Performance Improvement of Servo Motor Drive controls

by

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Abstract

This research program is being undertaken at the Industrial Research Institute of Swinburne University of Technology (IRIS) in Melbourne Australia as part of collaboration with the Cooperative Research Centre (CRC) for Intelligent Manufacturing Systems and Technologies (IMST) and ANCA Pty. Ltd. The research is expected to be completed by 2002. In broad terms, the objective of the research program is to enhance the performance of servo motor drive control systems as they pertain to precision machine tool applications. Specifically, the research here investigates the issue of so-called “dead-time effect”, which arises from the finite switch-off time associated with power semiconductor devices in motor drives – this is a period in which the transistors in a given portion of the motor drive are switched off to avoid short-circuiting. The dead-time effect leads to a number of performance degradation issues in motor drive systems The objective of this paper is to provide an overview of the problem at hand and the issues that are being investigated.

The software compensation of dead time effects is investigated in this research and presented herein. It is composed of a fully integrated digital set-up, implemented on a programmable logic device and digital signal processor (DSP). The technique is based on an adequate feed forward compensation of the transistor switching sequence generation on the basis of the stator phase current signs/polarity and of the switching state of the power modules.

1. Introduction

Servo axis motor and spindle motor drive systems are an integral part of modern computer numerical control (CNC) machine tool systems. In this research program, the research pertains to drives as they are fitted to CNC grinding machines but the issues and results will be generic to any CNC machine tool. Typically, CNC servo axis drives tend to be based upon either d.c. or a.c. (permanent magnet/synchronous) motors and spindle drives tend to be based upon induction motors. The power electronics drive arrangements for a motor drive system in a machine tool are shown schematically in Figure 1.

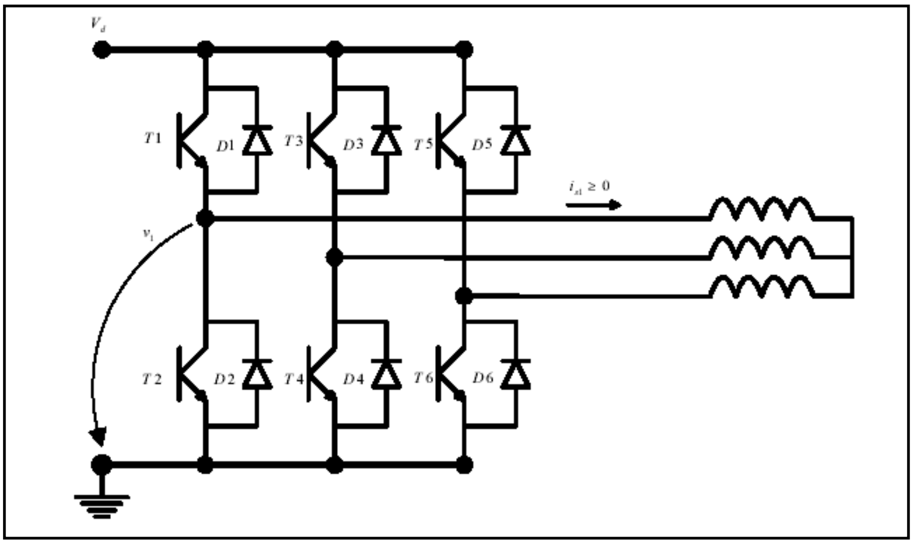


Figure 1 – Motor Power Drive, Showing Transistor Bridge Arrangement

Herein, the only method which is examined is the so-called "Speed Control with Slip Regulation" approach. This method is also known in the literature as "constant volts per hertz" (Volt/Hertz) or the "V/f". This technique is so named because the inverter voltage is varied in direct proportion with stator frequency to maintain the flux at a constant level over the operating range and torque is controlled by varying the slip frequency – this is discussed in Bose (2002).

The control of voltage, and/or current and frequency facilitates the control of an induction motor's speed, and/or torque or both. In modern systems, this is achieved by semiconductor switching of devices such as those shown in Figure 1. Such circuits require a dead-time or deadband to avoid the so-called "shoot through" effect in the circuit. This deadband effect is significant under low speed and torques. To address this problem, various issues had to be investigated, specifically:

(i) Various Space vector Modulation
(ii) Compensation of the dead band effect (dead-time compensation) by feed forward compensation.
(iii) Predictive current control

At the time of compiling this paper, issues (i) and (ii) have already been examined and the results are included herein.

2. Background - Analogue and Digital Motor Drives

The early approaches to PWM (Pulse Width Modulation) in the 1970s employed a concept known as "*naturally sampled sine-triangle modulation*" in analogue drives (also known as sine triangle modulation). While the concept of sine triangle modulation was straightforward, the detailed analysis was quite complex. One of the first researchers to solve this problem was Bowes (1975) , who developed a complete analytical expression for the harmonic components of the output switched waveforms and showed that the required low frequency target fundamental component was indeed obtained. However, it was soon recognised that a major limitation with naturally sampled PWM was the difficulty of implementation on then-emerging digital computers as it is computationally intensive to evaluate.

Developing the concept of “regular sampled sine triangulation modulation”, where the target fundamental waveform was held fixed for the duration of each carrier period, solved this difficulty. However, the resultant train of pulses had significantly different harmonic components compared to the naturally sampled PWM as shown by Bowes and Midoun (1988). The question of how best to sample the target fundamental was the subject of extensive research since Bowes’ early work, especially for use with devices such as voltage source inverters.

Many variations were proposed as shown by Holmes (1996) including, in particular

(i) Single edge modulation where only the position of the leading or trailing edge of the pulse is modulated (i.e. the saw tooth carrier)

(ii) Double edge symmetric modulation where the fundamental is held constant over a complete carrier period (i.e. triangular carrier)

(iii) Double edge asymmetric modulation where the fundamental is resampled at every half carrier period (also a triangular carrier)

A complete analysis and comparison of these alternatives were published by Boys and Walton (1985) and clearly identified (iii) as having a substantial harmonic advantage over the other regular sampled implementation.

In this research, the specific area of investigation relates to the switching of transistors used in the power stage of a servo motor drive (refer Figure 1) and, specifically, the fact that a small period in which there is (by practical design necessity) no conduction influences the performance of the drive system. The key issues in relation to dead-time are as follows:

- Dead-time introduces errors in the desired fundamental output voltage. which result in reduced fundamental output voltage, distorted machine currents and torque pulsations --Leggate and Kerkman (1997).

- Distortion from the dead-time occurs because a motor’s current flow –which is controlled by the PWM of the power stages—is non-linear during the dead-time interval. The net result is torque pulsations on the motor’s shaft and possible instability in the motor drive electronics.

- The PWM frequency directly affects dead-time distortions— higher frequencies raise the distortion. An a.c. induction motor, typically used for spindle control in machine tools, is most affected by the distortion at the low RPM.

- Dead-time distortion correction can be fixed by counter-modulating the original PWM signal to essentially provide noise cancellation.

This paper presents one method to compensate the effects of the dead time. The compensation algorithm was tested on the collaborating company's experimental hardware and the Software code used on the digital signal processor (DSP) controller associated with it.

3. Dead-Time effects and Compensation

This discussion pertains to the diagrams in Figure 1 and Figure 2. The effects of the dead time may be examined by considering only the first phase of the inverter. On this phase it is desired to obtain the reference PWM signal (v_1*) presented in Figure 2(a). The signals used to command the power devices are assumed to be active HIGH, which means that when they are HIGH, the power devices conduct (Figures 2(b) and 2(c)). The output signal v_1 obtained at the motor terminal depends on the sense of the current flowing in this phase:

In the case of the current flowing *from the inverter to the motor* (assumed positive sense), when T2 conducts:

> The phase terminal is linked to ground and the voltage v_1 is zero. During the dead-time period, when both power devices are turned OFF, the current continues to flow into the motor using the reverse recovery diode D2, so v_1 will continue to be zero. When the upper power device T1 conducts, the phase terminal is connected to V_d and v_1 is equal to V_d . During the second half cycle, the phenomenon repeats itself symmetrically. The final behaviour of v_1 is presented in Figure 2(d). It may be observed that the average value of v_1 is less than the reference value by an amount determined by the dead-time.
>
> $v_1 = v_1^* - ({}_1\mathrm{DT} / \mathrm{T_s})\, V_d$ …….(1)

In the case of the current flowing *from the motor to the inverter*, when T2 conducts:

> The phase terminal is linked to the ground and the voltage v_1 is 0. During the dead time period, the current continues to flow from the motor using the reverse recovery diode D1, so v will become equal to V_d .When the upper power device T1 conducts, the phase terminal is connected to V_d and v_1 will continue to be equal to V_d . During the second half, the phenomenon repeats itself symmetrically. The final behaviour of v_1 is presented in 2(c).. It may be observed that the average

value of v_l is greater than the reference value by an amount determined by the dead time.
$v_l = v_l* + ({}_l\mathrm{DT} / \mathrm{T_s})\, V_d$ …….(2)

Equations (1) and (2) provide the first method to compensate for the dead time:

These equations suggest that the distortion of the phase voltage can be approximated as a bipolar square wave, which is synchronised, to the phase current signal. From a review of Equations 1 and 2 and Figure 3, There are several characteristics about dead-time distortion worth noting:

(i) The amplitude of the distortion per unit of bus voltage is equal to the ratio of the dead-time to the PWM period. Since the dead-time is a system parameter that is usually fixed in accordance with the switching characteristics of the power devices, the problem is usually associated with higher PWM frequencies.

(ii) The voltage distortion causes a current distortion, and the net result is torque pulsations felt on the motor shaft, which translates into stability problems between the motor and drive under certain conditions.

(iii) The amplitude of the distortion is not affected by the modulation index. This means that the problem from a signal to noise point of view is minimised when the applied voltage is large or it means that the distortion is most severe when the voltage is small. In a.c. induction motors this occurs when the motor RPM is small and the momentum of the rotor cannot smooth out the torque pulsations. Overmodulation, in the form of a voltage boost, can be used to reduce this problem. However the torque pulsations from the distortions are still present.

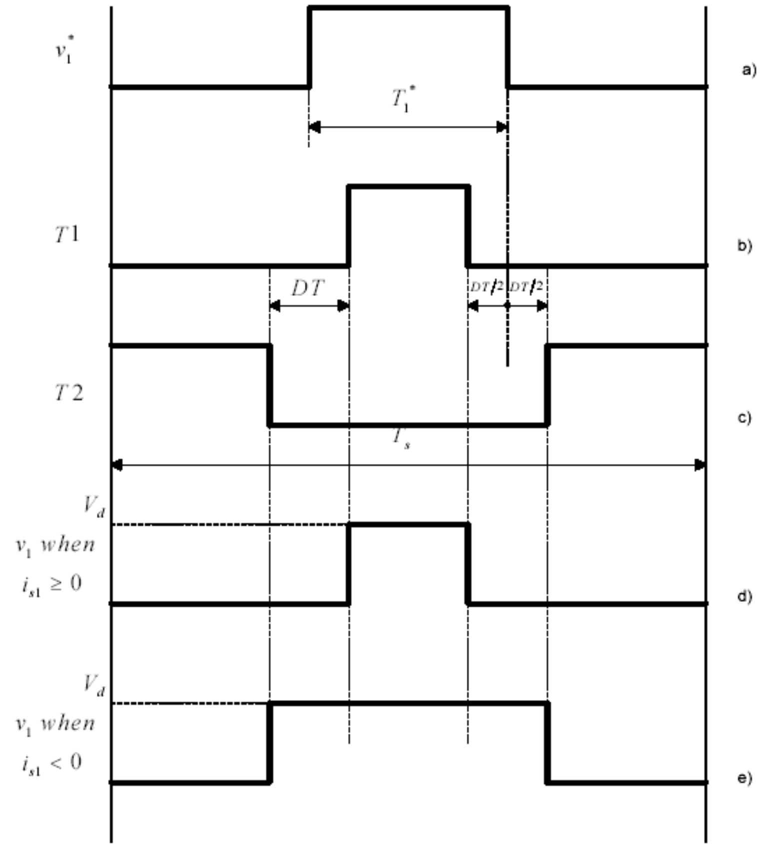


Figure 2 - The Influence of the Dead-time over the Output Phase Voltage

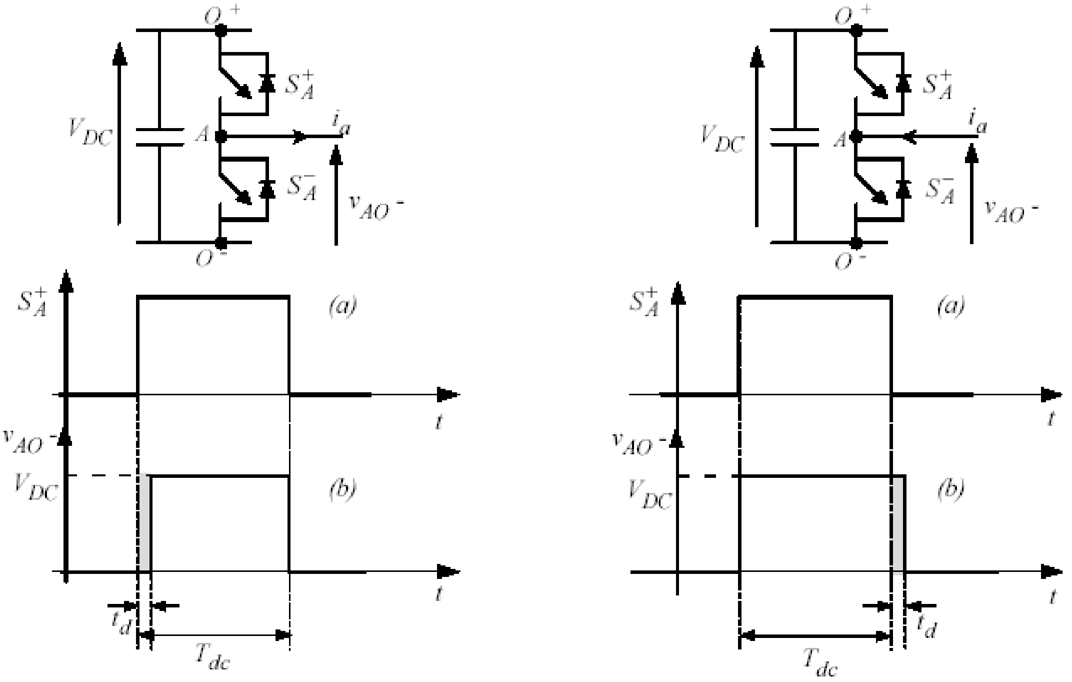


Fig 3 : The effect of sign of current on rising and falling edge of the PWM pulse (a)The Command signal (b) The Dead-time and ideal output voltages

An alternative is dead time compensation where the original PWM signal is counter modulated to essentially provide the noise cancellation. For specific consideration is the so-called feed-forward dead time compensation.

In feed-forward compensation, in relation to the current sense, the inverter phase will be commanded with a reference voltage v_1^{**} such that the voltage v_1 at the inverter terminal will become equal to the reference voltage v_1^{*} by counter modulating with the error signal $({}_1DT / T_s)\ V_d$ based on the direction / sign of the current :

$v_1^{**}{}^{*} = v_1^{*} + ({}_1DT / T_s)\ V_d$ …… when i>=0 (+ve current) ……...(3)

$v_1^{**}{}^{*} = v_1^{*} - ({}_1DT / T_s)\ V_d$ …… when i<0 (-ve current) ………(4)

These expressions mean that

(i) When the phase current is positive, the duty cycle T_1^{*} corresponding to v_1^{*} has to be increased by the dead time at the rising edge

(ii) When the phase current is negative, the duty cycle has to be decreased by the dead time on the falling edge.

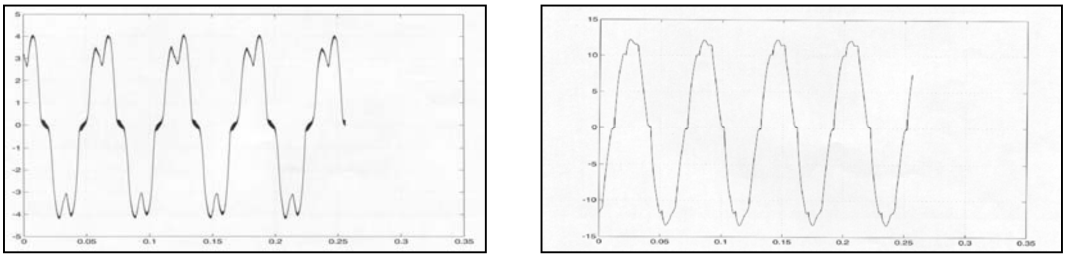
The only drawback of this method appears when the current changes its sign, because this moment cannot be foreseen. It is easily seen that when the sign is not correctly applied, an error of two times the dead-time is introduced.

In other methods, the actual inverter voltages are measured and compensation is achieved by adding to the reference phase voltage v_1^{*} a term proportional to the voltage error on that phase. However, this error voltage is not a pulse signal due to the non-linear characteristics during the switch off of the semiconductors. The drawback of this method is that all the inverter phase voltages need to be measured. The magnitude of these voltages are equal to V_d and, at this voltage level, electromagnetic interference (EMI) is introduced; hardware design issues become prominent, and the calculations for the correction signal becomes computationally intensive.

4. Current Project Status

This research program commenced in July 2001. Some of the basic issues, described above, have been investigated and the waveform distortion due to dead-time compensated in open loop v/f control by modifying the software algorithm. The frequency spectra, shown in Figure 5, before and after compensation, show that the magnitude of the fundamental harmonic increases while the amplitude of harmonics is generally reduced. The waveform of phase current, before and after dead-time compensation, is shown in Figures 4(a) and Figures 4(b).

The various algorithms for the programmable logic device in the collaborating company's motor drive system were programmed using the Altera Hardware description language (AHDL) and for the Digital Signal Processor (DSP) were programmed in C and ASM Language. All the work to date has been on the a.c. induction motor spindle drive system. Further work for the axis drives which use permanent magnet motors is being carried out using similar algorithms.



(a) (b)

Figure 4 Current waveform (a) before and (b) after dead-time compensation

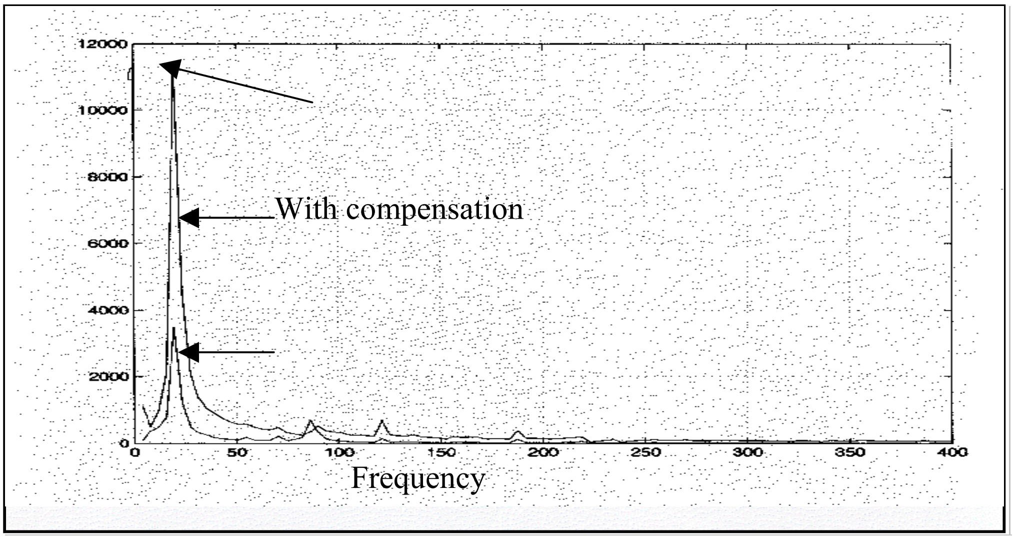


Figure 5 - Frequncy spectrum of U phase current on ANCA Drive and Motor

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