Open-Loop Vector Control of Induction Motor with Space Vector Pulse Width Modulation Technique

Karchung, S. Ruangsinchaiwanich

***Abstract*—**This paper presents open-loop vector control method of induction motor with space vector pulse width modulation (SVPWM) technique. Normally, the closed loop speed control is preferred and is believed to be more accurate. However, it requires a position sensor to track the rotor position which is not desirable to use it for certain workspace applications. This paper exhibits the performance of three-phase induction motor with the simplest control algorithm without the use of a position sensor nor an estimation block to estimate rotor position for sensorless control. The motor stator currents are measured and are transformed to synchronously rotating (d-q-axis) frame by use of Clarke and Park transformation. The actual control happens in this frame where the measured currents are compared with the reference currents. The error signal is fed to a conventional PI controller, and the corrected d-q voltage is generated. The controller outputs are transformed back to three phase voltages and are fed to SVPWM block which generates PWM signal for the voltage source inverter. The open loop vector control model along with SVPWM algorithm is modeled in MATLAB/Simulink software and is experimented and validated in TMS320F28335 DSP board.

***Keywords*—**Electric drive, induction motor, open-loop vector control, space vector pulse width modulation technique.

I. INTRODUCTION

INDUCTION motors with squirrel-cage rotor are widely used in industry due to their reliable operation, low cost, and rugged construction. However, compared to DC motors, induction motors are more difficult to control speed and are not suitable to cope up with high dynamic performance applications because of their complex intrinsic nonlinear dynamic characteristics [1]. So, induction motors have been used essentially to run at relentless speed and DC motors were preferred for variable-speed applications. In recent years, the field-oriented control of induction motor drive with power electronic inverters is widely used in high performance drive system and thus is now becoming superior to DC motors in high-performance control areas in industries. The vector-controlled induction motor drive behaves similar to separately excited DC motor drive where independent control of flux and torque occurs by means of coordinate transformation of current and voltage signals [2]-[4]. In vector control tropology, Forward Clarke and Park transformation are used [5] to transform 3-phase stator currents to 2-phase d-q currents which are aligned to rotor flux.

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Current aligned along q-reference is responsible for controlling the rotor output of the motor and current aligned along d-reference is used to control rotor magnetizing flux. Inverse Clarke and Park transformation is responsible for rotating the 2-phase d-q currents back to 3-phase voltage signals to generate pulse width modulation for the IGBT inverter. Open-loop control is also called sensorless control because the position sensor is absent to provide speed feedback to the system. The term open-loop control is rarely used, but in this paper, it is more convenient to use open-loop because the feed-forward block is also out of scope in this paper.

II. INDUCTION MOTOR AND VECTOR CONTROL MODEL

A. Dynamic Model of the Induction Motor

The mathematical model of the three phase induction motor and its drive system is modeled in computer to represent the physical system [6]. In order to predict the induction motor (IM) drive performance, a mathematical model is developed in the synchronously rotating (d-q) frame with stator voltages together with the developed fluxes (1) and electromagnetic torque (2). The mathematical model of IM could be expressed as [7]-[10]:

$$\begin{aligned} V_{ds} &= p\psi_{ds} + R_s i_{ds} - \omega_r \psi_{qs} \\ V_{qs} &= p\psi_{qs} + R_s i_{qs} + \omega_r \psi_{ds} \\ V_{dr} &= p\psi_{dr} + R_s i_{dr} - (\omega_r - \omega_e)\psi_{qr} \\ V_{qr} &= p\psi_{qr} + R_s i_{qr} + (\omega_r - \omega_e)\psi_{dr} \end{aligned} \quad (1)$$

where,

$$\begin{bmatrix} \psi_{ds} \\ \psi_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \quad (2)$$

And, electromagnetic torque [7], [8], [11] can be shown as:

$$T_e = \frac{3}{2} n_p \frac{L_m}{L_r} (\psi_{dr} i_{qs} - \psi_{qr} i_{ds}) \quad (3)$$

$$Jp(\omega_m) = T_e - T_l - B\omega_m \quad (4)$$

where p = differentiation operator ($\frac{d}{dt}$), $V_{ds}, V_{qs}, i_{ds}, i_{qs}, \psi_{ds}, \psi_{qs}$ = d- and q-component voltages, currents and magnetic fluxes on stator, $V_{dr}, V_{qr}, i_{dr}, i_{qr}, \psi_{dr}, \psi_{qr}$ = d- and q-component voltages, currents and magnetic fluxes on rotor, L_s and L_r = inductance of stator and rotor respectively, L_m = magnetizing inductance, n_p = number of pole pairs, T_l = load torque, J =

rotor inertia, T_e = electromagnetic generated torque, B = friction coefficient, ω_e = electrical speed (rad/sec), ω_m = rotor speed (rad/sec).

B. Vector Control of the Induction Motor

Vector control or Field Oriented Control (FOC) according to the vector control theory is explained in [1], [5] which has become most popular control techniques for IM. The operating principle of the vector control is based on the elimination of coupling between the direct (d-) and quadrature (q-) axes. This can be achieved by coordinate transformation, producing control very similar to that of separately excited DC motor [12]. The controller process requires two stages of transformation (Clarke and Park), so that the measured stator currents are transformed to i_{ds} and i_{qs} to match the reference control currents i_{d-ref} and i_{q-ref} respectively as shown in Fig. 1.

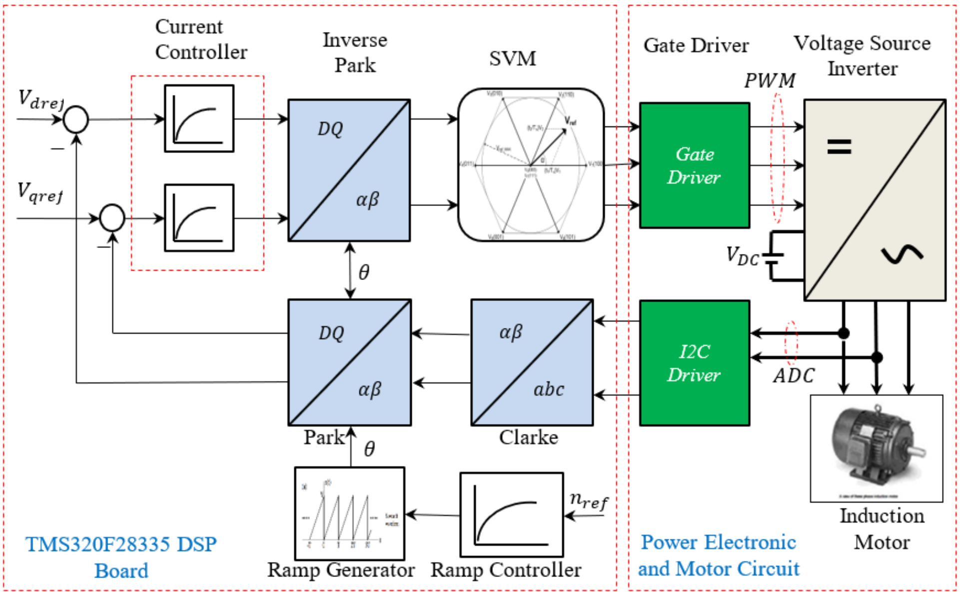

Fig. 1 Block diagram of the open-loop vector control

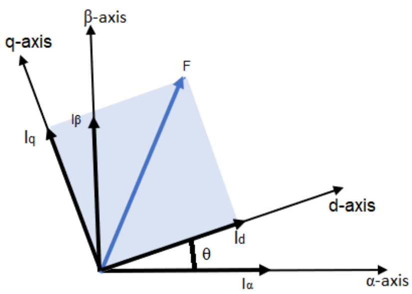

Fig. 2 Principle of vector control

Typically, vector control successfully decuples these two parts by forcing the d-axis to align with the rotor flux space vector [7], [11]. There are related as:

$$\psi_{qr} = p\psi_{qr} = 0 \quad (5)$$
$$\psi_r = \psi_{dr}$$

As the d- axis flux vanishes from (5), the torque equation of (3) can be restated as:

$$T_e = \frac{3}{2} n_p \frac{L_m}{L_r} (\psi_{dr} i_{qs}) \quad (6)$$

where,

$$\psi_{qr} = L_m i_{ds} \quad (7)$$

For considering i_{ds} constant, the electromagnetic torque is linearly dependent on i_{qs} which provides torque response as quickly as the response of i_{qs} [11], [13]. The principle of vector transformation from 3-phase to 2-phase and vice-versa is summarized in Fig. 2.

III. SVPWM Technique

The SVPWM technique generates PWM control signals for 3-phase voltage source inverters (VSI). It computes the duty cycle by dividing the two-dimensional vector plane into six-equal sectors [14]-[16]. SVPWM had advantage of generating higher output voltage for same DC-bus voltage, lower switching losses, and better harmonic performance [10], [17]. Two-level VSI with six IGBT bridge as shown in Fig. 3 is used to generated pulsating 3-phase voltage at the motor terminal by $2^3 = 8$-bit switching combinations/states $(000 - 111)$. As shown in Fig. 5, any of the combinations from switches S_1 to S_6 can happen, producing 8-sets of output voltages $(V_0 - V_7)$. The voltages for phase a, b and c with respect to point 0 will be:

$$V_{RO} = \pm\frac{1}{2}V_{dc}, V_{YO} = \pm\frac{1}{2}V_{dc}, V_{BO} = \pm\frac{1}{2}V_{dc},$$

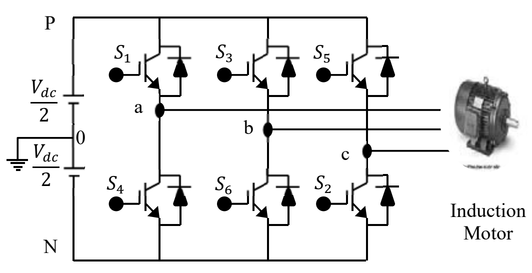

Fig. 3 IGBT inverter fed induction motor

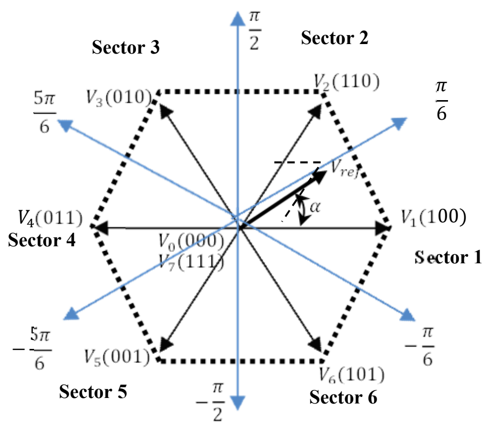

Fig. 4 Space vector diagram width modulation technique

Vector	A^+	B^+	C^+	A^-	B^-	C^-	V_{AB}	V_{BC}	V_{CA}	
$V_0 = \{000\}$	OFF	OFF	OFF	ON	ON	ON	0	0	0	Zero vector
$V_1 = \{100\}$	ON	OFF	OFF	OFF	ON	ON	$+V_{dc}$	0	$-V_{dc}$	Active vector
$V_2 = \{110\}$	ON	ON	OFF	OFF	OFF	ON	0	$+V_{dc}$	$-V_{dc}$	Active vector
$V_3 = \{010\}$	OFF	ON	OFF	ON	OFF	ON	$-V_{dc}$	$+V_{dc}$	0	Active vector
$V_4 = \{011\}$	OFF	ON	ON	ON	OFF	OFF	$-V_{dc}$	0	$+V_{dc}$	Active vector
$V_5 = \{001\}$	OFF	OFF	ON	ON	ON	OFF	0	$-V_{dc}$	$+V_{dc}$	Active vector
$V_6 = \{101\}$	ON	OFF	ON	OFF	OFF	ON	$+V_{dc}$	$-V_{dc}$	0	Active vector
$V_7 = \{111\}$	ON	ON	ON	OFF	OFF	OFF	0	0	0	zero vector

Fig. 5 SVPWM switching algorithm, for IGBTs and the resultant line voltage magnitudes

The six active (non-zero) voltage vectors labelled $V_1 - V_6$ and the two zero-vectors labelled V_0 and V_7 are converted to reference vector V_{ref}. The binary digits represent the states of three legs of the IGBT Inverter shown in Fig. 4. The most significant bit represents leg 'c', the middle represents leg 'b' and the least significant bit represents leg 'a', respectively. The switches must be controlled in such a way no both the switches in the same leg turns on or off at the same time. It is done to reduce switching frequency, and in worst case scenario, it may cause the short circuit in inverter causing damage to inverter and associated devices. The dead band is also created to create delay in complementary switching of two switches in same leg. The switching order of SVPWM is shown in Fig. 5.

For 3-phase induction motor control, the SVPWM technique can alternatively convert 3-phase voltages to 2-phase (V_α and V_β) which are right angle to each other as shown in Fig. 6. Thus, 2-phase voltages are mathematical simplification made to ease the calculation using Clarke transformation with the resultant m.m.f (V_{ref}) maintaining unaltered at angle (α) with voltage vectors. Also, V_{ref} is magnitude and α is the frequency of the V_α and V_β. Moreover, it is obviously located between the two adjacent non-zero vector and zero vector.

Magnitude and frequency can be obtained with [10]:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (8)$$

$$|V_{ref}| = \sqrt{V_\alpha^2 + V_\beta^2} \quad (9)$$

$$\alpha = \tan^{-1}\left(\frac{V_\beta}{V_\alpha}\right)$$

Equation (8) is the Clarke transformation matrix and (9) is the relationship between the reference vector, angle and the resultant magnitudes of the matrix.

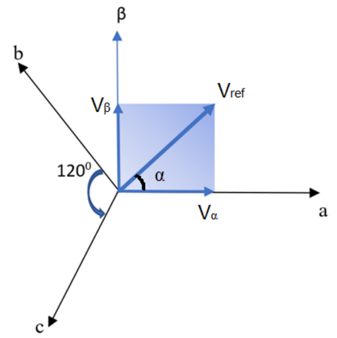

Fig. 6 Space vector diagram

IV. Experimental Drive Configuration

TABLE I
Parameter for Induction Motor

Symbol	Quantity	Value
P	Power Rating	0.25 hp
n_p	Number of pole pairs	2
v	Rated stator voltage/phase	110 v
i	Rated stator current	1.4 A
f	Rated Frequency	50 Hz
N_r	Rotor rated Speed	1425 rpm
R_s	Stator resistance/phase	10 Ω
R_r	Rotor resistance/phase	7.2 Ω
L_m	Magnetizing inductance	330 mH
L_{ls}	Stator leakage inductance	16.2 mH
L_{lr}	Rotor leakage inductance	16.2 mH
J	Moment of inertia	0.01

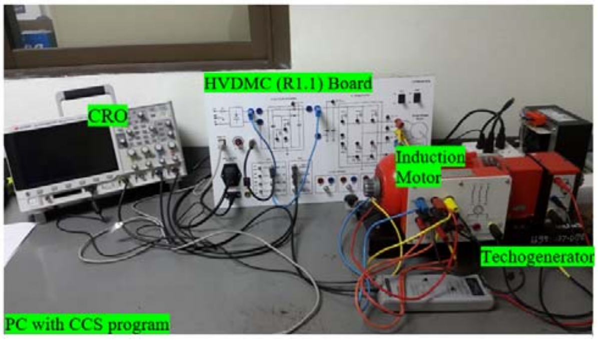

Fig. 7 Laboratory setup

In this work, the control system is based on the TMS320F28335 controller board which is incorporated into PC. Its software activates under a MATLAB/Simulink environment. The power driver is implemented with an induction motor equipped with a techo-generator coupled on the shaft of an Induction motor. It is capable of generating DC voltage corresponding to the speed of the machine. The DC voltage for VSI is achieved through a 3-phase diode bridge rectifier module inbuilt in the board. A Simulink model is developed and downloaded to the DSP board. The DAC channels are used to provide the desired signal outputs to the 20 MHz oscilloscope. The experimental setup is shown in Fig. 7, and the motor parameters are listed in Table I.

V. Simulation and Experimental Result

To verify and validate the efficiency of algorithm, series of practical tests were conducted on the motor under investigation and compared with the simulation results. The speed, current, torque, and voltage responses of IM have been observed under different operating conditions, such as rapid step change in reference speed and forward-reverse condition of the motor.

A. No-Load Test for Step-Change in Reference Speed

Step change in reference speed has been performed for no-load test in both simulation and laboratory experiment. It is discovered from Fig. 8 (a) that when the reference speed was increased from 200 rpm to 1,000 rpm at 2.25 sec, the actual speed correctly follows the reference speed with few milliseconds of delay to reach set speed. Although the IM is not so stable at lower speed (although voltage and currents are within permissible limit), it regains the stability as the speed approaches the rated speed.

Vector model tracks the change in reference speed by varying the pulse width of the IGBT inverter which can be understood from Fig. 8 (c). The starting torque is quite high and oscillating meaning that the machine is not stable but reduces with the rotor speed approaching to rated speed.

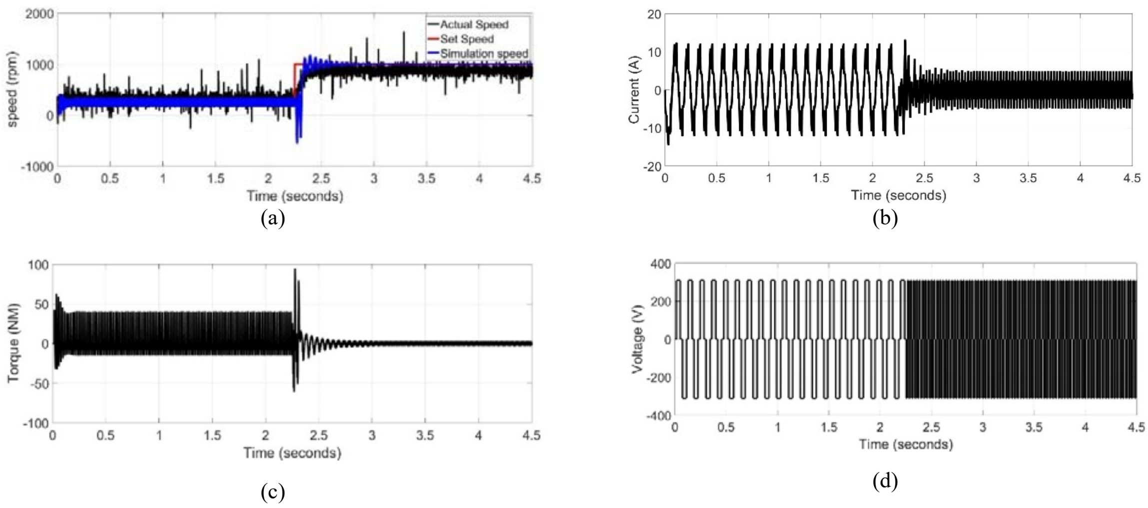

Fig. 8 (a) Speed, (b) current, (c) torque, and (d) voltage waveform for step change of speed setting

B. Forward-Reverse Action of IM

Modern industrial functions are mostly requiring the drives to have fast acting control forward-reverse action.

In this test, the forward-reverse test was performed at ± 1000 rpm and the switching action occurs every 2.75 sec. It is observed from Fig. 9 (a) that the actual speed correctly follows the reference speed although there is some time delay occurring to reach the final state. Also, it is evident from Fig. 9 (c) that the starting torque produced by the inductor motor is high. However, there is not any effect on the voltage and current.

VI. Conclusion

Due to the fact that the induction motor has widespread application and thus is highest consumer of energy in industry, it is of utmost importance to develop an appropriate controller with suitable switching technique. Vector control is used widely because of its high performance in dynamic behavior in IM. A vector control of induction motor in open-loop fashion is presented in where only stator currents are measured and is capable of controlling the motor speed by monitoring the d- and q-axis current vectors independently. The simulation model was developed in MATLAB/Simulink software. Open-loop vector control has greater advantage of not having to concern about speed encoder and related task of programing the speed signal. Moreover, open-loop unlike sensorless control does not have to estimate the speed. The SVPWM technique has advantage of producing higher voltage output with reduced harmonic distortion in the VSI. It provides tighter speed control, higher starting torque, and higher low-speed torque.

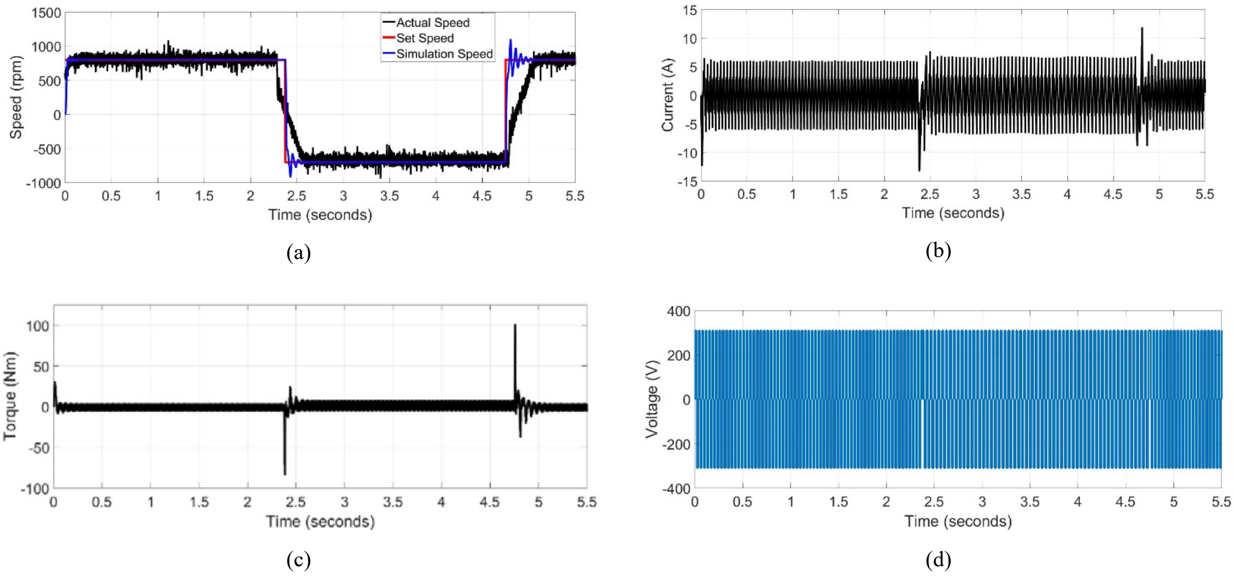

Fig. 9 (a) Speed, (b) current, (c) current, and (d) voltage simulation waveform for load rejection

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