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Using Space Vector Modulation in a DTC Scheme

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1. Abstract

Direct torque control (DTC) is known to produce quick and robust response in AC drives. However, during steady state, torque, flux and current ripple occur. An improvement of the electric drive can be obtained using a DTC scheme based on the space vector modulation (SVM) which reduces the torque and flux ripple. The proposed control scheme considers the rotor resistance variation.

This paper also discusses the application of artificial neural network (ANN) as a speed estimator.

The capability and precision of this scheme as a speed estimator is validated by simulation results, from which it is concluded that the proposed control scheme produces better results than the classical DTC.

Key words: DTC, SVPWM, ANN, Sensorless.

2. Resumen (Utilización de la modulación espacial en un esquema de DTC)

El control directo del par es muy conocido en los accionamientos eléctricos de velocidad variable, por presentar una respuesta rápida y robusta .

Uno de los grandes problemas durante su operación en estado permanente son las pulsaciones de corriente y par electromagnético.

Para mejorar el accionamiento eléctrico se puede emplear un esquema que se base en un PWM espacial (SVM), el cual puede reducir las pulsaciones de par y corriente en el motor. Así como el empleo de redes neuronales artificiales para la estimación de la velocidad del rotor se muestra dentro del esquema propuesto.

Los resultados de simulación como de implementación validan la mejora del esquema propuesto sobre el esquema convencional. Además de tener un estimador de velocidad basado en redes neuronales artificiales.

Palabras clave: DTC, SVPWM, ANN, sin sensor de velocidad.

3. Development

3.1 Direct torque control

Direct torque control principle was widely used for induction motor drives with fast dynamics. Despite its simplicity, DTC is able to produce very fast torque and flux control and, if the torque and flux are correctly estimated, it is robust with respect to motor parameters variations and perturbations. However during steady-state operation, notable torque, flux and current pulsations occur [1].

Although the motor is not controlled by a conventional field oriented method, PWM waveforms have been obtained owing to the on-off control of both the stator flux and the torque using an optimum switching table (six non zero voltage vectors with a phase displacement of 60 degrees from each other, and two zero voltage vectors are selected to stop the stator flux).

For this case, which must be performed with less sensitivity to the motor parameters [2], the stator flux and torque are

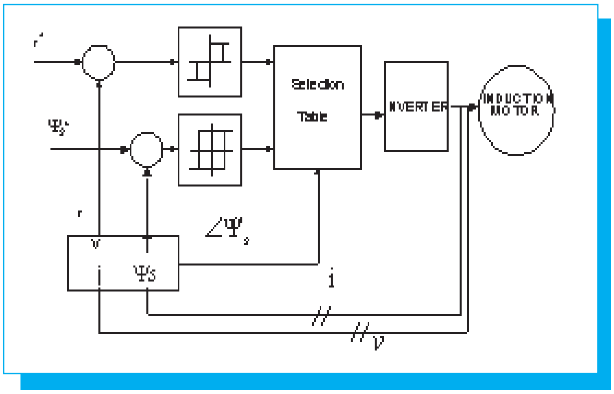


Fig. 1. Conventional direct torque control.

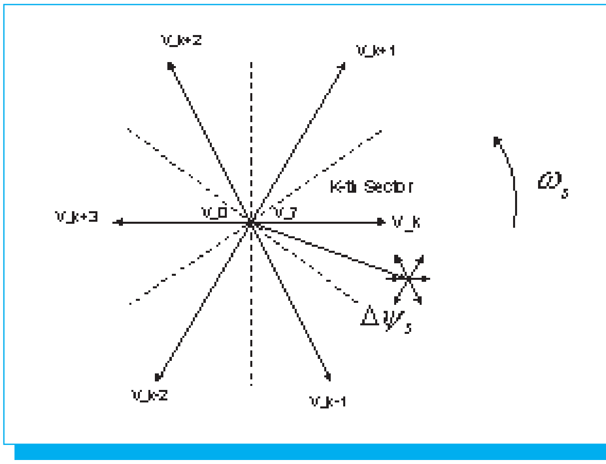


Fig. 2. Voltage space vectors.

either measured or estimated and used as feedback signals for control. The inputs of the selection table used are the torque error, the error in the magnitude of the stator flux space vector and the angle of the stator flux space vector. The magnitude of the error signal of the stator flux is discretized into two levels by means of a hysteresis comparator. The torque error signal is discretized into three levels by means of a three-stage hysteresis comparator. The output of the selection table gives the setting for the power-switching device of the inverter [3].

The basic equations for the DTC are shown below [2]:

$$\bar{v}_s = \bar{i}_s R_s + \frac{d}{dt}\bar{\psi}_s + j\omega_s \bar{\psi}_s \tag{1}$$

$$0 = \bar{i}_r R_r + \frac{d}{dt}\bar{\psi}_r + j(\omega_s - \omega_r)\bar{\psi}_r \tag{2}$$

$$\bar{\psi}_s = L_s \bar{i}_s + L_m \bar{i}_r \tag{3}$$

Table 1. Space vector voltage influence on torque and stator flux space vector.

	V_k	V_{k+1}	V_{k+2}	V_{k+3}	V_{k-2}	V_{k-1}	V_0 V_7
Stator Flux	↑↑	↑	↓	↓↓	↓	↑	—
Torque	↑↑	↑	↑	↓	↓↓	↓↓	↓

$$\bar{\psi}_r = L_r \bar{i}_r + L_m \bar{i}_s \tag{4}$$

$$T_e = \frac{3}{2} p L_m (\psi_{sd} i_{sq} - \psi_{sq} i_{sd}) \tag{5}$$

The change of stator flux and torque is defined by the selection of six zero voltage vectors and the zero voltage vectors (Fig. 2). A selection table can be obtained to control the stator flux and torque of an induction motor in an optimal way (table 1).

3.2 Space vector pulse width modulation

The modulation strategy applied in space vector pulse width modulation (SVPWM) is to approximate the voltage reference vector V_{ref} using a combination of two out of the eight possible vectors that can be generated from a three-phase inverter [4].

From Figure 3, the reference voltage V_{ref} can be expressed as:

$$\int_0^T \bar{V}_{ref}\, dt = \int_0^{T_1} \bar{V}_k dt + \int_{T_1}^{T_1+T_2} \bar{V}_{k+1} dt + \int_{T_1+T_2}^{T} \bar{V}_0 dt \tag{6}$$

In (6) V_0 does not affect the magnitude of the voltage since it is a null vector. Assuming that the vectors V_k or V_{k+1} are constants and given that V_0 is a null vector [2]:

$$\bar{V}_{ref} T = \bar{V}_k T_1 + \bar{V}_{k+1} T_2 \tag{7}$$

Expressing (7) in the d-q reference plane and considering the region 0<γ<π/3, it follows that

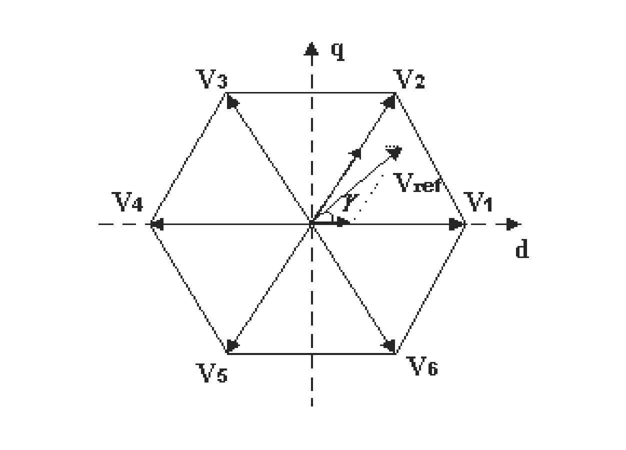


Fig. 3. Pulse width modulation using space vectors.

$$\frac{2}{3}T_1V_{cd}\begin{bmatrix}1\\0\end{bmatrix}+\frac{2}{3}T_2V_{cd}\begin{bmatrix}\cos(\pi/3)\\ \sin(\pi/3)\end{bmatrix}=T\left|\overline{V}_{ref}\right|\begin{bmatrix}\cos\gamma\\ \sin\gamma\end{bmatrix} \quad (8)$$

hence

$$T_1=\frac{\sqrt{3}T\,|\overline{V}_{ref}|}{V_{cd}}\sin\left(\frac{\pi}{3}-\gamma\right) \quad (9)$$

$$T_2=\frac{\sqrt{3}T\,|\overline{V}_{ref}|}{V_{cd}}\sin\gamma \quad (10)$$

$$T_3=T-T_2-T_1 \quad (11)$$

In order to determine the duration of the pulses in the other regions, the reference vector is rotated $-n\pi/3$ radians until its angle is equal to $0<\gamma<\pi/3$ [5].

In order to minimize the commutation frequency of the inverter devices and the harmonics generated, it is necessary to select a firing sequence in such a way that the transition from one state to another is achieved with the commutation of only one phase. One such sequence is achieved by beginning with a vector zero and two vectors different from zero and terminates with vector zero as shown in Figure 4.

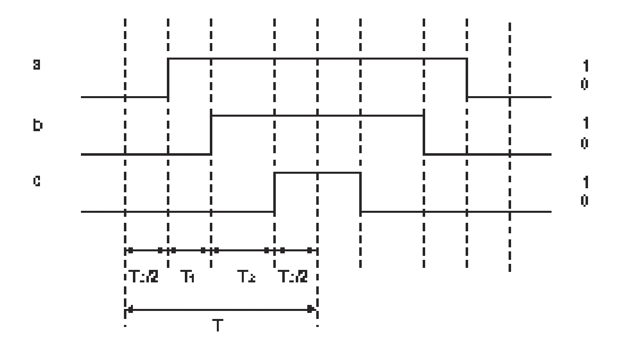


Fig. 4. Commutation sequence for the inverter [9].

3.3 Artificial neural networks

Artificial neural networks (ANN) are based on the model of the human brain and are constructed using artificial neurons. ANNs are capable of learning the desired mapping between inputs and outputs signals of a system without knowing the exact mathematical model of the system. Since ANN do not use the mathematical model of the system, the same ANN architecture can solve many problems. ANN are excellent non-linear systems estimators.

The basic elements of the ANN are the neurons. A neuron has four main parts [6].

- Input(s)
- Weighted summer and bias
- Activation function
- Output(s)

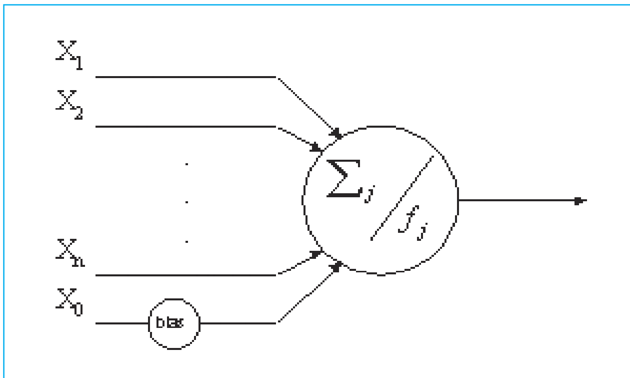


Fig. 5. Artificial neuron.

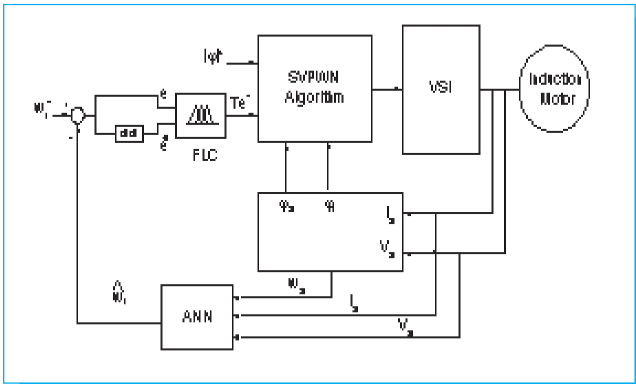


Fig. 6. Proposed control scheme.

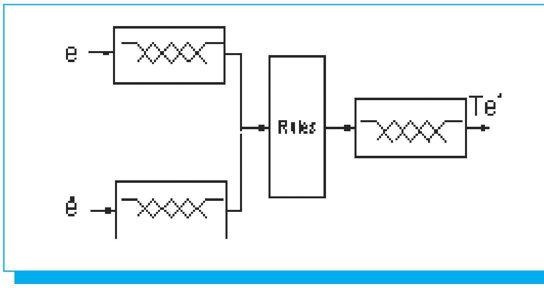


Fig. 8. Fuzzy logic control (Mandani type).

Multi-layer ANN are built with neuron blocks, the neurons are arranged in several parallel layer, this layers fall into the classifications input layer, hidden layer and output layer.

The architecture of the ANNs is not fixed, sometimes, one hidden layer is sufficient to perform non-linear input-output mapping of a system.

Training refers to the process, which adjusts the weights and biases [6] of a given ANN to a specific problem. The training algorithms can be supervised or non-supervised. A back-propagation algorithm was used in supervised training for the multi-layer feed-forward ANN used in this work.

In this work, the motor voltage, current and synchronous velocity were used as inputs and the estimated velocity as the output of the network during the training process.

3.4 Proposed control scheme

A closed loop sensorless control scheme shown in Figure 6 is proposed.

In this scheme, rotor and stator magnetic flux vectors are estimated using a dynamic model of the motor. Stator variables (current, voltage and synchronous velocity readings) are fed into the neural network from which an estimate of actual velocity is obtained. This is compared to the reference velocity and the error obtained is fed into a fuzzy controller (Mandani)[7], from which the electromagnetic reference is obtained. A space pulse

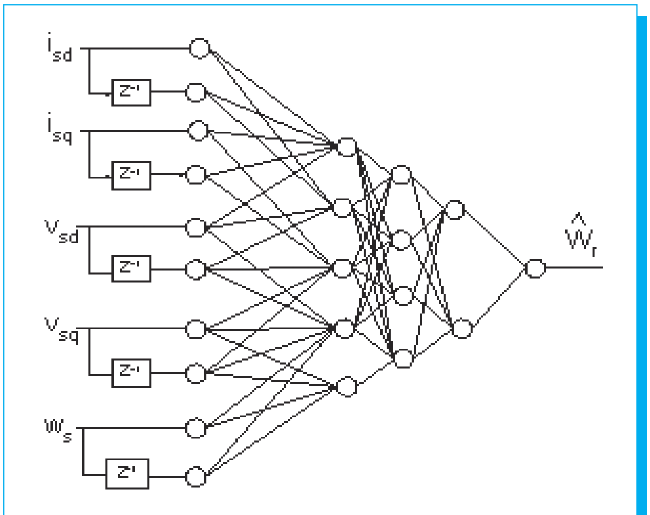


Fig. 7. Neural network scheme.

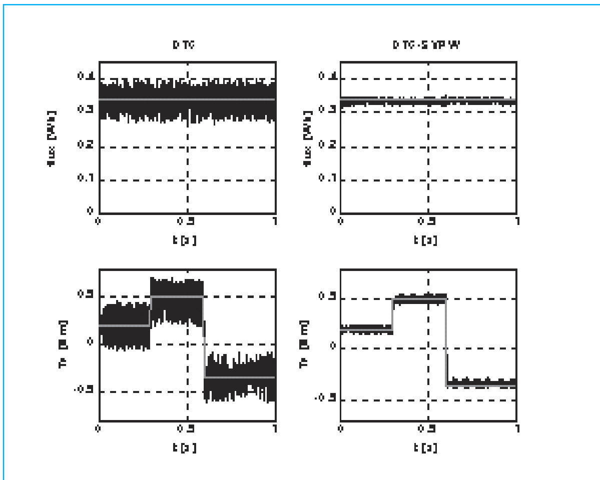


Fig. 9. A comparison of ripple in the torque and flux obtained using DTC and SVPWM. f= 5 Hz, fswitch=20kHz.

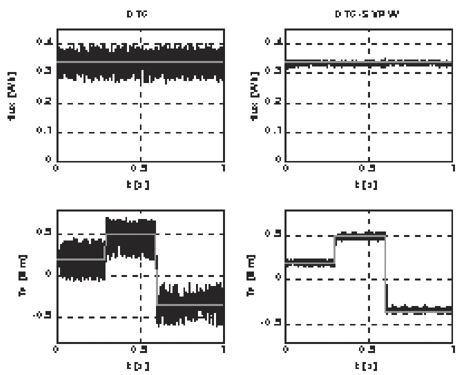


Fig. 10. A comparison of harmonics found in the stator current using DTC and SVPWM. f=5 Hz, fswitch=20kHz.

width modulation technique is used to select the voltage vector using the estimated torque and flux of the reference stator. The neural network used for estimation is shown in Figure 7 and the synchronous velocity is calculated using the voltage variation generated by the SVPWM.

The diffuse controller used is the Mamdani type [7] with 5 error membership functions, 5 membership functions for the derivative of the error found and 25 rules.

3.5 Simulation results

The results presented were obtained using the scheme shown in Figure 6.

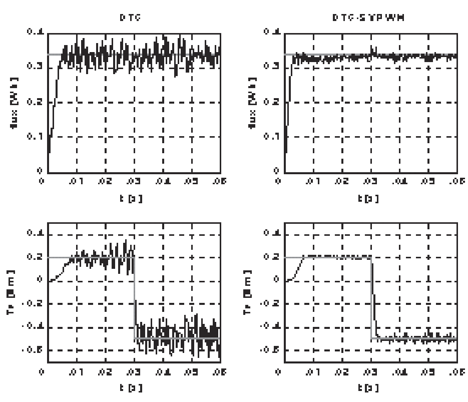


Fig. 11. A comparison of dynamic response for conventional DTC and DTC-SVPWM.

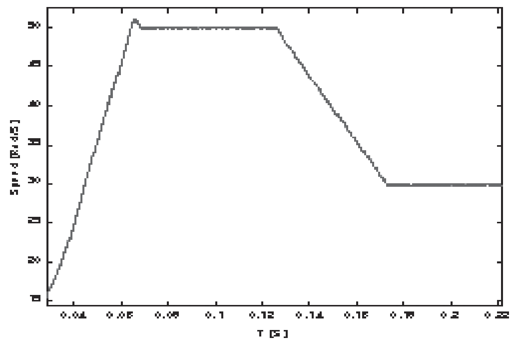


Fig. 12. A comparison for the speed calculated using the dynamic motor model and the speed estimated by ANN (an overlying response).

A comparison between the electromagnetic torque and the magnitude of the stator flux obtained in a conventional DTC and those obtained using the space vector scheme is shown in Figure 9. Figure 10 shows stator currents obtained using both schemes from which the harmonic content (5Hz) can be observed. The torque and flux dynamic response of both schemes is shown in Figure 11.

Figure 12 shows the estimated motor velocity after training the ANN and the velocity obtained from the dynamic model of the induction motor (one of them is superimpose). Nominal operating conditions are considered for the motor.

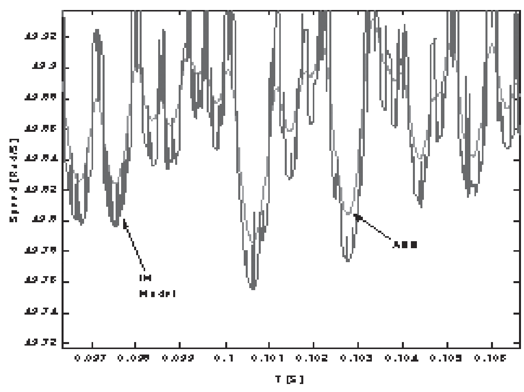


Fig. 13. A close lokk at Figure 12.

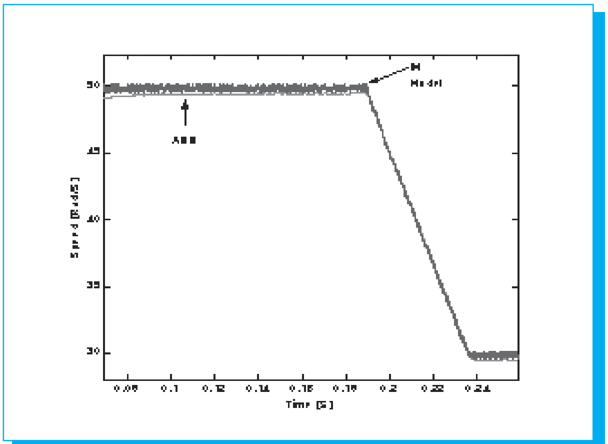


Fig. 14. A comparison between the velocity calculated using the dynamic model of the motor and the estimated velocity using ANN considering variations in rotor time constant.

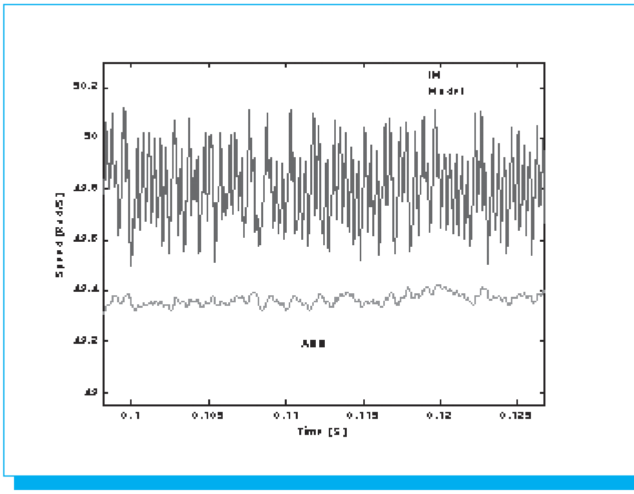


Fig. 15. A close look at figure 14.

In Figure 13, the performance of the scheme is observed as rotor time constant is varied up to 150% of its nominal value.

3.6 SVM Implementation

The low number of voltage vectors which can be applied using the conventional DTC scheme may cause torque and flux ripple.

The pulse width modulation (PWM) method used in AC drives influences the harmonic current content and torque pulsation. In order to investigate this two PWM are compared.

Motorola DSP56F80x has the necessary features to allow easy implementation of different electric motor control schemes and PWM techniques, the major features of DSP56f80x are [8,9]:

- DSP56F80x is optimised for motor control applications. It includes six PWM outputs.
- Software Development Kit (SDK) allows an easy configuration of PWM characteristics such as PWM period, PWM waveform alignment, and interrupts handling.
- The six PWM outputs may be used as three complementary channel outputs.
- An easy to use deadtime insertion avoids short-circuiting the DC bus.
- Independent output polarity control.
- 15-bit resolution PWM registers.

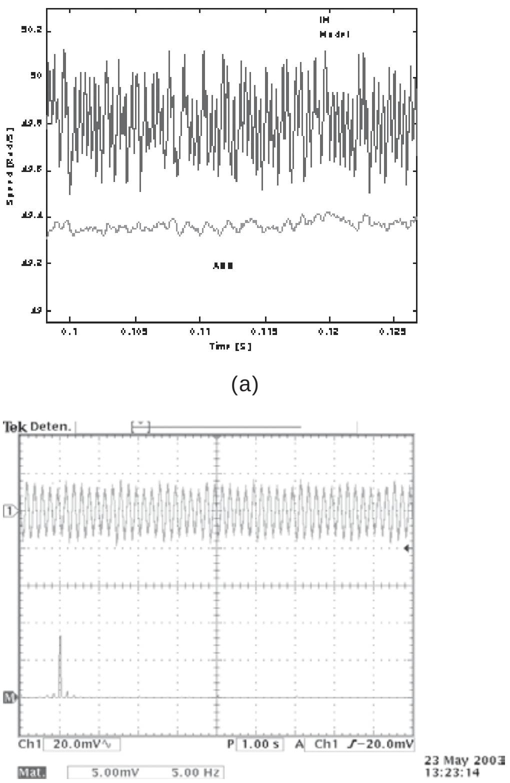
In figure 16 (a) a six-step technique and (b) SVM are compared. The current waveform and harmonic contents are presented.

5. Conclusions

This paper has introduced a new direct torque control scheme based on a fuzzy controller, voltage space vector and artificial neural network.

The main observations are as follows:

- SVM is observed to improve torque and flux response when applied in conjunction with DTC in the proposed control scheme.
- A neural network speed estimator was tested and shows insensitivity to rotor time constant change.
- The dynamic response of the proposed scheme shows good performance.



(a)

(b)

Fig. 16. Comparison of current and harmonic contents for (a) six steps and (b) SVM at 5 Hz.

The neural network used takes as inputs the synchronous velocity, stator voltage and current thus does not increase the number of sensors necessary in comparison with conventional DTC .

6. References

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