Constraint Condition Based on the Energy Balance of Dual PWM Converter

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***Abstract*—An energy mathematical model of dual PWM structure is established, basing on the energy relationship between the energy balance and the energy unbalance of the dual PWM converter. Aiming at the problem of unbalanced system energy caused by load mutation, a constraint condition of the DC bus voltage and the d-axis component of the network side current is proposed to ensure that the system energy can be quickly restored to the steady state. The rectifier's voltage outer ring and the power inner ring are modified by the constraint condition to realize the fast balance between the output energy of the rectifier side and the consumed energy of the inverter side, so as to achieve the coordination control of the dual PWM structure. The experimental results show that the control system can achieve fast follow-up response, restore and maintain the steady state when the load changes under the constraint condition designed in this paper, and verify the effectiveness of the strategy.**

Keywords—energy flow; constraint condition; energy balance; coordinated control

I. Introduction

Dual PWM converter has a wide range of applications in the field of new energy and high-voltage AC speed control system due to its unique advantages: the network side of the unit power factor is high and adjustable; the grid-side harmonic is less; DC bus voltage can be flexibly adjusted; rectifier and inverter energy can achieve two-way flow through the middle DC capacitor.

Double PWM conversion structure can be divided into rectifier side and inverter side. For the rectifier side control methods, they are as follows: Direct Power Control (DPC), Repetitive Control,(RC) and Model Predictive Control (MPC) . Considering instantaneous power, DPC controls directly on the input power of PWM rectifier. It has the advantages of high efficiency, fast response, good dynamic and static performance, and running under unit power factor.[3]In the literature [4] using Model Predictive Control (MPC), MPC is a kind of control method which takes the current control action by prejudging the state of the system in the future limited time domain. It is an optimized nonlinear control method, with good control, robust and strong features [5].But there is always a certain static difference which is difficult to eliminate, and it is too sensitive to the parameters of the system. In view of the advantages and disadvantages of each control method, the rectifier side adopts the direct power control while the rear end adopts the rotor flux directional control method to realize the control of the three-phase asynchronous motor and reflect the energy relationship between the various parts of the system.

There are many kinds of dual PWM control methods, such as independent control strategy and master and slave control strategy. Direct current control can suppress the DC voltage ripple by increasing the current feedback circuit of AC side. The independent control strategy is to treat the rectifier and the inverter as opposite structure and control them independently. With less difficulty in design, this control method is relatively simple, but has less robustness. In the direct current control and direct power control, they both need an additional compensator to correct the deviation. To solve the problem, the master-slave control strategy uses the inverter as the dominant system and the rectifier as a subordinate system, feeding back the information of the dominant system to the slave system to achieve the coordinated control of the two parts[6] In the literature [7], the power consumption of the capacitor is limited to 0 at the time of sudden change of the load power, so as to suppress the fluctuation of the DC bus voltage, however, it is still the master-slave control.

As the AC motor will often load mutation, at this point the system is no longer stable and it requires some time to adjust to steady state. So it is necessary to make the system restore quickly from the change time. One of the advantages of the dual PWM transform structure is that it can achieve two-way flow of energy. From the energy point of view, it can find the reasons caused the instability in system output and input, so it can be well controlled. In [8], it shows the power relationship between the various parts of the system, but the energetic relationship between each part of the system is not explained.

Therefore, the direct power control method is used in the rectifier side. For the whole dual PWM conversion structure, the system energy mathematical model is established, basing on the energy relationship between the various parts. Then according to the mathematical model, set the constraints on the inner-loop power and the voltage loop of rectifier to ensure the coordinated control in rectifier side and the inverter side. Finally, the simulation model is used to test the validity of the model.

II. Mathematical Model Analysis of Dual PWM Structure Power in d-q Rotating Coordinate System

A. Power Mathematical Model Analysis of PWM Rectifier in d-q Coordinate System

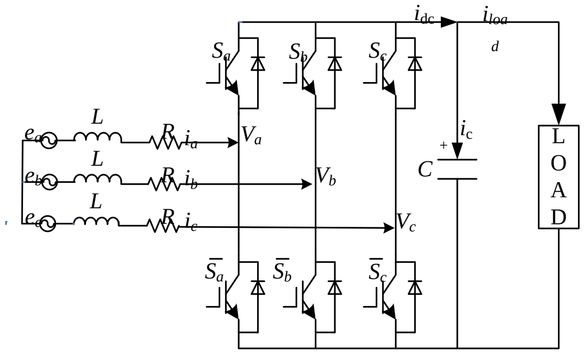


Figure.1. three-phase voltage-type PWM rectifier main circuit

In Fig.1, e_a、e_b、e_c are the network side electromotive forces; L_g is the network side filter inductance; R is the network side resistance; C_{dc} is the DC side capacitor; S_x is the power switch device switching signal; and V_a、V_b、V_c are the PWM rectifier input voltages.

Set the network side electromotive force as es, then in the two-phase α-β stationary coordinate system, it can be gotten that $e_\alpha = e_s \cos\omega t$、 $e_\beta = e_s \sin\omega t$. If the α-β stationary coordinate system is rotated at the synchronization angular frequency ω, it becomes the d-q rotating coordinate system, so the power supply electromotive force and the d axis are combined and the instantaneous power theory can be obtained. The instantaneous power expressions in the d-q rotating coordinate system are as follows:

$$p = e_d i_d \quad (1)$$

$$q = -e_d i_q \quad (2)$$

According to the literature [9] and combined with (1) (2) , the PWM rectifier power mathematical model can be obtained under d-q rotating coordinate system. It is just as follow:

$$L_g \frac{dp}{dt} = e_d^2 - Rp - \omega L_g q - e_d v_d \quad (3)$$

$$L_g \frac{dq}{dt} = -Rq + \omega L_g p + e_d v_q \quad (4)$$

$$\frac{1}{2} C \frac{du_{dc}^2}{dt} = p_{dc} - p_{load} \quad (5)$$

Show in formula: p、q are respectively the active power and reactive power output by the PWM rectifier; ω is the power rotation frequency; e_d、e_q are components on d-q axis of the electromotive force of electric source; v_d、v_q are input voltage components on the d-q axis of the PWM rectifier; p_{dc} is the DC side power and p_{load} is the load power.

B. Mathematical model of three - phase asynchronous motor under m - t coordinate

There are many ways to control the motor, such as direct torque control, rotor flux orientation control and so on. In this paper, the control method of rotor flux direction is adopted. The rotor flux direction control method is to combine the inverter with the three-phase asynchronous motor. The vector control is used to convert the rotor flux and d axis of d-q rotating coordinate system to a new system, also known as m-t axis rotating coordinate system, which rotating speed is ω, the synchronous frequency of stator flux linkage. According to the literature [9], what can be obtained is that the three-phase asynchronous motor mathematical model in m-t coordinate system.

Three-phase asynchronous motor voltage equation in m-t coordinate system is:

$$\begin{bmatrix} u_{sm} \\ u_{st} \\ u_{rm} \\ u_{rt} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_r & 0 \\ 0 & 0 & 0 & R_r \end{bmatrix} \begin{bmatrix} i_{sm} \\ i_{st} \\ i_{rm} \\ i_{rt} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \psi_{sm} \\ \psi_{st} \\ \psi_r \\ 0 \end{bmatrix} + \begin{bmatrix} -\omega_1 \psi_{sm} \\ \omega_1 \psi_{st} \\ 0 \\ (\omega_1 - \omega)\psi_r \end{bmatrix} \quad (6)$$

Three-phase asynchronous motor flux linkage equation in m-t coordinate system is:

$$\begin{bmatrix} \psi_{sm} \\ \psi_{st} \\ \psi_{rm} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \end{bmatrix} \begin{bmatrix} i_{sm} \\ i_{st} \\ i_{rm} \\ i_{rt} \end{bmatrix} \quad (7)$$

Three-phase asynchronous motor torque equation in m-t coordinate system is:

$$T_e = n_p L_m (i_{st} i_{rm} - i_{sm} i_{rt}) \quad (8)$$

Three-phase asynchronous motor motion equation in m-t coordinate system is:

$$\begin{cases} \dfrac{J d\omega}{n_p dt} = T_e - T_L \\ \dfrac{d\theta}{dt} = \omega \end{cases} \quad (9)$$

u_{sm}、u_{st}、u_{rm}、u_{rt} is the stator voltage component and the rotor voltage component of the m-t rotating coordinate system, respectively; i_{sm}、i_{st}、i_{rm}、i_{rt} is stator current component and the rotor current component; ψ_{sm}、ψ_{st}、ψ_{rm}、ψ_{rt} is stator flux linkage components and rotor flux components; ω_1 is the synchronization angle frequency; ω is the rotor frequency; R_s, R_r is stator winding resistance and rotor winding resistance, respectively. L_m is the mutual inductance between stator and rotor equivalent winding, $L_m = \frac{3}{2} L_{ms}$; L_{ms} is the inter-stator mutual inductance; L_s is the self-inductance of the stator equivalent phase windings, $L_s = \frac{3}{2} L_{ms} + L_{ls} = L_m + L_{ls}$; L_{ls} is the stator leakage inductance; L_r is the self-inductance of the equivalent two-phase winding of the rotor, $L_r = \frac{3}{2} L_{ms} + L_{lr} = L_m + L_{lr}$; L_{lr} is the rotor leakage inductance; T_e is electromagnetic torque; T_L is

Load torque; n_p is the pole pair of the motor; and J is the moment of inertia.

III. Analysis of Energy Mathematical Model of Double PWM Control Structures

A. Dual - PWM Control Structure Energy Mathematical Model

The energy in the dual PWM control structure can be divided into four parts: energy stored in the network side filter inductance, energy dissipation of the network side resistance, energy stored by the DC side capacitor and energy consumption of the load side motor. Based on the principle of energy balance, it can be obtained as follows:

$$P = P_L + P_R + P_C + P_M \tag{10}$$

P is the total power output on the network side; P_R is the network side resistance power; P_L is the network side filter inductance power; P_C is the DC side capacitance power; PM is the load motor consumes the power. Using direct power control, the system's reactive power is 0. In the d-q rotating coordinate system, the reactive current i_q is zero. So the output current of the grid is id in the d-q rotating coordinate system. The inductive power of line filter is :

$$P_L = \frac{1}{2} L_g \frac{di_d^2}{dt} \tag{11}$$

The first order reciprocal of (11) is discretized into:

$$P_L = \frac{1}{2} L_g \frac{i_d^2(t+1) - i_d^2(t)}{T_s} \tag{12}$$

In (12), T_s is the system sampling period. (12) shows the energy change of a sampling period. For n sampling periods, the inductive energy can be expressed as :

$$E_L = nT_s P_L = \frac{1}{2} nL_g [i_d^2(t+nT_s) - i_d^2(t)] \tag{13}$$

$i_d(t+nT_s)$ can be regarded as the system at time t, the expected current id at $t+nT_s$ time value, so $i_d(t+nT_s) = i_d^*(t)$. It can be rewritten (13)as:

$$E_L = nT_s P_L = \frac{1}{2} nL_g [i_d^{*2}(t) - i_d^2(t)] \tag{14}$$

DC side capacitor power:

$$P_c = \frac{1}{2} C_{dc} \frac{du_{dc}^2}{dt} \tag{15}$$

Similarly, the first order reciprocal of (15) is obtained and the energy of the sampling period is n:

$$E_C = nT_s P_C = \frac{1}{2} nC_{dc} [u_{dc}^{*\,2}(t) - u_{dc}^2(t)] \tag{16}$$

In (16), the value of the desired DC bus voltage $u_{dc}^*(t)$ at time $t+nT_s$ is the system at time t.

The power of the grid side is:

$$P_R = i_d^2 R \tag{17}$$

In (17), the upper limit of the integral is $t+nT_s$, and the consumption of the n system sampling period and the network side resistance is obtained.

$$E_R = \int_t^{t+nT_s} P_R(t)dt = \int_t^{t+nT_s} Ri_d^2(t)dt = \frac{1}{2}[i_d^{*2}(t) + i_d^*(t)]nT_s \tag{18}$$

Load three-phase asynchronous motor power:

$$P_{load} = u_{dc} i_{load} \tag{19}$$

Similarly, there are n system sampling cycle, asynchronous motor energy consumption:

$$\begin{aligned} E_{load} &= \int_t^{t+nT_s} P_{load}(t)dt = \int_t^{t+nT_s} u_{dc}(t) i_{load}(t)dt \\ &= \frac{1}{2}[u_{dc}^*(t) i_{load}^*(t) + u_{dc}(t) i_{load}(t)]nT_s \end{aligned} \tag{20}$$

In (20), $i_{load}^*(t)$ is the value at time t, and the expected load current is at $t+nT_s$. According to (9), it can be expressed as: $i_{load}^* = \sqrt{i_{sm}^{*\,2} + i_{st}^{*\,2}}$.

The output power of power grid is P, then the output power of the grid in n system sampling cycle can be obtained as:

$$E = \int_t^{t+nT_s} P(t)dt = \int_t^{t+nT_s} e_d i_d(t)dt = \frac{1}{2} e_d [i_d^{*2}(t) + i_d^*(t)]nT_s \tag{21}$$

Then according to the above analysis, the system can be obtained from t to $t + nT_s$ energy changes:

$$\Delta E = E(t+nT_s) - E(t) = E_L + E_R + E_C + E_{load} \tag{22}$$

If the system is in steady state, the system output energy and output energy are in balance, there are $i_d^*(t) = i_d(t)$, $u_{dc}^*(t) = u_{dc}(t)$, $i_{load}^*(t) = i_{load}(t)$.

At this time the energy change is:

$$\Delta E = e_d i_d(t) nT_s = Ri_d^2(t) nT_s + u_{dc}(t) i_{load}(t) nT_s \tag{23}$$

The energy output from the network side is absorbed by the network side resistance and the load motor, which conforms to the energy balance principle.

B. Principle Analysis of Energy Imbalance Control of Double PWM Control Structures

According to (23) we can see that when the system is in steady state, the energy relationship between the system input and output can be applied to most of the time. But for the AC-DC-AC variable frequency control system, the AC motor will often appear brake braking, speed mutation and torque mutation, etc. In this case, the system is no longer a steady state, and the system needs a certain time to adjust to a steady state. So it is necessary to analyze the energy relationship between the various parts of system from the moment of change to back to stable.

Assuming that the system is in an energy imbalance due to a sudden change in the load motor power, the system returns to steady state after nT_s. According to the above description of the system, the mathematical relationship in imbalance state is:

$$(i_d^* - i_d)e_d T_s = L_g(i_d^{*2} - i_d^2) + C_{dc}(u_{dc}^{*\,2} - u_{dc}^2) + RT_s(i_d^{*2} + i_d^2) + T_s(u_{dc}^* i_{load}^* + u_{dc} i_{load}) \quad (24)$$

Calculating (25) , it can be obtained as:

$$C_{dc}u_{dc}^2 - T_s u_{dc} i_{load} - C_{dc} u_{dc}^{*\,2} - T_s u_{dc}^* i_{load}^* = (RT_s - L_g) i_d^2 + i_d e_d T_s - i_d^* e_d T_s + L_g i_d^{*2} + RT_s i_d^{*2} \quad (25)$$

The left side of (25) is a function of the DC bus voltage u_{dc} as a variable, which can be regarded as the change of the energy of the motor load and the capacitance of the DC side. Equal sign on the right side can be regarded as the change of line output energy, resistance energy consumption and inductance energy, which is the change of rectifier energy. DC bus voltage u_{dc} is dependent variable, due to load mutation.

It is expected that the system can increase or decrease the energy in a smooth and stable state when the system is in the regulation state. This can reduce the fluctuation of the DC bus voltage. Therefore, the quadratic function of u_{dc} can be established according to the（25）as follows:

$$f(u_{dc}) = C_{dc}u_{dc}^2 - T_s u_{dc} i_{load} - C_{dc} u_{dc}^{*\,2} - T_s u_{dc}^* i_{load}^* \quad (26)$$

C_{dc} is positive and there is a real root. So there is a minimum in the function when the DC bus voltage to meet:

$$u_{dc} = \frac{T_s i_{load}}{2C_{dc}} \quad (27)$$

Under this constraint condition, the energy change rate of the inverter side is the smallest, and the energy change rate of the same rectification side is also the smallest.

Substituting the constraint condition (27) into (25) yields:

$$i_d^2 - \frac{e_d T_s}{L_g} i_d - i_d^{*2} + \frac{e_d T_s}{L_g} i_d^* + \frac{T_s^2}{4L_g C_{dc}} i_{load}^2 - \frac{C_{dc} u_{dc}^{*\,2}}{L_g} - \frac{C_{dc}}{L_g} u_{dc}^* i_{load}^* = 0 \quad (28)$$

(28) is a variable quadratic equation with a variable, and the constant in the equation can be expressed as:

$$M = \frac{e_d T_s}{L_g} i_d^* - i_d^{*2} - \frac{C_{dc} u_{dc}^{*\,2}}{L_g} - \frac{C_{dc}}{L_g} u_{dc}^* i_{load}^* \quad (29)$$

And according to the energy relationship we can see that M is always positive. Substituting (29) into (28) yields:

$$i_d^2 - \frac{e_d T_s}{L_g} i_d + \frac{T_s^2}{4L_g C_{dc}} i_{load}^2 + M = 0 \quad (30)$$

Solve the equation for the constraints of the variable. And there is only one suitable equation root as a system constraint:

$$i_d = \frac{e_d T_s}{2L_g} + \sqrt{M - \frac{T_s^2}{4L_g C_{dc}} i_{load}^2} \quad (31)$$

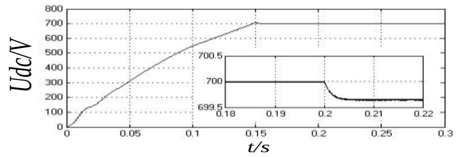
According to (27) and (31) we can see the direct relation between system DC bus voltage, network side d-axis current and load current. And the rectifier voltage outer ring and the power inner ring can be corrected according to the constraint condition to achieve smooth adjustment of the system energy.

IV. SIMULATION ANALYSIS

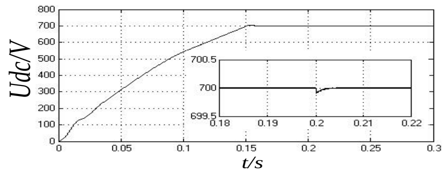
On the basis of the above theoretical research, a dual PWM simulation model is built on Simulink simulation platform. Simulation parameters: Rectifier phase voltage valid values 220V, network side inductance Lg = 15mH, DC side capacitor Cdc = 8000uF, DC bus voltage command value udc* = 700V, sampling frequency f = 5000Hz. The inverter output frequency is 50Hz. Three-phase asynchronous motor capacity 5000VA ,, sampling frequency fan f1 = 5000Hz, rotor inductance Lr = 0.002H, rotor resistance Rr = 0.816Ω, stator inductance Ls = 0.002H, stator resistance Rs = 0.435Ω, motor speed command value 800rad / s , Flux command value 1.

In order to verify the accuracy of the simulation, first replace the inverter side of the motor and the inverter with the resistance to verify the effectiveness of the correction of the PWM inner loop and the voltage outer ring under the constraint conditions. And then replace the resistor into the inverter and the motor to constitute a dual PWM structure by the simulation experiment to verify the overall performance of the system.

Compare the load power performance in the systems with constraints and without constrains when the PWM rectifier use direct power control. As shown in Fig.3, load resistance is 400Ω , while at 0.2s, the load resistance mutates to 200Ω. :



(a) DC bus voltage before correction



(b) DC bus voltage aftercorrection

Figure.2. Load power mutation DC bus voltage waveform

Fig.2 (a) is the voltage outer ring using PI controller and does not use the constraints of the control system. When the load power mutates at 0.2s, the decrease of DC bus voltage is about 0.3V. But the DC bus voltage is difficult to adjust because of the static difference. Fig.2 (b) is the use of constraints on the voltage outside the ring and the power of the inner ring to be amended at 0.2s when the load power mutation, the DC bus voltage drop is almost negligible, and there is no static difference, so the system can quickly return to stability state.

Grid side harmonic components and power factor are also an important measure of system performance. Take a phase of the network side as an example, as shown in Fig.3:

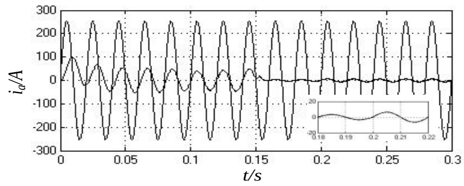


Figure.3. Network side a phase current voltage

In Fig.3, when the system is stable, the network side voltage and current can achieve the same phase. And in the load power mutation time, the voltage does not appear significant distortion and it is smooth and excessive. The power factor is shown in Fig.4:

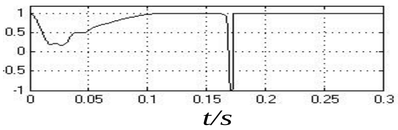
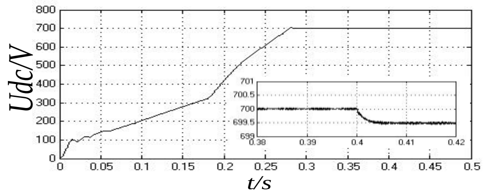


Figure.4. System power factor

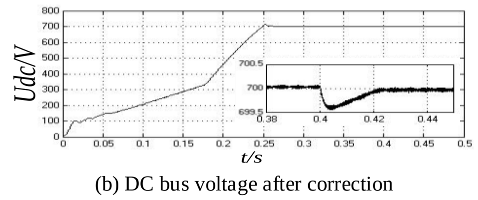
As shown in Fig.4, when the system is stable, the unit power factor output can be achieved.

According to the above simulation results of the resistive load of PWM rectifier, it can be explained that the correction of the system by using the constraint condition can eliminate the static voltage of the DC bus voltage, suppress the fluctuation of the DC bus voltage, and reduce the harmonic component of the network side. Therefore, this paper carries on the simulation analysis to the double PWM control structure. When the system is at 0.4s, the motor torque changes to 20N.m. The performance of control system with the constraint condition and the control system without the constraint condition are compared and analyzed.

Fig.5 is the dual PWM DC bus voltage fluctuations Figure:



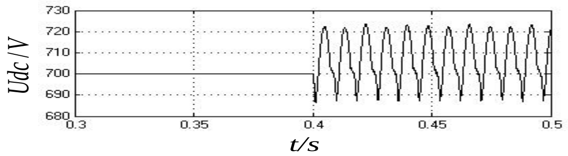
(a) DC bus voltage before correction



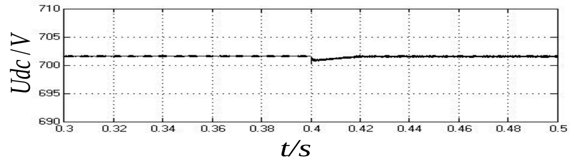
(b) DC bus voltage after correction

Figure.5. Motor torque change DC bus voltage waveform

According to the voltage fluctuation diagram, it can be seen that the modification of the system by using the constraint condition can eliminate the static difference due to the sudden change of the motor power, but the system adjustment time is increased compared with the pure resistance load mentioned above. The motor torque after the mutation to 40N.m, while reducing the system DC side capacitor is 2000uF. DC bus voltage shown in Fig.6:



(a) No correction torque 40N.m



(b) Correction after torque 40N.m

Figure.6. Motor torque 40N.m DC bus voltage waveform

It can be seen from Fig.6, the motor torque mutates to 40N.m, while reducing the DC side capacitor. The system in the case of no correction, DC bus voltage fluctuations in a wide range. When the torque changes to 40N.m by the constraint condition, the correction parameter has a certain error due to the reduction of the DC side capacitor, resulting in a static difference of about 2V, but the system DC bus voltage can still maintain the steady state.

No matter what kind of control method can be used, it can ensure the normal operation of three-phase induction motor. However, when the system is modified by the constraint condition, the load current fluctuates greatly from the DC bus, because the three-phase asynchronous motor is similar to the resistive load. Therefore, according to (9) the load current can be obtained..

The motor rotor flux is shown in Fig.7:

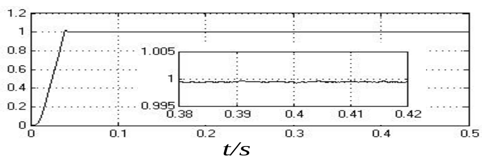
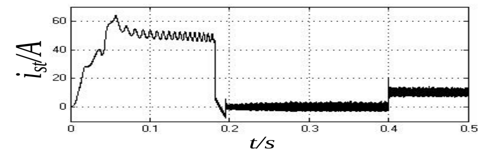
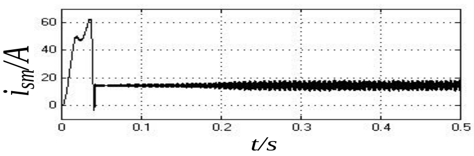


Figure.7. Motor rotor flux

Fig.7 shows that the motor rotor flux quickly stabilized, and the motor torque change does not affect the motor flux linkage, three-phase asynchronous motor can be partially equivalent to controlling the DC motor. However, due to the certain coupling between three-phase asynchronous motor excitation current and torque current, so there will be some static difference between the flux, which do little effect on the system. The excitation current and torque current are shown in Fig.8:



(a) Torque current



(b) Excitation current

Figure.8. Torque current and Excitation current

From Fig.8 we can see that the system excitation current quickly become constant, and the motor internal magnetic field is established. However, due to the coupling between the current, while the motor speed tends to the command value at 0.2s, the torque current drop, and the excitation current will be affected, with the waveform burr increasing and the static difference generating in rotor flux.

The motor speed is shown in Fig.9:

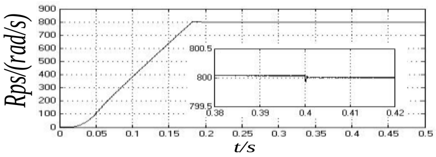


Figure.9. Motor speed

When the motor speed tends to command value at about 0.2s, there is about 0.1 turn of the static difference which is negligible. At 0.4s, the motor torque increases, and the decrease of motor speed drop is about 0.1 turn which is also negligible. Therefore, within the allowable range of motor power, the torque mutation has little effect on the motor speed.

V Concluding

In this paper, the characteristics of the energy flow of the double PWM structure are analyzed in detail, and the mathematical model of the energy change of the system is established from the point of view of energy flow. On the basis of the mathematical model, the constraint condition can adjust the energy power before and after the sudden change of the motor in a smooth way, so as to suppress the DC bus voltage fluctuation and reduce the harmonic component. According to the simulation results, it is shown that the correction of the rectifier side inner ring and the voltage outer ring by using the constraint condition can suppress the voltage fluctuation and reduce the harmonic current of the network side current. At the same time it can reduce the DC side capacitor capacity to ensure the normal operation of the motor and the coordinated control of dual PWM.

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