

Simulation Research of the Matrix Converter Based on Direct Torque Control

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Abstract: To advance the performance of AC adjustable speed system and to reduce the pollution to power network, this paper proposes a compound control strategy which combines Matrix Converter (MC) and direct torque control (DTC). The MC controlled by this strategy cannot only achieve DTC to a asynchronous machine but also acquire good input currents and adjustable power factor. The principle of this strategy is: firstly transform MC into an equivalent topology that is a combination of a rectifier and an inverter, and then perform DTC on inverter and current space vector modulation on the rectifier, at last combine two sides' strategies and change them into the control signals of the MC's nine bidirectional switches. A simulation about MC driving asynchronous machine has been done and the results prove that the strategy proposed by this paper is not only feasible but also excellent.

Index Terms: matrix converter; direct torque control; SVPWM

1 Introduction

The pivotal equipment of variable speed system is a frequency converter. At present variable speed system with middle and low power mainly adopts indirect converter (so called AC-DC-AC converter). Traditional indirect converter has a DC link consisted of a large inductance and a large capacitor. The dynamic response is slow and further more the input current of this converter contains a lot of harmonics which make pollutions to the power network and reduce the power factor of the variable system. Matrix converter (MC) overcomes the disadvantages of traditional indirect converter. Without DC energy storage link MC has good dynamic response characteristics. It can also get sinusoidal input current, sinusoidal output voltage and adjustable input displacement factor (IDF).

The early research about MC was focused on two key problems: the implementation and communication of four-quadrant switches (4QSW's) and the MC control. The former has been solved by combination of two-quadrant switches (2QSW's) and four step communication method^[1]. About the latter, many control algorithms have been put forward. These algorithms can be classified into two kinds: one is direct conversion method, another is indirect conversion method. The most widely used algorithms are space vector modulation (SVPWM)^[2] and instantaneous input voltage synthesis method^[3]. They are indirect conversion method. These methods aim to acquire expected open-loop sinusoidal output voltage. [4] presents an closed-loop vector control method for MC.

When MC is used to drive and control asynchronous machine, a close-loop control algorithm which combines MC and direct torque control (DTC) can be adopted. The main principle of DTC is to control the torque of motor by keeping the amplitude of stator's flux linkage and changing the angle between the stator's flux and rotor's flux. Compared to the vector control, DTC has its advantages. DTC gets rid of complex math transformation and it is not vulnerable to the impressible rotor's parameter. This paper presents a compound control strategy which combines Matrix Converter (MC) and direct torque control (DTC) based on SVPWM. The kernel principle of this strategy is as follows. First MC is transformed into an equivalent combination of rectifier and inverter^[2]. Then SVPWM is made on the rectifier to acquire the sinusoidal input current and adjustable power factor, DTC is made on the inverter to achieve a high-quality control for motor. The simulation results presented at the last part of this

paper show that the strategy presented in this paper is feasible.

2 Compound control strategy

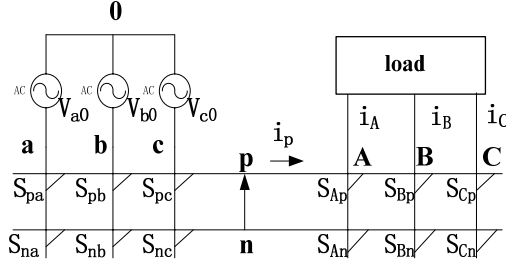


Fig.1 Equivalent virtual rectifier and inverter

According to the indirect conversion method, MC can be transformed into an equivalent combination of rectifier and inverter. As figure 1 shows. This equivalent structure has an virtual DC link.

To combine MC and DTC, we can implement DTC on the virtual inverter; to gain sinusoidal input current and adjustable power factor, it is needed to implement current SVPWM^[2]. At last the control strategies at both sides should be combined and changed into the compound control strategies of the nine bi-direction switches of MC.

(1) DTC on the virtual inverter

Based on the theory of asynchronous machine, it can be proved that the electromagnetic torque of machine under the stable $\alpha - \beta$ two axes reference frame can be calculated by (1)

$$T_e = n_p \cdot \frac{L_m}{L_s L_r - L_m^2} \cdot |\psi_1| \cdot |\psi_2| \cdot \sin \theta. \quad (1)$$

In (1) T_e is the electromagnetic torque; n_p is the pole number; L_s and L_r denote the inductance of stator and rotor respectively, L_m is the mutual inductance between stator and rotor. ψ_1 and ψ_2 are denote the flux linkage vector of stator and rotor respectively. θ is the angle between them. All these variable are under the $\alpha - \beta$ reference frame. And orthogonal transform is used in this paper to transform three phase system into two phase system. From (1)

we learn the electromagnetic torque is determined by the amplitude and angle of stator's and rotor's flux linkage. In practical operation, the amplitude of stator's flux linkage should be kept on the **nominal** level. Electromagnetic torque can be changed by changing θ ^[5]. The variation of θ is achieved by controlling the rotating speed of stator's flux linkage. This is implemented by choosing voltage vector of inverter eventually.

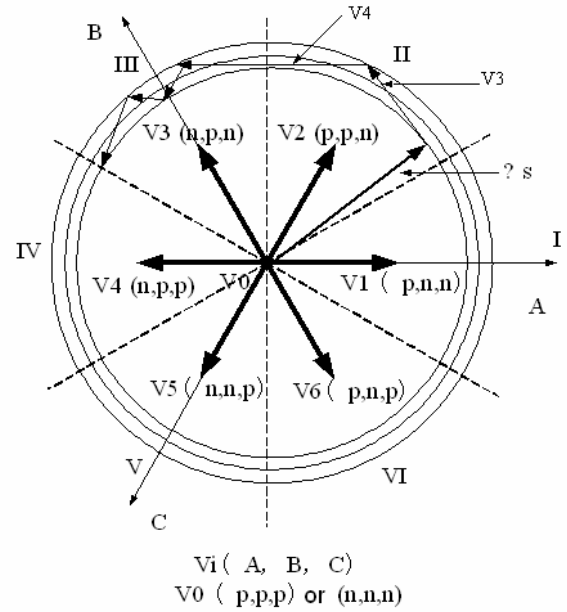


Fig.2 Voltage space vector on the virtual inverter side and flux trace of motor stator

If the middle point is defined as neutral point, the voltage vector, the axes of three phase of motor and sectors can be drawn as figure 2. In figure 2 the broken lines divided the plane into six sectors. In the three homocentric circles, the middle one denotes the reference value of stator's flux linkage, and the circles on two sides denote the tolerance. The amplitude of stator's flux linkage and torque are controlled by two hysteresis controllers respectively. The inverter has 8 voltage vectors $V_0 \sim V_7$. Every vector correspond to one state of inverter's switches. To keep the trace of flux linkage always in the tolerance and to insure the rotating speed of stator's flux linkage comply with the reference value of torque, we need to choose voltage vector in reason. It is based on sector signal n , flux

linkage error signal $\Delta\psi$ and torque error signal ΔT to choose the optimal voltage vector. For example, at a particular instant, the output voltage vector is in the first sector, if $\Delta\psi > 0$, then the actual flux linkage is smaller than the reference value and needed to increase. According to figure 2 two vectors can make the flux linkage increase. They are V2 and V6. If $\Delta T > 0$ meanwhile, that means the actual torque need be increased, then we can only choose vector V2 because only V2 can increase the rotating speed so as to increase the torque. Inversely if $\Delta T < 0$, only V6 can be chose. To reduce the frequency of switches, the torque hysteresis controller can be improved into a three-level comparator (see figure 3). It's principle is as follow: if $\Delta T > \mu$ (μ is torque tolerance), then increase torque; if $\Delta T < -\mu$, then reduce torque; if $-\mu < \Delta T < \mu$, then keep the stator's flux linkage stable by choosing zero vector V0 or V7.

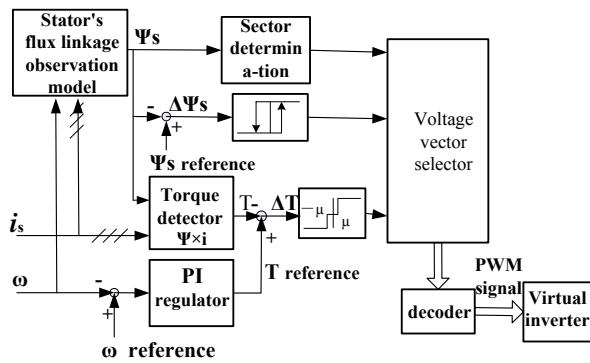


Fig.3 principle diagram of direct torque control on the virtual inverter side

Figure 3 is the block diagram of the principle of DTC on inverter side. To control the stator's flux linkage, estimate of torque and flux linkage is needed. About the estimation techniques Ref [5] presents many useful methods. In figure 3 the sector can be decided by the following method. First project the stator's flux linkage Ψ_s to the three phase axes to get three components Ψ_A, Ψ_B, Ψ_C . Then examine three components' polarity. Sector's serial number can be

decided by these polarities. For example, if three components' polarities are $+, -, -$, then Ψ_s is in sector 1 according to figure 2. The rest may be deduced by analogy.

(2) Current SVPWM on rectifier

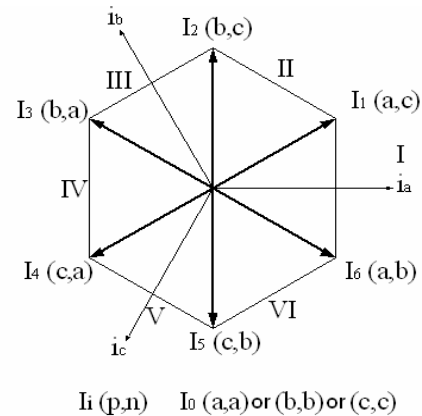


Fig.4 Current space vector and hexagon sector

The rectifier's current space vectors are shown as figure 4. There are six non-zero current vectors $I_1 \sim I_6$ and three different zero current vector denoted by I_0 . These vectors can be produced by rectifier directly and called switching state vectors (SSV's). The principle of current space vector modulation is to insert more current vectors in every sector so as to make the input current be more close to symmetrical sine wave. These inserted vectors can be synthesized by two adjacent SSV's and zero vectors according the synthesis principle of vector. [2] describes the principle of current SVPWM in detail.

(3) Compound control strategy

The current modulation on rectifier and DTC on inverter should be combined to form the control strategy of nine switches of MC. Each current vector I of rectifier and each voltage vector V of inverter can be combined to form an $I-V$ pair. Each $I-V$ pair correspond to only one state of MC's switches. Compound control can be implemented as follows. At each sample instant, execute the current SVPWM on virtual rectifier to choose the current vector I_i , execute DTC on virtual inverter to choose voltage vector V_j , then combine them to form vector pair I_i-V_j , at last

decode the vector pair $\mathbf{I}_i - \mathbf{V}_j$ to get the PWM signals of nine switches of MC. For example, the selected vector of rectifier and inverter are \mathbf{I}_1 and \mathbf{V}_1 respectively. Then the combined vector pair is $\mathbf{I}_1 - \mathbf{V}_1$. \mathbf{I}_1 correspond to the rectifier's state that S_{pa} and S_{nc} are closed and the others are open (see figure 1 and 4). \mathbf{V}_1 correspond to the inverter's state that S_{Ap} , S_{Bn} and S_{Cn} are closed and the others are open. Combining the switches' states on both side and making a transformation, we get the MC's state corresponding

to vector pair $\mathbf{I}_i - \mathbf{V}_j$. That is S_{aA} , S_{cB} and S_{cC} are closed and the others are open. The corresponding relationship between vector pair and switches' state of MC can be transformed into table and put into micro processor. Micro processor looks into this table and decodes it to produce the PWM signal of nine switches of MC.

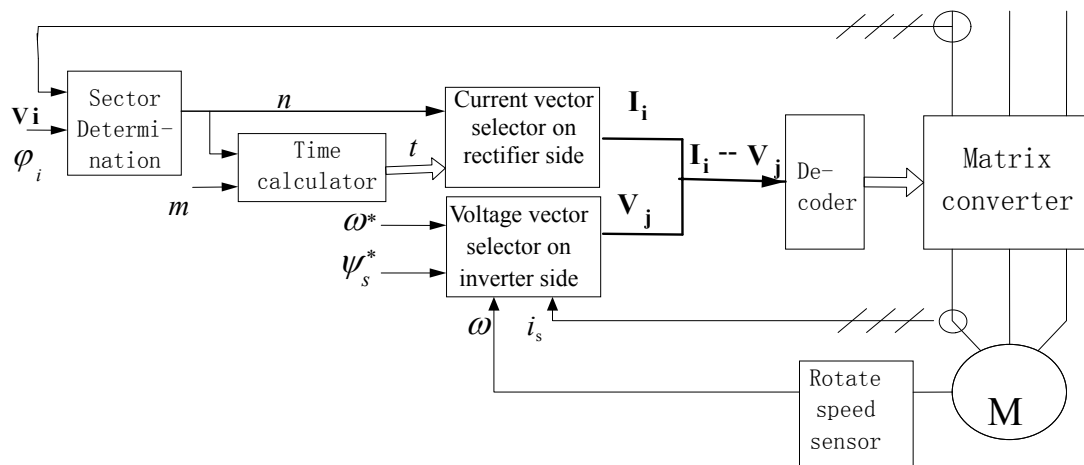


Fig.5 Combined controller block

Figure 5 is the block diagram of combined controller. φ_i is input power factor angle. It can be set arbitrarily. m is modulation index ($0 < m \leq 1$). It influences \bar{v}_{pn} that is the voltage of virtual middle DC link. The relationship between them is $\bar{v}_{pn} = \frac{3}{2} \times m \times V_{im} \times \cos \varphi_i$ [2]. To maximize the voltage of virtual middle DC link m can be set to unit. ω^* and ψ_s^* are the reference value of rotating speed and amplitude of stator's flux linkage respectively. This combined controller as figure 5 shows can be implemented by DSP.

3 Simulation result

Based on the strategy above, the author use software *Simulink* of *Matlab 7.0* to conduct a simulation. The simulation block diagram is shown in figure 5. The parameters of motor are as follows: $P_n = 4\text{kW}$, $V_L = 400\text{V}$, $n = 1430\text{rpm}$, $f_n = 50\text{Hz}$, $R_s = 1.045\Omega$, $R_r = 1.395\Omega$, $L_s = 178.039\text{mH}$, $L_r = 178.039\text{mH}$, $L_m =$

172.2mH , $J = 0.0131\text{kg}\cdot\text{m}^2$, Pole=2. The inductances above are all the equivalent inductance of motor's model under the $\alpha - \beta$ two stable axes reference frame. In the simulation course, ideal bi-direction switch is used as the main switches of MC. Fix-step four order Runge-Kutta method is used. The step is 0.05ms . The PI controller's parameter of rotate speed is: $P=0.8$, $I=5$. The input phase voltage of MC is 270V . The input power factor is set to unit. The amplitude of stator's flux linkage is kept on 1.2Wb .

Figure 6 is the dynamic response waveform when motor's rotate speed varies. The rotate speed command is $900\text{rpm} \rightarrow 1200\text{rpm} \rightarrow 900\text{rpm}$. In the simulation course, keep the load torque on $20\text{N}\cdot\text{m}$ that is 75% rating torque. In the figure ω_r is the rotator's speed, T_e is electromagnetic torque, i_{sa} is the current of phase a of stator. According to the figure, the dynamic response of rotate speed is rapid without overshoot. Response time of the system with load is not more than 0.3 second. Electromagnetic torque is

calm enough. Stator's current can enter into steady state rapidly. Start current of the motor with load is small enough, about 3~4 times bigger than rating current.

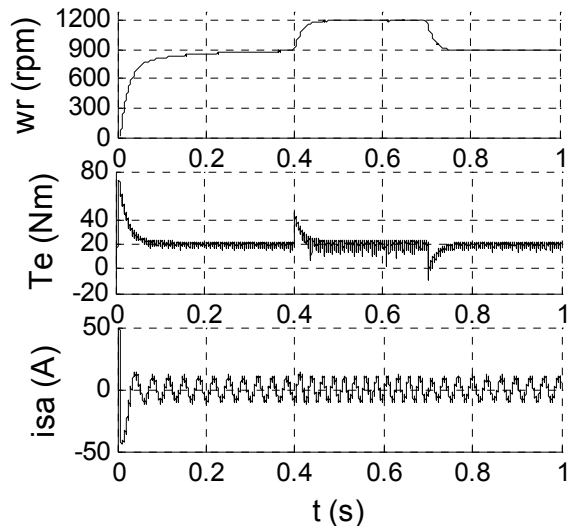


Fig.6 Dynamic response waveform under the variation of rotation speed

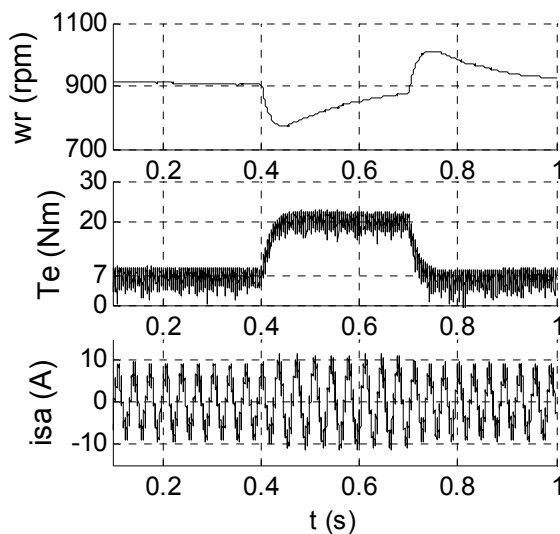


Fig.7 Dynamic response waveform under the variation of load

Figure 7 is the dynamic response waveform of the system when the load is sudden changed. The variation of load torque is: $7 \text{ N}\cdot\text{m} (25\% T_N) \rightarrow 20 \text{ N}\cdot\text{m} (75\% T_N) \rightarrow 7 \text{ N}\cdot\text{m} (25\% T_N)$. In simulation course the command of rotate speed is kept on 900 rpm. From the figure we can see that: when the load torque varies, the fluctuation is small, output electromagnetic torque can track the load torque rapidly.

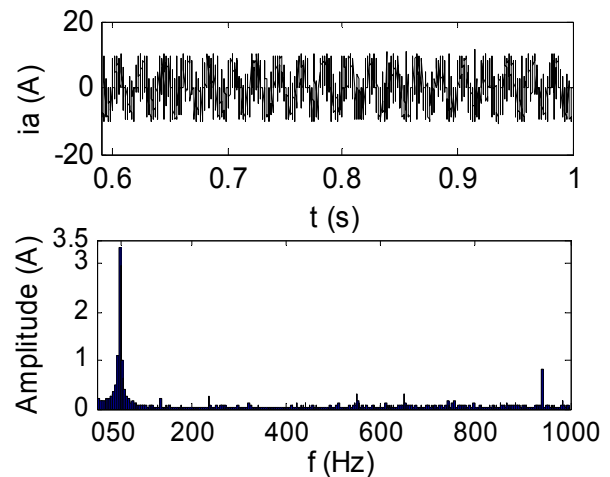


Fig.8 Waveform and spectrum of input phase a current

Figure 8 is the wave form and frequency spectrum of current of MC's input phase a. In simulation course keep rotate speed command on 900 rpm, load torque on 20N·m. From the figure we can see that: fundamental component is the main part in input current. There are also some high frequency harmonics. They can be easily filtered by adding a small filter. Figure 9 is the fundamental component's angle of the current of input phase a. the figure clearly shows that the input power factor can be reach 1. Figure 8 and indicate that the wave form of input current is very good and will cause little pollution to power network. Figure 10 is the trace plot of stator's flux linkage of motor. This circular plot corresponds to the demand of DTC.

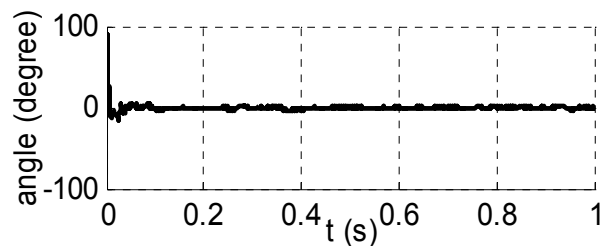


Fig.9 Fundamental wave's angle of input phase a current

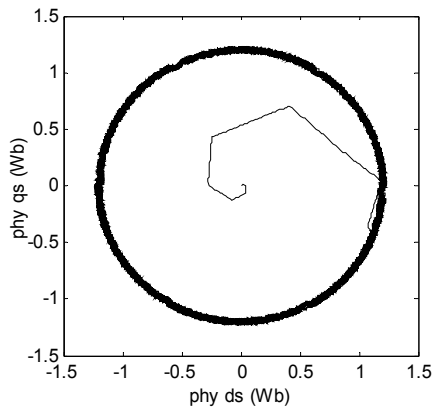


Fig.10 Flux vector trace of motor's stator

4 Conclusion

Based on the idea that using MC implements DTC, this paper proposed a compound control strategy for AC adjustable speed system. The MC controlled by this strategy cannot only achieve DTC to an asynchronous machine but also decrease pollutions to power network. The results of simulation show that when motor's speed or load varies, this strategy can make adjustable speed system exhibit good dynamic characteristics and can make MC have an input current closed to symmetrical sine wave. All these characteristics indicate that the compound control strategy proposed by this paper is not only feasible but also excellent.

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