# EVALUATION OF DIRECT TORQUE CONTROL USING SPACE VECTOR MODULATION FOR ELECTRIC VEHICLE APPLICATIONS

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**Abstract**

This paper presents the results of an investigation into the suitability of a Direct Torque Control method for an electric vehicle application. For this investigation, a 2.2kW specially rewound induction motor driven using a three-level IGBT inverter switching at 10kHz was used. The control scheme used and the test system that has been developed are explained. Simulated and experimental results are presented. The control scheme is computationally complex, but is shown to have low current distortion, low torque ripple, and a fast torque response.

## 1 INTRODUCTION

The University of Canterbury is currently developing an electric vehicle driven by a single 70kW, 10 000 RPM induction motor. This high-speed induction motor was chosen based on its high power to weight ratio. Such induction motors typically have low inductance and therefore need a controller with a fast current response.

A suitable torque controller is required for this high-speed induction motor. 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.

Matlab and Simulink were used to perform simulations on a number of control schemes. These schemes were Field Oriented Control, Direct Torque Control (DTC), DTC using Space Vector Modulation, and DTC with Minimal Torque Ripple [1]. DTC using Space Vector Modulation was chosen based on its low current distortion (therefore high system efficiency) and fast torque response. A disadvantage of this control scheme is its high computational complexity.

Initial simulations and testing have been based on a 2.2kW, 50Hz, induction motor that has been rewound to run at up to 150Hz (4500 rpm) from a 270 volt supply. This motor is being driven through a three-level 150 amp (peak) IGBT inverter switching at 10kHz [2].

A three-level inverter has the advantage of being able to produce three different levels of output phase 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. However, this improvement is at the expense of additional hardware and complexity.

In this paper, the Direct Torque Control method and the three-level Space Vector Modulation technique that were used are explained. Simulation results from Matlab/Simulink are presented. The test platform that has been developed is explained. Initial experimental results from the evaluation of the three-level inverter are presented.

## 2 DIRECT TORQUE CONTROL

Induction motor torque control has traditionally been achieved using Field Oriented Control (FOC). This involves the transformation of the stator currents into a synchronously rotating dq reference frame that is typically aligned to the rotor flux [3]. In this reference frame, the torque and flux producing components of the stator current are decoupled. A PI controller is then used to regulate the output voltage to achieve the required stator current and therefore torque. This PI controller limits the transient response of the torque controller.

Direct Torque Control (DTC) uses an induction motor model to predict the voltage required to achieve a desired output torque [4]. By using only current and voltage measurements, it is possible to estimate the instantaneous stator flux and output torque. An induction motor model is then used to predict the voltage required to drive the flux and torque to the demanded values within a fixed time period. This calculated voltage is then synthesised using Space Vector Modulation (SVM).

The stator flux vector, $\bar{\lambda}_s$, and the torque produced by the motor, $T_{em}$, can be estimated using (1) and (2) respectively. These only require knowledge of the previously applied voltage vector, measured stator current, and stator resistance.

$$\bar{\lambda}_s = \int (\bar{V}_s - r_s \bar{I}_s) dt \quad (1)$$

$$T_{em} = \frac{3}{2}\frac{P}{2}\left(\bar{\lambda}_s \times \bar{I}_s\right) \quad (2)$$

Once the current stator flux magnitude and output torque are known, the change required in order to reach the demanded values by the end of the current switching period can be determined.

An equivalent circuit of the induction motor in a stationary dq reference frame is shown in Figure 1. Over a short time period, the change in torque is related to the change in current and from the equivalent circuit equation (3) can be obtained. The voltage $\bar{E}$ can also be determined by using the stator flux and current vectors.

$$\Delta I_s = \frac{\bar{V} - \bar{E}}{L'_S} \Delta t \quad (3)$$

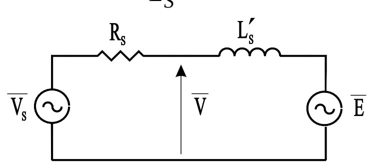


**Figure 1:** Equivalent circuit of an induction motor in a dq reference frame

By combining (2) and (3), an expression for the change in torque can be obtained as shown in (4). Equation (1) can also be rewritten as an expression for the change in the stator flux, as shown in (5).

$$\Delta T_{em} = \frac{3}{2}\frac{P}{2}\frac{\Delta t}{L'_S}\left(\bar{\lambda}_s \times \left(\bar{V} - E\right)\right) \quad (4)$$

$$\Delta \lambda_s = \left(\bar{V}_s - r_s \bar{I}_s\right)\Delta t = \bar{V}\Delta t \quad (5)$$

These two equations can be solved to find the smallest voltage vector, $\bar{V}$, 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 2, the voltage required to drive the error in the torque and flux to zero is calculated directly. The calculated voltage is then synthesised using Space Vector Modulation as described in Section 3. 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.

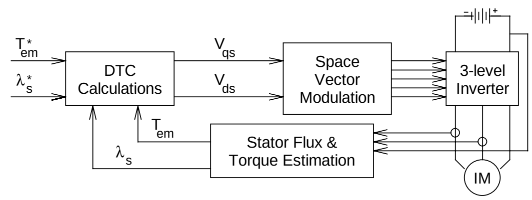


**Figure 2:** DTC using Space Vector Modulation Block Diagram

## 3 THREE-LEVEL SPACE VECTOR MODULATION

A three-level inverter differs from a conventional two-level inverter in that it is capable of producing three different levels of output phase voltage. The structure of a three-level neutral point clamped inverter is shown in Figure 3. When switches 1 and 2 are on the output is connected to the positive supply rail. When switches 3 and 4 are on, the output is connected to the negative supply rail. When switches 2 and 3 are on, the output is connected to the supply neutral point via one of the two clamping diodes.

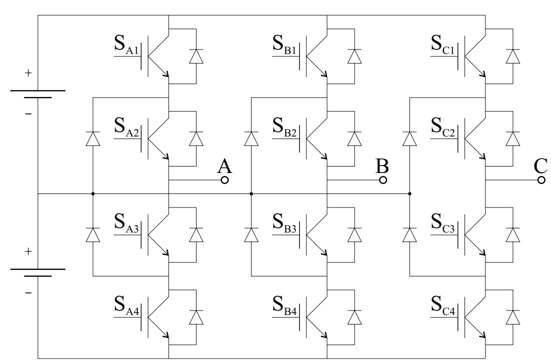


**Figure 3:** Three-Level Inverter

With three possible output states for each of the three phases, there are a total of 27 ($3^3$) possible switch combinations. The result of plotting each of the output voltages in a dq reference frame is shown in Figure 4.

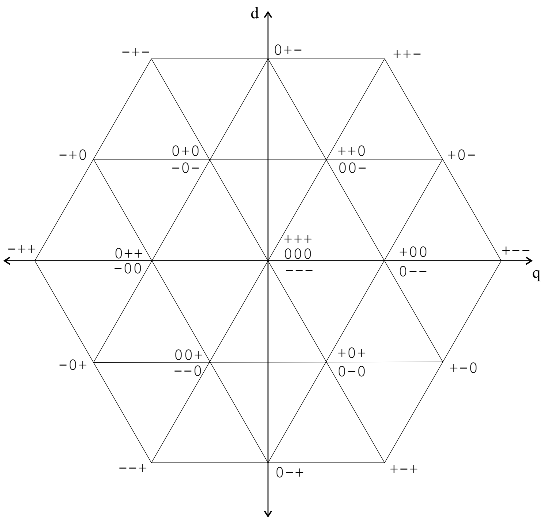


**Figure 4**: Three-Level Inverter Voltage Vectors

Figure 4 shows that the 27 switch combinations result in a total of 19 unique voltage vectors since some of the combinations produce the same voltage vector. These different combinations relate to different ways of connecting the load to the DC bus that result in the same voltage being applied to the motor.

Space Vector Modulation (SVM) is the approximation of an arbitrary vector in the dq vector space using the nearest three voltage vectors that the inverter can generate [5], [6]. The nearest three vectors are chosen by determining the triangle within the vector space in which the desired voltage vector resides.

The required on-duration of each of the vectors is determined by Equations (6) and (7). These specify that the demand vector, $\overline{V^*}$, is the geometric sum of the chosen three vectors ($\overline{V_1}$, $\overline{V_2}$, $\overline{V_3}$) multiplied by their on-durations ($d_1$, $d_2$, $d_3$) and that their on-durations must fill the complete cycle.

$$\begin{bmatrix} V_q^* \\ V_d^* \end{bmatrix} = \begin{bmatrix} V_{1q} & V_{2q} & V_{3q} \\ V_{1d} & V_{2d} & V_{3d} \end{bmatrix} \begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix} \qquad (6)$$

$$d_1 + d_2 + d_3 = 1 \qquad (7)$$

Equations (6) and (7) can be combined to produce Equation (8).

$$\begin{bmatrix} V_q^* \\ V_d^* \\ 1 \end{bmatrix} = \begin{bmatrix} V_{1q} & V_{2q} & V_{3q} \\ V_{1d} & V_{2d} & V_{3d} \\ 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix} \qquad (8)$$

Equation (8) can then be rearranged to obtain Equation (9). This is an expression for the vector duty cycles in terms of the desired voltage vector and the three nearest voltage vectors.

$$\begin{bmatrix} d_1 \\ d_2 \\ d_3 \end{bmatrix} = \begin{bmatrix} V_{1q} & V_{2q} & V_{3q} \\ V_{1d} & V_{2d} & V_{3d} \\ 1 & 1 & 1 \end{bmatrix}^{-1} \cdot \begin{bmatrix} V_q^* \\ V_d^* \\ 1 \end{bmatrix} \qquad (9)$$

## 4 SIMULATIONS

The Direct Torque Control method described in Section 2 and the Space Vector Modulation method described in Section 3 have been simulated using Matlab and Simulink.

An initial simulation was constructed using Matlab m-files and Simulink blocks to test the algorithms against a simulated induction motor. Once these were perfected, the control algorithms were written using the ‘C’ programming language such that they could also be run on a DSP. The resulting code was then complied as a Matlab S-function so that it could be run in Simulink.

The Matlab S-function developed takes the stator currents, DC voltage, torque and flux demand from the simulation. It calculates the voltage vectors required for the next cycle and the exact instant that they should be used. The simulation then calls back the S-function to get the next voltage vector at the required time.

For the simulations, a 10kHz switching frequency was used. The parameters of the 2.2kW test motor are listed in Table 1 in the Appendix.

Figure 5 shows the phase current for steady state operation at 1500rpm with a 10Nm load using a three-level inverter. The resulting current has a THD of about 1.3% including the high frequency current ripple due to switching.

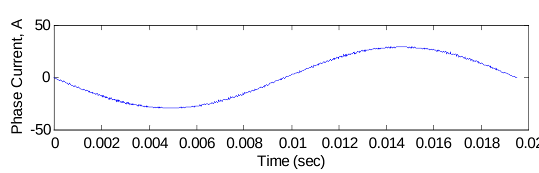


**Figure 5:** Steady State Phase Current

Figure 6 shows the steady-state torque ripple and the response to a step change in torque demand from 10Nm to 20Nm. The simulated load is linear and inertia-less, therefore the speed changes from 1500rpm to 3000rpm during this time. The torque has increased to the new demand value after about 0.3ms.

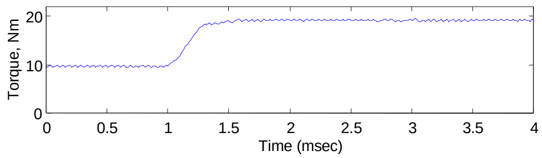


**Figure 6:** Torque Response

These simulations show that DTC using SVM can produce rapid changes in torque output under transient conditions while maintaining low current distortion in steady-state operation.

## 5 TEST PLATFORM

In order to experimentally evaluate this control scheme, a controller based on a TMS320VC33 32-bit floating-point DSP (75MIPS/150MFLOPs with 1.1Mbit of onboard RAM) and a Field Programmable Gate Array (FPGA) has been developed as shown in Figure 7. By using an FPGA it is possible to implement some of the functionality in hardware. This includes generating the switching signals, which are timing critical, and it also interfaces the DSP to the slower hardware. The DSP is then freed from these tasks and can be dedicated to performing the high speed mathematical computation that it was designed for.

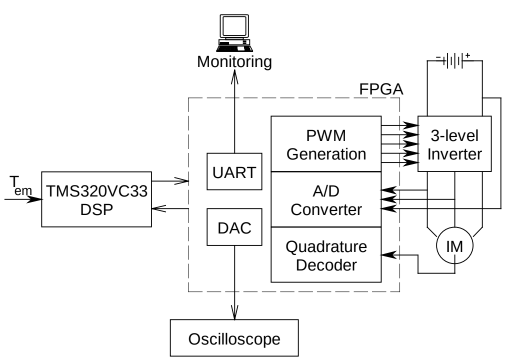


**Figure 7:** Hardware Platform

The Direct Torque Control and Space Vector Modulation algorithms run at 10kHz on the DSP and calculate the on-duration and order of each voltage vector for the next cycle. These are then transferred to a gate signal generation circuit, implemented within the FPGA. This logic then generates all the switching signals, including dead-time generation, for the next cycle without assistance from the DSP. It also ensures that invalid switch combinations can not be generated, and that under fault conditions all IGBTs are turned off.

The FPGA also interfaces the DSP to the rest of the hardware. This includes;

- Analogue to Digital (A/D) converters to sample the DC bus voltages, phase currents, and torque demand.
- A quadrature encoder interface to measure the motor speed for testing and over-speed protection.
- Digital to Analogue (D/A) converters to output internally calculated values so that they can be viewed on an oscilloscope.
- A UART to send data to a PC for further analysis.

## 6 EXPERIMENTAL RESULTS

The control hardware and SVM algorithms developed have been tested using a 150 amp (peak) three-level IGBT inverter. The inverter was operated in both two-level and three-level modes to obtain a comparison. Two-level operation of a three-level inverter is achieved by ignoring those voltage vectors that use the neutral point.

Figure 8 shows a comparison in the output voltage distortion when operated in two and three-level modes. In Figure 8 the modulation index is defined as the ratio of output voltage to the maximum output voltage possible without using over-modulation techniques. The voltage / frequency ratio was kept constant such that at a modulation index of one the maximum output voltage was produced at a frequency of 150Hz (4500rpm).

Using a constant voltage / frequency ratio simulates the typical output voltage that would be generated as a motor was run from stand-still to full speed. Figure 8 compares the total harmonic distortion (THD) taken over the first 20 harmonics. Three-level operation resulted in a significant lower THD at low modulation indices. At higher modulation indices, the distortion of both operating modes was very low with three-level operation having no measurable advantage.

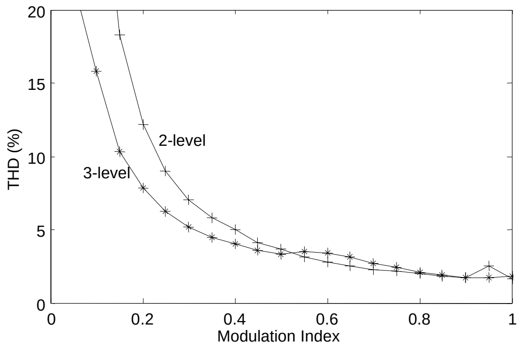


**Figure 8:** Comparison of output voltage distortion for two and three level inverter operation

Figure 9 and Figure 10 show the frequency spectrum of the phase current from zero to 50kHz. The harmonics due to the 10kHz switching frequency are clearly visible in Figure 9. In Figure 10, the fundamental switching frequency at 10kHz has reduced by about 15dB. This is because, in two level operation, every time the inverter switches the output voltage must change by the total bus voltage. For three-level operation it only changes by half the bus voltage at each switching instance. The audible noise due to the 10kHz switching is significantly reduced when operating in three-level mode compared to two-level mode.

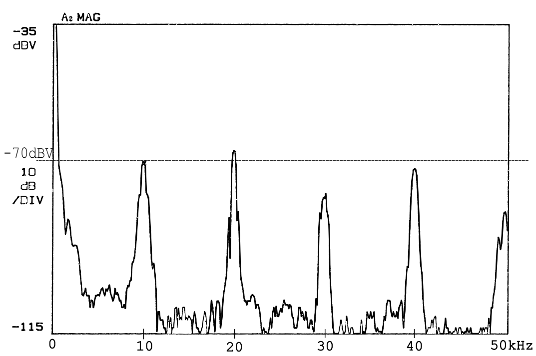


**Figure 9:** Current Harmonics – Two Level

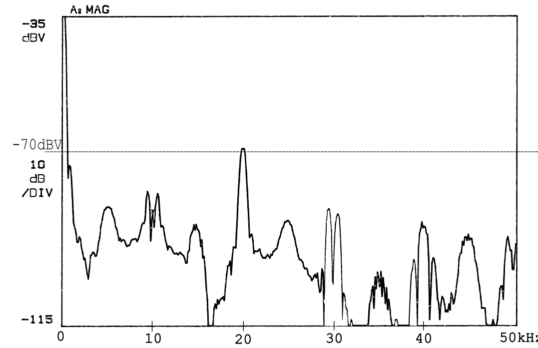


**Figure 10:** Current Harmonics – Three Level

## 7 CONCLUSION

Direct Torque Control using Space Vector Modulation was chosen for this electric vehicle application based on its low current distortion and fast torque response. Its high dynamic response is due to the absence of the PI current regulator normally used in torque controllers and its low current distortion is due to the use of Space Vector Modulation to synthesise the demand motor voltage. The performance of this control method has been demonstrated by simulations performed using Matlab / Simulink.

In order to experimentally evaluate this control scheme, custom hardware has been created based on a TMS320VC33 DSP and a Field Programmable Gate Array. The DSP executes the DTC and SVM algorithms while the FPGA generates the switching signals and interfaces the DSP to slower hardware such as the A/D and D/A converters.

Experimental testing of the three-level inverter, controller hardware and Space Vector Modulation algorithms is complete. The three-level inverter showed an improvement in output waveform distortion, particularly when generating small amplitude voltages, compared to a two-level inverter. Another advantage of the three-level inverter is a significant reduction in the 10kHz switching harmonics. This significantly reduced the 10kHz audible switching noise.

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## APPENDIX

**Table 1:** 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 |