COMPARISON BY SIMULATION OF THREE-LEVEL INDUCTION MOTOR TORQUE CONTROL SCHEMES FOR ELECTRIC VEHICLE APPLICATIONS

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Abstract

This paper presents the results of an investigation into suitable torque control schemes for an electric vehicle application. The electric vehicle drive consists of rewound induction motors and a three-level IGBT inverter switching at 10kHz. The schemes investigated are Field Oriented Control, Direct Torque Control (DTC), DTC using Space Vector Modulation, and DTC with Minimal Torque Ripple. 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 this application.

Keywords

Induction Motor, Field Oriented Control, Direct Torque Control, Space Vector Modulation

1 INTRODUCTION

The University of Canterbury has developed an electric vehicle over many years as the test bed for a variety of projects [1]. It is based on an 1962 Austin Farina body with 20 lead acid batteries providing a nominal 240 volt DC supply. It is driven by two 2.2kW 50Hz induction motors that have been rewound to operate with an applied frequency of up to 150Hz. The motors were originally driven by an SCR inverter, but recently new three-level IGBT inverters have been developed for each motor [1]. 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 utilisation of the available energy.

The three-level IGBT inverter that was developed was only tested under open loop conditions as no suitable controller was available [1]. A suitable closed loop torque controller is required to enable this new three-level inverter to be used in the electric vehicle. Torque control is preferred for electric vehicle applications instead of precise closed loop speed control because it mimics the operation of an internal combustion engine. It is important to make an electric vehicle drive like a standard vehicle.

An ideal electric vehicle motor drive system would have high efficiency and produce low torque ripple. By reducing the current distortion, 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, four different control schemes are investigated to determine their suitability for this application. A brief overview of the operation of each scheme is presented followed by results from Matlab-Simulink simulations. A comparison of the advantages and disadvantages of the four schemes is included.

2 CONTROL METHODS

A number of different control schemes for accurate torque control of an induction motor for this 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 to DTC, DTC using Space Vector Modulation and DTC with Minimal Torque Ripple were also simulated. These are briefly described in the following sections.

2.1 Field Oriented Control

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 [2]. 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.

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). (Refer to the Appendix for symbol definitions)

$$\lambda_{dr}^* = L_m i_{ds} \qquad (1)$$

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

$$T_{em}^* = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}\lambda_{dr}^* i_{qs} \qquad (2)$$

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.

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

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 synthesised by the inverter using space vector modulation (SVM) [3].

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.

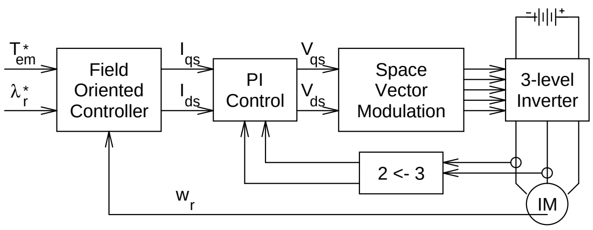

Figure 1: Field Oriented Control Block Diagram

2.2 Direct Torque Control

In the mid 1980s the direct torque control method was introduced [4]. 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.

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

$$T_{em} = \frac{3}{2}P\frac{L_m}{L_s' L_r}\left|\bar{\lambda}_r\right| \cdot \left|\bar{\lambda}_s\right| \cdot \sin\alpha \qquad (4)$$

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),

$$\bar{V}_s = \frac{d\bar{\lambda}_s}{dt} - \bar{I}_s r_s \qquad (5)$$

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

$$\Delta\bar{\lambda}_s = \bar{V}_s \Delta t \qquad (6)$$

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.

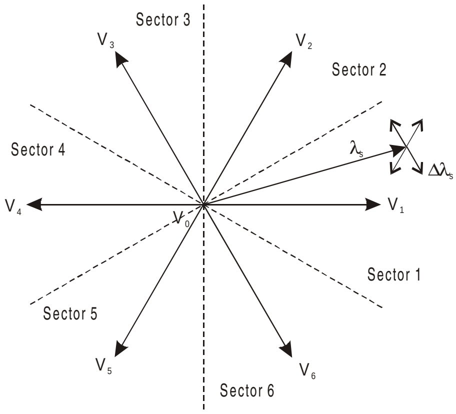

Figure 2: Direct Torque Control Operation (2-level)

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.

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

		Sector					
$\Delta\lambda$	ΔT_{em}	1	2	3	4	5	6
↑	↑	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_0	V_0	V_0	V_0	V_0	V_0
	↓	V_6	V_1	V_2	V_3	V_4	V_5
↓	↑	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_0	V_0	V_0	V_0	V_0	V_0
	↓	V_5	V_6	V_1	V_2	V_3	V_4

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

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

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

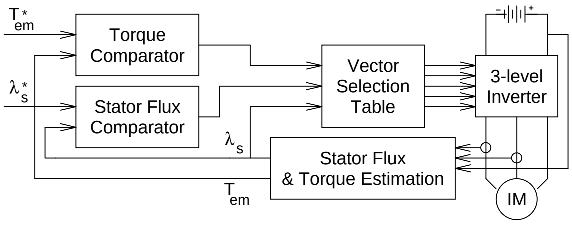

Figure 3: Direct Torque Control Block Diagram

2.3 Direct Torque Control using Space Vector Modulation

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 [5]. This calculated voltage is then synthesised using Space Vector Modulation.

As in Section 2.2, 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.

$$\Delta T_{em} = \frac{3}{2}\frac{P}{2}\left(\bar{\lambda}_S \times \Delta \bar{I}_S\right) \qquad (8)$$

As shown by Equation (6) in Section 2.2, 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, (9), and another for the change in stator flux, (10).

$$\Delta T_{em} = \frac{3}{2}\frac{P}{2}\frac{\Delta t}{L_S'}\left(\bar{\lambda}_S \times \left(\bar{V} - E\right)\right) \qquad (9)$$

$$\Delta \lambda_S = \bar{V}\,\Delta t \qquad (10)$$

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 synthesised 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.

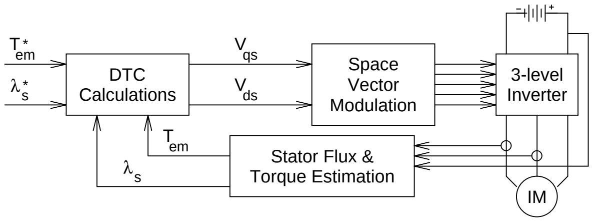

Figure 4: DTC using Space Vector Modulation Block Diagram

2.4 Direct Torque Control with Minimal Torque Ripple

As an improvement to the original DTC scheme described in Section 2.2, the switching instant between the non-zero and zero voltage vectors can be calculated to minimise torque ripple [6].

During steady state operation, DTC will switch between a non-zero voltage vector and the zero vector. Typically a non-zero vector is selected to increase the torque while maintaining control of the stator flux magnitude. Once the upper limit of the torque hysteresis band is reached, the zero vector is applied and the torque slowly decreases as shown in Figure 5.

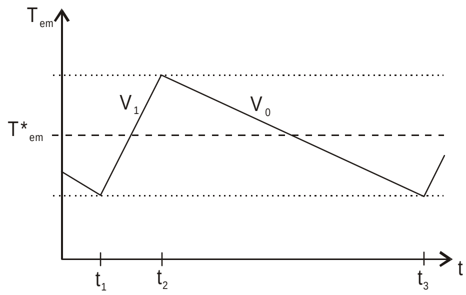

Figure 5: Effect of voltage vectors on output torque

By calculating the optimal time to switch between the non-zero and zero voltage vectors, the torque ripple can be minimised. This is achieved by calculating the rate of torque increase due to the selected non-zero voltage vector and the rate of torque decrease due to the zero voltage vector. The time to switch between the two vectors can be calculated such that the ripple in the torque over a fixed switching period can be minimised. The Torque Ripple Minimisation block in Figure 6 applies the selected voltage vector from t_1 to t_2 and the zero vector from t_2 to t_3.

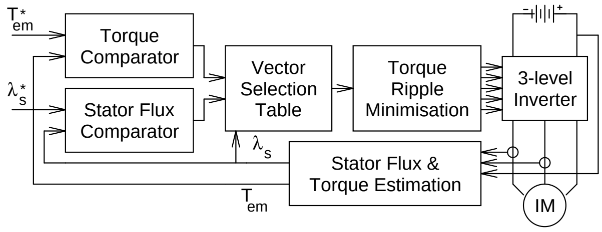

Figure 6: DTC with Minimal Torque Ripple Block Diagram

The duration of an applied voltage vector is calculated only to minimise torque ripple without concern for the effect on stator flux. The result is a much greater variation in stator flux compared to standard DTC. In standard DTC a new vector would be selected as soon as the stator flux leaves the hysteresis band however in this case a new vector is not used until the next cycle.

3 SIMULATIONS

All four of the control schemes described in Section 2 have been simulated using Matlab-Simulink. All simulations were performed using a model of the motors that are used in the electric vehicle. The parameters of the motors are given in the Appendix.

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 25µs was chosen to simulate the time required to sample currents and voltages, and calculate the new vector.

DTC with minimal torque ripple was simulated only for the case of a two level inverter. Very high current distortion (17.6% THD) was observed as shown in Figure 7. This is significantly higher than that observed for the other control schemes when simulated with a two-level inverter. Such high current distortion is unacceptable for this application and therefore this scheme was not extended to the case of a three-level inverter even though very low torque ripple and a fast torque response were observed.

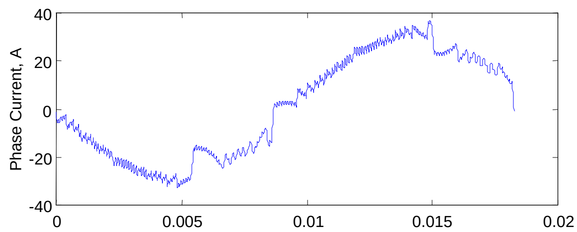

Figure 7: Phase current for DTC with minimal torque ripple

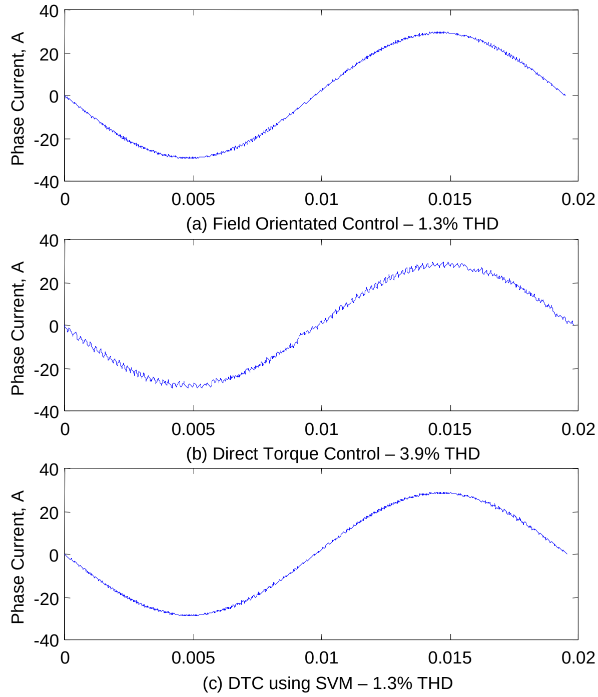

Figure 8: Phase Current with a 10Nm load

Figure 8 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.

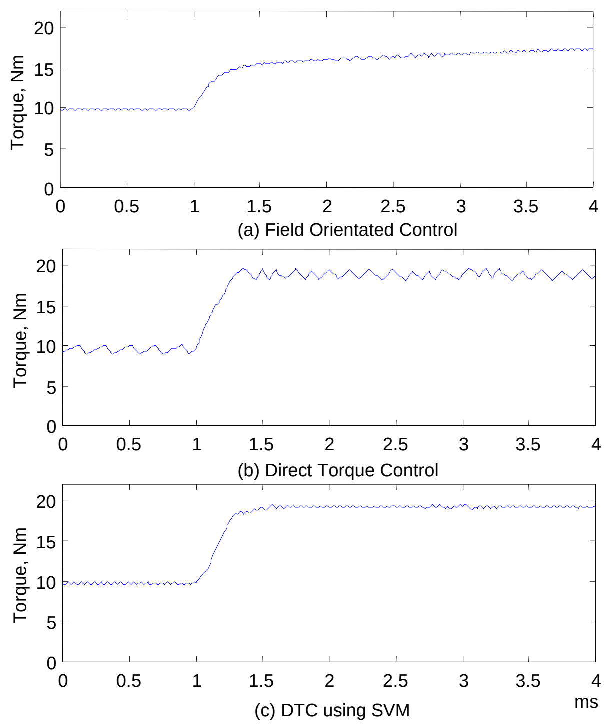

Figure 9: Response to step change in torque demand from 10 to 20 Nm

Figure 9 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.

4 COMPARISON

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 absence of the PI current regulator. A disadvantage of DTC is its comparatively high current distortion and torque ripple. The torque ripple minimisation strategy presented in Section 2.4 successfully minimised torque ripple while retaining the fast transient performance of DTC. This torque ripple minimisation strategy has the disadvantage of increased stator flux ripple and high current distortion. 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). DTC using SVM was chosen as the torque control scheme in this electric vehicle application.

Table 2 summarises the essential advantages and disadvantages of each control scheme.

Table 2: Advantages and disadvantages of the simulated control schemes

	Advantages	**Disadvantages**
Field Oriented Control	• Relatively simple high performance scheme • A proven technique that has been used for some time	• Relatively low dynamic performance due to the PI current regulator • Parameter detuning causes high torque and flux magnitude errors.
Direct Torque Control	• Fast torque response • Relatively simple • No speed or position encoder is required	• High current distortion • High torque ripple • Switching frequency changes with motor speed
DTC using SVM	• Fast torque response that is equivalent to standard direct torque control • Low steady state torque ripple and current distortion that is equal to FOC • Constant switching frequency • Not as parameter sensitive as FOC • No speed or position encoder is required	• The control algorithm is very complex compared to other control schemes. It requires a relatively fast processor to implement at the desired 10kHz switching frequency.
DTC with Minimal Torque Ripple	• Fast torque response • Very low steady-state torque ripple	• Large variation in stator flux magnitude • Very high current distortion

5 FUTURE WORK

The algorithm required for Direct Torque Control using Space Vector Modulation has been coded using the 'C' programming language and tested within Matlab-Simulink using an induction motor model. Hardware is currently being developed for the implementation of the controller as shown in Figure 10. A TMS320VC33 32-bit floating-point DSP (60MIPS/120MFLOPS, 1.1Mbit onboard RAM) is being used to implement the control algorithm. The Direct Torque Control and Space Vector Modulation algorithms will run at 10kHz on this DSP and calculate the on-duration and order of each voltage vector for the next cycle. These are then transferred to the gate signal generation circuit, implemented within a Field Programmable Gate Array (FPGA), that generates all the switching signals for the next cycle without assistance from the DSP. The FPGA also provides the DSP with interfaces to an ADC for measuring current and voltage and a serial interface to a PC. For development purposes the FPGA provide interfaces to a speed decoder and DAC.

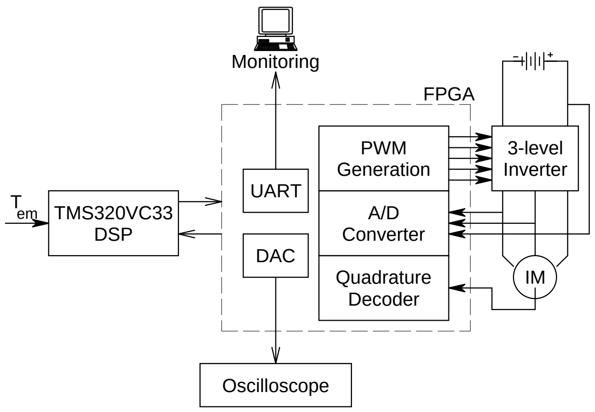

Figure 10: Proposed Hardware

6 CONCLUSION

Four different control schemes have been evaluated for induction motor torque control in an electric vehicle application. All three direct torque control techniques exhibited improved transient torque response compared to standard rotor flux FOC. The disadvantage these schemes have is increased current distortion. Since high efficiency is one of the prime requirements for an electric vehicle drive and high current distortion results in increase motor losses, this is unacceptable. DTC using space vector modulation is an exception that exhibited fast torque response (due to lack of a PI current regulator) and low current distortion and torque ripple (due to space vector modulation). A controller based on DTC using SVM is now being implemented on custom hardware that is based on a TMS320VC33 DSP and a Field Programmable Gate Array.

APPENDIX

Table 3: Induction Motor Parameters

Rated Power	2.2kW
Rated Line-Line Voltage @ 50Hz	90V
Rated Torque	12Nm
Number of Poles (P)	4
Stator Resistance (r_s)	0.104Ω
Stator Inductance (L_s)	9.15mH
Magnetising Inductance (L_m)	8.67mH
Rotor Resistance (r_r)	0.118Ω
Rotor Inductance (L_r)	9.15mH

REFERENCES

[1] X. Li, R. Duke and S. Round. Development of a three-phase three-level inverter for an electric vehicle. *Australasian Universities Power Engineering Conf.*, Darwin, Australia, 1999, pp 247-251

[2] D. W. Novotny and T. A. Lipo. *Vector Control and Dynamics of AC Drives*, Oxford University Press, 1997

[3] J. Holtz. Pulsewidth Modulation for Electronic Power Conversion. *Proc. of the IEEE*, Vol. 82, No. 8, pp. 1194 – 1213, Aug 1994.

[4] I. Takahashi and T. Noguchi. A new quick response and high efficiency control strategy for an induction motor. *IEEE Trans. Industry Applications.* Vol. IA-22, No. 5, pp. 820-827, Sept/Oct 1986.

[5] T.G. Habetler, F. Profumo, M. Pastorelli, and L.M. Tolbert. Direct Torque Control of Induction Machines using Space Vector Modulation. *IEEE Trans. Industry Applications*. Vol. 28, No. 5, Sept/Oct 1992

[6] J-K. Kang and S-K. Sul. New Direct Torque Control of Induction Motor for Minimum Torque Ripple and Constant Switching Frequency. *IEEE Trans. Industry Applications*, Vol. 35, No. 5, Sept/Oct 1999