COMPARISON BETWEEN THREE-LEVEL INDUCTION MOTOR TORQUE CONTROL SCHEMES+

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Abstract

This paper presents the results of an investigation into suitable torque control schemes for application.. The investigated schemes are Field Oriented Control, Direct Torque Control (DTC), and DTC using Space Vector Modulation. The results of Matlab- Simulink simulations and a comparison between the control schemes are presented. It is found that the DTC using Space Vector Modulation scheme is best for the application.

المستخلص

يتناول البحث نتائج التحري عن نظام السيطرة على العزم لاغراض امكانية تطبيقها. ان الأنظمة التي تم الخوض فيها هي : السيطرة بتغير اتجاه المجال (Field Orientation Control) والسيطرة عن طريق التغير المباشر للعزم (Direct Torque Control) وكذلك استخدام نظام تنغيم متجه المجال (Space Vector Modulation) في نظام السيطرة المباشرة على العزم. حيث استخدم (SIMULINK/MATLAB) في حل النماذج الرياضية وعرض النتائج للانظمة المقترحة. وقد وجد أن التغير المباشر للعزم (DCT) والذي يستخدم نظام تنغيم المجال هو الأفضل عند التطبيق العملي.

Introduction

The technique of the torque control of induction motors was developed and presented by I. Takahashi as direct torque control (DTC), and by M. Depen-brock as direct self control (DSC). Since the beginning, the new technique was characterized by simplicity, good performance and robustness.

By using DTC or DSC it is possible to obtain a good dynamic control of the torque without any mechanical transducers on the machine shaft. Thus, DTC and DSC can be considered as "sensorless type" control techniques.

The basic scheme of DSC is preferable in the high power range applications, where a lower inverter switching frequency can justify higher current distortion.

In this paper, the attention will be mainly focused on the basic DTC scheme, which is more suitable in the small and medium power range applications.[1].

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Several papers have been published on field-oriented control (FOC) and DTC in the last 30 years, but only few of them aimed to emphasize differences, advantages and disadvantages.

The name direct torque control is derived by the fact that, on the basis of the errors between the reference and the estimated values of torque and flux, it is possible to control directly the inverter states in order to reduce the torque and flux errors within the prefixed band limits.

Unlike FOC, DTC does not require any current regulator, coordinate transformation and PWM signals generator (as a consequence timers are not required). In spite of its simplicity, DTC allows a good torque control in steady-state and transient operating conditions to be obtained.

The problem is to quantify how good the torque control is with respect to FOC. In addition, this controller is very little sensible to the parameters detuning in comparison with FOC.

On the other hand, it is well known that DTC presents some disadvantages that can be summarized in the following points: [2]

- Difficulty to control torque and flux at very low speed.
- High current and torque ripple.
- Variable switching frequency behavior.
- High noise level at low speed.
- Lack of direct current control.

The aim of this paper is to give a fair comparison between the two techniques (FOC and DTC) in both steady-state and transient operating conditions. The comparison is useful to indicate to the users which one of the two schemes can be efficiently employed in the various applications that today require torque control.

In particular the following solutions have been developed to solve the above mentioned problems of DTC scheme:

- Use of improved switching tables.
- Use of comparators with and without hysteresis, at two or three levels.
- Implementation of DTC schemes for constant switching frequency operation with PWM or SWM techniques.
- Introduction of fuzzy or neuro-fuzzy techniques.
- Use of sophisticated flux estimators to improve the low speed behavior.

This has the advantage of being able to produce three different levels of output voltage compared to the standard two levels. With a greater number of available levels for the output voltage the desired sinusoidal voltage can be achieved more accurately without increasing the switching frequency.

This results in less current harmonics and therefore more efficient utilization of the available energy.

By reducing the current distortion, the losses in the motor are reduced. Current distortion could be reduced by increasing the inverter switching frequency, but this would result in increased switching losses in the inverter. Therefore, it is important for the control scheme to produce minimal current distortion for a given switching frequency.

In this paper, three different control schemes are investigated to determine their suitability for the application. A brief overview of the operation of each scheme is presented followed by results from Matlab- Simulink simulations.

CONTROL METHODS

A number of different control schemes for accurate torque control of an induction motor for electric vehicle application have been investigated. Field Oriented Control (FOC) and Direct Torque Control (DTC) were chosen for simulation as they are standard induction motor control techniques. Two improvements on DTC and DTC using *Space Vector Modulation* have been made. These are briefly described in the following sections.

1- Field Oriented Control (FOC)

Field Oriented Control refers to induction motor operation in a synchronously rotating dq reference frame that is aligned with one of the motor fluxes, typically the rotor flux.

In this mode of operation, control of the torque and flux is decoupled such that the d-axis component of the stator current controls the rotor flux magnitude and the q-axis component controls the output torque [2],[3],[4].

The required d-axis component of the stator current, i_{ds}, to achieve a given rotor flux magnitude demand, λ^*_{dr}, can be determined from Equation (1)

$$\lambda^*_{dr} = L_m \, i_{ds} \quad \text{..................} \quad (1)$$

The required q-axis component of the stator current i_{qs}, for a given torque demand (T^*_{em}), can be determined from Equation (2).

$$T^*_{em} = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\lambda^*_{dr} i_{qs} \quad \text{..........} \quad (2)$$

For the d-axis of the synchronously rotating reference frame to be aligned with the rotor flux the ‘slip relation’, Equation (3), must be maintained.

$$\omega_e - \omega_r = \frac{r_r}{L_r}\frac{i_{qs}}{i_{ds}} \quad \text{...........} \quad (3)$$

A diagram of the controller is shown in Figure (1). A proportional-integral controller regulates the stator voltage to achieve the calculated stator current.

The required voltage is then synthesized by the inverter using space vector modulation (SVM) [5].

During motor operation the actual rotor resistance and inductance can vary, for example with temperature. The resulting errors between the values used and the actual parameters cause an incomplete decoupling between torque and flux [3] , [6].

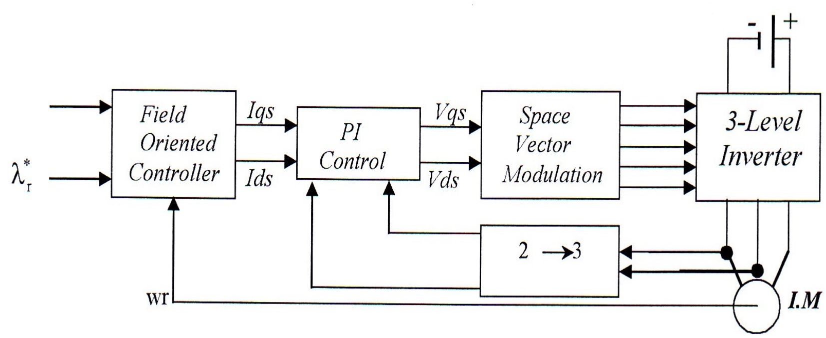

Fig. (1): Field Oriented Control Block Diagram

2- Direct Torque Control (DTC)

In the mid 1980s the direct torque control method was introduced [7]. In principle, the DTC method selects one of the inverter's six voltage vectors and two zero vectors in order to keep the stator flux and torque within a hysteresis band around the demand flux and torque magnitudes [8].

The torque produced by the induction motor can be expressed as in Equation (4),

$$T_{em} = \frac{3}{2} P \frac{L_m}{L_s^{'} L_r} |\overline{\lambda}_r| . |\overline{\lambda}_s| \sin(\alpha) \quad \text{................ (4)}$$

which shows the torque produced is dependent on the stator flux magnitude, rotor flux magnitude, and the phase angle between the stator and rotor flux vectors.

The induction motor stator Equation, (5),

$$\overline{V}_s = \frac{d\overline{\lambda}_s}{dt} - \overline{I}_s r_s \quad \text{.............. (5)}$$

can be approximated as Equation (6) over a short time period if the stator resistance is ignored.

$$\Delta\overline{\lambda}_s = \overline{V}_s \, \Delta t \quad \text{................. (6)}$$

This means that the change in the stator flux vector is determined by the applied voltage vector as shown in Figure (2). If a voltage vector is applied that changes the stator flux to increase the phase angle between the stator flux and rotor flux vectors, then the torque produced will increase.

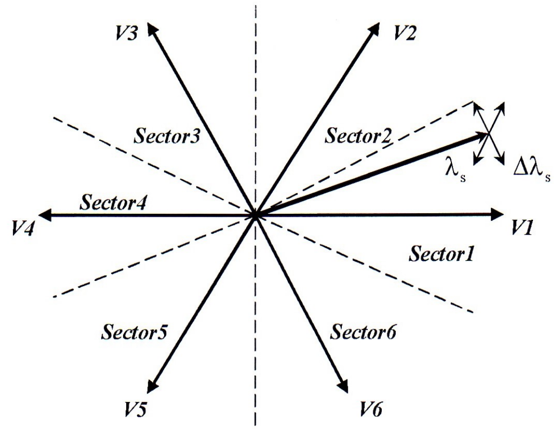

Fig. (2): Direct Torque Control Operation (2-level)

Since a two-level inverter is only capable of producing six non-zero voltage vectors and two zero vectors, it is possible to create a table that determines the voltage vector to apply based on the position of the stator flux and the required changes in stator flux magnitude and torque.

This is called the optimal vector selection table and is shown as Table (1) for the case of a two level inverter.

It is possible to expand the optimal vector selection table to include the larger number of voltage vectors produced by a three-level inverter.

The stator flux vector can be estimated using the stator voltage Equation, (5), as given in Equation (7).

$$\Delta\bar{\lambda}_s = \int (\bar{V}_s - r_s \bar{I}_s)dt \quad .... (7)$$

Table (1): Optimal Vector Selection Table (2-level)

		Sectors					
$\Delta\lambda$	ΔT_{em}	*1*	*2*	*3*	*4*	*5*	*6*
↑	↑	V2	V3	V4	V5	V6	V1
↑	*0*	V0	V0	V0	V0	V0	V0
↑	↓	V6	V1	V2	V3	V4	V5
↓	↑	V3	V4	V5	V6	V1	V2
↓	*0*	V0	V0	V0	V0	V0	V0
↓	↓	V5	V6	V1	V2	V3	V4

As shown in Figure (3), the estimated stator flux magnitude and torque output are compared to the demand values. A voltage vector is then selected that will drive the torque and flux towards the demanded values.

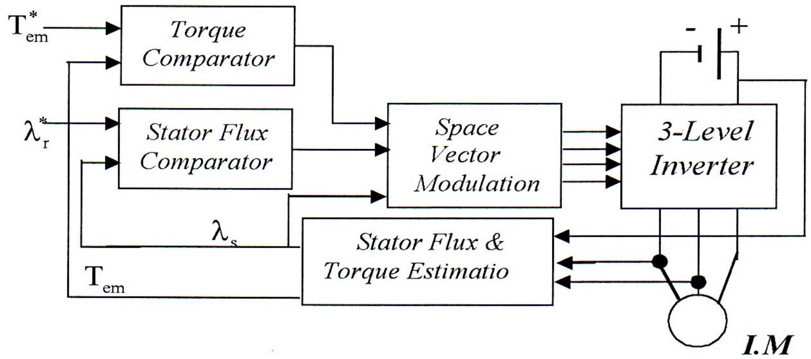

Fig. (3): Direct Torque Control Block Diagram

3- Direct Torque Control Using Space Vector Modulation (DTC using SVM)

Based on instantaneous current and voltage measurements it is possible to calculate the voltage required to drive the current output torque and stator flux to the demanded values within a fixed time period [9]. This calculated voltage is then synthesised using Space Vector Modulation.

The applied voltage and motor current can be used to estimate the instantaneous stator flux and output torque. From these the required change in output torque and stator flux in order to reach the demanded values by the end of the current switching period can be calculated.

Equation (8) shows that a change in torque corresponds to a change in stator current. The voltage, V, required to achieve that change in stator current can be calculated knowing the back EMF of the motor. The back EMF can be calculated from the stator flux and current.

$$\Delta T_{em} = \frac{3}{2}\frac{P}{2}(\bar{\lambda}_s \times \Delta\bar{I}_s) \quad .... (8)$$

As shown by Equation (6), the change in the stator flux vector is only dependent on V. To solve for the unknown voltage vector requires two equations, one for the required change in torque, (11), and another for the change in stator flux, (12).

$$\Delta T_{em} = \frac{3}{2}\frac{P}{2}\frac{\Delta t}{L_s^{'}}(\bar{\lambda}_s \times (\bar{V} - E)) \quad .... (9)$$

$$\Delta\bar{\lambda}_s = \bar{V}_s \,\Delta t \quad .... (10)$$

These two equations can be solved to find the smallest voltage required to drive both the torque and flux to the demand values. The required stator voltage can be calculated by adding on the voltage drop across the stator resistance calculated using the current measured from the last cycle.

As shown in Figure (4), the calculated voltage is then synthesized directly using space vector modulation. If the inverter is not capable of generating the required voltage then the voltage vector which will drive the torque and flux towards the demand value is chosen and held for the complete cycle.

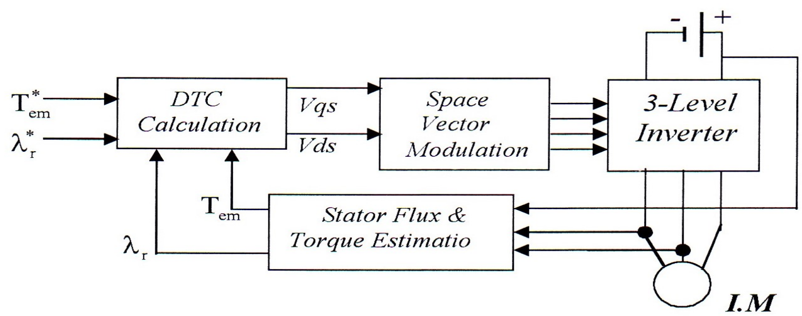

Fig. (4): DTC using Space Vector Modulation Block Diagram [10]

SIMULATIONS

All three the control schemes described in Section 2 have been simulated using Matlab-Simulink [8,11]. All simulations were performed using a model of the motors whose parameters are given in the Appendix [12].

For the control schemes that operate at a fixed switching frequency, an inverter switching frequency of 10kHz was used. For the standard DTC simulations, torque and flux hysteresis bands of 1Nm and 0.0016Wb respectively were used to give a switching frequency close to 10kHz at the chosen motor speed and load. A minimum vector hold time of 25 μs was chosen to simulate the time required to sample currents and voltages, and calculate the new vector.

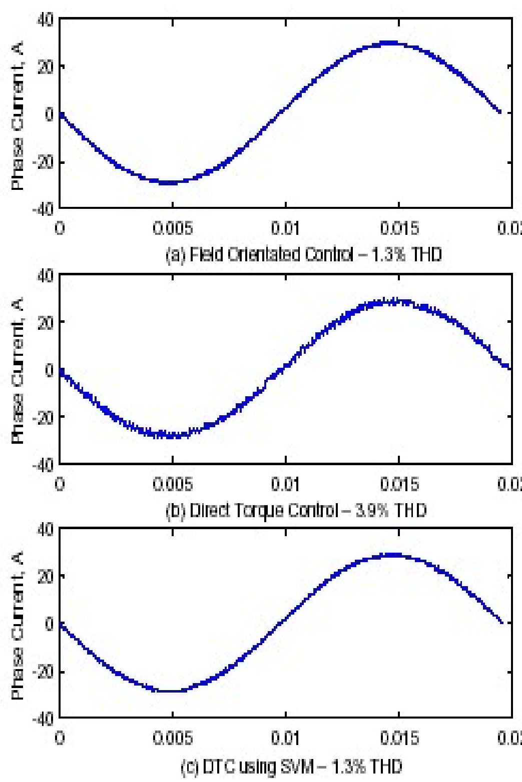

Fig. (5) Phase Current with a 10Nm load

Figure (5) shows the phase current for steady state operation at 1500rpm with a 10Nm load using a three level inverter. Both FOC and DTC using SVM show very low switching ripple, with a THD of about 1.3%. The DTC phase current waveform is still acceptable but it has comparatively high current distortion at 3.9% THD.

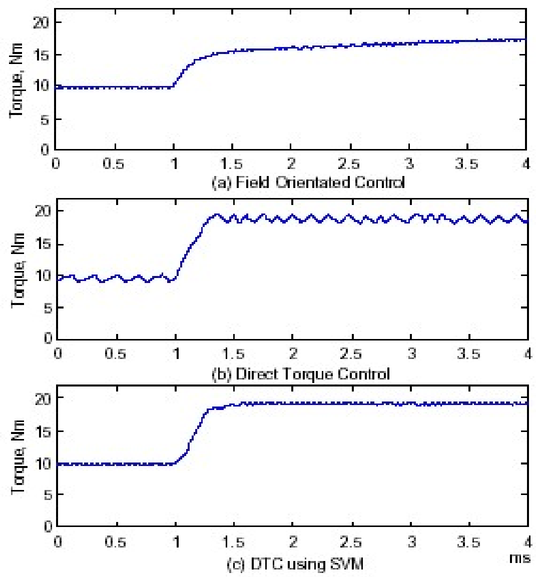

Fig. (6): Response to step change in torque demand from 10 to 20 Nm

Figure (6) shows the steady-state torque ripple and the response to a step change in torque demand from 10 to 20 Nm. The load is linear and inertia-less, therefore the speed changes from 1500 to 3000rpm during this time. For FOC the output torque initially rises quickly but it takes about 15ms to reach the new torque demand. For both DTC schemes the output torque reaches the new demand torque in about 0.3ms. DTC using SVM has significantly reduced steady state torque ripple, equal to that of FOC, which also uses SVM.

Conclusion

Direct Torque Control was developed as an alternative to FOC that had been in use for a number of years. DTC has the advantage of not requiring speed or position encoders and uses voltage and current measurements only. It also has a faster dynamic response due to the of the PI current regulator. A disadvantage of DTC is its comparatively high current distortion and torque ripple.

This higher current distortion would result in increased losses within the induction motor which is unacceptable in this application.

DTC using SVM is a different approach that involves a direct predictive calculation of the voltage required to be applied to the induction motor to change the stator flux and torque magnitudes to the demanded values. It combines the best features of the direct torque control schemes (fast torque response, no position encoder) with those of space vector modulation (low current distortion, fixed switching frequency).

APPENDIX

Table (2) Induction Motor Parameter

Rated Power	*2.2 kW*
Rated Line-Line Voltage	*90 V*
Rate Torque	12 Nm
Number of Poles (P)	*4*
Stator Resistance (rs)	*0.104 Ω*
Stator Inductance (L_s)	*9.15 mH*
Magnetizing Inductance(L_m)	*8.67 mH*
Rotor Resistance(r_s)	*0.118 Ω*
Rotor Inductance (L_s)	*9.15 mH*

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