Control of the Permanent Magnet Synchronous Motor Using Model Reference Dynamic Inversion

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Abstract: Worldwide energy-saving emission has stimulated extensive application of permanent magnet synchronous motor in industry. This work is a contribution to velocity control of the permanent magnet synchronous motor. The model of the permanent magnet synchronous motor has multi-variable, highly nonlinear, strong coupling character with external load; in order to control this complicated nonlinear model, the hierarchy model reference dynamic inversion control method has been developed. Based on the band of the different variables of the system, the control system can be divided into long period control loop and short period control loop. The model reference dynamic inversion method is proposed as the kernel controller in different loops. Based on the desired closed loop reference model, the open loop controller can be designed for the long period loop and short period loop respectively, and this open loop controller can make the response of the system the same as that of the reference model. Comparing with the traditional control method, this model reference dynamic inversion control method combine the virtues of the model reference controller with that of the dynamic inversion controller, and this method is a fully nonlinear control method in essence, which can avoid linearization error when using the approximate linearization controller and the problem of the parameter tuning when utilizing the traditional PI hierarchy controller. Finally, the simulation experiments have been set up and the simulation results have illustrated that this control method can control the permanent magnet synchronous motor stably and successfully.

Key words: Permanent Magnet Synchronous Motor (PMSM), Dynamic Inversion (DI), Velocity Tracking Control, model reference, hierarchy controller

1. Introduction

Permanent magnet synchronous motors (PMSMs) are of great interest, particularly for industrial applications in the low-medium power range, since it has superior features such as compact size, high torque/weight ratio, and high torque/inertia ratio [1]. Moreover, compared with induction motors, PM synchronous motors have the advantages of higher efficiency [2]; due to the absence of rotor losses and lower no-load current below the rated speed, its decoupling control performance is much less sensitive to the parameter variations of the motor[3,4].

The typical construction of a PMSM consists of a three phase stator winding and a solid iron rotor with magnets attached to its surface or inserted into the rotor body. Permanent magnet synchronous motor control system mainly consists of two parts, the main drive circuit and the control circuit. The main drive circuit topology remains basically unchanged, while the study of the control system focuses on the control circuit and control strategies. The construction of the PMSM results in a magnetic field fixed to the rotor position. Since such machines are not capable of directly starting from the mains, excitation by voltage source inverters (VSI) controlled by field orientation is required. Control techniques such as vector control [5] or direct torque control (DTC) [6] are standard for this type of drives.

Based on the characteristics of the model of permanent magnet synchronous motor, many modern control methods and intelligent control methods have been applied to the permanent magnet synchronous motor, such as nonlinear control [7,8] and sliding mode control[9] have been developed to address the speed and position control of PMSMs. The state feedback linearization of nonlinear systems control theory has been introduced into the motor control in [10]. The adaptive control strategy has been used in the control of permanent magnet synchronous motor in [11]. Besides these nonlinear control methods mentioned above, the intelligent control methods, such as the artificial intelligence expert system [12], fuzzy control [13], and neural networks [14, 15] have also been utilized in the motor drive system, and the great progress has been achieved. Brock [16] used fuzzy logic controllers to adjust the gain of a controller in a sliding mode controller for speed and position control of PMSM. The control strategies in which recurrent fuzzy neural networks (FNN) were used to adjust the gain of the SMC for position control of a PMSM was used by Wai [17].

The purpose of this paper is to address the application of a relatively new control system design approach known as model reference dynamic inversion to design the speed servo controller for high performance PMSMs. Dynamic inversion is the nonlinear control method in essence and has been successfully applied to large flexible complicated system in documents. There has been a considerable amount of work in the application of dynamic inversion to control helicopters [18] and other aircraft [19]. Dynamic inversion method has proven to be a very effective technique for the control of the nonlinear system. The model reference adaptive control has also been successfully used in many systems [20, 21]; with this control method, the response of the reference model to the input signal is the same as the reaction of the controlled system with the controller acted upon; In order to fulfill this function, the minus of the output of the response of desired model reference and the output of the reaction of the real system is utilized to adjust the open loop controller, which making the real reaction tracing that of the desired reference model. In order to use not only the virtue of the directly nonlinear control but also that of the model reference control, the model reference dynamic inversion control method is utilized to control the PMSM.

This paper is arranged as follows: In section 2 the model of the PM synchronous servo motor is introduced; In section 3, the kernel of the system controller, model reference dynamic inversion, is described in detail; the PMSM controller based on the hierarchy model reference dynamic inversion control method is designed in section 4; In section 5, the control effects and performance of the hierarchy model reference dynamic inversion controller on PMSM are evaluated under different loads with simulink in Matlab; Finally, conclusions are summarized in section 6.

2. Mathematical model of PMSM

A PMSM is composed of three phase's stator windings and permanent magnets mounted on the rotor surface (surface mounted PMSM) or buried inside the rotor (interior PMSM). The electrical equations of the PM synchronous motor can be described in the rotor rotating reference frame, written in the (dq) rotor flux reference frame [22].

The mathematic model of PMSM is based on the following assumptions:

(1) Neglecting the saturation of armature;

(2) Neglecting the wastages of eddy and magnetic hysterics;

(3) There is no rotor damp resistance.

The relations of voltage, torque and flux of PMSM are described as follows:

$$\begin{bmatrix} \dot{i}_q \\ \dot{i}_d \end{bmatrix} = \begin{bmatrix} -\frac{L}{R} & -\omega_r \\ \omega_r & -\frac{L}{R} \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 & 0 \\ 0 & \frac{1}{L} & -\frac{\omega_r}{L} \end{bmatrix} \begin{bmatrix} u_q \\ u_d \\ \phi \end{bmatrix} \quad (1)$$

where i_d and i_q are the d and q axis stator currents, R and L are the stator phase resistance and inductance respectively; ω_r is the rotor electrical speed; u_d and u_q are the stator voltages expressed in the dq reference frame and ϕ is the flux established by rotor permanent magnets; P is the number of pole pairs. Equation (1) describes electrical dynamics and is nonlinear since they involve products of state variables.

$$\omega_s = P\omega_r \tag{2}$$

ω_s is inverter frequency [23].

The electromagnetic torque is given by

$$T_e = 3P\left[\phi i_q + (L_d - L_q) i_d i_q\right] \tag{3}$$

If $i_d = 0$, the electromagnetic torque T_e is proportional to i_q. This description is similar to the torque generated in a DC motor with independent field excitation. This feature can simplify the controller design of the PMSM, which is used in the controller simulation experiment in this paper.

The equation of the motor dynamics is

$$T_e = T_L + B\omega_r + J\dot{\omega}_r \tag{4}$$

T_L stands for external load torque. B represents the damping coefficient and J is the moment of inertia of the rotor.

Thus, the mechanical dynamic of the PMSM can be rewritten as

$$\frac{d\omega_r}{dt} = -\frac{B}{J}\omega + \frac{3P\left[\phi i_q + (L_d - L_q) i_d i_q\right]}{2J} - \frac{T_L}{J} \tag{5}$$

The equation (5) shows that the electromagnetic torque is the product of state variables and it is nonlinear. The equations (1) and (5) constitute the whole control model of the PMSM. The state-space model of the interior PMSM is similar to the surface mounted PMSM only that the model of the surface mounted PMSM does not have the product of the currents d-axis and q-axis in the electromagnetic torque. However the control method of these two kinds of motor is similar, for simple, the surface mounted PMSM is chosen as the control object in this paper.

3. Control Scheme

Dynamic inversion has been shown to provide a systematic approach for development of feedback control algorithms for nonlinear continuous time systems. If given a nonlinear dynamic system described as

$$\dot{x} = f(x) + g(x)u(t) \tag{6}$$

In equation (6), $f(x)$ and $g(x)$ are nonlinear functions of the system state vector x. If $g(x)$ is invertible for all values of x, then the dynamic inversion control law can be designed by

$$u(t) = g^{-1}(x)[[\dot{x}]_{des} - f(x)] \tag{7}$$

Where $[\dot{x}]_{des}$ is the time derivative of the desired system state vector. Since the functions f and g are smooth, this control law will change the original system (6) into a controllable linear first order uncoupled differential equations. It can be noticed that when substituting the equation (7) into the equation (6), the equation (8) can be achieved:

$$\dot{x} = [\dot{x}]_{des} \tag{8}$$

This derivation is simple but very important for it formed the basis of the design of the model reference dynamic inversion controller of the PMSM.

The functions f and g, in general, depend on the nonlinear dynamic equation of the PMSM. It is easy to notice that the basic concept behind dynamic inversion is to cancel out the nonlinear dynamics so it will follow the desired value.

The dynamic inversion approach formulated above can be treated as two parts. The first part is equilibrium state when $\dot{x} \equiv 0$, the control input can be given as

$$u_0 = -g^{-1}(x) f(x) \quad (9)$$

The second part is v, which can de designed as

$$v(t) = g^{-1}(x)\left[\dot{x}\right]_{des} \quad (10)$$

Then, the whole control input is then taken as [19]

$$u(t) = v(t) + u_0(t) \quad (11)$$

Letting

$$[\dot{x}]_{des} = w \quad (12)$$

Combine with equation (8); using the Laplace transform, the equation can be derived below

$$sX(s) = W(s) \quad (13)$$

If the $W(s)$ is taken as

$$\mathrm{W}(s) = K(s)[X_{des}(s) - X(s)] \quad (14)$$

Then combining with equation (10), the equation can be given

$$sX(s) = K(s)[X_{des}(s) - X(s)] \quad (15)$$

According to the equation (15), the transfer function of the close loop is

$$D(s) = \frac{X(s)}{X_{des}(s)} = \frac{K(s)}{sI + K(s)} \quad (16)$$

Then if the transfer function of the desired close loop reference dynamic model is chosen as $D(s)$, then the open controller of the system could be selected as

$$K(s) = sD(s)[I - D(s)]^{-1} \quad (17)$$

When designing the open loop controller, the properties and dynamics of the resulting closed loop system can be selected according to the control request given by the application engineer.

4. Controller of the Permanent Magnet Synchronous Motor

The preceding derivation suggests that any given system with appropriate properties can have the desired dynamic response. The application of dynamic inversion control method requires that the control matrix g be invertible. The properties of the control law will depend on the properties of the control matrix. Obtaining an invertible control matrix with suitable properties depends on careful choices of the models to be used and the states to be fed back.

As for the high order system, such as the PMSM, the hierarchy control method, with model reference dynamic inversion as the kernel controller in each layer, can be utilized to fulfill such function. The approach is to apply dynamic inversion separately to the low frequency and high frequency dynamics of the system to be controlled. The similar approach was demonstrated successfully in the controller for the X-38[24].

The proposed structure is shown in Fig. 1. ω_d is the desired velocity given by the engineer and the i_{dcmd} and the i_{qcmd} are the desired currents of d-axis and q-axis respectively. The structure is similar in form to that used in classical control system design process, such as PI controller in the PMSM controller [25]. There is, however, a notable difference that the control laws in dynamic inversion blocks are decidedly nonlinear.

In both the cases of the long period and short period dynamics, the dynamics to be inverted will depend on both mechanical dynamics and electrical model of the PMSM.

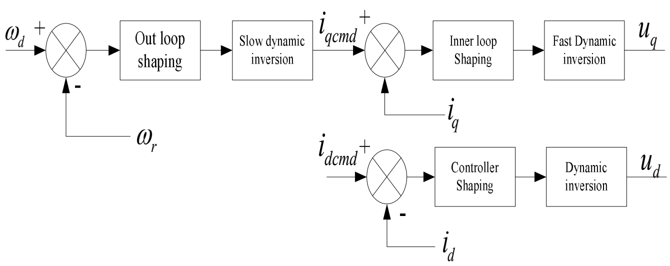

Fig. 1 the structure of the controller of the PMSM

The difference equation of the d-axis stator current model in equation (1) can be rewritten as

$$L\frac{di_d}{dt} = -Ri_d + N \tag{18}$$

The control value of d-axis stator current model will have the form

$$N = PL\omega_r i_q + u_d \tag{19}$$

The d-axis stator current is equilibrium state When $\dot{i}_d \equiv 0$, this control input can be given as u_{d0}

$$u_{d0} = -PL\omega i_q \tag{20}$$

The control voltage u_d will be taken as the sum of the trim value and control input as developed in the dynamic inversion formulation above

$$u_d = v + u_{d0} \tag{21}$$

The control value N can be defined as

$$N = v \tag{22}$$

The difference equation of the d-axis current model will be

$$L\dot{i}_d = -Ri_d + v \tag{23}$$

The control input v will be

$$v = L\left[\dot{i}_d\right]_{des} + Ri_d \tag{24}$$

For the current loop can be treated as the short period loop, the simplest of *1*st order transfer function can be selected as desired reference dynamics model. Then the desired loop transfer function can be taken as

$$D(s) = \frac{\omega}{s+\omega} \tag{25}$$

ω is the coefficient of the desired close loop function. Then, according to the derivation in section 3, the control value of the open transfer function in d-axis will be

$$K(s) = \left(\frac{s\omega}{s+\omega}\right)\left[1-\left(\frac{s}{s+\omega}\right)\right]^{-1} \tag{26}$$

$$= \omega$$

The desired current of i_d is given by

$$\left[\dot{i}\right]_{des} = \omega(i_{cmd} - i) \tag{27}$$

Then the d-axis control voltage will be

$$u_d = u_{d0} + L\left[\omega(i_{cmd} - i)\right] + Ri_d \tag{28}$$

Another control voltage u_q can be achieved by using the hierarchy control method. The out loop has long period while the inner loop has a short period. The out loop or long period dynamic inversion section will control velocity of the PSMS, and the variable to be controlled is ω_r. As the features of the surface mounted PMSM, the kinematics equation will be

$$\frac{d\omega_r}{dt} = -\frac{B}{J}\omega_r + \frac{3P\phi i_q}{2J} - \frac{T_L}{J} \tag{29}$$

The desired response for the long period variables is taken as a classic 2_{nd} order response

$$D(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \tag{30}$$

ω_n is the natural frequency of the desired 2nd system, and ξ is the damping ratio of the desired second-order system. The control value of the open transfer function of the velocity controller will be

$$K(s) = \frac{s\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}\left[1 - \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}\right]^{-1} \tag{31}$$

Which reduces to

$$K(s) = \frac{\omega_n^2}{2\xi\omega_n + s} \tag{32}$$

The control law is given by

$$\dot{\omega}_r = w \tag{33}$$

And then

$$\dot{w} = -2\xi w\omega_n + \omega_n^2\left[\omega_{cmd} - \omega_r\right] \tag{34}$$

The input to the long period controller shown above is the desired speed. This command comes directly from the system which the PMSM is used in. The desired q-axis current can be achieved with long period controller. The method of design the short period controller of q-axis control voltage is the same as that used in d-axis.

Discussion: This controller is the combination of the hierarchy controller, the model reference controller and the dynamic inversion controller; it is superior to the common used hierarchy PID controller in the PMSM control in that this method is nonlinear controller, and the controller and the parameters are achieved directly from the desired reference model. If the desired reference model is given, then controller will be designed according to the reference model and the controller will make the system trace desired trajectory the same as the reference model does.

5. Simulation Experiments

In this section, the proposed approach above has been carried out in PMSM to verify the performance of the model reference nonlinear dynamic inversion speed control scheme, using MATLAB/Simulink. The parameters of the PMSM are given in Tab. I. The simulation results are shown in Figs. 2-12.

The dynamic performance of the control system is evaluated by three simulation experiments using the step speed of 700 rad/sec as desired input and three kinds of different torques as load.

Tab. 1 PMSM Parameters

Machine parameters	value
Resistance of the stator windings(Ω)	2.875
Number of pole pairs	4
Combined inertia of rotor and load J (kg.m^2)	0.001
Amplitude of the flux induced by the permanent magnets of the rotor in the stator phases ϕ (Wb)	0.175
q and d axis inductances $L_q = L_d$ (H)	0.0085
Combined viscous friction of rotor and load B(N.m.s/rad)	0

In the first simulation, the desired velocity is 700rad/s, while desired current of the d-axis is 0A and the load is kept none all the time. Fig. 2 shows the velocity tracing process of the PMSM without load. The solid line (-) represents the desired velocity while the dot line (--) is the real-time simulation velocity. With the controller designed in last section, it can be seen that real-time velocity arrived at the desired velocity very fast and remain the desired velocity in no-load situation without any vibration. Fig. 3 and fig. 4 show the control current of the q-axis and d-axis separately. The d-axis current stays at zero all the time, while the q-axis current increases at the start process and keep static at almost 0.08A when the velocity of the PMSM arrives at the desired velocity, this current is no zero due to the resistance of the stator. In the no-load simulation, the result proves the validity of the controller.

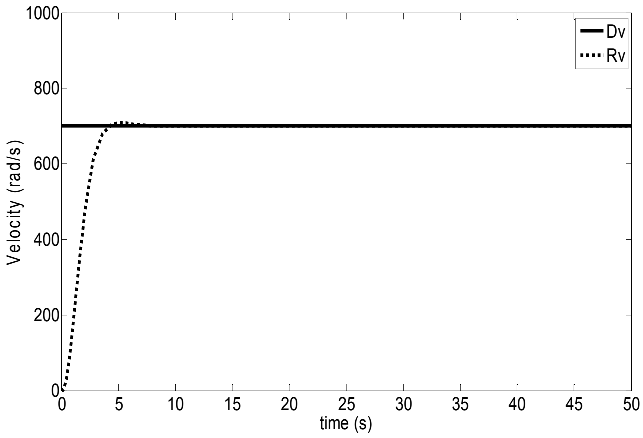

Fig.2 the process of the velocity tracing of the PMSM without load

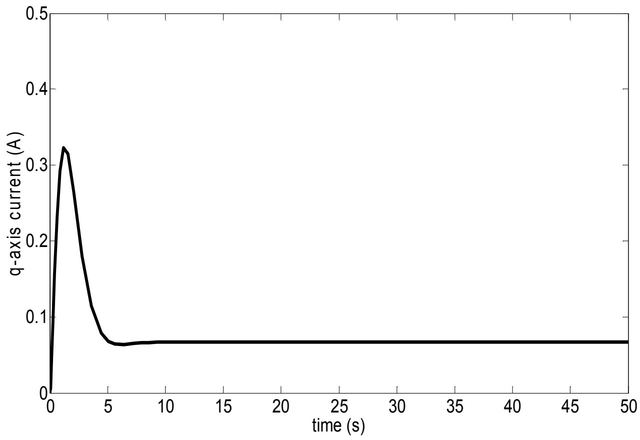

Fig. 3 the changing process of the current of the q-axis of the PMSM without load

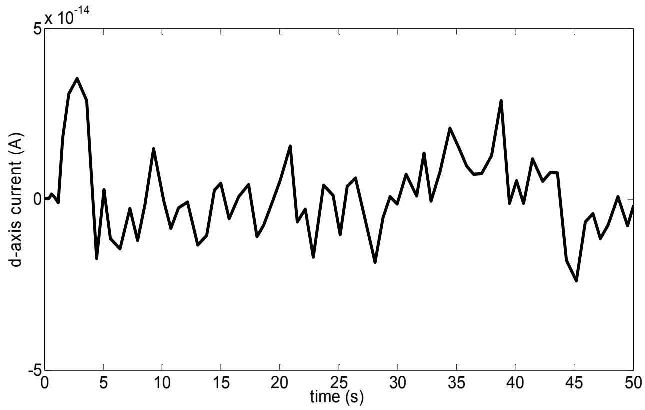

Fig. 4 the changing process of the current of the d-axis of the PMSM without load

The second simulation is to study and test the validity of the controller with abrupt plus step load. In the second simulation experiment, the desired velocity is 700rad/s, while desired current of the d-axis is 0A and a step load is acted upon the axis of the PMSM at one point after the PMSM has arrived at its desired velocity. Fig. 5 shows a step load with magnitude 0.2 N.m at 30s. This load is small because the PMSM chosen in the simulation has a very small power. It is clear from the velocity tracing process in fig. 6 and the d-axis current changing process in fig.7 when the load is acted upon on the motor, the velocity will decrease for a moment and will return to the desired velocity at once; as the load increases, the current of q-axis will increase too and will then return to the equivalent current in a few seconds; the current of d-axis will remain zero all the time. This simulation experiment have verified that this controller can control the PMSM with abrupt plus load.

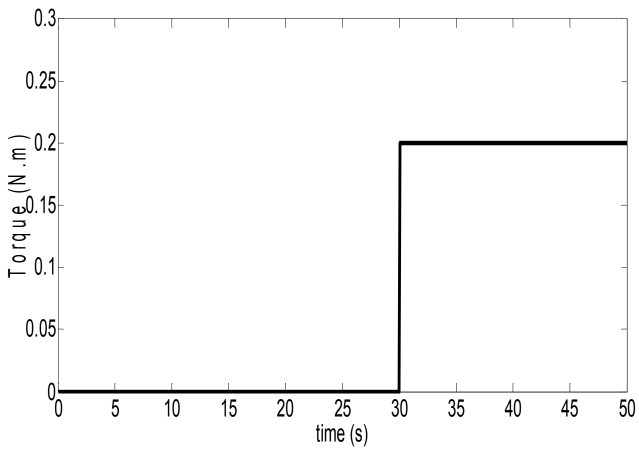

Fig.5 the plus step load acted upon the PMSM in simulation 2

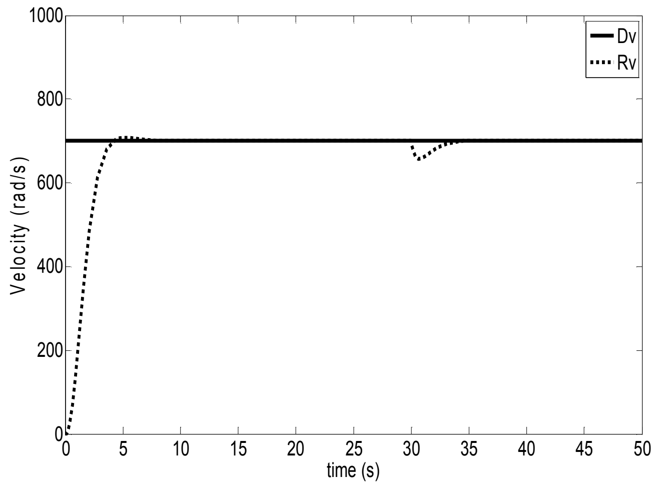

Fig.6 the process of the velocity tracing of the PMSM with a plus step load

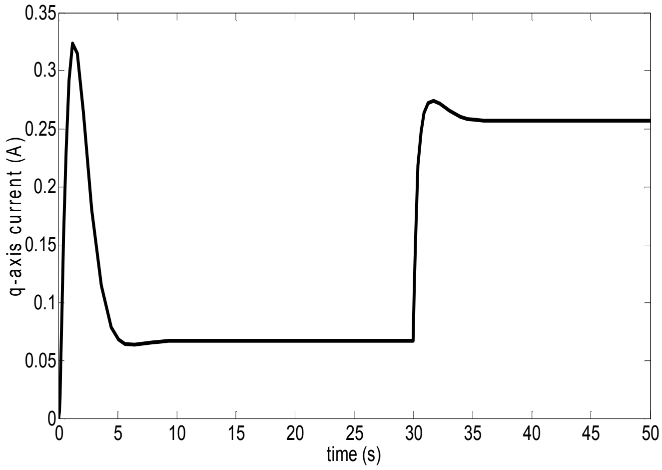

Fig.7 the changing process of the current of the q-axis of the PMSM with a plus step load

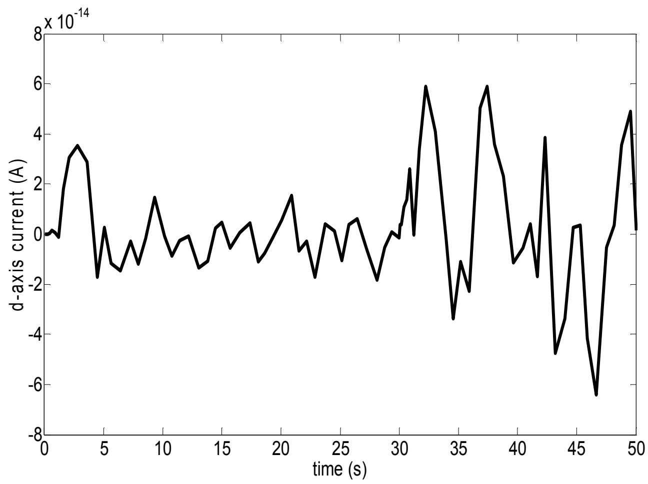

Fig. 8 the changing process of the current of the d-axis of the PMSM with a plus step load

When the PMSM works in the real situation, it will meet with the load which moves upward and downward all the time. Thus, this simulation is carried out to guarantee the motor can keep the desired velocity with abrupt changing load. In the third simulation experiment, the desired velocity is 700rad/s, while desired current of the d-axis is 0A,the load will have some abrupt plus and minus steps. In the simulation process, the load acted upon the PMSM is in series which will increase from 0N.m to 0.2N.m at 10s, and then remain static for 15s and then will increase to 0.3N.m and will remain at 0.3N.m for another 15s, and then will decrease to 0.2N.m and then remain 0.2N.m, which is shown in fig. 9.It is can be noticed in fig.10 that the real-time velocity can trace the desired velocity very well. The solid line (-) represents the desired velocity while the dot line (--) is the real-time simulation velocity. In fig.10, when the load is increasing, the velocity will drop a little and will return soon, and when the load is decreasing, the velocity will increase a little and will return soon. This changing situation coincides with the real control process. Fig.11 shows that change of the current of q-axis; it can be found that the current will goes to the static current soon and will keep at this value until the new load acted upon; only the time when the load has abrupt changes, the current will has some overshoots. These overshoots can be kept smaller by altering the coefficients of the out-loop controller or by changing the desired close loop reference model. Fig.12 shows the change process of the current the d-axis. It can be seen that the current of d-axis will keep zero all the time. The third simulation experiment shows that with the up-step and down-step load, the controller can also make the PMSM work.

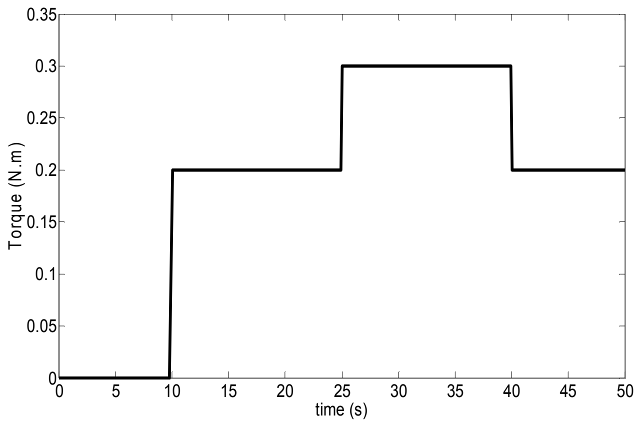

Fig. 9 the load series acted upon the PMSM in simulation 3

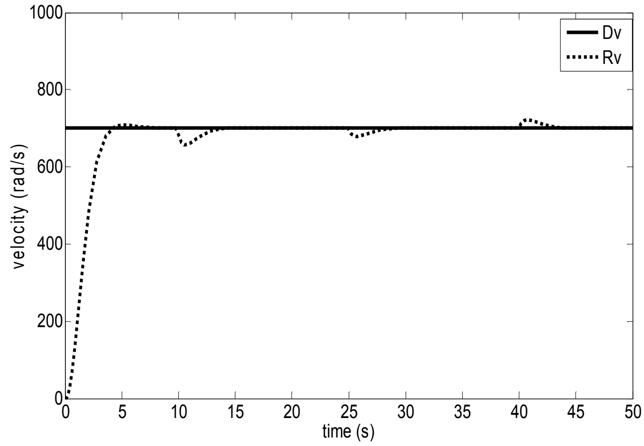

Fig. 10 the process of the velocity tracing of the PMSM with a series of changing load

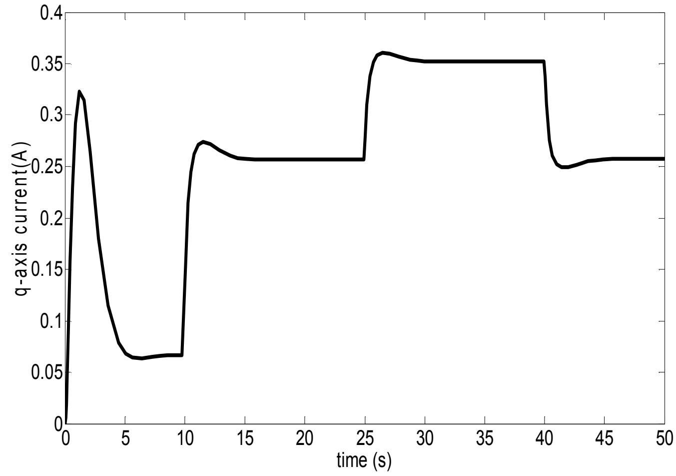

Fig. 11 the changing process of the current of the q-axis of the PMSM with a series of changing load

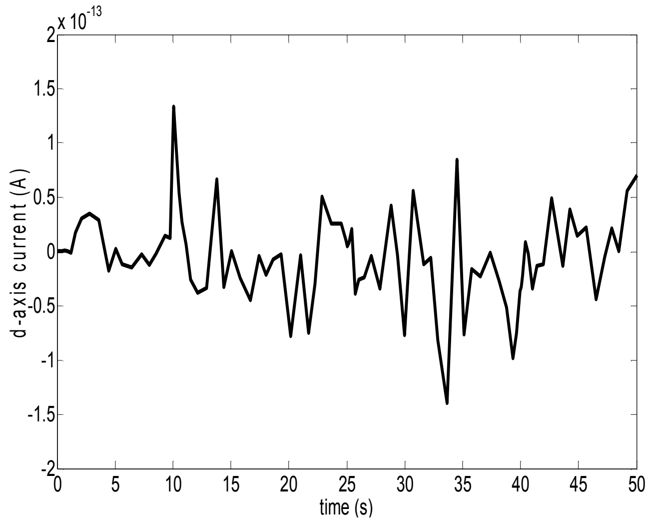

Fig. 12 the changing process of the current of the d-axis of the PMSM with a series of changing load

From the simulations above, it is noticeable that with the controller designed in the last section, the PMSM can keep desired velocity all the time, only when the load has an abrupt change, the real-time velocity will have a little overshoot and will return the desired velocity very soon. The control current of the q-axis will change along with the load. The control current of the d-axis will accurately at the desired value zero. The simulations above have guaranteed that the controller proposed above can control the PMSM and can be used quickly in the reality. For decoupling control performance of the PMSM is much less sensitive to the parameter variations [3,4], when the accurate parameters of the PMSM are given and the desired close loop reference model which is decided by the desired control performance is achieved, the controller designed above can be used in controlling the PMSM.

6. Conclusions

In order to meet with the worldwide demands for energy-saving emission, in many areas, permanent magnet synchronous motor is gradually replacing the traditional three-phase asynchronous motor. This motor is a complex multi-variable, nonlinear, strong coupling of the multiple-input multiple-output system. It is difficult to design the controller. Therefore, the study of the control strategy is currently a major problem in the industry.

According to the model of the PMSM, the hierarchy model reference dynamic inversion speed controller for PMSM has been designed. Dynamic inversion is the nonlinear control method which is based directly on the nonlinear model, which can keep the high fidelity nonlinear information of the nonlinear dynamics and electrical equation. The model reference method will make the system have the desired response. Compared to classical approaches, this compound method provided a much more systematic approach for control law design. Based on the model of the PMSM, the two time scale approach was utilized in the control structure. The velocity was controlled in the long period or outer loop controller and the current controller was utilized in the short period or inner loop. The control performance of the hierarchy model reference dynamic inversion controller appeared to be superior in all respects to the classical design for its high nonlinear character brought by dynamic inversion controller and it has the virtues of the model reference controller. Three simulation experiments have been done to test the controller with different load. The results show that the controller can control the velocity at desired value in different occasions. These simulation results guaranty the right and validity of the controller designed. From the descriptions above, it can be seen that hierarchy model reference dynamic inversion can be a viable approach for the control system design for PMSM.This compound method can be a preferable control method for the complicated multi-input and multi-output (MIMO) system.

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