which may have considerable amount of error. In the existing flux observer, the current model works on the nominal values of inductance and magnet flux linkage, which may vary considerably according to load condition and

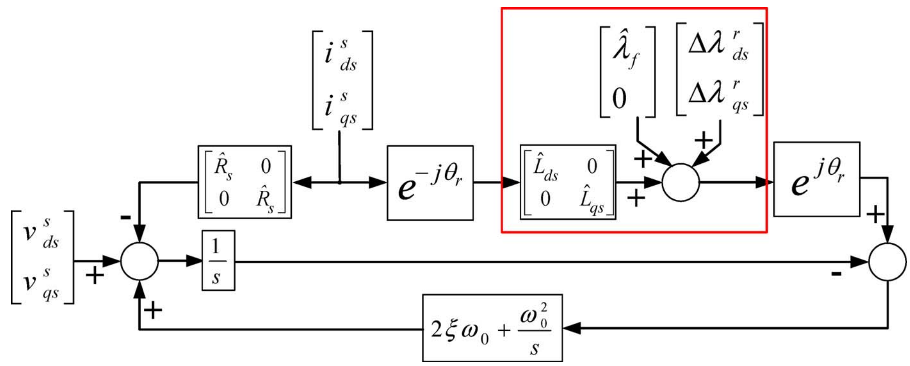

Fig. 3. Modified flux observer.

the operating temperature of the magnet. In the current model, the estimation error due to mismatched machine parameters can be derived as

$$\begin{bmatrix} \Delta\lambda^s_{ds\_est\_i} \\ \Delta\lambda^s_{qs\_est\_i} \end{bmatrix} = \begin{bmatrix} \left(L_{ds} - \hat{L}_{ds}\right) i^r_{ds} \cos\theta_r \\ \left(L_{ds} - \hat{L}_{ds}\right) i^r_{ds} \sin\theta_r \end{bmatrix} + \begin{bmatrix} -(L_{qs} - \hat{L}_{qs}) i^r_{qs} \sin\theta_r \\ (L_{qs} - \hat{L}_{qs}) i^r_{qs} \cos\theta_r \end{bmatrix} + \begin{bmatrix} (\lambda_f - \hat{\lambda}_f) \cos\theta_r \\ (\lambda_f - \hat{\lambda}_f) \sin\theta_r \end{bmatrix} = \begin{bmatrix} \cos\theta_r & -\sin\theta_r \\ \sin\theta_r & \cos\theta_r \end{bmatrix} \begin{bmatrix} \Delta\lambda^r_{ds} \\ \Delta\lambda^r_{qs} \end{bmatrix} \quad (13)$$

where $\Delta\lambda^s_{ds\_est\_i}$ and $\Delta\lambda^s_{qs\_est\_i}$ are the estimation error in current model.

As shown in (13), owing to mismatched machine parameters in the stationary reference frame, the estimated stator flux error reveals oscillatory responses whose frequency is equal to the electrical rotor speed.

The transfer function of the existing flux observer in the stationary reference frame can be derived as

$$\begin{bmatrix} \lambda^s_{ds\_est\_conv} \\ \lambda^s_{qs\_est\_conv} \end{bmatrix} = \frac{s^2}{s^2 + 2\xi\omega_0 s + \omega_0^2} \begin{bmatrix} \lambda^s_{ds\_est\_v} \\ \lambda^s_{qs\_est\_v} \end{bmatrix} + \frac{2\xi\omega_0 s + \omega_0^2}{s^2 + 2\xi\omega_0 s + \omega_0^2} \begin{bmatrix} \lambda^s_{ds\_est\_i} \\ \lambda^s_{qs\_est\_i} \end{bmatrix} \quad (14)$$

where $\lambda^s_{ds\_est\_conv}$ and $\lambda^s_{qs\_est\_conv}$ are the estimated stator flux linkage through the existing flux observer.

The first and the last terms on the right-hand side of (14) are from the voltage and the current models, respectively. The feedback compensator in Fig. 2 determines the damping ratio ξ and the crossover frequency ω_0 of the system. The voltage model is dominant over the crossover frequency while the current model is dominant below the crossover frequency. In other words, the estimated stator flux linkage can be distorted more severely in the low-frequency region due to the structure of the existing flux observer. In this point of view, since the current model is not as accurate as the voltage model in terms of parameter variation, the value of the crossover frequency is very important.

The estimated flux from the existing flux observer in the rotor reference frame can be deduced as

$$\left\{A^2 + 2\xi\omega_0 A + \omega_0^2 I\right\} \begin{bmatrix} \lambda^r_{ds\_est\_conv} \\ \lambda^r_{qs\_est\_conv} \end{bmatrix} = \left\{A^2 + 2\xi\omega_0 A\hat{L}L^{-1} + \omega_0^2 \hat{L}L^{-1}\right\} \begin{bmatrix} \lambda^r_{ds} \\ \lambda^r_{qs} \end{bmatrix} - \left\{2\xi\omega_0 A\hat{L}L^{-1} + \omega_0^2 \hat{L}L^{-1}\right\} \begin{bmatrix} \lambda_f \\ 0 \end{bmatrix} + \left\{2\xi\omega_0 A + \omega_0^2 I\right\} \begin{bmatrix} \hat{\lambda}_f \\ 0 \end{bmatrix} \quad (15)$$

where the matrixes are defined as $A = \begin{bmatrix} s & -\omega_r \\ \omega_r & s \end{bmatrix}$, $\hat{L} = \begin{bmatrix} \hat{L}_{ds} & 0 \\ 0 & \hat{L}_{qs} \end{bmatrix}$, and $L^{-1} = \begin{bmatrix} L_{ds} & 0 \\ 0 & L_{qs} \end{bmatrix}^{-1}$.

From (15), if the estimated inductance and magnet flux linkage is matched with the real value, the estimated flux would be equal to the real one. Otherwise, there are coupling terms between the estimated value and the real one, and the estimated flux linkage would have errors.

B. Modified Flux Observer

Fig. 3 shows the block diagram of the proposed modified flux observer. The proposed method compensates for the flux error in the current model by adding the flux error terms obtained from (10). The solid red line in Fig. 3 shows the compensated current model in the rotor reference frame.

Then, the transfer function of the proposed strategy in the stationary reference frame can be expressed as

$$\begin{bmatrix} \lambda^s_{ds\_est\_mod} \\ \lambda^s_{qs\_est\_mod} \end{bmatrix} = \begin{bmatrix} \lambda^s_{ds\_est\_conv} \\ \lambda^s_{qs\_est\_conv} \end{bmatrix} + \frac{2\xi\omega_0 s + \omega_0^2}{s^2 + 2\xi\omega_0 s + \omega_0^2} \begin{bmatrix} \cos\theta_r & -\sin\theta_r \\ \sin\theta_r & \cos\theta_r \end{bmatrix} \begin{bmatrix} \Delta\lambda^r_{ds} \\ \Delta\lambda^r_{qs} \end{bmatrix} \quad (16)$$

where $\lambda^s_{ds\_est\_mod}$ and $\lambda^s_{qs\_est\_mod}$ are the estimated stator flux linkage through the modified flux observer.

In addition, from Fig. 3, the estimated flux from the modified flux observer in the rotor reference frame can be derived as

$$\begin{aligned}\left\{A^2+2\xi\omega_0 A+\omega_0^2 I\right\}\begin{bmatrix}\lambda^r_{ds\_\mathrm{est\_mod}}\\ \lambda^r_{qs\_\mathrm{est\_mod}}\end{bmatrix} &= \left\{A^2+2\xi\omega_0 A\hat{L}L^{-1}+\omega_0^2\hat{L}L^{-1}\right\}\begin{bmatrix}\lambda^r_{ds}\\ \lambda^r_{qs}\end{bmatrix}\\ &\quad-\left\{2\xi\omega_0 A\hat{L}L^{-1}+\omega_0^2\hat{L}L^{-1}\right\}\begin{bmatrix}\lambda_f\\ 0\end{bmatrix}\\ &\quad+\left\{2\xi\omega_0 A+\omega_0^2 I\right\}\begin{bmatrix}\hat{\lambda}_f+\Delta\lambda^r_{ds}\\ \Delta\lambda^r_{qs}\end{bmatrix}\\ &= \left\{A^2+2\xi\omega_0 A+\omega_0^2 I\right\}\begin{bmatrix}\lambda^r_{ds}\\ \lambda^r_{qs}\end{bmatrix}\end{aligned} \tag{17}$$

where $\hat{L}L^{-1}\left[\begin{smallmatrix}\lambda^r_{ds}-\lambda_f\\ \lambda^r_{qs}\end{smallmatrix}\right]+\left[\begin{smallmatrix}\hat{\lambda}_f+\Delta\lambda^r_{ds}\\ \Delta\lambda^r_{qs}\end{smallmatrix}\right]=\left[\begin{smallmatrix}\lambda^r_{ds}\\ \lambda^r_{qs}\end{smallmatrix}\right]$.

As shown in (17), the estimated flux is equal to the real flux if the calculated flux error is reasonable.

By simply modifying the structure, the proposed observer becomes robust to both the inductance errors and the inaccuracy of the magnet flux linkage. Additionally, due to the modified flux observer's robustness to parameter variation, the crossover frequency of the proposed observer is not as critical as that of the existing one. Consequently, the proposed method reveals better performance at the low-frequency operation than the conventional one.

However, the flux error in (10) includes a division operation by the electrical rotor speed. Hence, the compensation cannot be applied around the zero speed, and it needs a limiter to circumvent the problem of division by zero or near zero. From (9) and (10), it can be understood that the flux error cannot be seen in the rotor reference frame voltage equation at zero speed, and the proposed strategy cannot used in such a operating condition. Fig. 4 shows the simulated comparison between the modified flux observer and the existing one when the IPMSM, whose parameters are shown in Table I, is running at -100 r/min, which is 1% of the maximum speed. Both flux observers used the nominal inductance and the magnet flux linkage. Additionally, the 1% sensor offset and the 0.1% rms sensor noise are included in the measured currents. In Fig. 4, $\lambda^s_{ds\_\mathrm{real}}$ and $\lambda^s_{qs\_\mathrm{real}}$ are the real flux in the stationary reference frame, $\lambda^s_{ds\_\mathrm{est\_exi}}$ and $\lambda^s_{qs\_\mathrm{est\_exi}}$ are the estimated value from the existing flux observer, and $\lambda^s_{ds\_\mathrm{est\_mod}}$ and $\lambda^s_{qs\_\mathrm{est\_mod}}$ are the one from the proposed strategy. The performance of the modified flux observer is much better than the existing one. In addition, the estimated error, $\Delta\lambda^s_{ds}$ and $\Delta\lambda^s_{qs}$, from the modified flux observer is reduced remarkably.

By the way, if an IPMSM is operated in the flux-weakening region, an overmodulation problem occurs inevitably. In this paper, the flux weakening strategy proposed in [4] is implemented. In [4], the minimum distance overmodulation strategy is used in the overmodulation region. Fig. 5 shows output voltages in the flux-weakening region in the d–q voltage plane. In the flux-weakening region, the output of the integrator in the current regulator exceeds the voltage limit hexagon in the stationary reference frame. Hence, it is necessary to redefine the

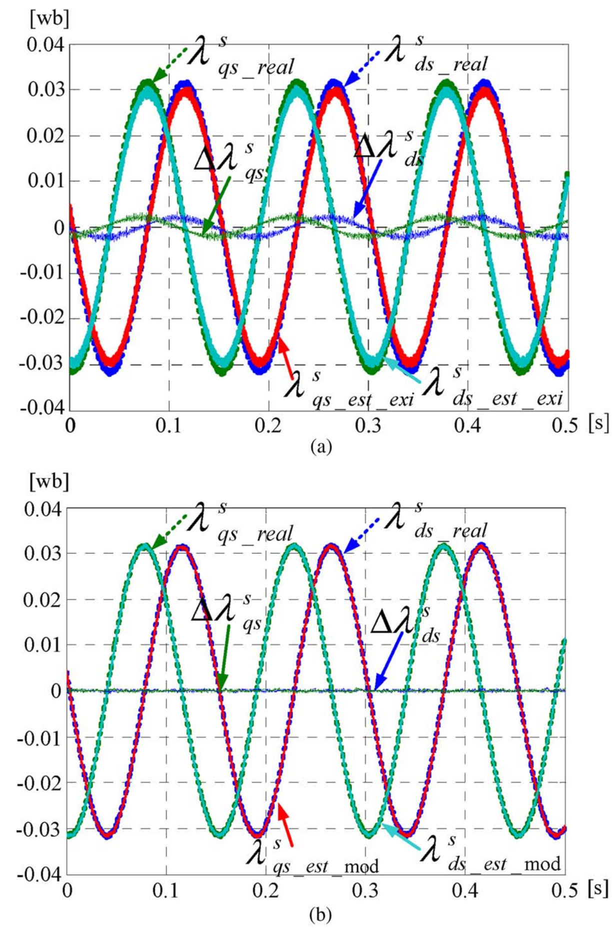

Fig. 4. Simulated performance comparison between existing flux observer and modified flux observer at -100 r/min. (a) Existing flux observer. (b) Modified flux observer.

TABLE I
PARAMETERS OF TESTED IPMSM

Quantity	***Value[unit]***
Constant rated power	4[kW]
Rated Speed	2,500[r/min]
Maximum Speed	10,000[r/min]
Number of poles	8
Rated line to line voltage	29.7[V_{rms}]
Rated current	300[A]
Nominal d-axis inductance	50[μH]
Nominal q-axis inductance	150[μH]

integrator information. According to Fig. 5, the output voltage of current regulator in (10) can be larger than the realizable voltage, thus it should be modified as

$$\begin{bmatrix}v^r_{ds\_i\_\mathrm{OVM}}\\ v^r_{qs\_i\_\mathrm{OVM}}\end{bmatrix}=\begin{bmatrix}v^r_{ds\_fb\_i}\\ v^r_{qs\_fb\_i}\end{bmatrix}-\begin{bmatrix}v^r_{ds\_\lim it\_\mathrm{filt}}\\ v^r_{qs\_\lim it\_\mathrm{filt}}\end{bmatrix} \tag{18}$$

where $v^r_{ds\_i\_\mathrm{OVM}}$ and $v^r_{qs\_i\_\mathrm{OVM}}$ are the redefined integral values in the overmodulation region, and $v^r_{ds\_\lim it\_\mathrm{filt}}$ and $v^r_{qs\_\lim it\_\mathrm{filt}}$ are filtered voltage references which lie outside the voltage limit hexagon.

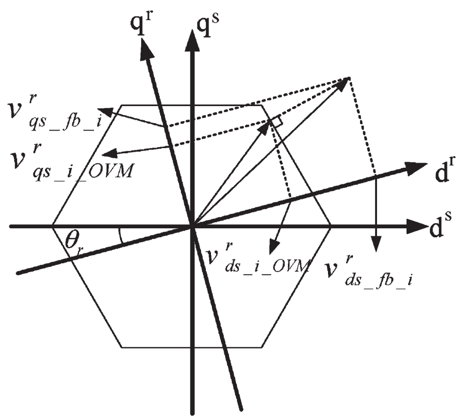

Fig. 5. Block diagram of output voltage in overmodulation region.

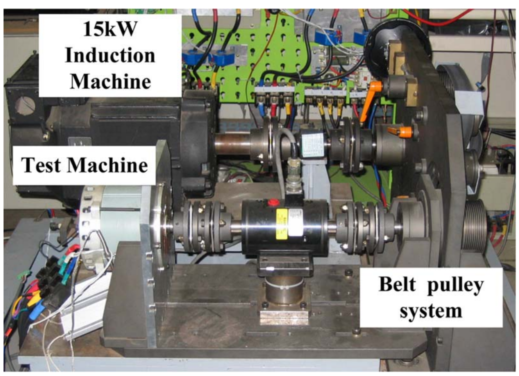

Fig. 6. Experimental setup.

In the flux-weakening region, the flux errors in (10) can be revised as

$$\begin{bmatrix}\Delta\lambda_{ds}^r\\ \Delta\lambda_{qs}^r\end{bmatrix}=\frac{1}{\omega_r}\begin{bmatrix}0 & 1\\ -1 & 0\end{bmatrix}\left(\begin{bmatrix}v_{ds\_i\_\mathrm{OVM}}^r\\ v_{qs\_i\_\mathrm{OVM}}^r\end{bmatrix}-\begin{bmatrix}R_s & 0\\ 0 & R_s\end{bmatrix}\begin{bmatrix}i_{ds}^r\\ i_{qs}^r\end{bmatrix}\right). \tag{19}$$

IV. Experimental Result

Fig. 6 shows the experimental setup. The target machine is an IPMSM which is designed for ISG applications; its parameters are listed in the Table I. As shown, the IPMSM is coupled with the load machine by the belt-pulley system, which results in mechanical vibrations, particularly in the low-speed region. The designed minimum steady state operating speed is 600 r/min. However, to show the performance of the proposed observer at the low speed clearly, the experiments are executed at 200 r/min where the mechanical vibration can be kept negligible.

The stator resistance variation according to the temperature can be considered by measuring the temperature of stator winding using a negative temperature coefficient resistor. The offline measured stator resistance variations are listed in Table II, and thus they can be applied to the voltage model shown in Figs. 2 and 3.

Fig. 7 shows the rotor reference frame d- and q-axis flux linkages which were measured at -1000 r/min. The measured data

TABLE II
Stator Resistance Variation According to Temperature

Quantity	*Value[unit]*
25℃	9.8[mΩ]
60℃	10.7[mΩ]
120℃	12.9[mΩ]

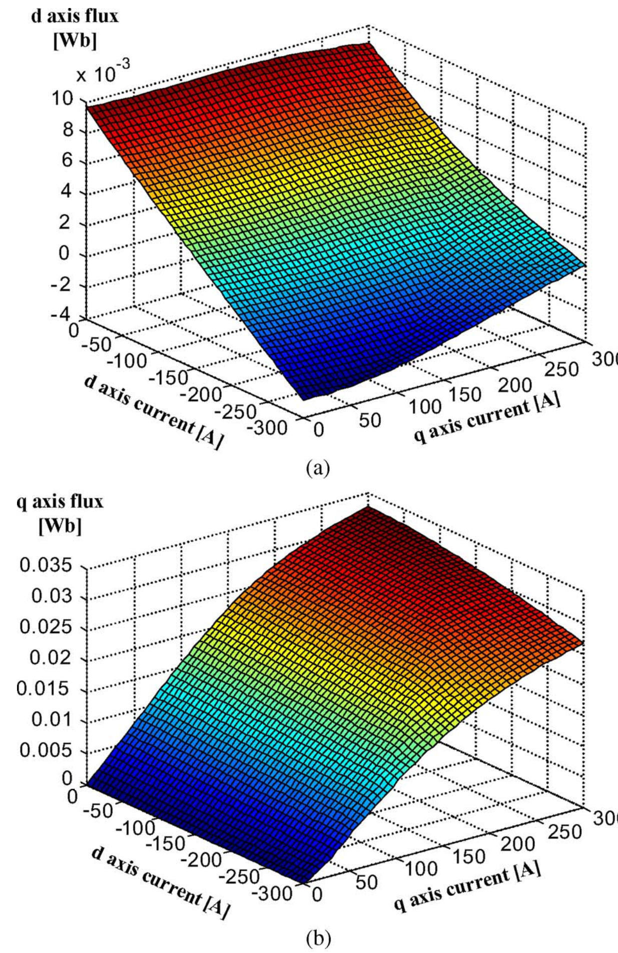

Fig. 7. d- and q-axis flux linkage data of test machine at -1000 r/min. (a) d-axis flux linkage in rotor reference frame. (b) q-axis flux linkage in rotor reference frame.

in Fig. 7 are from the rotor reference frame voltage equation in the steady state. A low-pass filter, whose cutoff frequency is several hertz, is used to get the average voltages, currents, and rotor speed. As shown in Fig. 7, since the flux linkage variation is quite large as the d- and q-axis current varies, it is not easy to determine the nominal inductance value. However, for convenience, the nominal d- and q-axis inductances are set to 50 and 150 μH, respectively.

Fig. 8 shows the experimental results. For the comparison between the conventional method and the proposed method, the estimated nominal magnet flux linkage is changed from the nominal value (I) to 150% of the nominal value (II), to 50% of the nominal value (III), and to the nominal value (IV) again. In Fig. 8(a), the IPMSM is operated at -1250 r/min in the MTPA region with torque reference of 40 N $\cdot$ m. To show the performance on the flux weakening operation in Fig. 8(b), the operating speed increases to -5000 r/min while the torque

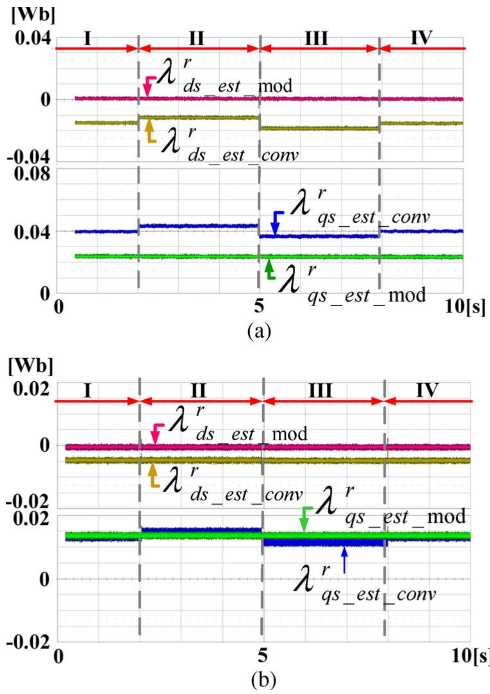

Fig. 8. Comparison between conventional method and proposed method in rotor reference frame (I: $\hat{\lambda}_f = \lambda_{f\_\text{nom}}$, II: $\hat{\lambda}_f = 1.5\lambda_{f\_\text{nom}}$, III: $\hat{\lambda}_f = 0.5\lambda_{f\_\text{nom}}$, IV: $\hat{\lambda}_f = \lambda_{f\_\text{nom}}$). (a) At −1250 r/min. (b) At −5000 r/min.

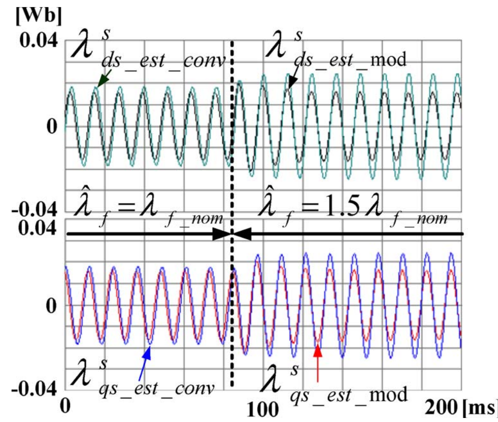

Fig. 9. Comparison of the conventional method and the proposed method in stationary reference frame.

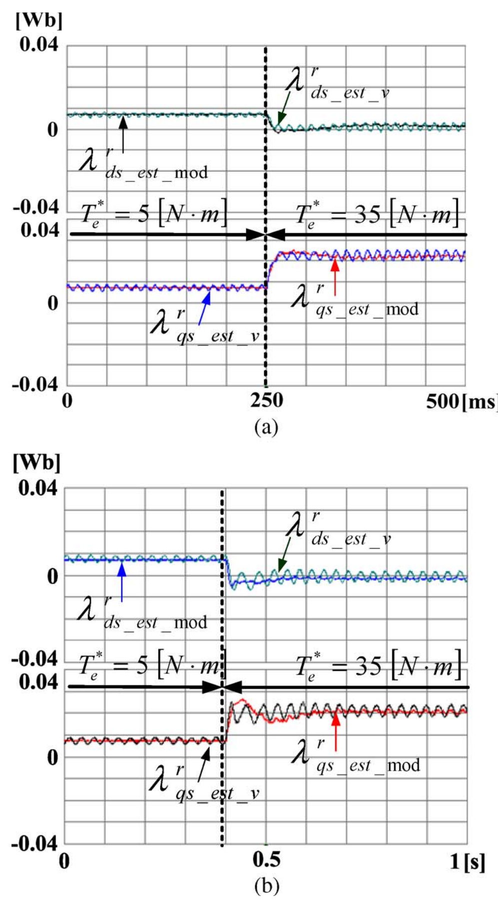

Fig. 10. Comparison of the flux linkage only by the voltage model and the flux linkage by the proposed method in rotor reference frame. (a) At −500 r/min. (b) At −200 r/min.

reference is 40 N · m. In Fig. 8, $\lambda^r_{ds\_\text{est\_conv}}$ and $\lambda^r_{qs\_\text{est\_conv}}$ are the estimated d- and q-axis flux linkage from the conventional method whereas $\lambda^r_{ds\_\text{est\_mod}}$ and $\lambda^r_{qs\_\text{est\_mod}}$ are from the proposed flux observer. As shown in Fig. 8, even if the magnet flux linkage is inaccurate, d- and q-axis flux estimated by the proposed observer does not change. However, in the conventional method, the initial value of the magnet flux linkage determines the final value of the estimation. In the high-speed region, since the voltage model is dominant, the difference between the existing and the proposed methods is not severe. Nevertheless, there is still some offset in the d-axis flux and some fluctuation in the q-axis flux in the conventional method.

Fig. 9 shows the experimental results of comparison between the conventional method and the proposed method in the stationary reference frame. The machine under the test is running at −500 r/min, and the estimated nominal magnet flux linkage is changed from the nominal value to 150% of the nominal value. The estimated flux linkage from the proposed method does not change in the steady state, while the estimated value from the conventional method is sensitive to the preset nominal values. The variation of estimated flux linkage from the proposed method in the transient was caused by the forced machine parameter change.

In Fig. 10, the estimated flux by the proposed method is compared to the one obtained only by the voltage model in the rotor reference frame. $\lambda^r_{ds\_\text{est}\_v}$ and $\lambda^r_{qs\_\text{est}\_v}$ are the estimated d- and q-axis flux linkage by the voltage equation, respectively. In Fig. 10(a), the test machine is running at −500 r/min and the torque reference is changed from 5 to 35 N · m in step manner. As shown in Fig. 10(a), the estimated flux linkage from the voltage model is oscillatory. Normally, by the step change of the torque reference, the voltage references of the current regulator are apt to be large due to the proportional gain of the current regulator. This can cause the oscillation in the estimated flux directly when only the voltage model is used for the flux estimation. The oscillation in the estimated flux is more severe in the low-speed region, as shown in Fig. 10(b). However, as the estimated flux linkage from the proposed flux observer is compensated by the integrating the terms of

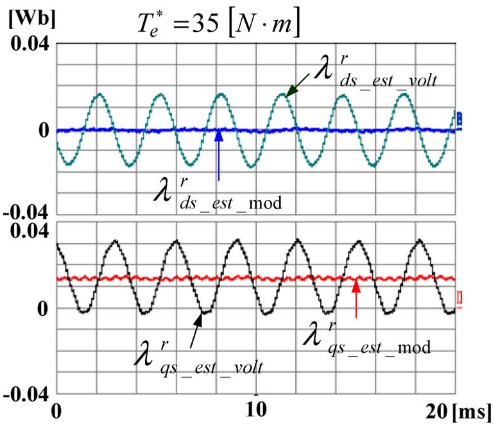

Fig. 11. Comparison of the voltage model and the proposed method in the synchronous reference frame.

the current regulator, the estimated flux by the proposed observer does not reveal any oscillation at step torque command. This structure of the proposed method improves the estimation performance even in the transient. As shown in Fig. 10, the modified flux observer works well around −200 r/min which is only 2% of the maximum speed of the motor under test.

Fig. 11 shows the results of comparison between the voltage model and the proposed method in the synchronous reference frame. $\lambda^r_{ds\_\text{est}\_\text{volt}}$ and $\lambda^r_{qs\_\text{est}\_\text{volt}}$ are the estimated d- and q-axis flux linkage from the voltage model, respectively. The IPMSM is operated at 2000 r/min, and the torque command is 35 $\text{N} \cdot \text{m}$. As shown, although the estimated flux linkage by the voltage model has large oscillation, the one from the proposed flux observer tracks the average value of the voltage model well.

V. Conclusion

In this paper, a modified flux observer has been proposed, which is robust to the inductance variation as well as the inaccuracy of the magnet flux linkage. The calculated values from the integral terms of the PI current regulator are used to compensate for the variation and inaccuracy. The proposed strategy is easy to implement and works well over all ranges of operation from the MTPA region to the flux-weakening region. In addition, because of its robustness, the proposed observer can estimate the flux without bumps even at the step change of torque command. Experimental results have been shown to verify the feasibility and superiority of the proposed observer.

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