Demagnetization fault diagnosis of permanent magnet in synchronous motor

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Abstract

Permanent Magnet (PM) embedded in the rotor simplifies the mathematical model of Permanent Magnet Synchronous Motor (PMSM), making its control method simple and flexible, and improving its power factor. But in the actual operating environment, the biggest risk of PMSM lies in demagnetization of rotor permanent magnet material. High temperature would make PM in the rotor suffer demagnetization, which is irreversible. If it develops without sufficient attention, there will be a major accident. From the detection state of the rotor flux, the stator magnetic flux equation is analysed under the demagnetization and the flux observer system is reconstructed, in order to obtain a quantitative analysis of the d-q axis flux and the demagnetization flux angle. Finally, the respective simulations will be made from three perspectives, such as no demagnetization, amplitude demagnetization and angle demagnetization of PM in the motor. It turns out that the flux observer can be used to real-time monitor the demagnetization of PM in the PMSM and the similar case, and can timely make an accurate fault diagnosis.

Keywords: permanent magnet (PM); demagnetization fault diagnosis; permanent magnet synchronous motor (PMSM); flux observer

1 Introduction

PMSM is essentially a motor with PM, which replaces the exciting winding of the general motor. The PM material determines the characteristics of PMSM. At present, the PMSM adopted can get rid of electro-magnetic and slip rings and improve the power efficiency and stability of the system. What's more, it bears the advantages of small volume, light weight, good control performance and obvious economic benefit, which make it a popular motor, widely used in the fields of electric vehicles, the wind power system and air system and so on. However, during the operation, PM in the motor may suffer partial and irreversible demagnetization under the influence of high temperature and vibration. These failures directly affect the life, output efficiency and operating reliability of the motor. Therefore, there is a necessity of real-time motoring of PM flux in order to take appropriate measures as soon as possible.

At present, the solution commonly adopted is to optimize the magnetic circuit structure when designing the motor so as to reduce the risk of demagnetization [1], while this solution has limited effects and also increases manufacturing costs. The demagnetization of motor during operation can only be detected after obvious failures which cause the motor to stop, while the demagnetization has been very serious at this time. In addition, many scholars have made deep research into the characteristics of permanent magnetic materials and the reasons of demagnetization. Qi has studied the temperature stability of magnetic materials and has obtained the mathematical expression of magnetic loss under particular cases [2]. However, there are lack of approaches to detection of PM flux state in the motor. When the PMSM demagnetization occurs, there will be specific harmonic in the stator current [3]. Thus, the signal transformation method will be adopted to analyze stator harmonic current and obtain its current frequency spectrum to determine the demagnetization of PM and severity degree. The principle of this method is simple. But at different speeds, the harmonic frequency and methods judged on the faults are different and more complex to achieve. Ruiz puts forward to make frequency spectrum analysis of stator current with the methods of CWT and DWT according to the specific harmonics [4]. Based on the principle of equivalent magnetic flux, we can construct equivalent magnetic network in the motor, find out the flux of each unit and obtain the relevant parameters. This method has high accuracy, but in fact, it's difficult to establish an accurate equivalent magnetic network, which limits its application. Farooq proposes a semi analytical model, using equivalent magnetic network to simulate PMSM and judging the demagnetization based on the comparison of electromotive force and torque computed through magnetic permeability network and the normal motor [5]. On the basis of the accurate mathematical model of PMSM, we obtain the flux information by motoring the variation of some parameters. Zhang puts forward an online monitoring method of PM magnetic field condition of PMSM based on Kalman filter. This method considers rotor currents and PM flux as state variables in the magnetic field of a synchronous rotating reference frame and an observer of the PM flux magnitude and angle is constructed [6]. But the calculation of Kalman filter is too large, which is unable to meet the requirement of real-time monitor.

In this paper, a state observer is constructed to obtain` the demagnetization flux magnitude and angle on the basis of mathematical model and d, q axis flux as unknown input after demagnetization of the rotor PM of PMSM. It realizes the quantitative analysis of the PM flux in PMSM and other the similar cases, and timely provides accurate information of demagnetization fault diagnosis. Meanwhile, the algorithm is simple and fast so that it can meet the requirement of real-time monitoring during operation. Finally, in the model of PMSM, we set failures to the model artificially. Results show that the observer can accurately judge the

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current PM demagnetization and realize demagnetization fault diagnosis.

2 PMSM model

There are symmetrical three-phase windings in the stator of PMSM and the rotor is PM. In the static reference frame, the mathematical model of PMSM is an electromagnetic system with high order, multi variables and strong coupling. In order to control easily, there is a necessity of order reduction of the mathematical model. The model of PMSM in two-phase static reference frame and two-phase rotating reference frame is shown in Fig. 1 as follows:

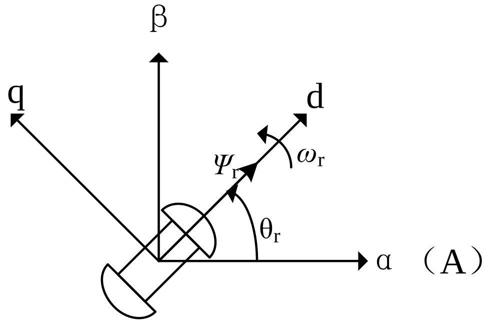

FIGURE 1 PMSM model in two-phase static and rotating reference frame

According to the principle of vector control, the PM flux is located in d axis and in A axis in the three-phase static coordinate. ωr is the actual speed of the rotor and ϴr is the actual position angle of the rotor. After decoupling transformation, the equation of PMSM in two-phase rotating reference frame is shown as follows:

$$\begin{cases} u_d = R_s i_d + \dfrac{d\psi_d}{dt} - \omega_e \psi_q \\ u_q = R_s i_q + \dfrac{d\psi_q}{dt} + \omega_e \psi_d \end{cases}. \quad (3)$$

The flux equation of PMSM is:

$$\begin{cases} \psi_d = L_d i_d + \psi_r \\ \psi_q = L_q i_q \end{cases}, \quad (4)$$

where: u_{sd}, u_{sq} are the d, q axis stator voltages, i_d, i_q are the d, q axis rotor currents, ψ_d, ψ_q are the d, q axis stator fluxes, ψ_r is the flux of rotor permanent magnetic material. L_d, L_q are the d, q axis stator inductances, R_s is the stator resistance, ω_e is the rotor electric angular speed.

At the time of demagnetization, the amplitude and angle of PM flux will change, as shown in Fig. 2 and the flux equation of PMSM is shown as equation (3):

$$\begin{cases} \psi_d = L_d i_d + \psi_{rd} \\ \psi_q = L_q i_q + \psi_{rq} \end{cases}. \quad (5)$$

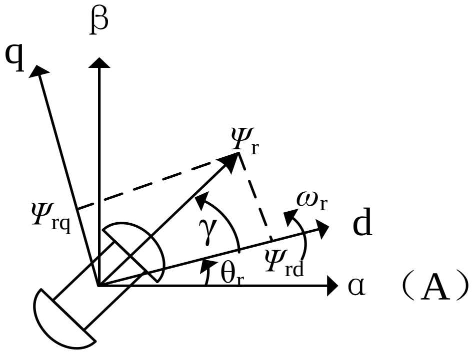

FIGURE 2 The PM demagnetization flux

In the practical engineering case, the rate of the motor flux is more slowly than the rate of currents. So the change rate of d-q axis is approximately equal to zero. The mathematical equation of PMSM is changed into (4):

$$\begin{cases} \dot{i}_d = \dfrac{1}{L_d}\left(-R_s i_d + \omega_e L_q i_q + \omega_e \psi_{rq} + u_d\right) \\ \dot{i}_q = \dfrac{1}{L_q}\left(-R_s i_q - \omega_e L_q i_d - \omega_e \psi_{rd} + u_q\right) \end{cases}. \quad (6)$$

3 PM FLUX obsever

3.1 THE EXISTENCE CONDITIONS OF THE OBSERVER

PM of PMSM will generate d, q axis rotor flux in the case of demagnetization, the amplitude and the direction of PM rotor demagnetization flux can be estimated through the observer. For the MIMO nonlinear system (5) as follows, if it satisfies the following four conditions, there exists equation (6), which can estimate the unknown inputs.

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{f}(\mathbf{u}, \mathbf{v}, \mathbf{x}) \\ \mathbf{y} = \mathbf{C}\mathbf{x} \end{cases}, \quad (7)$$

Where, $\mathbf{x} = \left(\mathbf{x}^1 \quad \mathbf{x}^2 \quad \cdots \quad \mathbf{x}^q\right)^T \in \mathbf{R}^n$ are the states of the system. $\mathbf{x}^i = \left(x_1^i \quad x_2^i \quad \cdots \quad x_{\lambda_i}^i\right)^T \in \mathbf{R}^{n_i}$, $\mathbf{f} = \left(\mathbf{f}^1 \quad \mathbf{f}^2 \quad \cdots \quad \mathbf{f}^q\right)^T \in \mathbf{R}^n$ are nonlinear functions. $\mathbf{f}^i = \left(f_1^i \quad f_2^i \quad \cdots \quad f_{\lambda_i}^i\right) \in \mathbf{R}^{n_i}$, $f_j^i \in R^{p_i}$, $i = 1 \cdots q$, $j = 1 \cdots \lambda_i$, $\sum_{i=1}^{q} n_i = \sum_{i=1}^{q} p_i \lambda_i = n$, outputs $\mathbf{y} \in \mathbf{R}^p$, inputs $\mathbf{u} \in U \subset \mathbf{R}^{s-m}$, unknown inputs $\mathbf{v} \in V \subset \mathbf{R}^m$, $\mathbf{C} = diag\left[\mathbf{C}_1 \cdots \mathbf{C}_q\right]$, $\mathbf{C}_i = \left[\mathbf{I}_{p_i} \ \mathbf{0} \cdots \mathbf{0}\right]$.

When the following conditions are satisfied, the unknown input is available [7]

Condition 1 State $\mathbf{x}(t)$, control signal $\mathbf{u}(t)$ and the unknown inputs $\mathbf{v}(t)$ are all bounded.

Condition 2 There exist $\alpha_f, \beta_f > 0$, so that $\forall x \in X$,

$\forall(u,v)\in U\times V$,

$$0<\alpha_f^2\mathbf{I}_{n_{i+1}}\le\left(\frac{\partial\mathbf{f}^i}{\partial\mathbf{x}^{i+1}}(u,v,x)\right)^T\left(\frac{\partial\mathbf{f}^i}{\partial\mathbf{x}^{i+1}}(u,v,x)\right)\le\beta_f^2\mathbf{I}_{I_{n_{i+1}}}.$$

Condition 3 Output $\mathbf{x}^1$ can be divided into following two parts: $\mathbf{x}^1=\left(\mathbf{x}_1^1\quad\mathbf{x}_2^1\right)^T$. Among them, $\mathbf{x}_1^1\in\mathbf{R}^{m_1}$, $\mathbf{x}_2^1\in\mathbf{R}^{p-m_1}$, $(m\le m_1\le p)$. The nonlinear function $\mathbf{f}^1=\left(\mathbf{f}_1^1\quad\mathbf{f}_2^1\right)^T$ needs to meet the following two conditions:

There exist $\alpha_v,\beta_v>0$, for $\forall x\in R^n$, $\forall(u,v)\in U\times V$,

$$0<\alpha_v^2\mathbf{I}_m\le\left(\frac{\partial\mathbf{f}_1^1}{\partial\mathbf{v}}(u,v,x^1,x^2)\right)^T\left(\frac{\partial\mathbf{f}_1^1}{\partial\mathbf{v}}(u,v,x^1,x^2)\right)\le\beta_v^2\mathbf{I}_m.$$

$$Rank\begin{pmatrix}\dfrac{\partial\mathbf{f}_1^1}{\partial\mathbf{x}^2}(u,v,x^1,x^2) & \dfrac{\partial\mathbf{f}_1^1}{\partial\mathbf{v}}(u,v,x^1,x^2)\\ \dfrac{\partial\mathbf{f}_2^1}{\partial\mathbf{x}^2}(u,v,x^1,x^2) & \dfrac{\partial\mathbf{f}_2^1}{\partial\mathbf{v}}(u,v,x^1,x^2)\end{pmatrix}=n_2+m\quad,$$

among them, $\left(\mathbf{x}^1,\mathbf{x}^2\right)\in\mathbf{R}^{n_1+n_2}$.

Condition 4 The time derivative of unknown input V, that is $\mu(t)$, which is uniformly bounded that $\sup\limits_{t\ge0}\|\mu(t)\|\le\gamma$, where the real number $\gamma>0$.

The unknown input can be estimated through the following model:

$$\dot{\hat{\mathbf{x}}}=\hat{\mathbf{f}}-\left(\mathbf{\Lambda}(\mathbf{u},\mathbf{v},\mathbf{x})\right)^+\boldsymbol{\theta}\left(\mathbf{C}\hat{\mathbf{x}}-\mathbf{y}\right)=\hat{\mathbf{f}}-\mathbf{K}\left(\mathbf{C}\hat{\mathbf{x}}-\mathbf{y}\right),\qquad(8)$$

Where, $\hat{\mathbf{x}}=\left(\hat{\mathbf{x}}^1\quad\hat{\mathbf{x}}^2\right)^T$, $\hat{\mathbf{x}}^1=\left(\hat{\mathbf{x}}_1^1\quad\hat{\mathbf{x}}_2^1\right)\in\mathbf{R}^{2m_1}$, $\hat{\mathbf{x}}^2=\left(\hat{\mathbf{x}}_1^2\quad\hat{\mathbf{x}}_2^2\quad\cdots\quad\hat{\mathbf{x}}_q^2\right)^T\in\mathbf{R}^{q(p-m_1)}$; $\hat{\mathbf{f}}=\left(\hat{\mathbf{f}}^1\quad\hat{\mathbf{f}}^2\right)^T$, $\hat{\mathbf{f}}^1=\left(\hat{\mathbf{f}}_1^1\quad\mathbf{0}\right)^T\in\mathbf{R}^{2m_1}$, $\hat{\mathbf{f}}^2=\left(\hat{\mathbf{f}}_2^1\quad\hat{\mathbf{f}}_1^2\quad\cdots\quad\hat{\mathbf{f}}_q^2\right)^T\in\mathbf{R}^{q(p-m_1)}$; $\mathbf{C}=diag\left[\mathbf{C}_1,\mathbf{C}_2\right]$, $\mathbf{C}_1=\left[\mathbf{I}_{m_1}\ \mathbf{0}\right]$, $\mathbf{C}_2=\left[\mathbf{I}_{q(p-m_1)}\ \mathbf{0}\right]$; $\mathbf{K}=\mathbf{\Lambda}^+\boldsymbol{\theta}=diag\left[\mathbf{K}_1,\mathbf{K}_2\right]$, $\mathbf{K}_1\in\mathbf{R}^{2m_1}$, $\mathbf{K}_2\in\mathbf{R}^{q(p-m_1)}$, $\boldsymbol{\theta}=diag\left[\boldsymbol{\theta},\boldsymbol{\theta}^m\right]$, $\boldsymbol{\theta}\in\mathbf{R}^{2m_1}$, $\boldsymbol{\theta}^m\in\mathbf{R}^{q(p-m_1)}$; $\mathbf{\Lambda}^+=diag\left[\mathbf{\Lambda}_1^+,\mathbf{\Lambda}_2^+\right]$, $\mathbf{\Lambda}_1^+=\left[\mathbf{I}_{m_1}\ \dfrac{\partial\mathbf{f}_1^1}{\partial\mathbf{v}}\left(\mathbf{u},\mathbf{v},\mathbf{x}^1,\mathbf{x}^2\right)\right]$,

$$\mathbf{\Lambda}_2^+=\left[\mathbf{I}_{p-m_1}\ \frac{\partial\mathbf{f}_2^1}{\partial\mathbf{v}}(\mathbf{u},\mathbf{x})\cdots\frac{\partial\mathbf{f}_1^1}{\partial\mathbf{x}^2}(\mathbf{u},\mathbf{x})\prod_{i=1}^{q-1}\frac{\partial\mathbf{f}^i}{\partial\mathbf{x}^{i+1}}\right].$$

4 Rotor flux observer

Based on the principle of the above observer, the unknown factors ψ_{rd}, ψ_{rq} in formula (5) can be estimated through the observer, and the amplitude and the angle of demagnetization of PM can be calculated. Therefore, the d, q axis current observation equation, which has the above unknown factors as unknown input is proposed.

$$\begin{cases}\dot{\hat{i}}_d=\dfrac{1}{L_d}\left(-R_s\hat{i}_d+\omega_eL_q\hat{i}_q+\omega_e\hat{\psi}_{rq}+u_d\right)-k_1\theta\left(\hat{i}_d-i_d\right)\\ \dot{\hat{i}}_q=\dfrac{1}{L_q}\left(-R_s\hat{i}_q-\omega_eL_q\hat{i}_d-\omega_e\hat{\psi}_{rd}+u_q\right)-k_1\theta\left(\hat{i}_q-i_q\right)\\ \dot{\hat{\psi}}_r=-k_2\theta^m\Lambda^+\left(\hat{i}-i\right)\end{cases}.\qquad(9)$$

Here, $i=\left(i_d\ \ i_q\right)^T$ is the rotor d, q axis current, $\hat{i}=\left(\hat{i}_d\ \ \hat{i}_q\right)^T$ is the rotor d, q axis current estimated value, $\hat{\psi}_r=\left(\hat{\psi}_{rd}\ \ \hat{\psi}_{rq}\right)^T$ is the rotor d, q axis flux estimated value, $\Lambda^+=\left[\omega_e/L_d\ \ -\omega_e/L_q\right]^+$, ω_e is the rotor speed, k_1, k_2, θ, m are the design parameters.

Based on the obtained amplitude of d, q axis rotor flux, the angle between rotor flux and d axis can be further achieved:

$$\gamma=\tan^{-1}\left(\psi_{rq}/\psi_{rd}\right).\qquad(10)$$

5 Simulation analysis

Based on the above mathematical model and the proposed observer, this paper builds a speed control model of PMSM on the Simulink platform. The simulation principle is shown in Fig. 3, with the control method of id=0. The parameters of PMSM in simulation are shown in table 1. Considering the PM demagnetization of PMSM in actual operation includes amplitude demagnetization and angle demagnetization, the paper will respectively simulate the following four conditions at the given speed of 120rad/s: no demagnetization, amplitude demagnetization, angle demagnetization and amplitude and angle demagnetization. There is a need to explain that the blue lines represent the actual stator flux values and the red ones show the estimated stator flux values through the observer in the following simulation results figures.

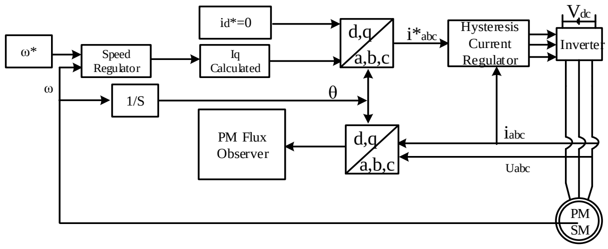

FIGURE 3 principle of flux observer in PMSM control

TABLE 1 PMSM parameters

parameter name	parameter value
Stator resistance Rs	2.875Ω
d axis flux Ld	8.5m·H
q axis flux Lq	8.5m·H
Rotor Fluxψr	0.175Wb
Pole-pairs p	4
Inertia J	0.0008Kg·m2

No demagnetization: At the given speed of 120rad/s, the torque is changed from 0 to -15N·m at 0.1s. In the whole speeding process, the rotor speed and rotor flux are not changed, so the flux amplitudes of d, q axis are not changed (Fig. 4, 5). Rotor flux orientation coincides with d axis (Fig.

6), which is consistent with the actual situation. The estimation values of the stator flux varies with the changes of the actual values (Fig. 7).

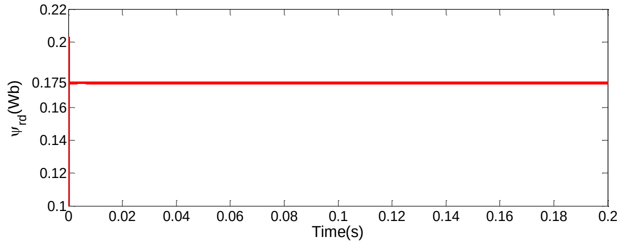

FIGURE 4 d axis rotor flux

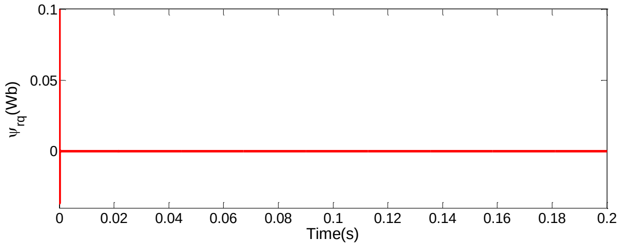

FIGURE 5 q axis rotor flux

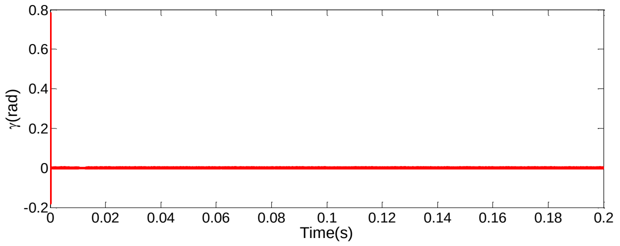

FIGURE 6 the angle between rotor flux and d axis

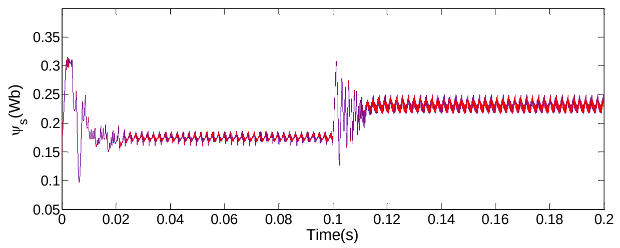

FIGURE 7 actual and estimated stator flux

Amplitude demagnetization: At the given speed of 120rad/s, the rotor flux magnitude is reduced by 20% at 0.1s. As the PMSM is controlled in the way of rotor field oriented control, so the direction of rotor field coincides with d axis. From the simulation results, the flux value is reduced to 0.14 Wb (Fig. 8), while the flux value of q axis is still zero (Fig. 9). The flux direction is not changed, which is still consistent with d axis (Fig. 10). The stator flux reduces when the rotor flux decreases (Fig. 11).

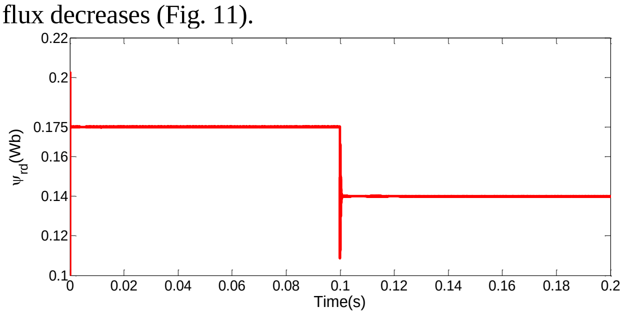

FIGURE 8 d axis rotor flux

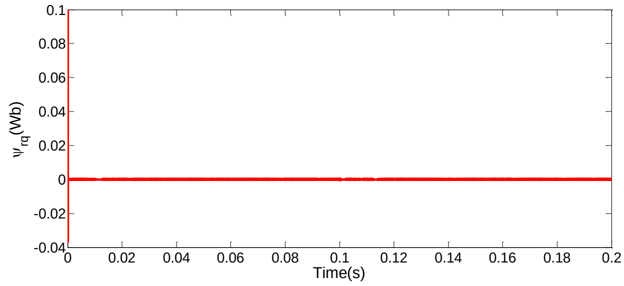

FIGURE 9 q axis rotor flux

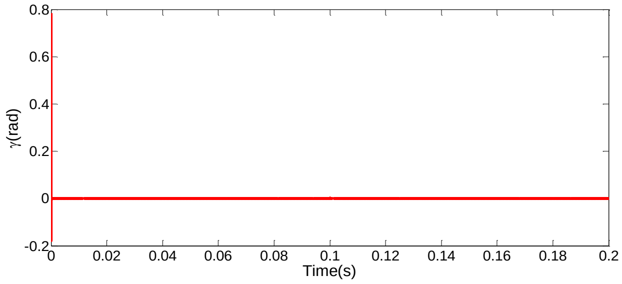

FIGURE 10 the angle between rotor flux and d axis

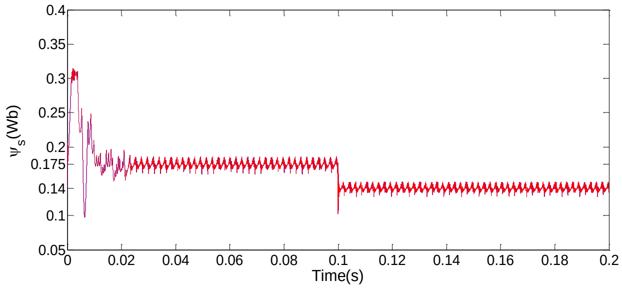

FIGURE 11 actual and estimated stator flux

Angle demagnetization: At the given speed of 120rad/s, γ is changed from 0 rad to π/3 rad at 0.1s. At this time, demagnetization flux produces d, q axis flux. In Fig. 2, their values are the projections of flux respectively in each axis (Fig. 12, 13). The angle of the direction between PM after demagnetization and d axis is changed into π/3 rad (Fig. 14). But the value of stator flux is not largely affected (Fig. 15). The whole transition process is very fast.

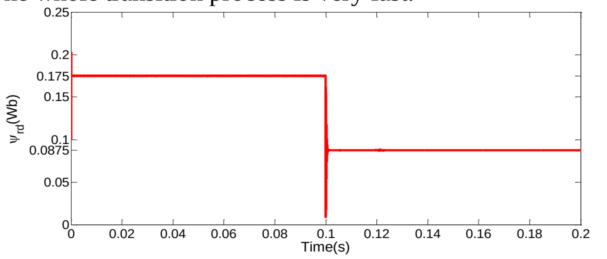

FIGURE 12 d axis rotor flux

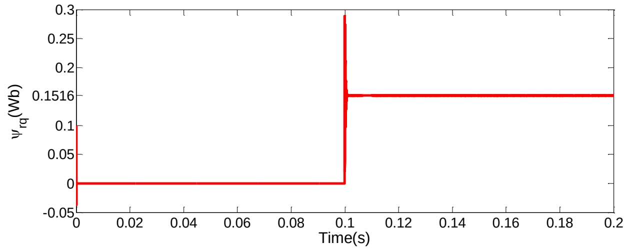

FIGURE 13 q axis rotor flux

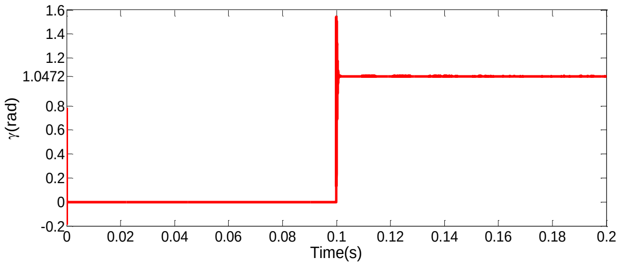

FIGURE 14 the angle between rotor flux and d axis

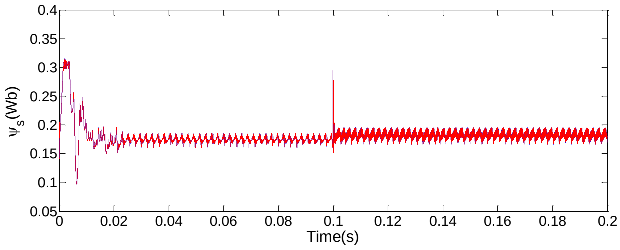

FIGURE 15 actual and estimated stator flux

For the condition of both amplitude and angle demagnetization, if they happen at the same time, it can be considered angle demagnetization occurring exactly after amplitude demagnetization, which is a special condition of the above angle demagnetization. So the illustration is omitted.

6 Conclusion

Based on the mathematical model of PMSM after demagnetization, an observer is constructed which makes d-q axis demagnetization flux as the unknown inputs, realizes the quantity analysis of d-q axis rotor flux and can also obtain the real-time information of demagnetization amplitude and angle of rotor flux. It can be used for the demagnetization fault diagnosis of PM in PMSM and other similar cases. Finally, through the respective simulations of no demagnetization, amplitude demagnetization, angle demagnetization and amplitude and angle demagnetization of PM, the results show that the designed observer can accurately obtain the necessary information of PM demagnetization in real time.

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