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Air gap field-oriented vector control strategy for high-power electrically excited synchronous motor based on full-order flux linkage observer

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This paper raises a full-order flux linkage observer for the high-power electrically excited synchronous motor and proposes a design for its feedback matrix based on modern control theories which ensure excellent dynamic and static performances of this full-order flux linkage observer. On the basis of the said full-order flux linkage observer, an air gap field-oriented vector control strategy for the electrically excited synchronous motor based on the full-order flux linkage observer has been established and it is possible for the electrically excited synchronous motor to operate with the unity power factor. Through simulation and experiments, the effectiveness of the full-order flux linkage observer as well as the control strategy has been further verified.

Key words: Electrically excited synchronous motor, full-order flux linkage observer, air gap field-oriented vector control.

INTRODUCTION

As a typical AC drive motor, the electrically excited synchronous motor beats the asynchronous motor in power factor, efficiency, overload magnification and rotational inertia (Beliaev and Weinger, 2005). Therefore, the application mode of electrically excited synchronous motor based on IGCT three-level neutral point clamped inverter become the mainstream in the field of high-power high-performance industrial drive and thus is widely applied to industries such as mine hoisting, metallurgy and steel rolling, and marine propulsion. There are mainly two kinds of control of the electrically excited synchronous motor, that is, vector control (Szabo, 2006) and direct torque control (Pyrbonen, 1998; Pyrhonen et al., 1997). In order to achieve high-performance control, flux linkage is required for both of them. As control performance is largely depend on the accuracy of flux linkage, an accurate flux linkage model is crucial to control performance. In the literature (Szabo et al., 2010), an open-loop model is used to observe excitation, which is greatly influenced by the motor parameters; in the literature (Wu and Tan, 2010), a voltage-current model is adopted, with a filter for switchover to observe the flux linkage, but it is essentially a reduced-order model with limited properties. This paper raises a full-order flux linkage observer for the electrically excited synchronous motor based on the dynamic mathematical model of the electrically excited synchronous motor, thus making it possible to obtain accurate flux linkage value.

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FULL-ORDER FLUX LINKAGE OBSERVER OF ELECTRICALLY EXCITED SYNCHRONOUS MOTOR MATHEMATICAL MODEL OF ELECTRICALLY EXCITED SYNCHRONOUS MOTOR

Flux-linkage and Voltage equations:

$$\begin{bmatrix}\psi_{sd}\\ \psi_{sq}\\ \psi_f\\ \psi_D\\ \psi_Q\end{bmatrix}=\begin{bmatrix}L_{sd} & 0 & L_{ad} & L_{ad} & 0\\ 0 & L_{sd} & 0 & 0 & L_{ad}\\ L_{ad} & 0 & L_f & L_{ad} & 0\\ L_{ad} & 0 & L_{ad} & L_D & 0\\ 0 & L_{ad} & 0 & 0 & L_Q\end{bmatrix}\begin{bmatrix}i_{sd}\\ i_{sq}\\ i_f\\ i_D\\ i_Q\end{bmatrix} \qquad \begin{bmatrix}u_{sd}\\ u_{sq}\\ u_f\\ u_D\\ u_Q\end{bmatrix}=\begin{bmatrix}R_s & 0 & 0 & 0 & 0\\ 0 & R_s & 0 & 0 & 0\\ 0 & 0 & R_f & 0 & 0\\ 0 & 0 & 0 & R_D & 0\\ 0 & 0 & 0 & 0 & R_Q\end{bmatrix}\begin{bmatrix}i_{sd}\\ i_{sq}\\ i_f\\ i_D\\ i_Q\end{bmatrix}+\frac{d}{dt}\begin{bmatrix}\psi_{sd}\\ \psi_{sq}\\ \psi_f\\ \psi_D\\ \psi_Q\end{bmatrix}+\begin{bmatrix}-\omega_r\psi_{sq}\\ \omega_r\psi_{sd}\\ 0\\ 0\\ 0\end{bmatrix}$$

Torque equation:

$$T_e = \psi_{sd} i_{sq} - \psi_{sq} i_{sd}$$

Full-order flux linkage observer of electrically excited synchronous motor

Based on the mathematical model, a state equation of the electrically excited synchronous motor is established with stator, rotor and damped flux linkages as state variables:

$$\dot{x} = Ax + Bu \qquad x = \left[\psi_{sd} \;\; \psi_{sq} \;\; \psi_f \;\; \psi_D \;\; \psi_Q\right]^T$$

$$y = Cx \qquad u = \left[u_d \;\; u_q \;\; u_f \;\; 0 \;\; 0\right]^T$$

$$y = \left[i_d \;\; i_q \;\; i_f\right]^T$$

Where x is a state variable, u is an input variable and y is an output variable. Where coefficient matrixes of A, B and C are respectively as follows:

A full-order state observer for the electrically excited synchronous motor can be established with modern control theories and on the basis of the state equation, as shown below:

$$\dot{\hat{x}} = A\hat{x} + Bu + G(y - \hat{y})$$

$$\hat{y} = C\hat{x}$$

Where ^ refers to the observed quantity of state and G is a feedback matrix.

$$A=\begin{bmatrix}-\frac{R_s m}{1+mL_{s\sigma}} & \omega_r & \frac{R_s}{(1+mL_{sl})L_{f\sigma}} & \frac{R_s}{(1+mL_{sl})L_{D\sigma}} & 0\\ -\omega_r & -\frac{R_s n}{1+nL_{sl}} & 0 & 0 & \frac{R_s}{(1+nL_{sl})L_{Q\sigma}}\\ \frac{R_f}{(1+mL_{s\sigma})L_{f\sigma}} & 0 & -R_f\frac{(1+mL_{sl})L_{f\sigma}-L_{sl}}{(1+mL_{sl})L_{f\sigma}^2} & \frac{R_f L_{sl}}{(1+mL_{sl})L_{f\sigma}L_{D\sigma}} & 0\\ \frac{R_D}{(1+mL_{s\sigma})L_{D\sigma}} & 0 & \frac{R_D L_{sl}}{(1+mL_{sl})L_{f\sigma}L_{D\sigma}} & -R_D\frac{(1+mL_{sl})L_{D\sigma}-L_{sl}}{(1+mL_{sl})L_{D\sigma}^2} & 0\\ 0 & \frac{R_Q}{(1+nL_{sl})L_{Q\sigma}} & 0 & 0 & -R_Q\frac{(1+nL_{sl})L_{Q\sigma}-L_{sl}}{(1+nL_{sl})L_{Q\sigma}^2}\end{bmatrix}$$

$$B=\begin{bmatrix}1 & 0 & 0 & 0 & 0\\ 0 & 1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0\end{bmatrix} \quad C=\begin{bmatrix}\frac{m}{1+mL_{sl}} & 0 & -\frac{1}{(1+mL_{sl})L_{f\sigma}} & -\frac{1}{(1+mL_{sl})L_{D\sigma}} & 0\\ 0 & \frac{n}{1+nL_{sl}} & 0 & 0 & -\frac{1}{(1+nL_{sl})L_{Q\sigma}}\\ -\frac{1}{(1+mL_{sl})L_{f\sigma}} & 0 & \frac{(1+mL_{sl})L_{f\sigma}-L_{sl}}{(1+mL_{sl})L_{f\sigma}^2} & -\frac{L_{sl}}{(1+mL_{sl})L_{f\sigma}L_{D\sigma}} & 0\end{bmatrix}$$

$$m=\frac{1}{L_{md}}+\frac{1}{L_{D\sigma}}+\frac{1}{L_{f\sigma}} \qquad n=\left(\frac{1}{L_{mq}}+\frac{1}{L_{Q\sigma}}\right)$$

Feedback matrix design for full-order flux linkage observer of electrically excited synchronous motor

The performance of the full-order flux linkage observer depends on the feedback matrix. In order to obtain accurate flux linkage values, the feedback matrix must be designed properly. First, the form of the feedback matrix should be determined. As there are 5 state variables and 3 output variables, the feedback matrix should be a 5 × 3 matrix; meanwhile, the system is a 5-order one, so there can be 5 degrees of freedom for the configuration of the feedback matrix. The rotor flux linkage is related to intensity of rotor current, so rotor current errors can be independently used to correct the rotor flux linkage, and as the rotor current is single-phase DC, only one degree of freedom is required; the stator flux linkage is related to intensity of stator current, so stator current errors can be independently used to correct the stator flux linkage, and as the stator current is symmetrical three-phase current, two degrees of freedom are required; the damper current is immeasurable, so there is no way to correct damped flux linkage with damper current, but as there are two degrees of freedom left for the feedback matrix, it is reasonable to correct the damped flux linkage with the stator current. To sum up, the determined form of the feedback matrix is as follows:

$$G=\begin{bmatrix}g_1 & -g_2 & 0\\ g_2 & g_1 & 0\\ 0 & 0 & g_3\\ g_4 & -g_5 & 0\\ g_5 & g_4 & 0\end{bmatrix}$$

Then, values of the feedback matrix should be determined. The feedback matrix is decisive for the pole position of the flux linkage observer, i.e. for the performance of the flux linkage observer. In order to ensure faster convergence of the flux linkage observer than that of the actual flux linkage, the pole of the flux linkage observer can be allocated K times of that of the original motor; the larger the K value is, the higher convergence rate the flux linkage observer has and the more sensitive the observer is to external disturbance. Therefore, selection of K should achieve a compromise between the rapidity and sensitivity to disturbance and noise. Since the form and the pole position of the feedback matrix has been determined, the design method based on the modern control theory for the full-order state observer can be used to calculate and obtain the feedback matrix. However, as the system is a 5-order one, analytical expressions of the feedback matrix are rather formidable, so mathematical tools such as maple and matlab can be used for calculation, thus to obtain the feedback matrix.

AIR GAP FIELD-ORIENTED VECTOR CONTROL FOR THREE-LEVEL ELECTRICALLY EXCITED SYNCHRONOUS MOTOR

Air gap field-oriented mathematical model of electrically excited synchronous motor

Voltage equation:

$$u_{sm} = R_s i_{sm} - L_{sl} i_{st} \omega_r$$
$$u_{st} = R_s i_{st} + (\psi_\sigma + L_{sl} i_{st}) \omega_r$$

Torque equation:

$$T_e = \psi_\sigma i_{st}$$

Control of unity power factor

In order to improve the system efficiency, the electrically excited synchronous motor generally operates at the unity power factor. Due to stator leakage reactance, the conventional control mode of ism = 0 cannot meet the requirement of the unity power factor.

Operation at the unity power factor is to ensure in-phase of stator voltage and stator current, that is,

$$\frac{i_{sm}}{i_{st}} = \frac{u_{sm}}{u_{st}}$$

Substitute the equation into the above equation:

$$L_{sl} i_{sm}^2 + \psi_\sigma i_{sm} + L_{sl} i_{st}^2 = 0$$

Rearrange the above equation:

$$i_{sm} = \frac{\sqrt{\psi_\sigma^2 - 4 L_{sl}^2 i_{st}^2} - \psi_\sigma}{2 L_{sl}}$$

As long as the magnetic component of stator current meets the equation, the electrically excited synchronous motor can operate at the unity power factor.

Air gap field-oriented vector control based on full-order flux linkage observer

To sum up, it is possible to develop an air gap field-oriented vector control strategy for the electrically excited synchronous motor based on the full-order flux linkage observer, and the control block diagram is shown in Figure 1.

SIMULATION AND EXPERIMENTAL VERIFICATION

Simulation verification

According to the full-order flux linkage model of and the air gap field-oriented control strategy for the electrically excited synchronous motor mentioned above, an air gap-oriented vector control model of the electrically excited synchronous motor is established on the matlab/simulink simulation platform, with simulation results as follows:

It can be seen from Figure 2 that no matter in the steady-state or dynamic-state process, the air gap flux linkage observed by the full-order flux linkage model stays the same as the actual flux linkage of the motor and the full-order flux linkage model presents high steady-state precision and excellent dynamic-state performance, which indicates effectiveness and accuracy of the full-order flux linkage model of the electrically excited synchronous motor.

Figure 3 shows the simulation results of the air gap field-oriented vector control for the electrically excited synchronous motor based on the full-order flux linkage observer. It can be seen that the no matter in the steady-state or dynamic-state process, the control strategy presents excellent performance, and the reactive power is zero after the control is stabilized, thus realizing unity power factor control of the electrically excited synchronous motor.

Experimental verification

To further verify the effectiveness of the control strategy, an experimental system for the high-power electrically excited synchronous motor is established. Table 1 shows the three-phase electrically excited synchronous motor parameters.

Figure 4 shows the experimental waveforms recorded by the monitoring software CSR_DRIVE. It can be seen that the speed of the electrically excited synchronous motor is kept stable, thus realizing the air gas field-oriented vector control strategy for the electrically excited synchronous motor and the motor presents excellent dynamic and static performances. Meanwhile, during this process, the voltage at the DC side is kept stable as well. Figure 5 shows the torque step response of electrically excited synchronous motor. It can be seen that the system has rapid response and small overshoot.

Figures 6 and 7 show the waveforms of voltage and current of the electrically excited synchronous motor saved by the analysis software (Xviewer) from experimental data recorded by the oscilloscope (DLM2032). It can be seen from Figure 6 that, in the diode-clamped three-level circuit, the phase voltage is three-level, so the line voltage is five-level. The three-level circuit system is well controlled and the current of the electrically excited synchronous motor is kept stable and symmetrical. It can be seen from Figure 7 that phase voltage and phase current of the electrically excited synchronous motor are in phase, so the power factor is 1, realizing the air gap field-oriented control strategy for the electrically excited synchronous motor based on the full-order flux linkage observer.

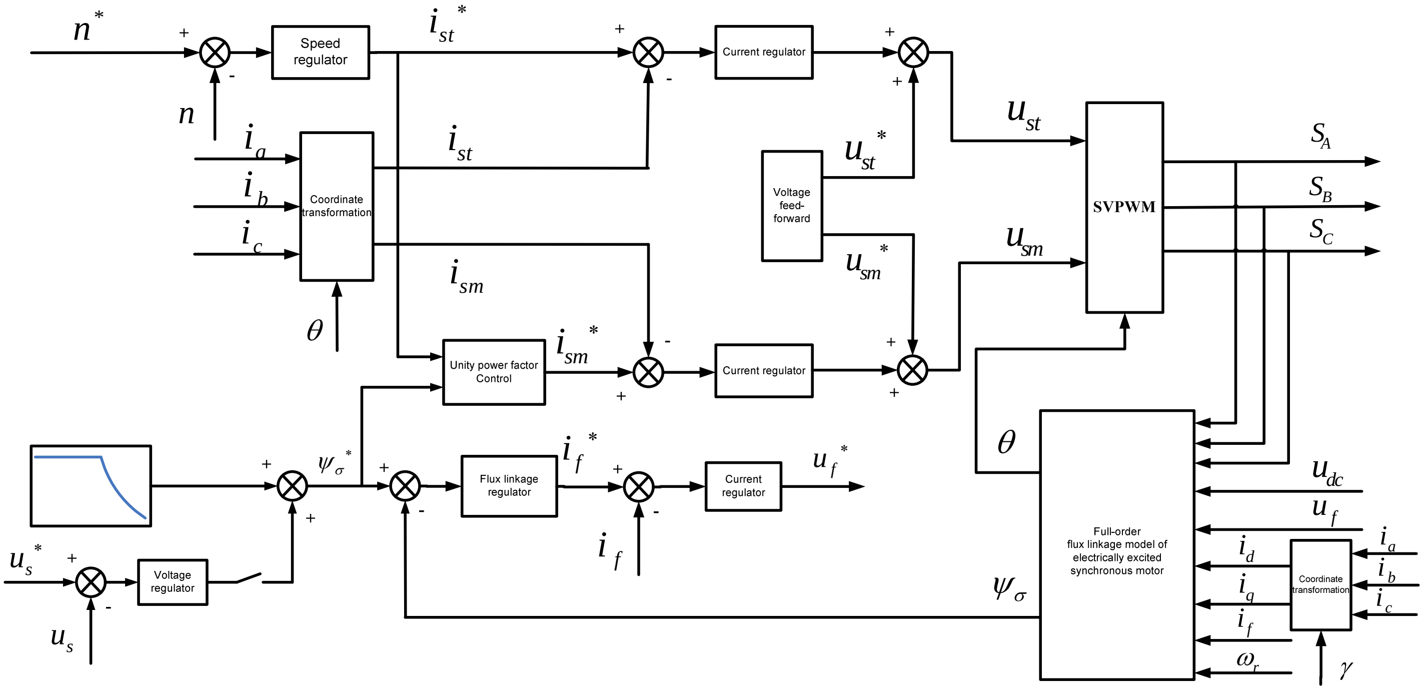

Figure 1. Diagram of air gap field-oriented vector control for electrically excited synchronous motor based on full-order stator flux observer.

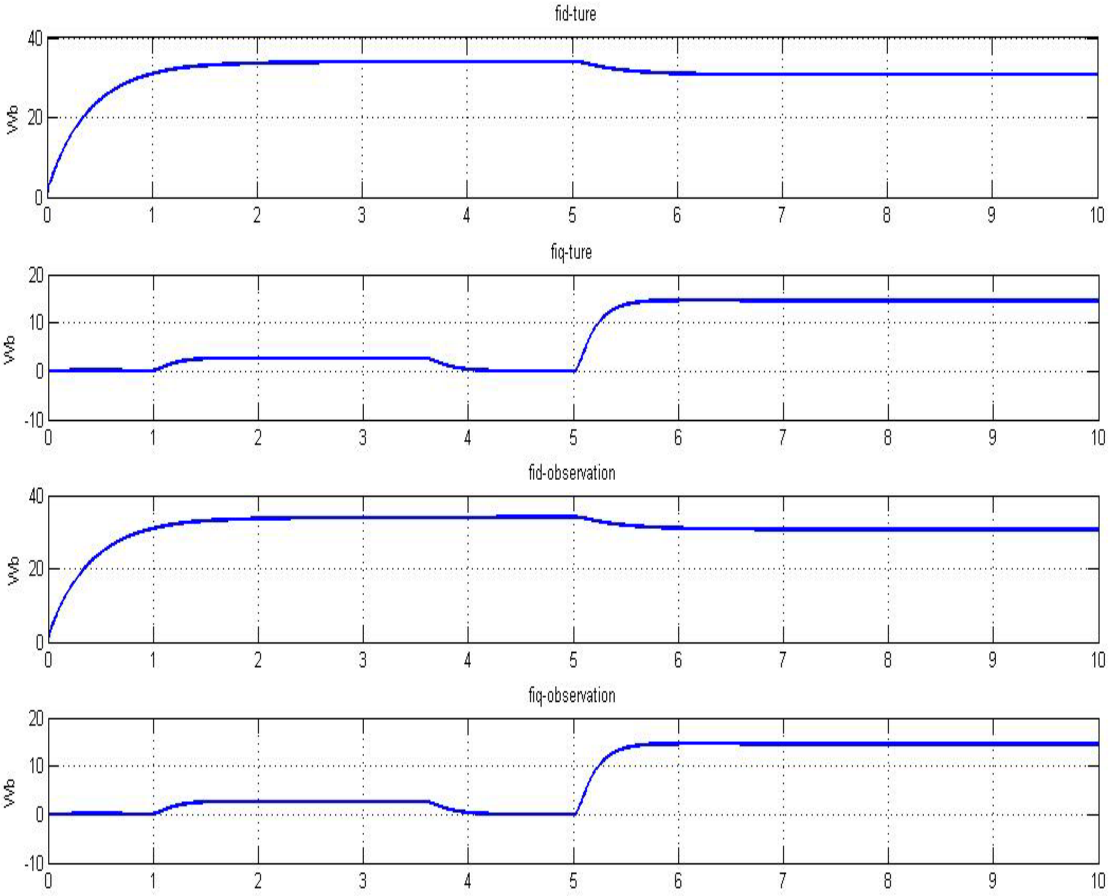

Figure 2. Actual and observed values of d-axis and q-axis components of air gap flux linkage.

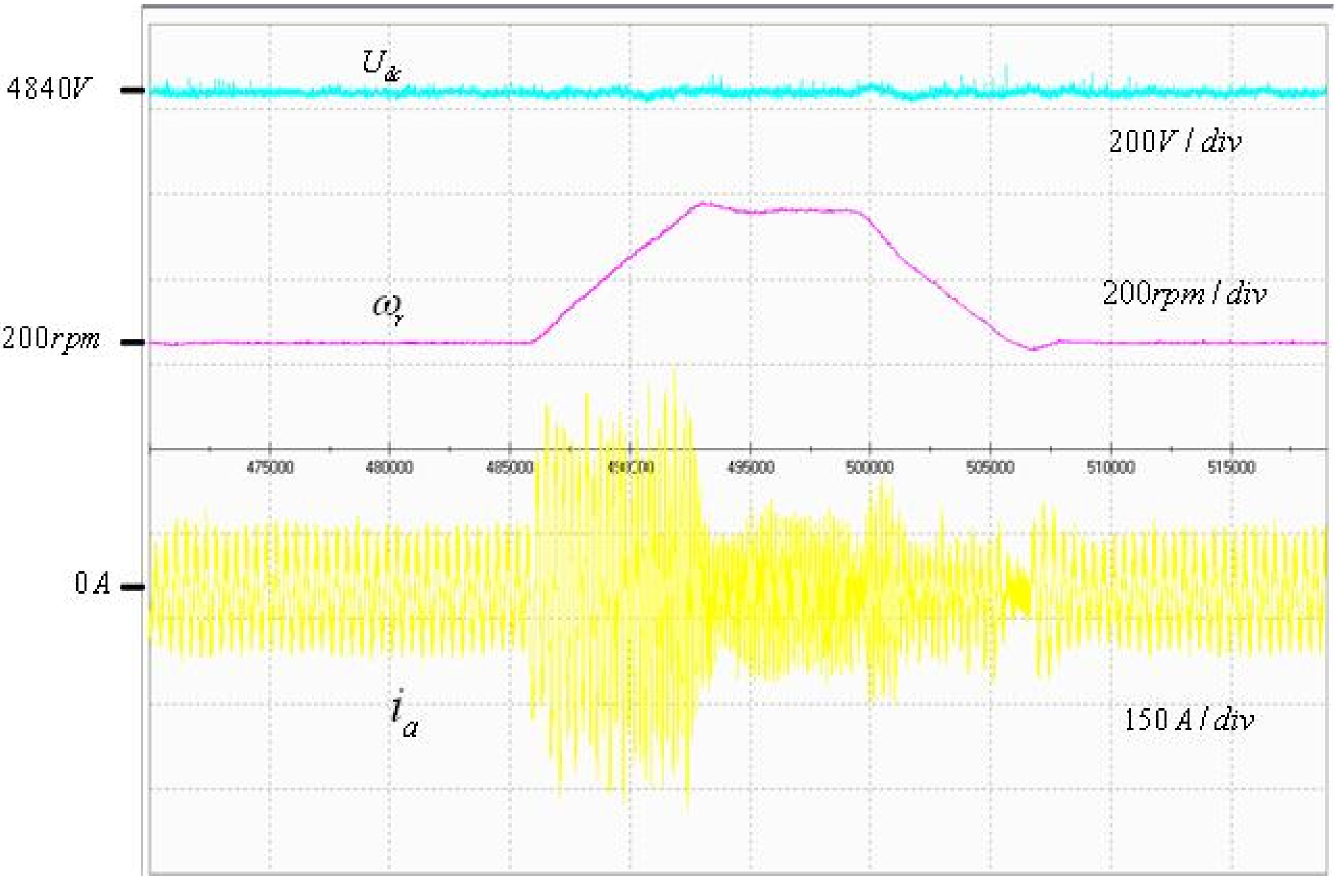

Figure 4. Waveforms of rotating speed, a-phase current and voltage at dc side of electrically excited synchronous motor.

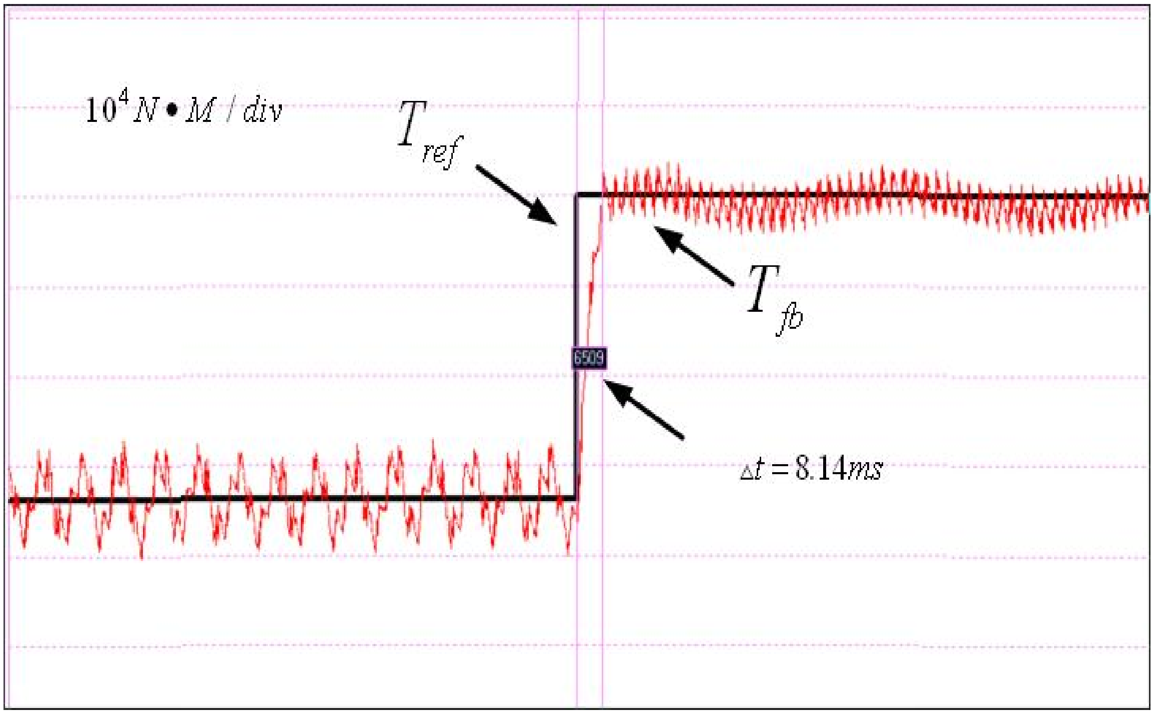

Figure 5. Waveforms of torque step response of electrically excited synchronous motor.

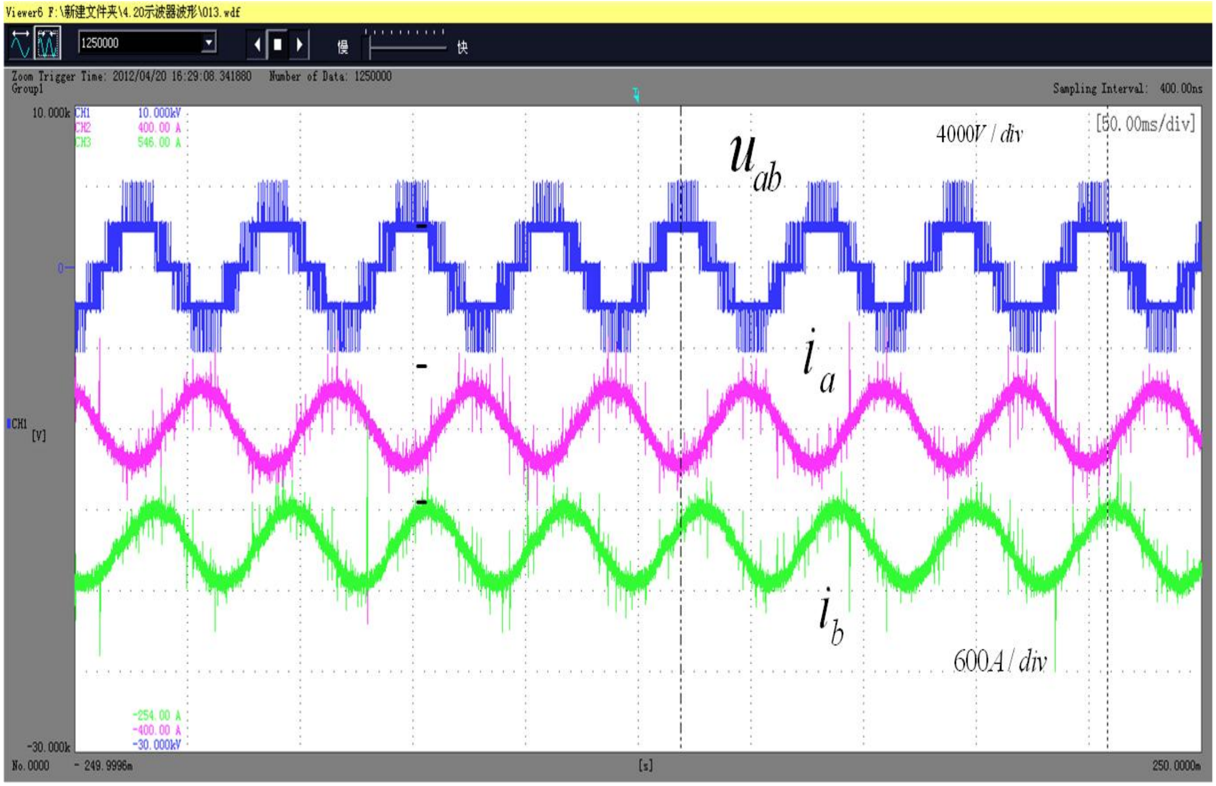

Figure 6. Waveforms of line voltage, a-phase current and b-phase current of electrically excited synchronous motor.

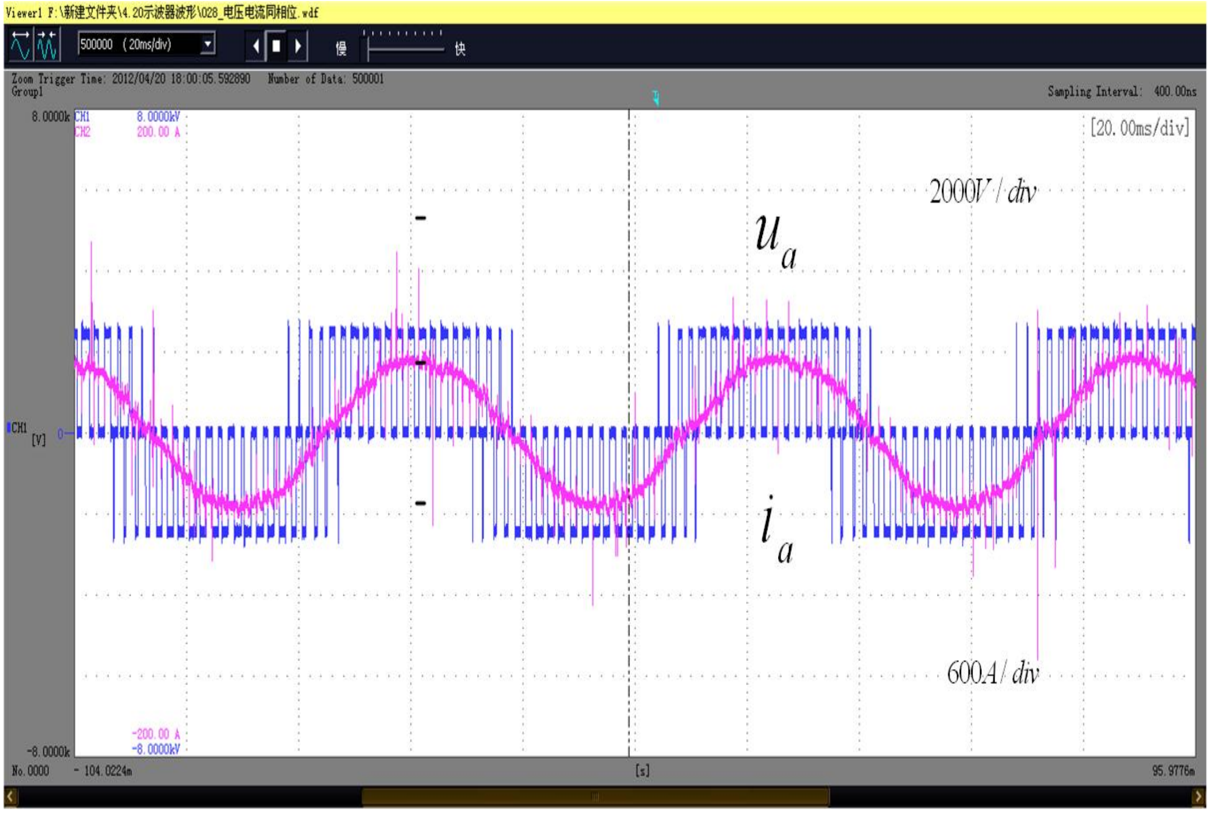

Figure 7. Waveforms of a-phase voltage and a-phase current of electrically excited synchronous motor.

Conclusions

This paper raises a full-order flux linkage observer for the electrically excited synchronous motor on the basis of the mathematical model of the electrically excited synchronous motor on the d-p axis and proposes a design method for feedback matrix of the full-order flux linkage observer. The full-order flux linkage observer proposed in this paper can not only obtain accurate flux linkage values under the steady state, but also present excellent performance under the dynamic state, thus fully meeting the requirements of the high-performance control strategy. Based on the full-order flux linkage observer proposed in this paper, an air gap field-oriented control strategy for the electrically excited synchronous motor is developed and a control method for the unity power factor is proposed.

Conflict of Interests

The author(s) have not declared any conflict of interests.

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