# A SINGLE-INVERTER MULTI-MOTOR SYSTEM BASED ON DIRECT TORQUE CONTROL

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*This paper presents a method of controlling multi motors and deduces a universe equation based on the direct torque control with a single inverter. And the simulation results have verified the result of theoretical analysis. Through the simulation and experimental research, the feasibility of single-inverter multi-motor DTC system has been verified.*

**Keywords**: direct torque control, single-inerter multi-motor, average algorithm

## 1. Introduction

In conventional industrial applications, one motor is generally driven by one inverter. With the rapid development of modern industry, conventional single-inverter single-motor system cannot satisfy the need of industrial applications such as electrical railway and high power drive systems. Multi-motor system can drive multiple motors simultaneously and coordinately. In considering of the different field of controlling dual motors simultaneously, there are three control strategies: dual-inverter dual-motor system (independent control of dual motors); dual-inverter dual-motor system (coordinate control of dual motors); single-inverter dual-motor system. The application of single-inverter dual-motor system can make the whole system low cost, flexible operation, high compactness and high reliability.

Direct torque control (DTC) technology is a new and high efficient motor control scheme following of vector control [1]. Based on the basic theory of direct torque control, in order to implement the single-inverter multi-motor system, an innovative method based on the average field-oriented direct torque control scheme is proposed. The feasibility of the single-inverter multi-motor DTC system is verified with the help of PSIM. By all kinds of disturbance, both the stable response and the transient response perform well, which can satisfy the requirements of the control characteristics.

Considering the high stable and transient performance of DTC scheme, the project aims to successfully apply this technology to high-power and high-speed electric locomotive, subway and urban trolley in the transmission system [2-3].

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Experimental and simulation results verify that the single-inverter multi-motor DTC system can drive difference motors with different loads. And using the TMS320F28335 DSP as core of the system to build the hardware control platform, which can be used to generate the PWM (pulse width modulation) waves, realize the algorithm, AD conversion and fault detection, then this technology will be used in the real life in the end.

## 2. DTC Strategy of the Inverter Driving n Sets of Induction Motors

At first, the dynamic model of the induction motor DTC has been established, its equations[4-5] are described below:

Voltage equation:

$$\begin{cases} v_{sd} = R_s i_{sd} + p\psi_{sd} - \omega_s \psi_{sq} \\ v_{sq} = R_s i_{sq} + p\psi_{sq} + \omega_s \psi_{sd} \\ 0 = R_r i_{rd} + p\psi_{rd} - (\omega_s - \omega_r)\psi_{rq} \\ 0 = R_r i_{rq} + p\psi_{rq} + (\omega_s - \omega_r)\psi_{rq} \end{cases} \tag{1}$$

Flux equation:

$$\begin{cases} \psi_{sd} = L_s i_{sd} + L_m i_{rd} \\ \psi_{sq} = L_s i_{sq} + L_m i_{rq} \\ \psi_{rd} = L_r i_{rd} + L_m i_{sd} \\ \psi_{rq} = L_r i_{rq} + L_m i_{sq} \end{cases} \tag{2}$$

Torque equation:

$$T_e = n_p \frac{L_m}{L_r}(i_{sq}\psi_{rd} - i_{sd}\psi_{rq}) = n_p \frac{L_m}{L_r}(i_s \times \phi_r) \tag{3}$$

where $v_s$ is the stator voltage of the stationary $\alpha - \beta$ plane; $i_s$ and $i_r$ are the stator and rotor current; $\psi_s$ and $\psi_r$ are the stator and rotor flux; $L_s, L_r, L_m$ are self-inductance and mutual-inductance.

When one inverter drives several motors, the current distortion of each motor will be unbalance whether the load changes or not. According to the conventional DTC theory, the magnetic torque of each motor with different load is different; also each rotor flux angle is different. So we have to improve the conventional DTC to meet the need of multi-motor system.

### 2.1 The Current and Voltage Model of the Parallel Models

In a single-inverter driving double motors DTC system, the two motors run in parallel, the input voltage of two motors are same. But due to the difference in their working state, load situation and loss; the current distribution of the two motors is unbalance.

In the theoretical derivation process, an average algorithm has been obtained [6]-[9]. The current of each motor can be calculated in terms of current's average value and the difference of the two motor's currents. Then the inverters can be controlled to drive the motors normally according to the feedback. The relationship of the different motor current is shown in Fig.1.

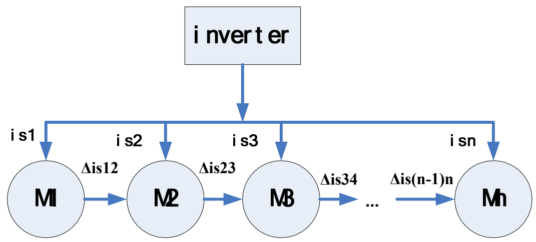



Fig.1 the current relationship of different motors

Then,

$$\bar{i}_s = \frac{1}{n}(i_{s1} + i_{s2} + \cdots i_{sn}) \tag{4}$$

$$\begin{cases} \Delta\bar{i}_{s_{12}} = \dfrac{i_{s_2} - i_{s_1}}{2}; \\ \Delta\bar{i}_{s_{13}} = \dfrac{i_{s_3} - i_{s_1}}{2}; \\ \dots \\ \Delta\bar{i}_{s_{ij}} = \dfrac{i_{s_j} - i_{s_i}}{2}; \\ \dots \\ \Delta\bar{i}s_{(n-1)n} = \dfrac{is_n - is_{n-1}}{2}; (i, j = 1 \dots n, i < j) \end{cases} \tag{5}$$

So,

$$\begin{cases} i_{s_1} = \bar{i}_s + \dfrac{2}{n}(-\Delta\bar{i}_{s_{12}} - \Delta\bar{i}_{s_{13}} \dots - \Delta\bar{i}_{s_{1n}}); \\ i_{s_2} = \bar{i}_s + \dfrac{2}{n}(\Delta\bar{i}_{s_{12}} - \Delta\bar{i}_{s_{23}} \dots - \Delta\bar{i}_{s_{2n}}); \\ \dots \\ i_{s_n} = \bar{i}_s + \dfrac{2}{n}(\Delta\bar{i}_{s_{1n}} + \Delta\bar{i}_{s_{2n}} \dots + \Delta\bar{i}_{s_{(n-1)n}}); \end{cases} \tag{6}$$

Similarly, the voltage model of different motors can also be adopted through the average algorithm.

$$
\begin{aligned}
&U_{S1} = \bar{U}_S + \frac{2}{n}(\Delta\bar{U}_{S12} + \Delta\bar{U}_{S13} + \cdots + \Delta\bar{U}_{S1n}) \\
&U_{S2} = \bar{U}_S + \frac{2}{n}(\Delta\bar{U}_{S22} + \Delta\bar{U}_{S23} + \cdots + \Delta\bar{U}_{S2n}) \\
&\ldots\ldots \\
&U_{Sn} = \bar{U}_S + \frac{2}{n}(\Delta\bar{U}_{Sn2} + \Delta\bar{U}_{Sn3} + \cdots + \Delta\bar{U}_{Sn(n+1)})
\end{aligned} \tag{7}
$$

where,

$$\Delta\bar{U}_{12} = \frac{U_2 - U_1}{2}; \Delta\bar{U}_{13} = \frac{U_3 - U_1}{2}; \ldots; \Delta\bar{U}_{ij} = \frac{U_j - U_i}{2}; \ldots; \Delta\bar{U}_{(n-1)n} = \frac{U_n - U_{n-1}}{2}; (i, j = 1 \ldots n, i < j)$$

### 2.2 The Flux and Torque Model of Different Motors

By the use of the average algorithm, the different motors' flux model can be obtained from basic flux of the mean and difference value [10-12]:

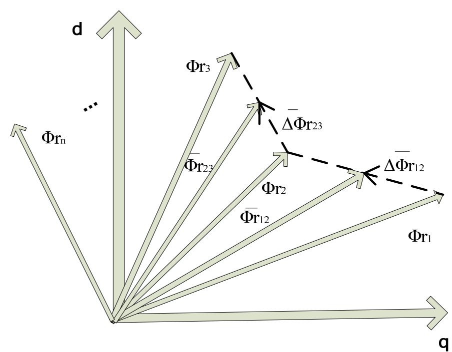



Fig.2 the rotor flux model of different motors

From the equation (1), (2):

$$\frac{d}{dt}\bar{\psi}^e = \bar{U}_S^e - \bar{i}_S^e R_S \tag{8}$$

where $\bar{\psi}^e$ is the coordinate of flux, $\bar{U}^e$ is voltage vector, $\bar{i}_S^e$ is stator current vector, $R_S$ is the stator resistance, then average different motors:

$$\bar{\phi}_r^e = \frac{\phi_{r1}^e + \phi_{r2}^e + \ldots + \phi_{rn}^e}{n}; \tag{9}$$

$$
\begin{aligned}
&\Delta\bar{\phi}_{r1}^e = \frac{2}{n}(-\Delta\bar{\phi}_{12}^e - \Delta\bar{\phi}_{13}^e \ldots - \Delta\bar{\phi}_{1n}^e); \\
&\Delta\bar{\phi}_{r2}^e = \frac{2}{n}(\Delta\bar{\phi}_{12}^e - \Delta\bar{\phi}_{23}^e - \ldots - \Delta\bar{\phi}_{2n}^e); \\
&\ldots\ldots \\
&\Delta\bar{\phi}_{rn}^e = \frac{2}{n}(\Delta\bar{\phi}_{1n}^e + \Delta\bar{\phi}_{2n}^e + \ldots + \Delta\bar{\phi}_{(n-1)n}^e);
\end{aligned} \tag{10}
$$

For the torque model of different motors is the same from each induction motor, using the equation (8), each motor torque formula will be accumulated by using average algorithm. By means of calculating the average torque through the average value and difference value of the flux, the torque equation can be got with the average torque and difference value of each motor and some motor parameters:

$$\overline{T} = n_p \frac{L_m}{L_r}\overline{T_e} - \frac{2}{n^2} n_p \frac{L_m}{L_r}(\Delta\overline{T}_{12} + \Delta\overline{T}_{13} \cdots + \Delta\overline{T}_{1n} + \Delta\overline{T}_{12} + \Delta\overline{T}_{13} \cdots + \Delta\overline{T}_{2n} + \cdots \Delta\overline{T}_{(n-1)n} \quad (11)$$

where $T_{e1}, T_{e2}, ..., T_{en}$ are the each motor torque respectively.

$$\overline{T_e} = \frac{T_{e1} + T_{e2} + ... + T_{en}}{n}; \Delta\overline{T}_{e12} = \frac{\left(T_{e2} - T_{e1}\right)}{2}; \Delta\overline{T}_{e13} = \frac{\left(T_{e3} - T_{e1}\right)}{2}; ...; \Delta\overline{T}_{eij} = \frac{\left(T_{ej} - T_{ei}\right)}{2};$$
$$...; \Delta\overline{T}_{e(n-1)n} = \frac{\left(T_{en} - T_{e(n-1)}\right)}{2}; (i, j = 1...n, i < j) \quad (12)$$

where the motor parameter $M = \frac{L_m}{L_r}$ can be got according to the average algorithm:

$$A = \left( \frac{\Delta\overline{M_1^{'}}}{\overline{M^{'}} + \Delta\overline{M_1^{'}}} + \frac{\Delta\overline{M_2^{'}}}{\overline{M^{'}} + \Delta\overline{M_2^{'}}} + ... + \frac{\Delta\overline{M_n^{'}}}{\overline{M^{'}} + \Delta\overline{M_n^{'}}} \right); \quad (13)$$

$$\overline{M^{'}} = \frac{1}{n}\left( \frac{M_1}{L_{r1}} + \frac{M_2}{L_{r2}} + \frac{M_3}{L_{r3}} + ... + \frac{M_n}{L_{rn}} \right); \quad (14)$$

$$\overline{M_{ij}} = \left( \frac{\Delta\overline{M_j^{'}}}{\overline{M^{'}} + \Delta\overline{M_j^{'}}} - \frac{\Delta\overline{M_i^{'}}}{\overline{M^{'}} + \Delta\overline{M_i^{'}}} \right); \left(i, j = 1...n, i < j\right); \quad (15)$$

In the practical applications, the rail traffic generally uses only one inverter to drag two motors. When the number of motors is 2, it means the single converter drives two motors, then the control voltage, torque and flux can be got. Using the differential value formula, every Δ in the DTC system can be dealt through average algorithm:

$$\overline{i_s^{'}} = \overline{P\psi_s - Q\psi_r} = \overline{P}\overline{\psi_s} - \overline{Q}\overline{\psi_r} + \frac{1}{2}\left[\left(\Delta P_1 \Delta\psi_{s1} + \Delta P_2 \Delta\psi_{s2}\right) - \left(\Delta Q_1 \Delta\psi_{r1} + \Delta Q_2 \Delta\psi_{r2}\right)\right] \quad (16)$$

where : $P = -\sigma \frac{L_m}{L_s L_r}\begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}$, $Q = -\sigma \frac{L_m}{L_s L_r}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $\sigma = 1 - L_m^2 / \left(L_s L_r\right)$

$$\overline{\psi_s} = \int\left(\overline{u_s} - \overline{R_s i_s}\right)dt = \int\left\{\overline{u_s} - \left[\overline{R_s}\,\overline{i_s} + \frac{1}{2}\left(\Delta R_1 \Delta i_{s1} + \Delta R_2 \Delta i_{s2}\right)\right]\right\}dt \quad (17)$$

$$\overline{T_e} = n_p\left(\overline{\psi_s \times i_s}\right) = n_p\left[\overline{\psi_s} \times \overline{i_s} + \frac{1}{2}\left(\Delta\overline{\psi_{s1}} \times \Delta\overline{i_{s1}} + \Delta\overline{\psi_{s2}} \times \Delta\overline{i_{s2}}\right)\right] = n_p\left(\overline{\psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha}}\right)$$
$$= n_p\left[\overline{\psi_{s\alpha}}\,\overline{i_{s\beta}} - \overline{\psi_{s\beta}}\,\overline{i_{s\alpha}} + \frac{1}{2}\left(\Delta\psi_{s\alpha1}\Delta i_{s\beta1} + \Delta\psi_{s\alpha2}\Delta i_{s\beta2}\right) - \frac{1}{2}\left(\Delta\psi_{s\beta1}\Delta i_{s\alpha1} + \Delta\psi_{s\beta2}\Delta i_{s\alpha2}\right)\right] \quad (18)$$

For the parameters of the two motors are same, the stator resistance, stator and rotor inductance and mutual inductance are all equal, then these Δ parameters are zero in the difference formula. As a result, the above equation can be simplified as:

$$\overline{i_s^{'}} = \overline{P\psi_s - Q\psi_r} = \overline{P\psi_s} - \overline{Q\psi_r} \tag{19}$$

$$\overline{\psi_s} = \int\left(\overline{u_s} - \overline{R_s i_s}\right)dt = \int\left(\overline{u_s} - R_s\overline{i_s}\right)dt \tag{20}$$

$$\overline{T_e} = n_p\left(\overline{\psi_s \times i_s}\right) = n_p\left(\overline{\psi_s} \times \overline{i_s}\right) = n_p\left(\overline{\psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha}}\right) = n_p\left(\overline{\psi_{s\alpha} i_{s\beta}} - \overline{\psi_{s\beta} i_{s\alpha}}\right) \tag{21}$$

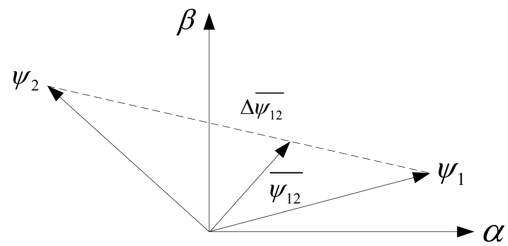



Fig.3 the average stator flux vector of the two induction motors

As shown in Fig.3, the average flux formula in the $\alpha$ □ $\beta$ plane can be got respectively:

$$\overline{\psi_{s\alpha}} = \frac{\overline{\psi_{s\alpha 1}} + \overline{\psi_{s\alpha 2}}}{2} \tag{22}$$

$$\overline{\psi_{s\beta}} = \frac{\overline{\psi_{s\beta 1}} + \overline{\psi_{s\beta 2}}}{2} \tag{23}$$

From the above formula, we can find if the parameter of the induction motors have no difference in speed; the different motors can be regarded as one motor.

## 3. The Simulation Research of the Single-Inverter Dual Motor System

According to the theatrical analysis, the simulation model of the single-inverter dual-motor DTC system has been built in PSIM (shown in Fig.4). The motor parameters and simulation results are shown in Table 1, Fig.5 and Fig.6.

*Table-1*

**Motor parameter**

| $R_s/\Omega$ | $L_s/mH$ | $R_r/\Omega$ | $L_r/mH$ | $L_m/mH$ | $p$ |
|---|---|---|---|---|---|
| 0.087 | 4.27 | 0.228 | 4.27 | 3.47 | 2 |

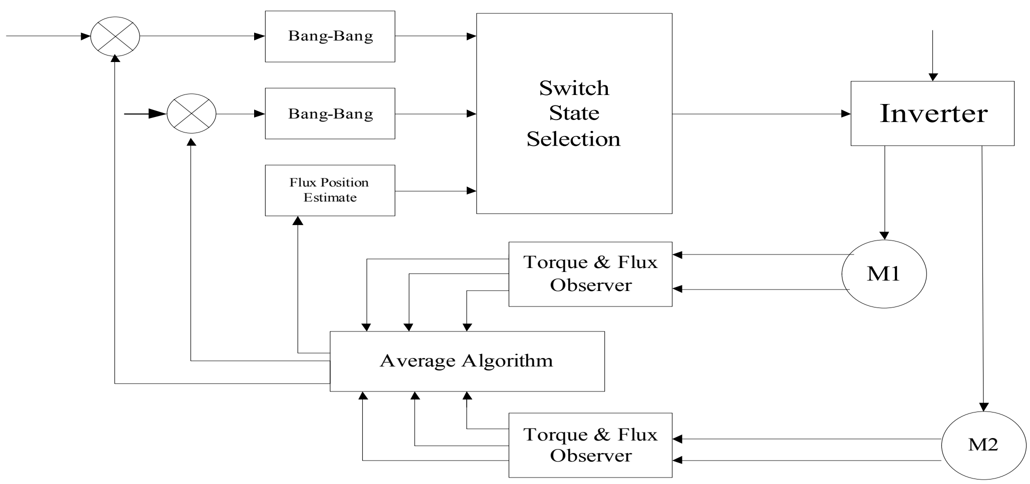
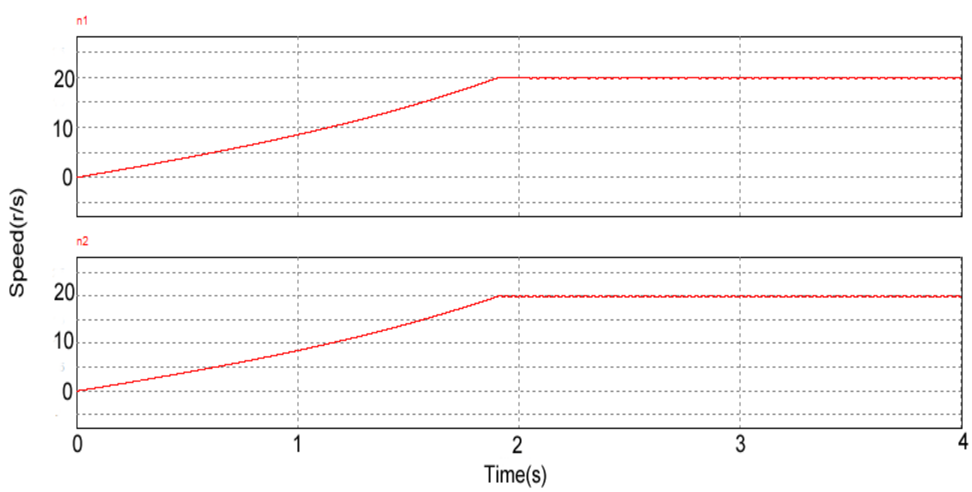


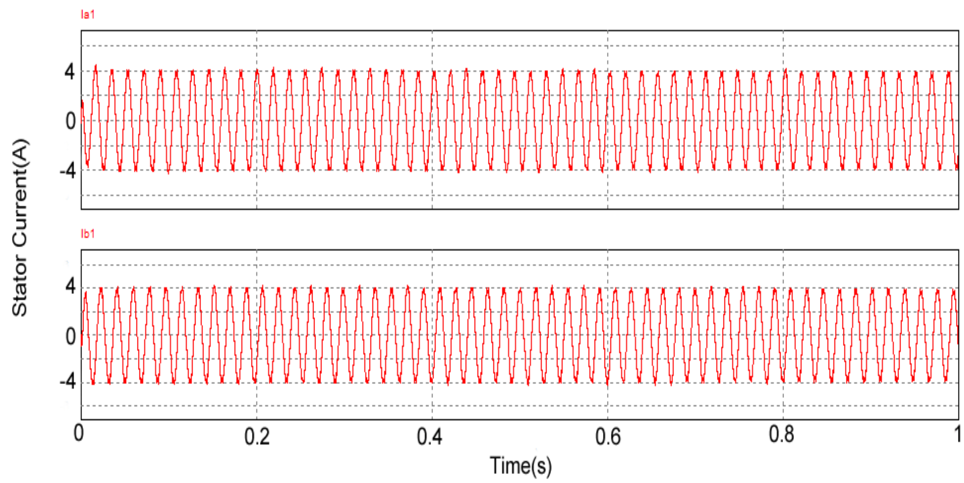

Fig.4 The basic structure of single-inverter dual-motor DTC system

Fig.5 shows the speed and current waveform of the two motors. The given speed is 20 r/s and the given loads are 0.




(a)

Fig.5 (a) speed waveform of dual motors

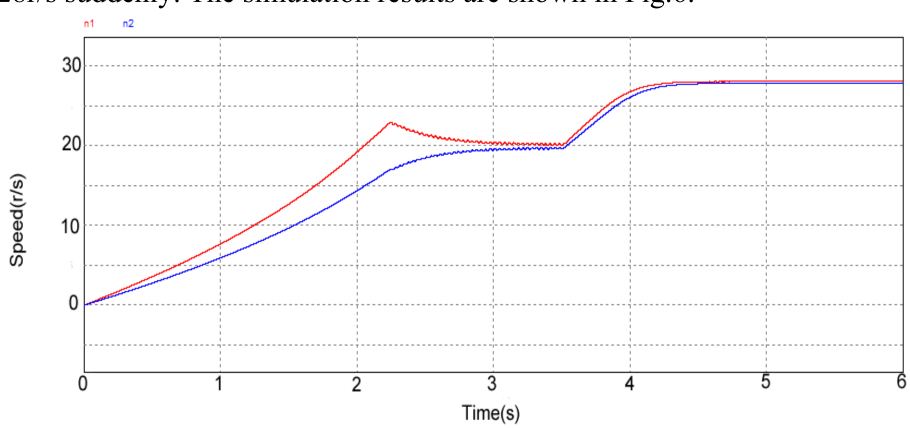



(b)

Fig.5 (b) current waveform of dual motors

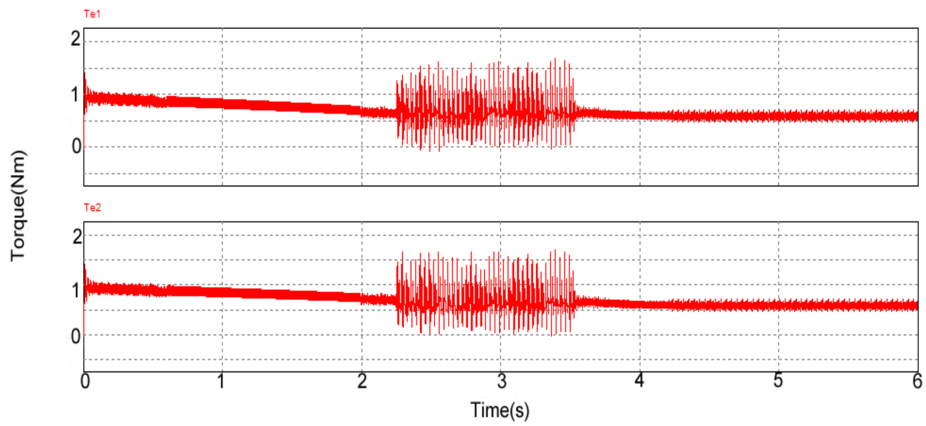
In the figure, the single-inverter dual-motor DTC system performs well in transient response.

The loads of the two motors are different, load1 is 0.1 Nm, load2 is 0.4 Nm; the given speed is 20r/s. In the simulation process, the given speed is turned to 28r/s suddenly. The simulation results are shown in Fig.6.




(a)

Fig.6 (a) speed waveform of dual motors




(b)

Fig.6 (b) torque waveform of dual motors

From the simulation result, the whole system performs well in transient response and in following the given speed. As shown in Fig.6 (a), the red line is the speed of motor1; the blue line is the speed of motor2. When the given speed is added to 28 r/s suddenly, both the two motors can follow the given speed quickly. So the single-inverter dual-motor DTC system has favorable static and dynamic performance.

## 4. The Experimental Research of Single-Inverter Dual-Motor DTC System

The system uses TMS320F28335-DSP to implement a control platform, and which can produce vector controlling PWM wave, the realization of the algorithm, AD transform, and fault detection etc.

### 4.1 The Hardware Architecture of the Control System

This system separates each function modularly by the form of circuit board. The hardware architecture of this system includes main control circuit, signal input circuit, PC communication circuit. The main control circuit is responsible for the realization of control algorithm; main circuit control the induction motors by the instruction of the controlling circuit; signal input circuit is responsible for the external analogue inputs and speed detection; the communication card is connected to the PC to test and debug easily with PC.

Intelligent power module (IPM) is used as the single inverter. The whole system includes the main circuit, speed detection circuit, system protection and other peripheral circuit design. The hardware architecture diagram of the control system is shown in Fig.7.

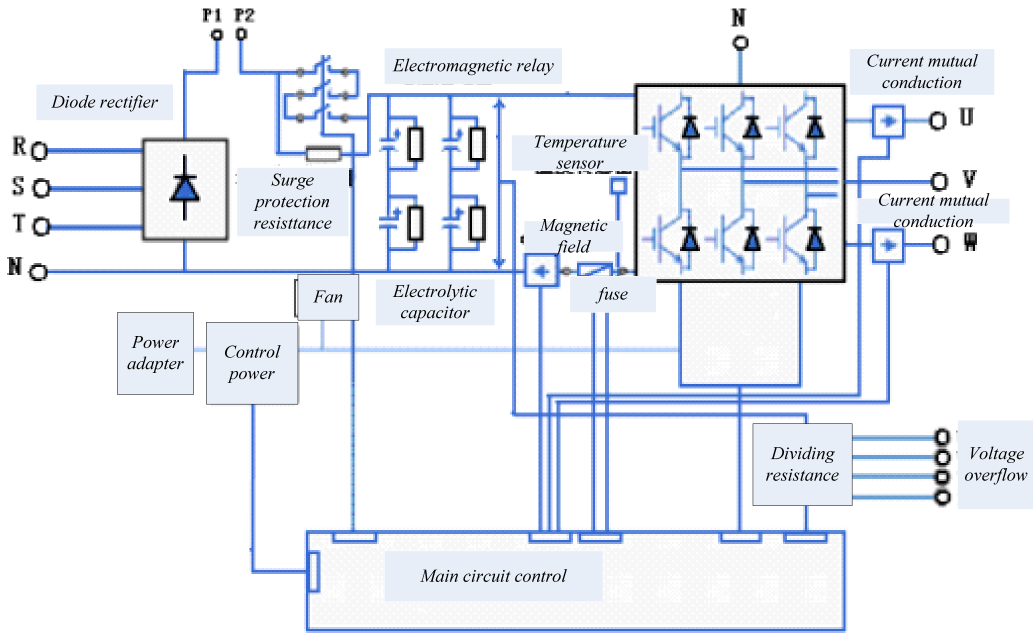



Fig.7 the hardware architecture diagram of the system

### 4.2 The Prototype Implementation of the Whole System

The whole prototype includes control platform, IPM module, speed and current detection board, debug board, relays, speed sensors, loads and PC. The photos of the prototype and multi-motor system can be seen in Fig.8.

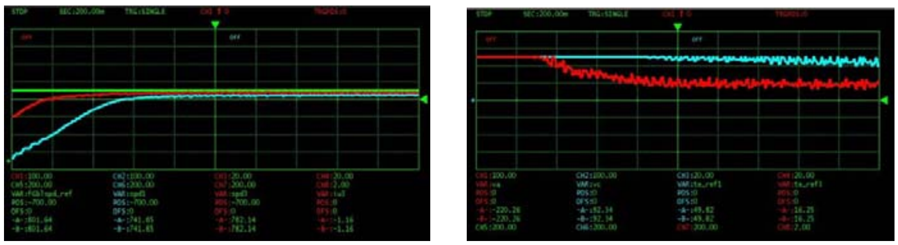
Fig.8(a) shows the hardware implementation of the control system which includes control board, speed and current detection board and Fig.8(b) shows the photo of multi-motor system which includes 4 AC motors.

(a) (b)

Fig.8 (a) Photo of the control system (b) Photo of the multi-motor system

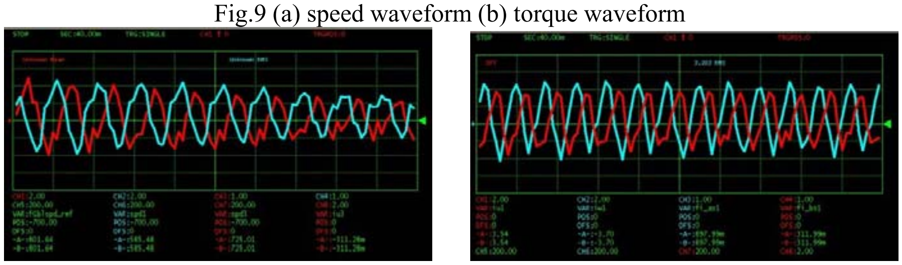
### 4.3 The Experimental Results and Analysis

The motor parameters in the experiment are the same with the parameters in simulation research. Choosing the magnetic power as the load, then the load can be changed by adjusting its current. The sampling frequency is 20 KHZ. When the given speed is 1100 r/min, the load of motor1 is 1 Nm, the load of motor2 is 3 Nm. The experimental results are shown in Fig.9 and Fig.10.



(a) (b)

Fig.9 (a) speed waveform (b) torque waveform



(a) (b)

Fig.10 (a) stator current waveform of motor1 (b) stator current waveform of motor2

When the loads are different, motor1 can reach the given speed quicker. And the steady speed of motor1 is larger than the steady speed of motor2. The stator currents of dual motors are shown in Fig.10. So from the experimental results, the prototype of single-inverter dual-motor DTC system performs well in both stable and transient process, but it still has torque ripple.

### 5. Conclusions

This paper is focused on a new control strategy based on the DTC and an average algorithm to realize the average motor control. In this paper, the DTC controlled multi-motor algorithm is given. The feasibility of the theory is proved through the simulation and experiment research. Both simulation and experimental results have verified that the purposed control strategy can perform well in transient response and robustness with unbalanced load. The multi-motor speed can quickly follow the given speed; the rising time and adjust time are short; the overshoot is small and has better efficiency, which realizes the coordinative operation of each motor. The application of single-inverter dual-motor system can make the whole system low cost, flexible operation, high compactness and high reliability.

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