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Implementation of Indirect Rotor Field Oriented Control for Three-Phase Induction Motor Drive based on TMS320F28335 DSP

***Abstract**. This paper presents an implementation of three-phase induction motor control based on the indirect rotor field oriented control (IFOC) principle. The parameters which are necessary to control such as stator current, rotor current, rotor flux vector, slip speed and electromagnetic torque in rotating reference frame are analysed and calculated. Furthermore, these proposed techniques are used to design the PI controller parameters for regulating the rotor flux and the electromagnetic torque. For overall driver system, the TMS320F28335 digital signal processor compatible with MATLAB/Simulink is employed. The experimental results show the high dynamic performance of the forward and reverse speed and the electromagnetic torque in four quadrants operation. The PI controller design can achieve the produced currents to control the rotor flux and electromagnetic torque in stationary and rotating reference frame based on variable motor speed control and disturbed load torque condition.*

Streszczenie.** Przedstawiono metodę sterowania trójfazowym, silnikiem indukcyjnym bazującą na nie-bezpośrednim sterowaniu kierunkiem pola wirtnika. Prąd stojana, prąd wirnika, wektor strumienia wirnika I moment elektromagnetyczny były analizowane i obliczane. Do sterowania strumieniem wirnika wykorzystano sterownik PI I procesor TMS320F28335. **Wykorzystanie kontroli kierunku pola wirnika do sterowania trójfazowym silnikiem indukcyjnym z wykorzystaniem procesora TMS320F28335

Keywords: Indirect Field orientation control, Rotor flux vector, TMS320F28335, PI current loop controller.
Słowa kluczowe: silnik indukcyjny, sterowanie, strumień wirnika.

Introduction

The three-phase induction motor is widely used in industrial applications because of its high reliability and low maintenance. Nowadays, the induction motor can usually be controlled by using voltage source inverter technology to regulate speed and torque under various load torque conditions. For the high performance of driving conditions, a short response time, a low overshoot and a low steady-state error are needed. Furthermore, the driving system must be robust to the deviation of operating parameters and has a high range of bandwidth control [1]. The control methods for induction motors can be divided into two types including scalar control and vector control. Vector control is a more complex control method while scalar control cannot be applied to control system with dynamic behaviour [2]. The basic concepts of vector control method also known as field-orientated control (FOC) have been proposed in many researches. The technique of vector control imitates the principle of separately excited DC motor that torque and magnetic flux are independently controlled [3][9]. In this study, vector control technique is chosen to improve the performance of motor control. This study proposes the control technique of indirect rotor flux oriented control (IFOC) for three-phase induction motor using TMS320F28335 DSP with MATLAB/Simulink [4]. The proposed motor controls are tested to achieve the high performance in term of torque and speed control in four quadrants operation.

Induction machine model

The principle of vector control bases on the independent control of both magnetic flux and torque like a separately excited DC motor. Therefore, a model of three-phase induction motor for FOC controlling is modified to be the separately excited DC motor as illustrated in Fig. 1.

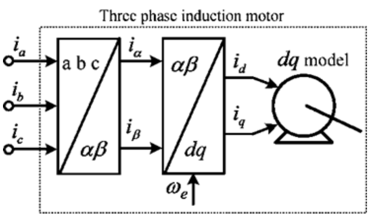

Fig. 1. Three-phase induction motor in d-q frame.

As shown in Fig. 1, i_a, i_b, and i_c are defined as the stator current in three-phase system modified as two-phase system in the stationary reference frame α-axis, β-axis and DC system in the rotating reference frame d-axis, q-axis. Flux producing current, i_d and torque producing current, i_q are adjusted to control magnetic flux and torque, respectively. The stationary reference frame and the rotating reference frame are transformed by using the transformation equation in arbitrary reference frame as given by Eq. (1) where ω is arbitrary speed in electrical radians per second [5]. When ω is zero, the system is in the stationary reference frame whereas ω is arbitrary speed of rotating magnetic field; system is in the rotating reference frame.

$$\left[T_{dq(\omega t)}\right]=\frac{2}{3}\begin{bmatrix}\cos\omega t & \cos\left(\omega t-\frac{2\pi}{3}\right) & \cos\left(\omega t+\frac{2\pi}{3}\right)\\ -\sin\omega t & -\sin\left(\omega t-\frac{2\pi}{3}\right) & -\sin\left(\omega t+\frac{2\pi}{3}\right)\end{bmatrix} \quad (1)$$

The equivalent circuit of motor in rotating reference frame is derived from the analysis of stator voltage of all three phases according to the Kirchhoff's voltage law. The three-phase stator voltage (v_s^{abc}) can be calculated by [6]-[7]

$$v_s^{abc}=R_s i_s^{abc}+\frac{d\lambda_s^{abc}}{dt} \quad (2)$$

Where R_s is stator resistance, i_s^{abc} three-phase stator current and λ_s^{abc} is three-phase stator flux. The three-phase rotor voltage (v_r^{abc}) can be determined by

$$v_r^{abc}=R_r i_r^{abc}+\frac{d\lambda_r^{abc}}{dt} \quad (3)$$

where R_r is rotor resistance, i_r^{abc} three-phase rotor current and λ_r^{abc} is three-phase rotor flux. A relationship between stator flux, rotor flux, stator current and rotor current is given by

(4) $$\begin{bmatrix} \lambda_s \\ \lambda_r \end{bmatrix} = \begin{bmatrix} L_s & L_m \\ L_m & L_r \end{bmatrix} \begin{bmatrix} i_s \\ i_r \end{bmatrix}$$

where L_m is Mutual inductance, L_s stator inductance $(L_{ls} + L_m)$ and L_r is Rotor inductance $(L_{lr} + L_m)$. L_{ls} and L_{lr} are called leakage inductance. The stator voltage obtaining from Eq. (2) can be transformed to the rotating reference frame at arbitrary speed by multiplying both sides of Eq. (2) by Eq. (1) so it is written as

(5) $$v_s^{dq} = \omega \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \end{bmatrix} \lambda_s^{dq} + p\lambda_s^{dq} + R_s i_s^{dq}$$

where a superscript *dq* is referred to the rotating reference frame and *p* represents d/dt.

Eq. (5) can be rearranged to be the stator voltage in rotating reference frame at $\omega = \omega_e$ as follows:

(6) $$v_{ds} = -\omega_e \lambda_{qs} + p\lambda_{ds} + R_s i_{ds}$$

(7) $$v_{qs} = \omega_e \lambda_{ds} + p\lambda_{qs} + R_s i_{qs}$$

where ω_e is synchronous speed.

The rotor voltage given by Eq. (3) can be transformed to the rotating reference frame at arbitrary speed by multiplying both sides of Eq.(3) by Eq.(1) and substituting $\omega = \omega_e - \omega_r$. Therefore, the rotor voltage can be obtained by

(8) $$v_r^{dq} = (\omega_e - \omega_r) \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \end{bmatrix} \lambda_r^{dq} + p\lambda_r^{dq} + R_r^{dq} i_r^{dq}$$

where ω_r is rotor speed in electrical term.

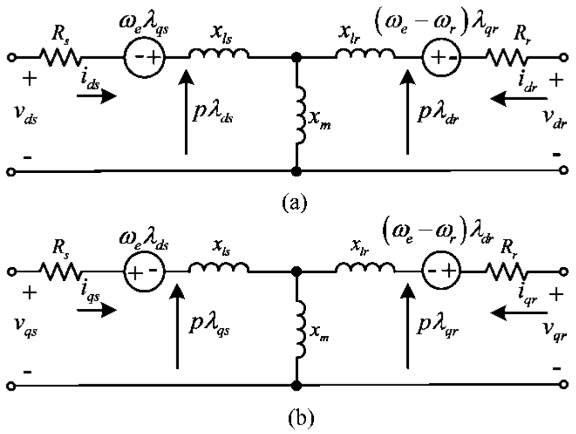

Fig. 2. Equivalent circuit in rotating reference frame.

From Eq. (8), the rotor voltage in rotating axis system can be written as

(9) $$v_{dr} = -(\omega_e - \omega_r)\lambda_{qr} + p\lambda_{dr} + R_r i_{dr}$$

(10) $$v_{qr} = (\omega_e - \omega_r)\lambda_{dr} + p\lambda_{qr} + R_r i_{qr}$$

As mentioned, Eqs. (6), (7), (9) and (10) can be used to draw the equivalent circuit [7] as shown in Fig. 2. The electromagnetic torque (T_{em}) in term of stator current and rotor flux is given by

(11) $$T_{em} = \frac{P}{2}\frac{L_m}{L_r}\left(i_{qs}\lambda_{dr} - i_{ds}\lambda_{qr}\right)$$

Indirect rotor flux orientation control

An indirect vector control can independently be controlled torque and rotor flux like a control of separately excited DC motor when the value of slip speed has to be calculated appropriately and correctly because a detector of magnetic flux in air gap is not installed. However, in practice, a small error of slip speed calculation affects by the change of motor such as rotor time constant, rotor resistance, leakage factor, core saturation, heat, etc [3][10].

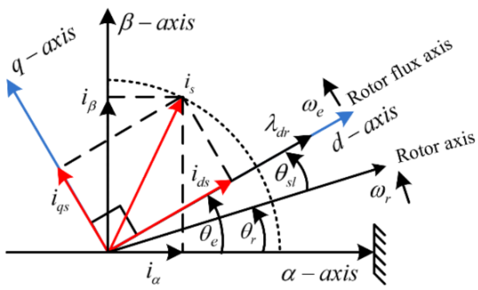

Fig. 3. Position of rotor flux vector for indirect FOC control.

Fig. 3 shows the rotor flux vector positioning for indirect rotor field orientated control in rotating reference frame (d-q). The rotor flux vector is located in the same position of rotating magnetic field speed with exactly calculated slip speed. A quantity of rotor flux and magnetic torque is produced by i_{ds} and i_{qs}, respectively, at which both of the producing currents are independently controlled the same as DC motor. Moreover, the vectors of rotor flux λ_{dr} and current i_{qs} are perpendicular to each other at all times at synchronous speed like a control of separately excited DC motor. A calculation of rotor flux can be analyzed from the equation of rotor voltage in rotating reference frame when an equal value of angular speed (ω) and synchronous speed (ω_e) is specified. Then, the slip speed can be derived by $\omega_e - \omega_r = \omega_{sl}$. The quantity of rotor voltage in Eq. (9) and Eq. (10) can be rearranged [6] as follows:

(12) $v_r = \omega_{sl}\lambda_r + p\lambda_r + R_r i_r$ and $0 = (\omega_{sl} + p)\lambda_r + r_r i_r$

Where the rotor voltage is zero ($v_r = 0$) because of using a squirrel rotor. In the matrix equation of Eq. (4), the current i_r in rotor circuit can be written as

(13) $$i_r = \frac{1}{L_r}(\lambda_r - L_m i_s)$$

Substituting Eq. (13) into Eq. (12) in order to determine the relationship of rotor flux yields

(14) $$p\lambda_r = \frac{1}{\tau_r}\left[L_m i_s - (1 + j\omega_{sl}\tau_r)\lambda_r\right]$$

Rearranging the equation gives

(15) $$\lambda_r\left(1 + \tau_r\left(p + j\omega_{sl}\right)\right) = L_m i_s$$

The rotor flux can be estimated by $\lambda_{qr} = 0$ and $\lambda_r = \lambda_{dr}$ and the current can be calculated by $i_s = i_{ds} + ji_{qs}$; therefore, rearranging Eq. (15) gives

(16) $$\lambda_{dr} + \lambda_{dr}\tau_r p + \lambda_{dr}\tau_r j\omega_{sl} = L_m i_{ds} + L_m ji_{qs}$$

Eq. (16) can be factorized into two parts: real part and imaginary part when the real part is expressed by

(17) $$\lambda_{dr}\left(1+\tau_r p\right) = L_m i_{ds}$$

In addition, the imaginary part from Eq. (16) is expressed by

(18) $$\lambda_{dr}\tau_r\omega_{sl} = L_m i_{qs}$$

The slip speed can be calculated from Eq. (17) as follows:

(19) $$\omega_{sl} = \frac{L_m}{\tau_r}\frac{i_{qs}}{\lambda_{dr}}$$

From Eq. (18), when the value of τ_r is fixed as a constant, the equation of rotor flux can be written as

(20) $$\lambda_r = \lambda_{dr} = L_m i_{ds}$$

When the currents, i_{ds} and i_{qs} are represent as the requirement for producing rotor flux and magnetic torque of induction motor, respectively. The current, i_{ds} in Eq. (17) for dynamic behavior and i_{qs} in Eq. (11) setting λ_{qr} to zero can be rearranged as follows:

(21) $$i_{ds} = \frac{1+\tau_r p}{L_m}\lambda_{dr} \quad \text{and} \quad i_{qs} = \frac{T_{em}}{K_T\lambda_{dr}}$$

where $K_T = \frac{P}{2}\frac{L_m}{L_r}$

A Block diagram of IFOC system can be drawn by using Eqs. (17) – (21) as demonstrated in Fig. 4.

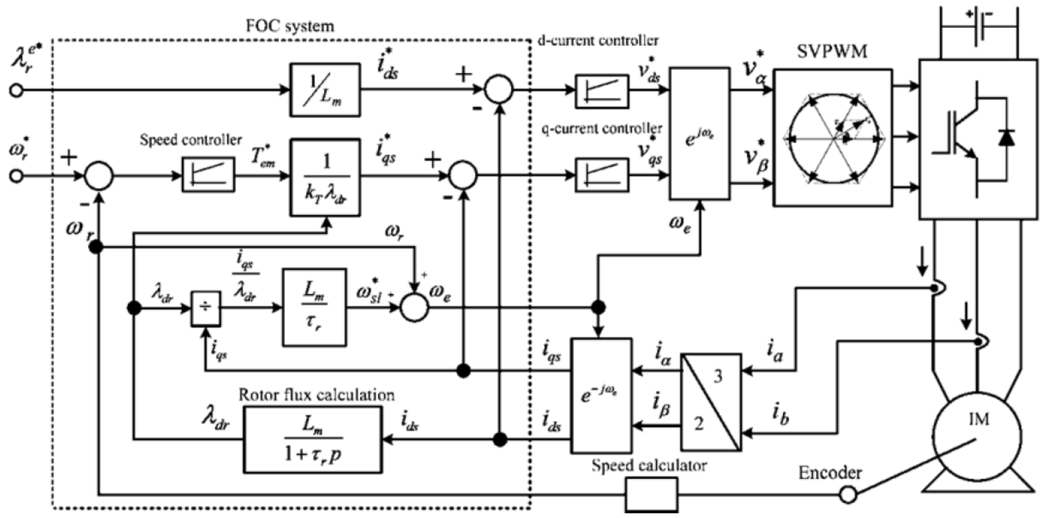

Fig. 4. Schematic block diagram of indirect rotor flux orientation system (IFOC).

Rotor flux estimation

As mentioned above, the analysis of parameters using for IFOC system were presented. The parameters were determined by experimental testing as shown in Table 1. and also used for drawing an equivalent circuit in the steady state condition as shown in Fig. 5.

Table 1. Three phase induction motor parameters.

1/4hp, 190/230V, 1.4/0.7A, 50Hz, 1425rpm, 4-pole Low voltage connected (dual voltage star)	
Nominal Parameters	SI Units
Stator resistance (Ω)	R_s = 10
Rotor resistance (Ω)	R_r= 7.2
Stator leakage inductance (H)	L_{ls} = 0.0162
Rotor leakage inductance (H)	L_{lr} = 0.0162
Magnetizing inductance (H)	L_m = 0.33

Based on the equivalent circuit in Fig. 5, at phase voltage (V_{phase}) of 110 V_{rms} and slip speed of 5%, a stator current (i_s) of $1.17\angle-51.45^0$ and a rotor current (i_r) of $0.68\angle181.15^0$ are calculated. A rotor flux of 0.3 wb was determined by Eq. (4) when $\lambda_r = L_m i_s + L_r i_r$. Using Eq. (20), a rotor flux producing current (i_{ds}) of 0.91 A is derived by λ_{dr}/L_m, and a rotor time constant τ_r of 0.0486 is calculated. Torque is equal to 0.63 N.m. At K_T of 1.886, a torque producing current (i_{qs}) of 1.114A is calculated by Eq. (21). Using Eq. (19), a slip speed (ω_{sl}) is 16.81 rad/sec. All these calculated parameters are then used for designing control parameters of rotor flux.

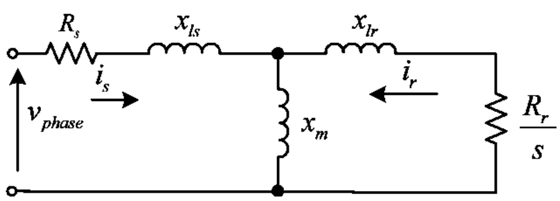

Fig. 5. Equivalent circuit of 3-phase motor per phase.

d-q current loop controller design

The control for i_{ds} and i_{qs} in the rotating reference frame to produce rotor flux and magnetic torque can be estimated from the relationship of stator voltage resulting from leakage factor [5].

The process transfer function for controlling the current i_{ds} and i_{qs} can easily be estimated as the first-order process given by

(22) $$\frac{i_{dq}}{v_{dq}}(s) = G_P(s) = \frac{1}{\sigma L_s s + R_s}$$

When leakage factor $\sigma = 1 - \frac{L_m^2}{L_s L_r}$.

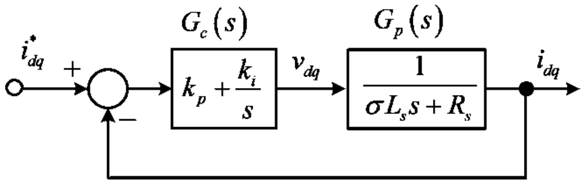

Fig. 6. Block diagram of d-q current loop controller.

Fig. 6 shows a block diagram of d-q current control system using proportional-integral (PI) controller which has two parameters, proportional gain K_p and integral gain K_i. For the frequency response design, the phase margin of 60 degrees was chosen to decrease the overshoot [1] and substituting the calculated parameters into Eq. (22) gives

(23) $$G_P(s) = \frac{28.57}{s + 285.71}$$

where $\sigma = 0.1$

The settling time (t_s) and phase margin (ϕ_M) are designed as 0.005 sec and 60 degrees, respectively. The crossover frequency (ω_1) can be written as [8]:

(24) $$\omega_1 = \frac{8}{t_s \tan \phi_M}$$ = 924 rad/sec

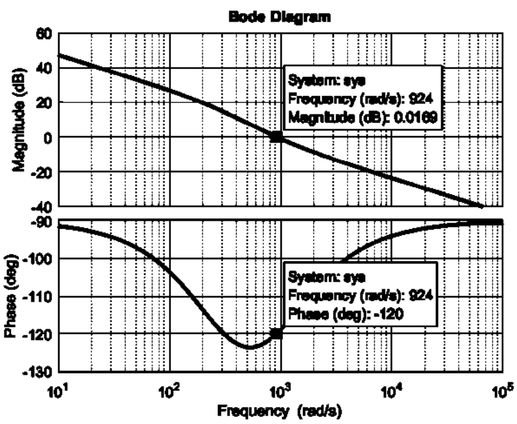

Fig. 7. Bode plot of IFOC system for current control loops.

The stability control system can be obtained when the controller gain was set at crossover frequency of 924 rad/sec where the gain is 0 dB. Consequently, K_p of 23 and K_i of 22,974.50 were determined and the open loop transfer function of the IFOC control system can be obtained by

(25) $$G_c(s)G_p(s) = \frac{657.11s + 656381.46}{s^2 + 285.71s}$$

In this study, the controller gains, K_p and K_i, were determined by the frequency response technique using the Bode plot which is the most common of graphical representations of gain-phase plot derived from the open loop transfer function of the control loop system as shown in Fig. 7. The phases of -120 degrees were obtained as demonstrated in Fig. 7, so the phase margin, ϕ_M of 60° was then calculated.

Experimental results

Fig. 8. demonstrates a set of hardware implementation for the proposed IFOC control system. An overall system of implementation is illustrated in Fig. 9. The main components of this system are composed of an three-phase inverter for voltage supply, a high voltage motor control and a PFC developer's kit using TMS320C2000 of Texas instrument using a processor of TMS320F28335 DSP for producing control signal and gate driver signal from space-vector modulation to regulate the three-phase inverter. The testing parameters of motor used in this study are given in Table 1.

Fig. 8. Hardware implementation.

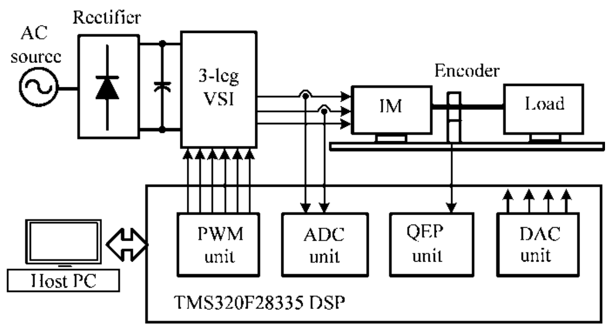

Fig. 9. Overall system for implementation.

Fig. 10 shows a diagram of MATLAB/Simulink according to the block diagram of IFOC control system in Fig. 9. An ADC block is applied for adjusting the stator current i_u and i_v from two sets of current sensors to transform to be the currents, i_{ds} and i_{qs} in rotating reference frame using Clarke and Park Transformation, respectively. These two currents, i_{ds} and i_{qs} are then fed back in a current loop to control rotor flux and magnetic torque, respectively. Consequently, the PI controller converts the currents, i_{ds} and i_{qs} to be the voltages, v_{ds} and v_{qs} in the rotating reference frame via the Inverse Park Transformation for the space vector pulse width modulation using modules of ePWM1, ePWM2 and ePWM3 with defined frequency of 10 kHz and sampling time of 100 μs. A speed sensor with the Enhanced Quadrature Encoder Pulse (eQEP) module receiving signal from encoder to convert the speed sent back to PI speed controller. The ePWM5 and ePWM6 modules are applied for a set of operating display of DAC and the pulse signal via low pass filter equipment is then demonstrated on digital oscilloscope. The performance of the IFOC control were evaluated in term of 4-quadrant operation that 3 testing conditions are 1) the forward and reverse direction at $\pm$ 1500 rpm, 2) the decrease and increase speed of +500 rpm and +1500 rpm and 3) a disturbed load torque condition. For the first condition, the responses of electromagnetic torque, T_{em}, torque-producing current i_{qs}, and reference and actual speed are shown in Fig. 11. Fig. 12. demonstrates the responses of flux-producing current, i_{ds}, torque-producing current i_{qs}, and reference and actual speed. The responses of stator current, i_α and stator current, i_β in the stationary reference frame, and reference and actual speed are shown in Fig. 13. For the second condition, Fig. 14 shows the responses of stator current, i_α and stator current, i_β in the stationary reference frame when the rotational speed decreases and increases. Fig. 15 illustrates the responses of flux-producing current, i_{ds} and torque-producing current, i_{qs} in the rotating reference frame. Fig. 16 illustrates the responses of a disturbed load torque condition at 0.4 Nm.

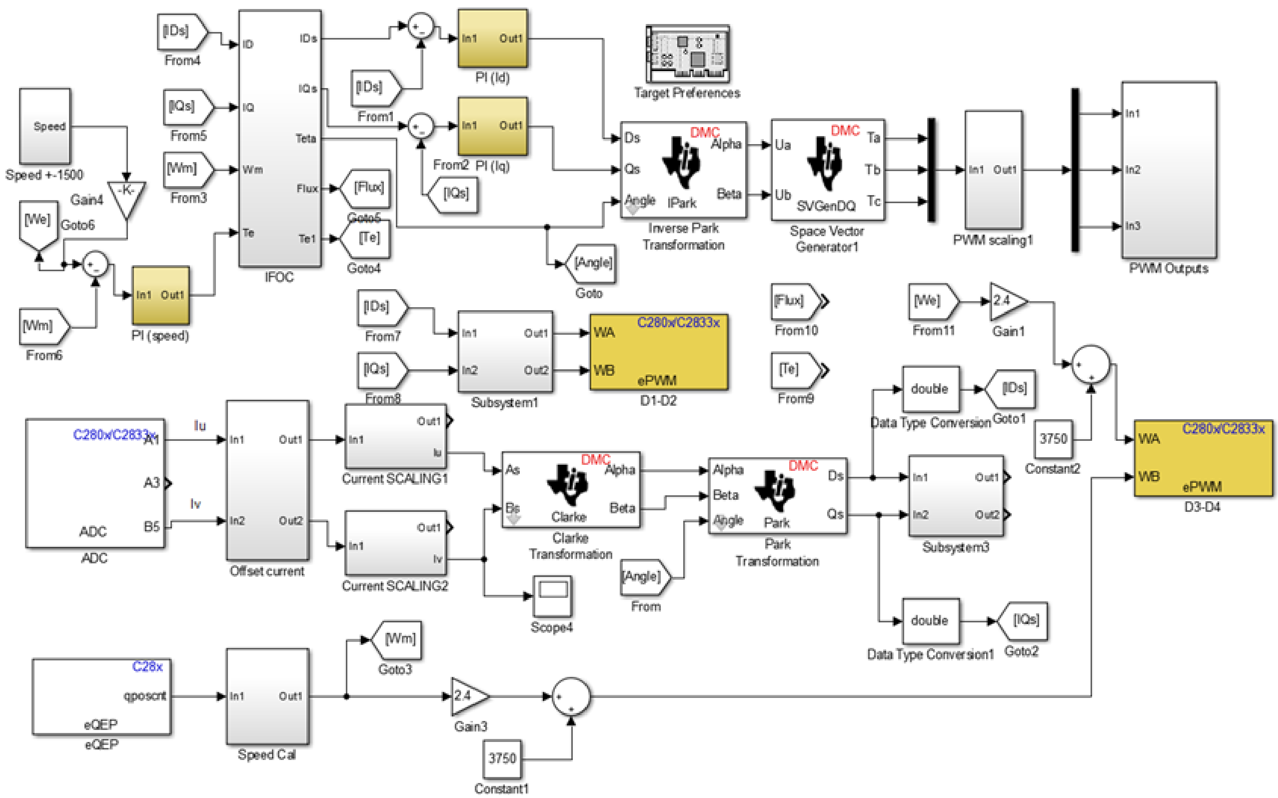

Fig. 10. MATLAB/Simulink for indirect rotor flux orientation system.

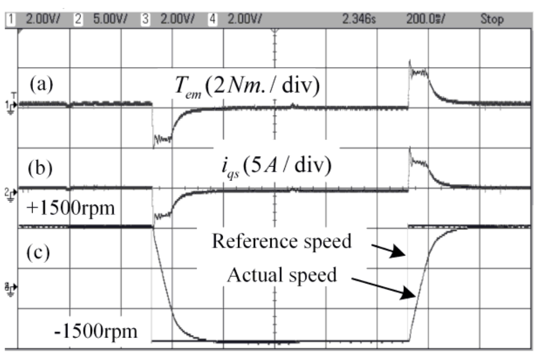

Fig. 11. Forward and reverse direction at ± 1500 rpm (a) electromagnetic torque T_{em} (b) torque-producing current i_{qs} (c) reference and actual speed.

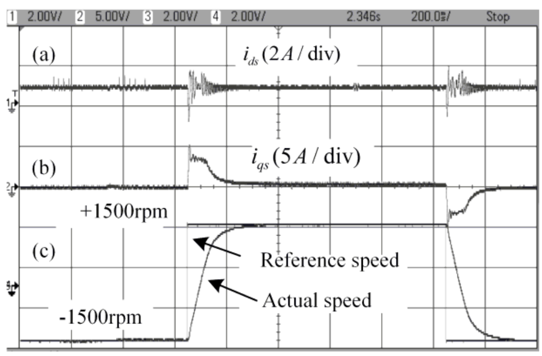

Fig. 12. Forward and reverse direction at ± 1500 rpm (a) flux-producing current i_{ds} (b) torque-producing current i_{qs} (c) reference and actual speed.

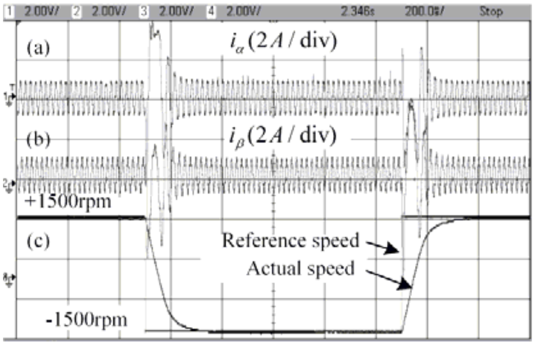

Fig. 13. Forward and reverse direction at ±1500 rpm (a) stator current i_α (b) stator current i_β (c) reference and actual speed.

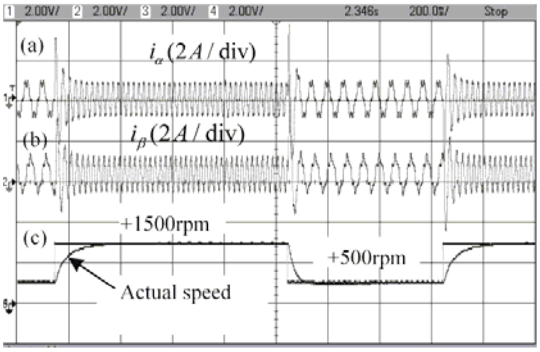

Fig. 14. Decrease and increase speed of +500 to +1500rpm (a) stator current i_α (b) stator current i_β (c) reference and actual speed.

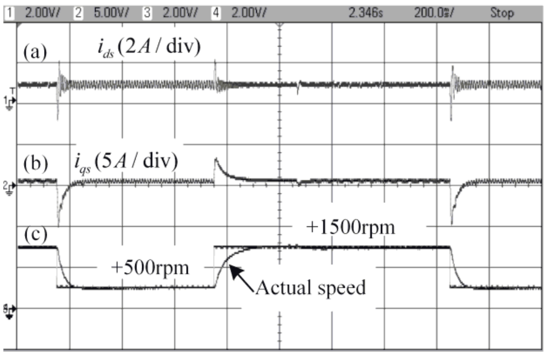

Fig. 15. Reducing and increasing speed at +500 to +1500rpm (a) flux-producing current i_{ds} (b) torque-producing current i_{qs} (c) reference and actual speed.

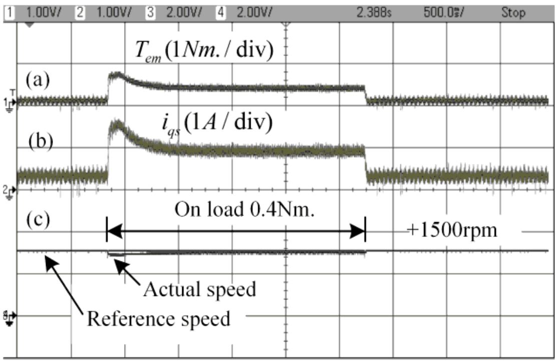

Fig. 16. A disturbed load torque condition (a) Electromagnetic torque (b) torque-producing current i_{qs} (c) reference and actual speed.

Conclusion

The indirect rotor field oriented control for three-phase induction motor is performed and the PI controller parameters for regulating the rotor flux and the electromagnetic torque are designed by using the frequency response technique. This study has concentrated on the hardware implementation including the TMS320F28335 DSP with MATLAB/Simulink and the system testing. The changes of the forward and reverse direction, the decrease and increase of rotor speed and the disturbed load torque condition are tested to observe the responses of operating parameters. The experimental results show that this IFOC system can provide the high performance to control rotor speed, electromagnetic torque and stator currents in stationary and rotating reference frame.

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