A COMPLETE IMPLEMENTATION OF VECTOR CONTROL FOR A FOUR-SWITCH THREE-PHASE INVERTER FED IM DRIVE

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ABSTRACT

This paper presents an entire implementation for Vector Control of Induction Motor using Four-Switch Three-Phase Inverter (FOC-FSTPI-IM) for high performance industrial drive systems. In the proposed realization, instead of a usual 6-switch three-phase inverter (SSTPI) a 4-switch three-phase inverter (FSTPI) is used. A cost effective FSTPI fed IM drive using Field-Oriented-Control and Space-Vector PWM controller (with new control SVPWM approach) is implemented in real time. This reduces the price of the inverter, the switching losses, and the complication of the control board for generating 6 PWM logic signals. The complete vector control schema for the FSTPI for the induction drive system is verified by simulation using Matlab/Simulink and also experimentally by using DSP TI TMS2407a card. The designed inverter fed IM drive is found suitable considering its cost decrease and the robustness.

Index Terms— Vector Control, Space Vector, Pulse-Width-Modulation, Field-Oriented Control, Four-Switch Three-Phase Inverter (FSTPI), Six-Switch Three-Phase Inverter (SSTPI), Rotor Flux.

1. INTRODUCTION

Over the years induction motor (IM) has been utilized as a workhorse in the industry due to its easy build, high robustness, and generally satisfactory efficiency [1]. By tradition, 6-switch 3-phase inverters have been widely used for variable speed IM drives.

Recently, several scientific researches have been done for Four-Switch Three-Phase Inverters (FSTPI) with the target for reducing the cost of electric drives. Several inverter schemes with reduced number of switches have been proposed. Most of the reported works on FSTPI for IM drives [2-6] did not investigate the close-loop vector control scheme with the space vector PWM for VSI, which is important for high performance drives: robotics, rolling mills, machine tools, etc.

The last work on FSTPI for IM drives investigated the performance of a 4-switch, 3-phase inverter fed cost effective induction motor in real time, which has been implemented by vector control. In this scheme, two sinusoidal band hysteresis current controllers are used to force the phase currents \( i_{sa}, i_{sb} \) to follow their command [7]. Therefore, this system has disadvantages of current hysteresis controller, such as high current ripple and variable switching frequency.

Fig. 1. FOC schema for FSTPI-Induction Motor

In this paper, to overcome above mentioned disadvantages, a cost effective FSTPI fed IM drive with Field-Oriented-Control and Space-Vector PWM controller is implemented in real time. The
dynamic performance of an induction motor can be significantly improved using vector control theory where motor variable are transformed into an orthogonal set of d-q axes such that flux and torque can be controlled separately.

2. SPACE VECTOR PWM CONTROLLER FOR FSTPI AND THE PRINCIPLE OF SIMPLE FIELD ORIENTED CONTROL

2.1. Space Vector PWM Controller

According to the scheme in Fig.2 the switching status is represented by binary variables $S_1$ to $S_4$, which are set to “1” when the switch is closed and “0” when open. In addition the switches in one inverter branch are controlled complementary (1 on, 1 off), therefore:

$$S_1+S_2 = 1$$
$$S_3+S_4 = 1$$  \hspace{1cm} (1)

Phase to common point voltage depends on the turning off signal for the switch:

$$V_{ao} = (2S_1-1) \frac{V_{dc}}{2};$$
$$V_{bo} = (2S_3-1) \frac{V_{dc}}{2};$$

$$V_{co} = 0$$  \hspace{1cm} (2)

Combinations of switching $S_1$-$S_4$ result in 4 general space vectors $\vec{V}$ (Fig.2, Table 1), components $\alpha \beta$ of the voltage vectors are gained from abc voltages by using Clark’s transformation:

$$\vec{V} = V_a + jV_b$$

Table 1 Combinations of switchings and voltage space vectors

<table>
<thead>
<tr>
<th>$S1$</th>
<th>$S3$</th>
<th>$\vec{V}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>$\vec{V}<em>1 = \frac{V</em>{dc}}{3} e^{j\pi/3}$</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>$\vec{V}<em>2 = \frac{2V</em>{dc}}{3} e^{j\pi/3}$</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>$\vec{V}<em>3 = \frac{V</em>{dc}}{3} e^{j2\pi/3}$</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>$\vec{V}<em>4 = \frac{2V</em>{dc}}{3} e^{j2\pi/3}$</td>
</tr>
</tbody>
</table>

Fig. 2. Basic voltage space vectors for FSTPI

Table 2 Similarity between space vectors of FSTPI and SSTPI

<table>
<thead>
<tr>
<th>Used voltage space vectors for SSTPI</th>
<th>Used voltage space vectors for FSTPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>V23M</td>
</tr>
<tr>
<td>V2</td>
<td>V3</td>
</tr>
<tr>
<td>V3</td>
<td>V43M</td>
</tr>
<tr>
<td>V4</td>
<td>V14M</td>
</tr>
<tr>
<td>V5</td>
<td>V1</td>
</tr>
<tr>
<td>V6</td>
<td>V12M</td>
</tr>
<tr>
<td>V0, V7</td>
<td>V0M</td>
</tr>
</tbody>
</table>

$$[V_a, V_\beta] = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} [V_a, V_\beta]$$  \hspace{1cm} (3)

where $V_a, V_\beta$: output phase voltages on the load (Y connection), defined by:

$$V_a = \frac{1}{3} (2V_{ao} - V_{bo}); V_\beta = \frac{1}{3} (2V_{bo} - V_{ao});$$

$$V_\gamma = -\frac{1}{3} (V_{ao} + V_{bo})$$  \hspace{1cm} (4)

The SVPWM controller in this paper uses the principle of similarity where the formation of the required reference voltage space vector is done in the same way as for 6-switch 3-phase by using the additional effective vectors (Fig.3, Table 2). This facilitates the SVPWM calculation for 4-switch 3-phase and some studies on 6-switch 3-phase can be applied for FSTPI as well through this approach, e.g. SVPWM for the overmodulation. The detail of this control approach in order to synthesize the reference space vector has been presented in our another work [8], where the duty cycles $d_{ton}, d_{t0n}$ for generating gate control signals have been found.
for 3 modes of operation: under, overmodulation mode 1 and 2.

2.2. Field Oriented Control

In high performance drives, the decoupled flux and torque control of an induction machine can be realized by control of instantaneous phase current values, which in turn can be achieved by stator current space vector magnitude and position control with respect to the chosen flux space vector. Vector control can be achieved by indirect orientation as well, where position of rotor flux space vector is estimated again on the grounds of induction machine model in rotor flux oriented reference frame. In order to achieve orientation it is theoretically necessary to measure only rotor speed or position [9].

Indirect orientation principle is described as follow (Fig.4):

\[
i_d = \frac{\Psi_r^*}{L_m};
\]

\[
i_q = \frac{\omega_d^* \cdot T_r \cdot \Psi_r^*}{L_m};
\]

\[
\theta_r = \int (\omega_d^* + \omega) dt;
\]

where, \(i_d^*, i_q^*\) are reference d, q-axis components of stator space vector current, respectively; \(\Psi_r^*\) is the reference rotor flux; \(L_m\) is the mutual inductance; \(\omega_d^*, \omega\) are the reference slip speed and feedback rotor speed, respectively; \(T_r\) is the rotor constant and \(\theta_r\) is the rotor position.

In this method, three PI regulators are used to control speed, flux (\(i_d\)) and torque (\(i_q\)) correspondingly. The estimation of rotor position \(\theta_r\) is required to realize Park’s and inverse Park’s transformations.

3. SIMULATION OF THE PROPOSED FOC-SVPWM METHOD FOR FSTPI-IM

A Simulink/Matlab is used to validate the proposed FOC-SVPWM method for FSTPI-IM The induction motor model for the simulation studies has the follows parameters:

Type: Three-phase, squirrel-cage induction motor.

380V, 2HP, 1420r/min, \(R_s = 0.3827; R_r = 1.1142\Omega; L_s = 0.5853H; L_r = 0.5853H; L_m = 0.5688H; P = 2, J_m = 0.001 (kgm²).

The parameters used in simulation are given below:

- Reference flux \(\psi_r^* = 1 \text{ [p.u.]}\)
- Reference speed (p.u.): \(\omega^* = 0\) when \(0 \leq t \leq 2\) s; \(\omega^* = 0.2\) when \(2 \leq t \leq 4\) s; \(\omega^* = 0.4\) when \(4 \leq t \leq 6\) s; \(\omega^* = 0.6\) when \(6 \leq t \leq 8\) s; \(\omega^* = 1\) when \(8 \leq t \leq 10\) s; \(\omega^* = 0.5\) when \(10 \leq t \leq 12\) s; \(\omega^* = 0\) when \(12 \leq t \leq 16\) s; \(\omega^* = -0.5\) when \(16 \leq t \leq 20\) s.
- Sample time : \(T_s = 5e-4\)
- Load torque \(T_L = 3 \text{ N.m at t=1s.}\)
- Time of simulation \(t = 20\) s.

Simulation results demonstrate the performance of the implementation of FOC-SVPWM control method for FSTPI-IM, while the good responses of the flux, torque, rotor speed and currents are obtained (fig.6 - 10).
4. EXPERIMENTAL RESULTS

To implement the proposed FOC-SVPWM for FSTPI-IM drive an experiment has been set up (Fig.11). The Field-Oriented-Control and SVPWM control strategy are programmed by Code Composer Studio CCStudio 3.1 and downloaded in the control board TMS320LF2407A to generate the command pulses for FSTPI (IGBT SKM 75GB 123D, Driver SKHI 22A).

The output from FSTPI was connected to a three phase induction motor, which has the following parameters: Type: Three-phase, squirrel-cage induction motor, 400V, 50Hz, 1.66A, 1HP, 1395r/min; \( R_s = 2.0497\Omega \); \( R_r = 4.0382\Omega \); \( L_s = L_r = 1.1305H \); \( L_m = 1.0824H \).

The switching frequency of IGBT is 5 kHz. The DC link voltage was adjusted at 600V, and the split capacitors are rated at 3300\( \mu F \).

The Hall-effect LEM current sensors (\( i_{sa,ib,ic} \)) and rotary encoder Metronix 2000ppr, which have been used to receive current and speed feedback signals, are HX-05P and H40-8-2000VL respectively.

An interface between DSP2407a and PC was built using Visual Basic to obtain the speed response (Fig. 12). The reference speed is 1000 rpm.

The rotor speed response in case of acceleration and deceleration is shown in Fig. 12.
5. CONCLUSION

A cost effective FSTPI fed IM drive with Field-Oriented-Control and Space-Vector PWM controller in real time has been presented. The Space Vector PWM in this implementation is based on the principle of similarity between FSTPI and SSTPI (Six-Switch Three Phase Inverter). An indirect vector control method is utilized to gain the high performance of IM drive.

The validity of this complete implementation is verified by simulation and experimental results using Matlab/Simulink and DSP TMS320LF2407A. Simulation and experimental results demonstrate the good performance of the FOC-SVPWM for FSTPI-IM, while the good responses of the flux, torque, and speed are obtained.

REFERENCES