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Direct torque control system for induction machine fed by space vector modulated matrix converter

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Abstract: Matrix converter (MC) has been studied widely for its advantages over the traditional converters. It is gradually employed for applications with its maturity in theoretical studies. A novel control strategy is put forward in this paper, which properly combines the space vector modulation of matrix converter with the direct torque control of induction machine through PI regulation of flux and torque. It improves the control performance of the system effectively, especially for the electric magnetic torque at low speed. This PI regulator is simpler and has better robustness compared with the deadbeat space vector modulation. First, conventional principles of DTC and space vector modulation of matrix converter were described. Then, the combination of the two was given in detail for PI regulator of flux and torque. Third, simulation model was set up for this new type of variable speed system. Finally, the simulation research was carried out for three types of loads. Simulation results have verified the feasibilities and strong adaptability of this novel control strategy, indicating that it is worth further studying.

Key words: matrix converter; induction machine; direct torque control; PI regulator; space vector modulation

空间矢量调制矩阵变换器驱动的异步电机直接转矩控制系统

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摘要: 矩阵变换器较传统的变换器具有一系列优点而成为研究热点, 随着其理论研究的接近成熟, 逐渐转向应用研究.提出了一种新颖控制策略. 通过磁链和转矩的PI调节, 把矩阵变换器的空间矢量调制与异步电机的直接转矩控制有机地结合起来, 改进了系统的控制性能, 尤其是电磁转矩的低速性能. 这种PI调节器相对简单和具有较强的鲁棒性, 比较无差拍空间矢量调制而言. 本文首先阐述了传统的直接转矩控制原理和矩阵变换器的空间矢量调制, 接着利用磁链和转矩的PI调节, 详细论述了两者的结合和实现过程, 并且在此基础上, 建立这种新型交流调速系统的仿真模型, 最后按照3种负载情况进行了仿真研究. 仿真结果验证了这种新颖控制策略的可行性和较强的鲁棒性.

关键词: 矩阵变换器; 异步电机; 直接转矩控制; PI调节器; 空间矢量调制

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1 Introduction

The research of matrix converter has been carried on for nearly 30 years with many theoretical achievements[1∼5]. These achievements along with the emergence of bidirectional switch make it possible to apply the matrix converter to practical applications. For example, An Chuan electric machine company in Japan has put forward their matrix converter products to the market[6]. In 2001, Casadei et al. set up a test system of conventional DTC for matrix converter-induction machine in experiments[7]. Meanwhile, scholars in China also began their research in their respect[8]. In 2006, K. B. Lee and F. Blaabjerg put forward the direct torque control strategy for matrix converter based on deadbeat space vector modulation[9]. He improved Casadei's conventional direct torque control. The advantage is that any space voltage vector can be produced to reduce the pulse of electric magnetic torque at low speed. However, it needs complicated calculation and may be difficult to implement. A novel control strategy is put forward based on PI regulator in this paper which improves the existing research achievements of inverter-

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induction machine DTC[10] by making full use of the the space vector modulation of matrix converter and the direct torque control of induction machine. It simplifies the calculation and gives good results.

2 Conventional principle of DTC

An AC variable speed system of three-phase induction machine fed by two-level inverter is taken as an example[11]. Three-phase output voltages are obtained respectively from 8 different safely switching combination modes. The space vectors of output voltages are defined by the formula of PARK transformation (6 working vectors, 2 zero ones) to form a vector hexagon. Two-level hysteresis control is used for flux control. A three-level one is used for electric magnetic torque control. The set-point value of electric magnetic torque is determined by the PI regulator based on the desired value of speed and the measured speed. The switching combination vector table of clock-wise and counter-clockwise stator flux is achieved according to various combination cases, corresponding to changes of flux and torque in each sector of output voltage vector hexagon. Direct torque control strategy is conducted by looking up this table for different combinations of the outputs of flux and torque hysteresis control. Thus, the required switching vector is achieved, producing the switching control signals for the required control.

3 Space vector modulation for matrix converter

The conventional three-phase to three-phase matrix converter is shown in Fig. 1.

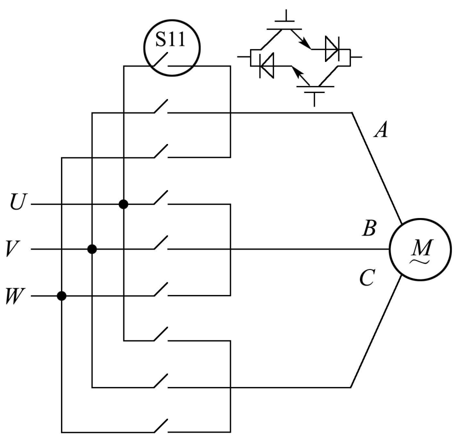

Fig. 1 The simplified topology of 3-3 MC

Its modulation process consists of two processes of AC-DC and DC-AC[1]. Its equivalent topology is represented in Fig.2. The control signals for bidirectional switches come from the control circuits and drive circuits. The ratio cycles of 9 bidirectional switches correspond to a 3×3 matrix in each switching period.

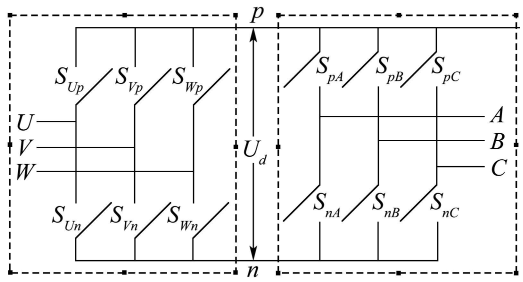

Fig. 2 The equivalent topology of 3-3 matrix converter

3.1 Space vector modulation of DC-AC converter

6 power switches of inverter with 8 possible combinations shown in Fig.1 are corresponding to 6 effective voltage space vectors $U_1 \sim U_6$ and 2 zero vectors U_0, U_7. The phase angle between one effective voltage space vector and the adjacent one is 60 degrees. They constitute 6 uniform segments. The three digits in brackets express the linking states between three-phase output A, B, C and the input DC, such as $M = 101$ which represents the switching of switches S_{pA}, S_{nB}, S_{pC}.

The output voltage space vectors and the corresponding switching states are represented in Fig.3. Any expected output voltage space vector U_J is formed by adjacent two basic output voltage vectors U_M, U_N and zero output voltage U_0 or U_7.

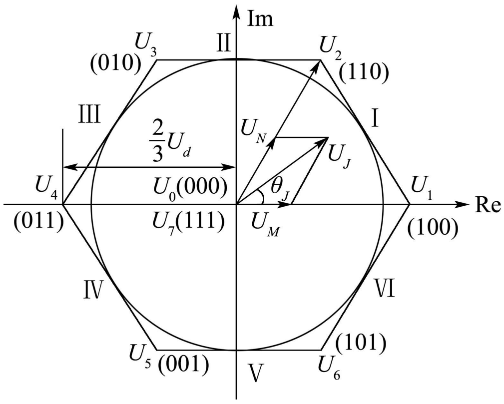

Fig. 3 The composition of output voltage vectors and its switching states

Suppose the angle between U_J and U_M is θ_J, Then

$$U_J = d_M U_M + d_N U_N + d_0 U_0. \tag{1}$$

Where d_M, d_N and d_0 are the ratio cycles of U_M, U_N and U_0 respectively. And

$$d_M = T_M/T_s = m_v \sin(60^\circ - \theta_J), \quad (2)$$

$$d_N = T_N/T_s = m_v \sin\ \theta_J, \quad (3)$$

$$d_0 = 1 - d_M - d_N. \quad (4)$$

Where T_M, T_N is the switching time of vectors U_M and U_N respectively. T_s is the switching period of PWM, m_v is the modulation index of output voltage. And

$$m_v = \left(\frac{2}{3}\right)^{1/2} U_{om}/(U_{im} m_c \cos\ \varphi_i). \quad (5)$$

Where V_{om} and V_{im} are the amplitudes of output voltage and input voltage, m_c is the input current modulation index, generally set $m_c = 1.0$, φ_i is the input power factor angle.

When the rotating space vector U_J locates in a segment, the local average of output voltage can be formed by two adjacent basic voltage space vectors constituting this segment and one zero voltage space vector. For example, the reference voltage vector locates in the first segment, the local average of the line to line output voltage is represented as follow:

$$[U_{AB} U_{BC} U_{CA}]^{\mathrm{T}} = [(d_1 + d_2) - d_1 - d_2]^{\mathrm{T}} U_d = T_{VSI} U_d. \quad (6)$$

Where T_{VSI} is the switching function conversion matrix. Please see Reference[1].

3.2 The space vector modulation of AC-DC converter

The space vector modulation process of AC-DC is completely similar to the modulation process of DC-AC. Its topology is represented in the left dotted line frame of Fig.2. The corresponding formulas are similar as well. After rectification, the DC voltage is

$$U_d = V_{VSR}^{\mathrm{T}} [U_a U_b U_c]^{\mathrm{T}} = 1.5 m_c U_{im} \cos\varphi_i. \quad (7)$$

The formula can be seen from Reference [1].

3.3 Synthesis of the two processes

The DC voltage and current are generated by matrix converter. In fact, the rectification and inversion are carried out in the same time. The following formula can be derived from formula (6) and (7):

$$[U_{AB} U_{BC} U_{CA}]^{\mathrm{T}} = T_{VSI} T_{VSR}^{\mathrm{T}} [U_a U_b U_c]^{\mathrm{T}}. \quad (8)$$

Where $T_{VSI} T_{VSR}^{\mathrm{T}} = T_{phl}$ is the modulation function matrix for matrix converter based on SVM.

In the modulation process, there are five switching combinations in a switching period. Correspondingly, there are 5 ratio cycles as well, which are as follows after synthesis:

$$D_1 = d_M d_\alpha = m \sin(60^\circ - \theta_J) \sin(60^\circ - \theta_k), \quad (9)$$

$$D_2 = d_N d_\alpha = m \sin\theta_J \sin(60^\circ - \theta_k), \quad (10)$$

$$D_3 = d_M d_\beta = m \sin(60^\circ - \theta_J) \sin\theta_k, \quad (11)$$

$$D_4 = d_N d_\beta = m \sin\theta_J \sin\theta_k, \quad (12)$$

$$D_0 = 1 - (D_1 + D_2 + D_3 + D_4). \quad (13)$$

There are 6 segments for input currents and output voltages respectively. So there are 36 switching combinations while each combination includes the case of a switching period. Therefore, there are 180 switching combinations altogether. See Reference[9].

4 Realization of the new control strategy

The DTC for induction machine and SVM for matrix converter are properly combined by PI regulator of flux and torque in this paper. This PI regulator is simpler and has better robustness compared with deadbeat space vector modulation[9]. It makes the system being controlled as a whole, and the shortcoming of torque fluctuation being effectively removed at low speed. The detailed process is represented in Fig.4. On the one hand, the phase angle of the input voltage is determined in two steps. First, the three-phase voltage is transformed from the stationary coordinates to the two-phase voltage stationary coordinates (3/2) to obtain two phase voltages u_α and u_β; and then, they are transformed from the stationary coordinates to the polar coordinates (K/P) to obtain the phase angle of the input voltage. Because the input power factor is set to unity based on the characteristic of matrix converters, thus, the phase angle of the input current is the same as the phase angle of the input voltage. Consequently, the segment mumber S_I of the input current, and the associate phase angle θ_1 of the input current in this segment can be determined. On the other hand, the measured speed of three-phase induction machine is compared with the set-point value, then the set-point electric magnetic torque T_e^* is obtained through PI regulator. The voltage component u_{qs} and u_{ds} of q-axis and d-axis are obtained in the synchronous rotating coordinate system by PI regulator in which T_e^* is compared with the calculated electric magnetic torque T_g. The components $u_{\beta s}^*$ and $u_{\alpha s}^*$ are obtained in two-phase stationary coordinate system through rotational transformation. Consequently, the modulation index m_v, segment number S_V and current phase angle θ_2 of output voltage can be calculated. Finally, the acting time $t_1 \sim t_4$ and t_0 of 5 switching combinations are calculated for a switching cycle by θ_1, θ_2 and m_v (set input current modulation index $m_c = 1.0$); the comprehensive switching table[12] is looked up to get 5 switching combinations in a switching period by segment signals S_I and S_V. The 9 switching control signals are produced by decoding the switching combination of each time segment of a switching period in sequences. These signals control the matrix converter to produce the variable frequency and amplitude of output voltages. Thus, the three-phase induction machine is driven, and the novel DTC AC variable speed control is realized (Bidirectional switches are chosen as ideal switches).

The calculation of flux and torque is very important. Flux is calculated by $u - n$ model[11]. There are four parameters to be given.

The output voltage amplitude U_{om} of expression (5) is calculated:

$$U_{om} = ((u^*_{\alpha s})^2 + (u^*_{\beta s})^2)^{1/2}. \tag{14}$$

The electric magnetic torque T_e is as follow:

$$T_e = \frac{3}{2}(\Psi_{s\alpha} i_{s\beta} - \Psi_{s\beta} i_{s\alpha}). \tag{15}$$

5 Modeling and simulation

The system simulation model is shown in Fig.4 based on the former analysis. Several S-functional models are used to realize the predication of segments, calculation of phase angles, look-up table of switching combinations, and decoding of switching signals, etc.[13~16].

The basic parameters for three-phase induction machine: $S_N = 3$ kVA, rated line to line voltage $U_N = 380$ V, $f_N = 50$ Hz, $Rs = 0.435\ \Omega$, $Ls = 2.0$ mH, $Rr = 0.816\ \Omega$, $Lr = 2.0$ mH, $Lm = 69.31$ mH, the number of pairs of poles is 2.

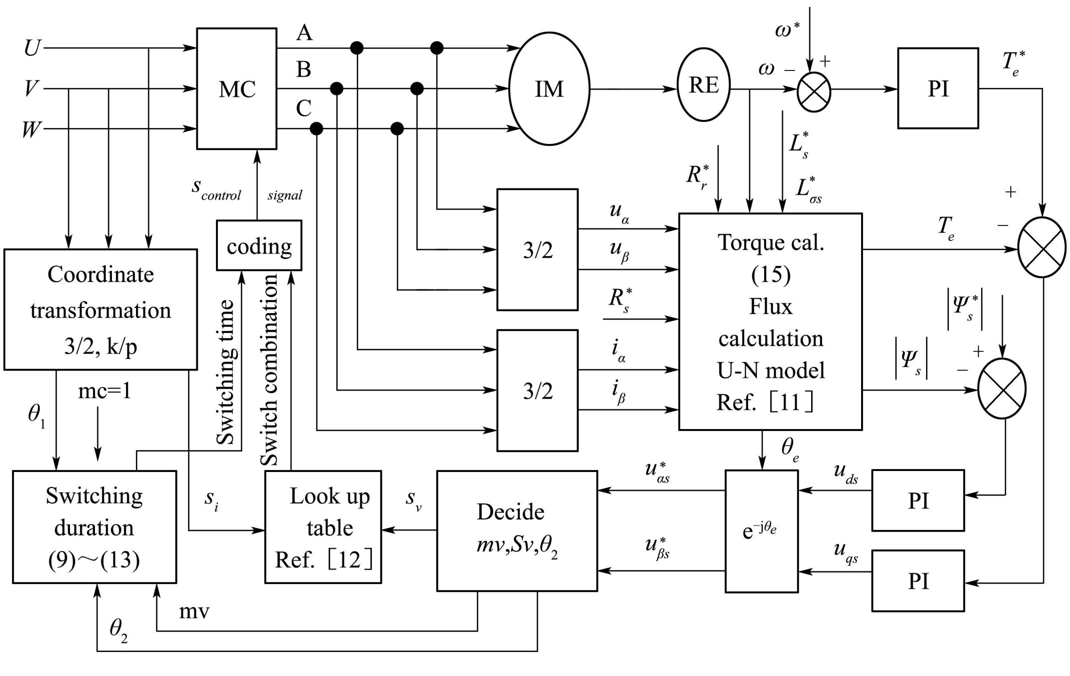

Fig. 4 Matrix converter-DTC novel control strategy system based on PI controller

The line-to-neutral voltages of the three-phase input are 220 V, input frequency is 50 Hz.

1) Induction machine operation with no load: rotating speed is 360 r/min, the simulation waveforms are represented in Figs.5 to 7.

2) Induction machine operation with constant load: rotating speed is 360 r/min, loads torque $T_m = 15$ N·m, the simulation waveforms are represented in Figs.8,9.

3) Induction machine operation with variable load: rotating speed 360 is r/min, load torque $T_m = 30$ N·m~10 N· m, the simulation waveforms are rep-

resented in Figs.10 to 12.

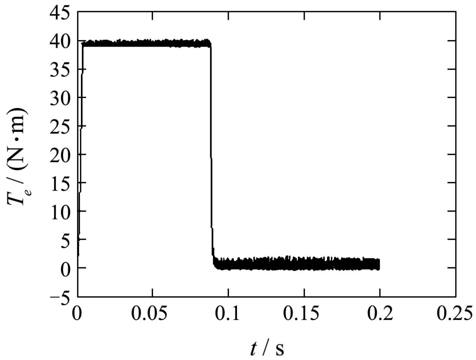

Fig. 5 The waveform of electric magnetic torque

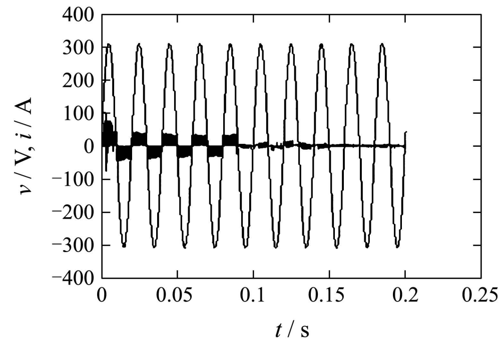

Fig. 6 The input voltage and current of matrix converter

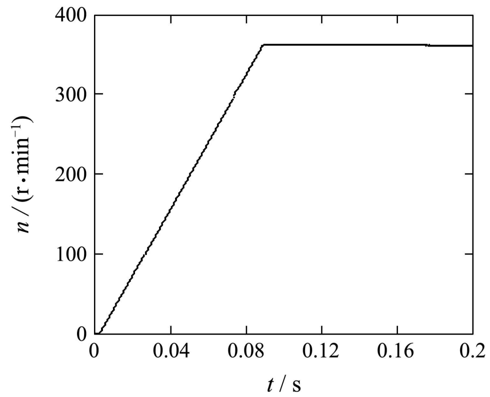

Fig. 7 The response of rotating speed of induction machine

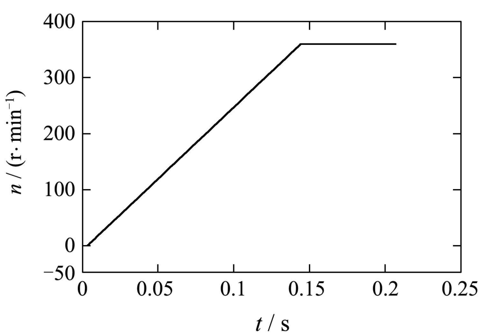

Fig. 8 The response of rotating speed of induction machine

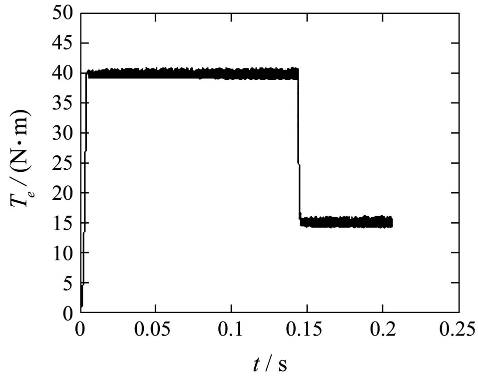

Fig. 9 waveform of electric magnetic torque

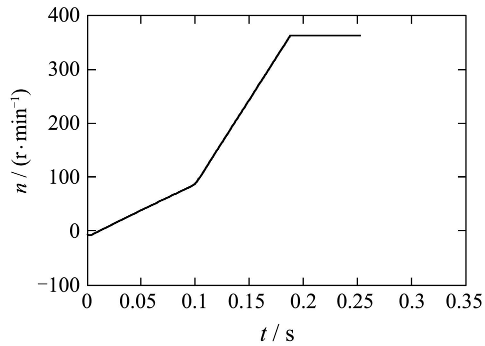

Fig. 10 The response of rotating speed of induction machine

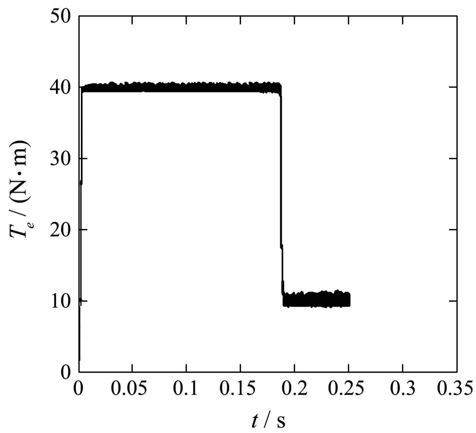

Fig. 11 The waveform of electric magnetic torque

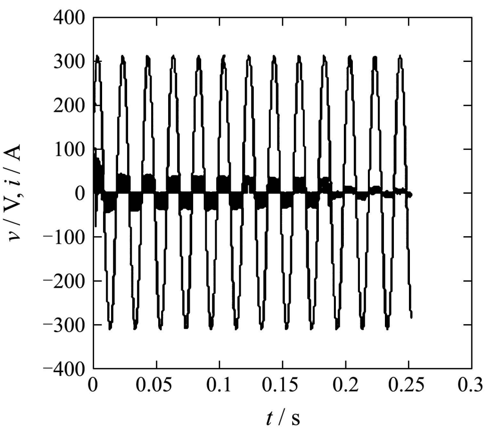

Fig. 12 The input voltage and current of matrix converter

In the above three cases, the response of rotating speed of induction machine is fast; electric magnetic torque is stably controlled; input power factor reaches 1.0, and the application efficiency of input voltages is high. So the novel control strategy is feasible and advantageous.

6 Conclusion

1) The novel control strategy is calculated simply and implemented easily.

2) The novel control strategy makes the fluctuation of electric torque of induction machine small and stable.

3) The novel control strategy makes the application efficiency of voltages high.

In conclusion, the novel control strategy is simple and feasible. It has advantages and good future. It is worth further studying.

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