A New Space Vector PWM Scheme for Current-Regulated Indirect Vector Control

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Abstract - The system performance of an AC variable speed drive directly depends on the current regulation. In this paper, a new space vector PWM scheme for current-regulated indirect vector control is developed. Motor currents are regulated by generating appropriate inverter output voltage vectors via software implemented comparators and switching table. Switching table based on angular coordinate enables the inverter to generate optimal voltage vectors. Operation principles of the proposed scheme are described and verified by laboratory test. Both simple hardware design and good current response are obtained.

I. INTRODUCTION

Current-regulated voltage source PWM inverters have been widely used in the industry for AC variable speed drives for two decades. In such systems, the system performance directly depends on the performance of current regulation. A quick-response and harmonics-free current regulation implies quick response speed and low pulsation torque. Recently, various studies based on space vector scheme for obtaining better current regulation have been proposed [1-6]. The space vector PWM analyzes the inverter output voltage vectors to approximate desired current waveforms instead of generating phase-to-neutral voltage waveforms as usually employed in conventional PWM inverter scheme. It has been proven that the space vector scheme has the advantage of lower current harmonics and a possible higher modulation index [2].

A particular sampling and a current prediction technique were proposed to get a zero dead time in the current control system and better space voltage vectors for PWM pattern. However, this method requires complex calculation [3].

Another space-vector-based hysteresis current regulator was proposed to suppress the high order current harmonics in steady state, and to give quick current response in transient state [4]. But, it still uses an estimation of the counter EMF based on the derivative of high frequency current components.

Among the various methods for generating appropriate voltage vectors, constructing switching tables is remarkably simple and effective. A simple current control strategy based on an EPROM switching table has been presented by Y. P. Kazmierkowski [5,6] as shown in Fig. 1(a). The current loop input commands are the field-oriented dc components of the stator current vector (i_{xc} , i_{yc} , where i_{yc} is proportional to the rotor flux amplitude, and i_{xc} is proportional to the torque. The measured stator currents (i_a, i_b, i_c) are transformed into the synchronously rotating frame (i_{sx}, i_{sy}), which serve as the feedback signals. The current errors are fed to the hardware-implemented three-level hysteresis comparators. The inverter voltage vectors are selected according to the comparator outputs in order to force the current errors to zero. The accuracy of current formation and the switching frequency are determined by the width of hysteresis zone of the three-level comparators. The control algorithm is simple. However, the hardware-implemented

Fig. 1. Comparison between two space vector PWM: (a) Conventional scheme with two three-level hysteresis controllers and a hardware-implemented switching table; (b) proposed scheme with software-implemented switching table and comparators.

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III. INDIRECT VECTOR CONTROL

The induction machine is a nonlinear multivariable highly-coupled device. The instantaneous torque is the vector product of the interlinkage flux and the torque component of the stator currents, which is orthogonal to the flux. Vector control provides a chance of decoupling the two components of stator current, one producing the air gap flux and the other producing the torque. Therefore, it provides independent control of torque and flux, which is similar to a separately excited dc machine. The magnitude and phase of the stator currents are controlled in such a way that the flux and torque components of current remain decoupled during dynamic and transient states [8].

Basically, this scheme can be classified into two groups: 1.) the direct vector control; 2.) the indirect vector control. Owing to its simplicity, the indirect vector control gains increasing popularity. Fig. 5 shows the block diagram of the indirect vector control.

Fig. 5. Block diagram of the indirect vector control

The indirect vector control inputs the amplitude of the flux component current i_d^* and the desired rotor speed ω_m^* . The flux component current i_d^* is selected in such a way to get rated air gap flux. The torque current command i_q^* is proportional to torque command T^* obtained from the speed control loop. The inputs of coordinate transformation are (i_d^*, i_q^*) and synchronously rotating angular position θ^* ; the outputs are current reference vector based on the stator coordinate (i_x^*, i_y^*) . Speed regulation is achieved by controlling the stator currents i_x and i_y to follow (i_x^*, i_y^*) .

IV. SWITCHING TABLES

To incorporate space vector method into indirect vector control, the synchronously rotating d-q frame current commands (i_d^*, i_q^*) and measured stator currents i_a, i_b , and i_c are transformed into complex space vectors (i_x^*, i_y^*) and (i_x, i_y) based on stator coordinate respectively. The current errors $(\Delta i_x, \Delta i_y)$ are computed to be:

$$\begin{aligned} \Delta i_x &= i_x - i_x^* \\ \Delta i_y &= i_y - i_y^* \end{aligned} \quad (4)$$

To accomplish current control, $(\Delta i_x, \Delta i_y)$ are fed into the three-level comparators which generate three discrete outputs 1, 0, -1. There are nine possible combinations of (d_x, d_y) , which divide the error plane into nine regions as illustrated in Fig. 6.

The voltage vectors are chosen according to these comparator output combinations as shown in Table 1. When the current error is located in one of the nine regions, then the voltage vector in the opposite direction is chosen to draw the error backward to zero. For example, if current error is located in $(-1, 0)$ then u_1 is chosen, if $(0, 0)$ then u_0 or u_7 is chosen to free-wheel. In

Fig. 6. Outputs of three-level comparator and voltage vectors

this method, both the accuracy and the width of comparator is determined by the sampling frequency.

Table 1. Switching table used in rectangular coordinate

$dy \backslash dx$	-1	0	1
1	u_6	u_0	u_3
0	u_1	u_0	u_4
-1	u_2	u_3	u_5

This switching table is direct and simple. However, there are 19 vectors available, but only nine comparator output combinations exist to choose the voltage vectors. Clearly, the voltage vectors can not be fully utilized. Moreover, the voltage vectors radiate from the origin point symmetrically; each of the long or short vectors occupies a fan-shaped region of the equal area as its folk are considered. It is direct and convenient to express complex space vectors in the angular coordinate instead of in rectangular as illustrated in Fig. 7. In the proposed method the current errors (i_x^*, i_y^*) are transformed into angular coordinate as:

$$\begin{aligned} (\Delta i_x, \Delta i_y) &= \Delta i_x + j\Delta i_y = |\Delta i| \angle \Delta i_1 \\ \text{where } |\Delta i| &= \sqrt{(\Delta i_x)^2 + (\Delta i_y)^2} \\ \angle \Delta i_1 &= \tan^{-1}(\Delta i_y / \Delta i_x) \end{aligned} \quad (5)$$

Fig. 7. Current error vector in angular coordinate.

The magnitude of current error vector is fed into a three-level comparator; and the angle determines its orientation.

Table 2. Switching table used for angular coordinate

hysteresis comparators and EPROM switching table make the hardware design complicated and expensive.

In this paper, a novel control scheme for current-regulated space vector PWM inverter incorporated in indirect vector control for a three-phase induction motor is proposed as shown in Fig 1(b). The comparators and switching tables are implemented in software. This greatly simplifies the hardware complexity. Additionally, formerly proposed switching tables based on rectangular coordinates are too rough to precisely select the inverter voltage vectors. A new switching table based on angular coordinate is proposed to improve the accuracy of selecting inverter voltage vectors. Optimal voltage vectors are acquired by the proposed scheme. The theoretical operation principles are described in the following sections. The proposed system is implemented and tested in the laboratory.

II. SPACE VECTOR SCHEME

In the analysis of AC machines, the concept of space vector is very helpful and frequently employed. In an induction motor, the flux density is usually assumed to be sinusoidally distributed in

Fig. 2 (a) Conceptual diagram of an inverter-fed induction motor. (b)(c) representation of voltage vectors as space vectors according to the switching states.

space around the air gap. For such machines, it is convenient to represent three-phase quantities (currents, voltages, or fluxes) f_A, f_B and f_C as a complex space vector, indicating the magnitude and angular position of the rotating sinusoidal distribution [7]:

$$f = f_A + af_B + a^2f_C \quad (1)$$

where $a = e^{j2\pi/3}$

Fig. 2(a) shows the conceptual diagram of an inverter-fed induction motor, where Sa, Sb, and Sc denote the switches of inverter legs A, B, and C respectively. For $S_K = 1$ the corresponding upper switch is conducting, i.e. $u_{KM} = \frac{1}{2}u_d$. For $S_K = 0$ the lower switch is conducting, i.e. $u_{KM} = -\frac{1}{2}u_d$. Therefore the voltage output vector can be represented as a function of the switches state of the inverter denoted as $u_K = S(Sa, Sb, Sc)$. For example, u_1 is corresponding to the switch state $S(1, 0, 0)$. Consequently an inverter can generate eight distinct complex voltage vectors according to the states of the switches of inverter as shown in Fig. 2(b), where

$$u_K = \begin{cases} (2/3)u_d e^{j(K-1)\pi/3} & \text{for } K = 1 \dots 6 \\ 0 & \text{for } K = 0, 7 \end{cases} \quad (2)$$

Moreover, switching twice in one sampling period gives the inverter the possibility to synthesize more effective voltage vectors. Fig. 3 shows conceptually how a vector is synthesized by two neighboring vectors. u_1 is generated over the first half of the sampling period and u_2 is generated over the second half of the sampling period. Consequently an equivalent voltage vector u_{12} is obtained, where

$$u_{12} = \frac{1}{2}u_1 + \frac{1}{2}u_2 \quad (3)$$

Fig. 3. Vector synthesis using two neighboring vectors.

This method enables the inverter to generate nineteen distinct vectors including a zero, six short and twelve long vectors, as shown in Fig 4.

Fig. 4. Available space vectors.

The inverter output voltage vector is kept constant during a switching period. If the sampling frequency is high enough, then the displacement of current vectors can be considered proportional to the voltage vectors. By generating appropriate voltage vectors, we can control the inverter current waveforms as desired.

Fig. 8. Block diagram of the proposed current-regulated space vector PWM scheme.

When the current error locates in the most outlying region, which is divided into twelve sectors, one of the 12 long vectors is chosen in accordance with the sector it scatters. When current error lies in the center bracelet, one of the six short vectors; and when the inner circle, the zero vector is chosen. Table 2 illustrates this idea. The generated PWM patterns may be more precise than other methods in rectangular frame.

V. EXPERIMENTAL TESTS AND RESULTS

An indirect-vector-control system for testing the proposed space vector scheme is developed. The block diagram of the proposed system is shown in Fig. 8, where the left side of the dotted line is implemented in software and the right side in hardware. The control function is performed using a PC-386. The proposed approach features simple hardware design. All the control schemes including the vector control scheme, space-vector-based current regulation, and switching table are implemented in software.

The vector control inputs the amplitude of the flux component current i_d^* and the desired rotor speed ω_m^* . Rated air gap flux is acquired by selecting an appropriate i_d^* . The feedback signal of the speed control loop is the rotor angular speed ω_m measured by the tachometer. The torque component current command i_q^* is proportional to the torque command T^* obtained from the speed control loop. For saving the computational time, i_q^* is directly calculated from PI controller. The relationship between T^* and i_q^* is pre-calculated and included in the PI controller. The current reference (i_x^*, i_y^*) based on stator coordinate are transformed from the synchronously rotating currents (i_d^*, i_q^*) and served as inputs to the current regulation block.

Stator currents i_a and i_b are measured by Hall effect current sensors and transformed into (i_x, i_y) based on stator coordinate. The magnitude $|\Delta i|$ and angular position $\angle \Delta i$ of current error are delivered to the comparators, whose outputs act as indices of the switching table. The inverter switching commands are sent directly from the computer according to the switching table outputs. This fully-digitized design greatly simplifies the hardware complexity.

The new proposed space vector scheme and the switching tables are tested in the laboratory. The steady state current waveforms are recorded and shown in Fig 9. The current harmonic contents are analyzed in Fig 10. Both the sampling and total harmonic distortion (T.H.D.) are given in Table 3.

(a)

(b)

Fig. 9. (a) (b) the current waveforms for switching table 1. and 2. respectively.

Table 3. Comparison of sampling frequencies and T.H.D. between the switching tables based on rectangular and angular coordinate.

	rectangular	angular
sampling frequency	3.20 kHz	2.64 kHz
T.H.D.	15.92 %	13.07 %

Fig. 10. (a) (b) the harmonics contents for switching table 1. and 2. respectively.

VI. CONCLUSIONS

A space-vector-based current-regulated inverter with new switching tables is designed. This system is tested in the laboratory as a variable speed drive for an indirect-vector-controlled induction motor. Significant advantages have been obtained.

1.) Hardware design is very simple, since hysteresis comparators and switching tables are implemented in software and the inverter switching commands are sent directly from the computer. High reliability is inherent in this system.

2.) No motor counter EMF calculations are needed for obtaining switching commands, thus the sampling frequency is comparatively high [3].

3.) Current harmonic contents have been improved by the proposed switching table in angular coordinate.

Owing to its accurate selection of space vectors, the proposed switching table offers better harmonic contents, even the coordinate transformation slows down the sampling frequency. When high speed CPUs and DSP chips are inexpensively available, the proposed method will make its popularity.

REFERENCE

- [1] I. Takahashi, and T. Noguchi, "A New Quick-Response and High-Efficiency Control Strategy of an Induction Motor," *IEEE Trans. Ind. Appl.* Vol. IA-22, No. 5, pp. 820-827, 1986.
- [2] H. W. Broeck, H. C. Skudelny, and G. V. Stanke, "Analysis and Realization of a Pulsewidth Modulator Based on Voltage Space Vectors," *IEEE Trans. Ind. Appl.*, Vol. IA-24, No. 1, pp. 142-149, 1988.
- [3] I. Miki, O. Nakao, and S. Nishiyama, "A New Simplified Current Control Method for Field-Oriented Induction Motor Drives," *IEEE Trans. Ind. Appl.*, Vol. IA-27, No. 6, pp.

1081-1086, 1991.

- [4] A. Nabae, S. Ogasawara, and H. Akagi, "A Novel Control Scheme for Current-Controlled PWM Inverters," *IEEE Trans. Ind. Appl.* Vol. IA-22, No. 4, pp. 697-701, 1986.
- [5] M. P. Kazmierkowski, M. A. Dzieciakowski, and W. Sulkowski, "Novel Space Vector Based Current Controller for PWM-Inverters," *IEEE Trans. Power Electronics*, Vol. 6, No. 1, pp. 158-165, 1991.
- [6] M. P. Kazmierkowski, and W. Sulkowski, "A Novel Vector Control Scheme for Transistor PWM Inverter Fed Induction Motor Drive," *IEEE Trans. Ind. Electronics*, Vol. 38, No. 1, pp. 41-47, 1991.
- [7] G. R. Selmon, "Modelling of Induction Machines for Electric Drives," *IEEE Trans. Ind. Appl.*, Vol. IA-25, No. 6, pp. 1126-1131, 1989.
- [8] E. Ho, and P. C. Sen, "Decoupling Control of Induction Motor Drives," *IEEE Trans. Ind. Electronics*, Vol. 35, No. 2, pp. 253-262, 1988.