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Design of Energy Feedback System of Permanent Magnet Synchronous Motor

Peng Xue[1], Su Pan[2] and Wei Wei[1]

[1]*Department of Electrical and Electronic Engineering, Changchun University Of Technology, Changchun, China*

[2]*Department of Orthopedics, the Second Hospital of Jilin University, Changchun, Jilin Province, China*

xuepeng2015@ccut.edu.cn

Abstract

In this paper, both braking operation principle of PMSM (permanent magnet synchronous motor) and topological structure of voltage source inverter are analyzed. On this basis, mathematical model of energy feedback system is built in synchronously rotated dq coordinates according to design requirements of PMSM energy feedback system; and adopting SVPWM algorithm of direct current control, independent control of the active component and reactive component of grid-connected feedback current is realized, grid-connected feedback current is made able to track the change of grid voltage in real time and energy feedback of unity power factor is realized as well.

Keywords: *PMSM, energy feedback, grid connection, SVPWM*

1. Introduction

With constant development of science and technology, speed-regulating motor is widely used in industrial production. In many industrial production equipment, it requires the speed-regulating motor starts and stops rapidly, runs forward and backward frequently or unloads the weight with potential energy, which needs four-quadrant operation, namely the motor is in power regeneration. As controller of common speed-regulating motor generates DC energy while the motor is in braking generation and capacity of power storage device of the controller is limited, in order not to raise DC voltage, it generally uses chopper to consume the DC energy on power resistor or uses active energy feedback unit to feed the DC energy back to AC grid [1].

However, current energy feedback system is mainly used together with frequency converter. And as it costs much and is complex to be controlled and its quick response cannot meet PMSM's requirement, it is not suitable to be used together with PMSM. Therefore, an energy feedback system based on grid voltage orientation is designed to be used together with PMSM, which will feed the energy generated while the motor runs in braking operation back to three-phase AC grid, so as to realize the energy feedback from PMSM to DC bus and then from DC bus to three-phase AC grid[1].

2. Design of Energy Feedback System

2.1. Working Principle of Energy Feedback System

Powered by PMSM, three-phase stator poles of the system are L_u, L_v and L_w, as it is shown in Figure 1. Then, its braking operation principle refers that: when power switch turns on, support capacitance C_1 will provide pre-excitation current to the three-phase

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stator winding separately to make it generate braking torque so as to absorb all the mechanical energy, then convert the absorbed mechanical energy into electromagnetic energy and store it in the three-phase stator winding. As the three-phase stator winding of PMSM is alternative and conductive, when the motor is under power generation, the current sent from stator winding to DC bus is impulse current and the voltage at both ends of support capacitance C_1 is also impulse voltage. And when rotate speed of the motor increases, frequency of voltage pulsation will also increase and amplitude of impulse voltage will increase with feedback power of the motor as well.

Energy feedback system refers to feeding the energy generated by the motor back to AC grid, so as to realize the energy feedback from motor to AC grid [2]. And PWM converting technology is the most effective way to realize it. Overall Structure Diagram of Energy Feedback System is shown in Figure 1. When PMSM is in braking operation, voltages at a , b and c could be controlled through controlling the three-phase currents that flow through grid-connected filter inductance. And while keeping bus voltage stable, the energy generated by motor will be inverted to the alternating current that shares the same frequency and phase with grid voltage.

While designing energy feedback system, it not only needs to meet the requirements of the motor to operate under different environments and the grid connection standards of IEC, but also needs to save cost, so as to avoid unnecessary wastes. Therefore, it only needs to consider the main circuit of inverter in the dashed box shown in Figure 1 and its control segment.

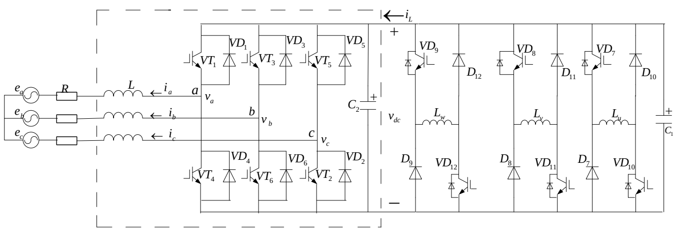

Figure 1. Overall Structure Diagram of PMSM Energy Feedback System

2.2. Mathematical Model Of Energy Feedback System

As it is shown in Figure 1, the inverter circuit in dashed box adopts three-phase full-bridge topological structure and it is connected with grid by filter inductance. When inverter conducts grid-connected feedback with unity power factor, the current output by energy feedback system is the alternating current that shares the same frequency and phase with three-phase grid voltage. If ignoring high-frequency component, low frequency mathematical model of energy feedback system could be concluded from KVL (Kirchhoff Voltage Law) as:

$$\begin{bmatrix} L\frac{di_a}{dt} \\ L\frac{di_b}{dt} \\ L\frac{di_c}{dt} \end{bmatrix} = \begin{bmatrix} -R & 0 & 0 \\ 0 & -R & 0 \\ 0 & 0 & -R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} - \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{1}$$

In the above equation: e_a , e_b and e_c refer to three-phase grid voltages; i_a , i_b and i_c refer to three-phase grid-connected currents;

L refers to three-phase filter inductance and R is for its equivalent resistance; v_a , v_b and v_c refer to output voltages of inverter.

It can be concluded from this mathematical model that the system needs to control the three-phase currents that flow though filter inductance. And as all of them are time-varying AC components, they are not easy to be controlled. In order to solve this problem, vector decouple might be used. Through coordinate conversion, three-phase static ABC coordinates shall be converted to synchronously rotated dq coordinates (rotational angular velocity $\omega = 2\pi f$, hereinto, f =50Hz). Then its vector transformation relation diagram is shown in Figure 2.

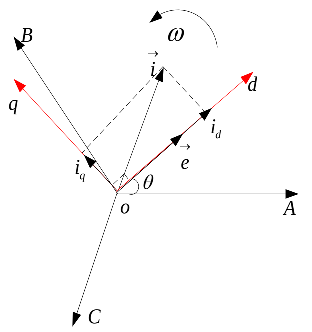

Figure 2. Vector Relation Diagram on ABC-dq Coordinate Conversion

θ is the included angle between voltage vector $\vec{e}$ and A-axis. Then instantaneous values of the three-phase grid voltages are the projections of voltage vector $\vec{e}$ on ABC coordinate axes. Direction of d-axis is the coordinate direction after A-axis rotates for θ . Set grid voltage vector $\vec{e}$ coincides with d-axis and project the resultant vector $\vec{i}$ of three-phase grid currents on dq coordinate axes, then i_d , the projection of $\vec{i}$ on d-axis is the active component of current and i_q , the projection of $\vec{i}$ on q-axis is the reactive component of current. Under initial conditions, d-axis coincides with A-axis. Then mathematical model of grid-connected inverter under synchronously rotated two-phase rectangular coordinates could be obtained, as it is shown in the following Equation 2. Active power and reactive power of energy feedback system could be controlled through controlling i_d and i_q separately [3].

$$\begin{bmatrix} L\frac{di_d}{dt} \\ L\frac{di_q}{dt} \end{bmatrix} = \begin{bmatrix} -R & \omega L \\ -\omega L & -R \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} v_d \\ v_q \end{bmatrix} - \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} e_d \\ e_q \end{bmatrix} \quad (2)$$

3. Analysis and Design of Control Strategy of Energy Feedback System

3.1. Direct Current Control

Direct current control based on grid voltage orientation is adopted in this system. Set reactive component of this system as $i_q^{\bullet} = 0$. Through sampling two-phase grid voltages e_a and e_b , e_c could be calculated with program. Then make phase lock to get voltage frequency and phase signal, which could be used as set value of the frequency and phase of feedback current [4]. Sampling feedback current at the same time, i_d and i_q could be obtained after coordinate conversion. Conduct PI regulation with the given benchmarks $i_d^{\bullet}$ and $i_q^{\bullet}$ inside the program, then decouple the result after PI regulation and conduct feedforward control on grid voltage, and U_α and U_β could be obtained after dq -$\alpha\beta$ coordinate conversion. After making SVPWM operation on U_α and U_β obtained after coordinate conversion, duty ratio signal could be obtained that drives IGBT to break over, so as to realize grid-connected feedback of unit power.

3.2. Design of DPLL (Digital Phase-Locked Loop)

In order to guarantee the feedback current output by energy feedback system could follow grid voltage in real time and ensure strictly the same frequency and phase with it, so as to realize feedback grid connection of unity power factor, phase-lock technique needs to be used. Through hardware circuit and software programming of this system, grid phase voltages e_a, e_b and e_c could be obtained, and e_α and e_β, e_d and e_q could be obtained upon coordinate conversion as well. Phase angle θ used during this process is the output phase angle of phase-locked loop. Hereinto:

$$\begin{cases} e_\alpha = e_d \cos\theta - e_q \sin\theta \\ e_\beta = e_d \sin\theta + e_q \cos\theta \end{cases} \tag{3}$$

In order to make feedback current output by energy feedback system follows three-phase grid voltages completely, e_d could be defined as active component of three-phase voltages. Then reactive component e_q of three-phase voltages could be controlled indirectly to make it 0[5][6]. Then:

$$\theta = \arctan \frac{e_\beta}{e_\alpha} \tag{4}$$

With lookup method, phase-lock angle θ could be obtained through arctan function table built in DSP program.

3.3. Design of Current Regulator of Energy Feedback System

In order to meet the dynamic response of PMSM during four-quadrant operation, mobility and rapid dynamic response of current inner loop need to be considered while designing PI regulator. Thus, PI regulator will be designed with typical I-type system and its transfer function can be expressed as:

$$G_c(s) = (k_p S + k_i)/S \tag{5}$$

In the above equation: k_i refers to integral coefficient, $k_i = k_p/\tau_i$; τ_i refers to integral time constant.

If considering sampling delay $G_h(s) = 1/(1 + T_s S)$, hereinto, T_s refers to switching period of PWM and analyzing according to small-signal modeling, before adding disturbance quantity of grid voltage, open-loop transfer function of current regulator of energy feedback system can be expressed as the following Equation 6:

$$G_i(s) = \frac{K_c K_{PWM}}{(1 + T_s S)(R + SL)} \tag{6}$$

Hereinto: K_c refers to current feedback coefficient; K_{PWM} refers to PWM equivalent gain of inverter; T_s refers to switching period of PWM.

This system involves 2 poles. If set time constant of filter inductance as dominant pole, after Equation 6 is adjusted with PI regulator, open-loop transfer function of current regulator of energy feedback system can be expressed as the following Equation 7:

$$G^{`}(s) = \frac{K_c K_{PWM} k_p (1 + \tau_i S)}{\tau_i (1 + T_s S)(R + SL) S} \tag{7}$$

Let $\tau_i = L/R$, then open-loop transfer function of current regulator of energy feedback system can be expressed as the following Equation 8:

$$\Phi_i(s) = \frac{\dfrac{K_c \cdot K_{PWM} \cdot k_p}{L T_s}}{S^2 + \dfrac{1}{T_s} S + \dfrac{K_c \cdot K_{PWM} \cdot k_p}{L T_s}} \tag{8}$$

Let $\xi = \frac{1}{2}\sqrt{\frac{L}{K_c K_{PWM} k_p T_s}}$ and $\omega_n = \sqrt{\frac{K_c K_{PWM} k_p}{L T_s}}$, then Equation 8 can be simplified as:

$$\Phi_i(s) = \frac{\omega_n^2}{S^2 + 2\xi\omega_n S + \omega_n^2} \tag{9}$$

According to second-order best setting method, $\xi = 0.707$ can be referred and with integral time constant $\tau_i = \frac{L}{R}$, it could be concluded that:

$$k_p = \frac{R\tau_i}{2K_c K_{PWM} T_s} \tag{10}$$

When switching frequency of energy feedback system is large enough, T_s will be small enough and S^2 could be ignored. Then closed loop transfer function of the system $\Phi_i(s)$ could be simplified as:

$$\Phi_i(s) = \left(1 + \frac{R\tau_i}{K_c K_{PWM} k_p} S\right)^{-1} \tag{11}$$

When current regulator of energy feedback system is designed according to typical I-type system, current loop could be approximately regarded as first-order inertia transfer function. Then its inertia time constant is $2T_s$. It is obvious that when switching frequency is big enough, switching period of PWM T_s will be small enough and then current regulator will be provided with a rapid dynamic response.

And bus voltage U_{dc} of PMSM needs to be sampled at the same time. After comparing with the reference value U^*_{dc} given by the program, adjust the obtained deviation to make bus voltage of PMSM stable in a short time to make the system be of better static performance and disturbance resistance.

4. Analysis of Experimental Results

An experimental platform for 7.5kW PMSM energy feedback system controlled based on DSP MS320F2812 is built with switching frequency of 3.3kHz, grid phase voltage of 220V and frequency of 50Hz. Double closed-loop control with current inner loop and bus voltage outer loop is adopted in this energy feedback system, three-phase grid voltage signals e_a , e_b and e_c could be sampled trough detection circuit and conditioning circuit of voltage and current, and phase currents i_a , i_b and i_c upon grid-connected feedback and DC bus voltage signal V_{dc} will be converted into 0~3V analog signals and then sent into DSP2812A\D port. Upon coordinate conversion, incremental PI regulation and SVPWM modulation, six-way PWM pulse signal output by PWM port is used to drive six-way IGBT, and it has the advantages of slow start, overcurrent protection and overvoltage protection. Overall Structure Diagram of Energy Feedback System Grid-connection Experiment is shown in the following Figure 3. While making grid-connection experiment, add power resistor first, turn on grid-connected switch and then turn on driven switch. Feedback current that has been output rises slowly from 0A within 0.3s to the current value given by the program. Current amplitude is decided by required grid-connected power, as it is shown in Figure 3.

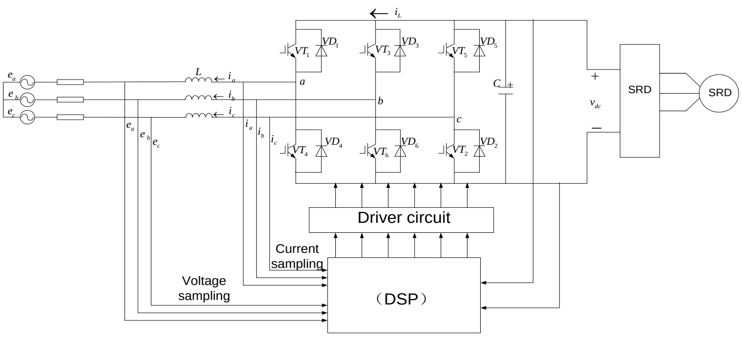

Figure 3. Overall Structure Diagram of System Grid-Connection Experiment

Figure 4 shows the PWM trigger signals of IGBT of Arm 1, Arm 3 and Arm 5 on the inverter of energy feedback system.

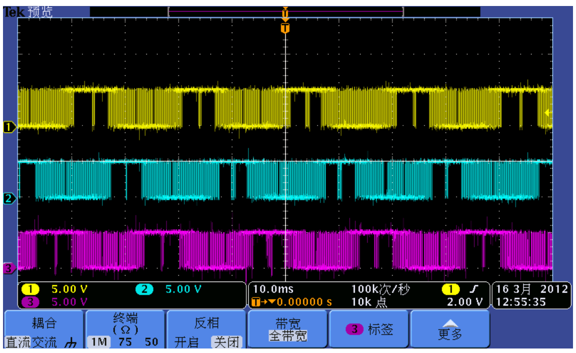

Figure 4. PWM Trigger Signal Waveform of IGBT of the System

When bus voltage rises to 650V, which means it reaches the threshold voltage of grid-connected feedback of energy feedback system, the entire feedback system will start grid-connected feedback, as it is shown in Figure 5. Hereinto, CH1 shows linear voltage waveform of U_{AB} at grid side, CH2 shows linear voltage waveform of U_{BC} at grid side, CH3 shows the waveform of output feedback phase current I_a and CH4 shows the waveform of output feedback phase current I_b. As phase of line voltage U_{AB} of the grid is 120° ahead of front line voltage U_{BC}, it could get to know that detected voltage phase is correct. And as phase of output feedback phase current I_a is 30° behind grid line voltage U_{AB}, namely feedback current I_a and A-phase voltage U_A share the same direction, so that efficient energy feedback of unity power factor has been realized.

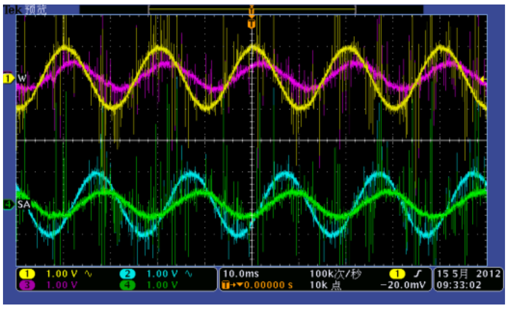

Figure 5. Gird Voltage Waveform and Grid-connected Feedback Phase Current Waveform

5. Conclusion

Without changing original main circuit of PMSM, the energy feedback system based on grid voltage orientation is researched and designed to be used together with PMSM, through which the energy generated by PMSM under braking operation could be fed back to three-phase grid, so as to take off brake resistor. This energy feedback system is a mathematical model built under synchronously rotated three-phase dq coordinates to resolve the output grid-connected current into active component and reactive component under dq coordinates. In order to realize unity power factor grid connection, reactive component of the current in system control strategy is given as 0. It could be concluded from experimental results that such control algorithm could optimize output grid-connected current waveform, reduce current harmonics and improve dynamic response of the system.

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