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On-Line Dead Time Compensation Technique for Open-Loop PWM-VSI Drives

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***Abstract* — A new on-line dead-time compensation technique for low cost open-loop PWM-VSI drives is presented. Because of the growing numbers of open-loop drives operating in the low speed region, the synthesis of accurate output voltages has become an important issue where low cost implementation plays an important role. The so-called average dead time compensation techniques rely on two basic parameters to compensate for this effect: the magnitude of the volt-seconds lost each PWM cycle and the direction of the current. In a low cost implementation it is impractical to attempt an on-line measurement of the volt-seconds error introduced each cycle, instead an off-line measurement is favored. On the other hand the current-direction detection must be done on-line. This becomes increasingly difficult at lower frequencies and around the zero crossings leading to erroneous compensation and voltage distortion. This paper presents a simple and cost effective solution to this problem by using an instantaneous back calculation of the phase angle of the current. Given the closed loop characteristic of the back calculation, the zero crossing of the current is accurately obtained thus allowing for a better dead time compensation. Experimental results validating the proposed method are presented.**

I. INTRODUCTION

One of the main problems encountered in open-loop PWM-VSI drives is the non-linear voltage gain caused by the non-ideal characteristics of the power inverter. The most important non-linearity is introduced by the necessary blanking time to avoid the so-called shoot-through of the DC link. To guarantee that both switches in an inverter leg never conduct simultaneously a small time delay is added to the gate signal of the turning-on device. This delay, added to the device's finite turn-on and turn-off times, introduces a load dependent magnitude and phase error in the output voltage [1-4]. Since the delay occurs in every PWM carrier cycle the magnitude of the error grows in proportion to the switching frequency, introducing a serious waveform distortion and fundamental voltage drop [7]. The voltage distortion increases with switching frequency introducing harmonic components that, if not compensated, may cause instabilities as well as additional losses in the machine being driven [6, 8, 9]. Another source of output voltage distortion is the finite voltage drop across the switches during the on-state [2, 5].

The dead time problem has already been investigated by the industry [8, 9] and various solutions have been tried [2, 4-5, 7-10]. In most cases the compensation techniques are based on an average value theory, the lost volt-seconds are averaged over an entire cycle and added vectorially to the commanded voltage. More recently a pulse based compensation method has been proposed by Leggate, et al. [8], where the compensation is realized for each PWM pulse. This provides a more accurate compensation but increases the overhead on the processor since it requires double sampling per carrier period.

Regardless of the method used, all dead time compensation techniques are based on the polarity of the current, hence current detection becomes an important issue. This is specially true around the zero-crossings where an accurate measurement is needed to correctly compensate for the dead time [2, 8]. To compensate for the dead-time the reference voltage is changed by adding or subtracting the required volt-seconds. Although in principle this is simple, the dead time also depends on the magnitude and phase of the current as well as the switch used. Several authors have dealt with this problem by using a start up measurement and calibration procedure. However, this type of compensation becomes mistuned as the operating conditions change due to loading and temperature.

In this paper a new low cost on-line dead-time compensation technique based on a back calculation of the current phase angle is presented. The method has been tested in the lab as a part of a constant V/f motor drive giving excellent results.

II. DEAD-TIME COMPENSATION

The name "dead-time compensation" often misleads since the actual dead time, which is intentionally introduced, is only one of the elements accounting for the error in the output voltage, for this reason here it is referred as volt-second compensation. The volt-second compensation algorithm developed is based on the well known average voltage method. Although this technique is not the most accurate method available it is simple to understand and gives good results for steady state operation. To understand the principle of operation we just need to look at the voltages in one of the inverter legs over one carrier period. Fig. 1 shows idealized waveforms of the triangular and reference voltages.

It also shows the gate signals, V_{g+} and V_{g-}, ideal output voltage, V^*_{AN}, and actual pole voltage for positive current. It is not difficult to shown that for positive current the actual average pole voltage over one PWM carrier period is:

$$\overline{V}_{AN} \approx V_{dc}\left[\frac{1}{2}+\frac{V^*}{V_{dc}}\right]-\Delta V \qquad (1\text{-a})$$

and for negative current is

$$\overline{V}_{AN} \approx V_{dc}\left[\frac{1}{2}+\frac{V^*}{V_{dc}}\right]+\Delta V \qquad (1\text{-b})$$

where the term ΔV represents the error due to the non-ideal switching and is found to be

$$\Delta V = \frac{t_d + t_{on} - t_{off}}{T_c}\left[V_{dc} - V_{sat} + V_d\right] + \frac{V_{sat} - V_d}{V_{dc}}V^* + \frac{V_{sat} + V_d}{2} \qquad (2)$$

The times t_d, t_{on} and t_{off} are the delay and actual turn-on and turn-off times of the switching device. V_{sat} and V_d are the on-state voltage drop across the switch and the diode respectively. V_{dc} is the DC-link voltage and T_c is the PWM carrier period. Since the difference $V_{sat} - V_d$ is small and V_{dc} is much greater than V^*, (2) can be approximated to

$$\Delta V \approx \frac{t_d + t_{on} - t_{off}}{T_c}\left[V_{dc} - V_{sat} + V_d\right] + \frac{V_{sat} + V_d}{2} \qquad (3)$$

As shown in Fig. 1, the volt-second error can be interpreted as the difference in areas between the commanded voltage and the actual voltage. The (+) and (-) signs in the bottom trace indicate that in part of the cycle there is a gain in voltage and in part of it there is a loss of volt-seconds. The compensation algorithm is based on commanding a voltage modified by ΔV such that, after passing through the inverter, the average output voltage is equal to the ideal commanded voltage V^*.

Experimental data illustrating the relative importance of the magnitude ΔV and its dependence on the load current is presented in Table I. In all cases the commanded voltage was set to 25 V and the switching frequency was 8 kHz. The switch was a standard 50 Amp IGBT module. The dead time t_d was set to 2.5 μs. It can be seen that in this particular case the total dead time effect accounts for nearly 15 volts. Here it is important to point out that the amount of volt-seconds lost per fundamental cycle does not depend on the magnitude of the commanded voltage thus its impact will be much more severe for low output fundamental voltages.

A. *Magnitude correction*

A successful compensation of the dead-time effect requires a correct estimation of the magnitude of the error ΔV as well as accurate knowledge of the current direction [1].

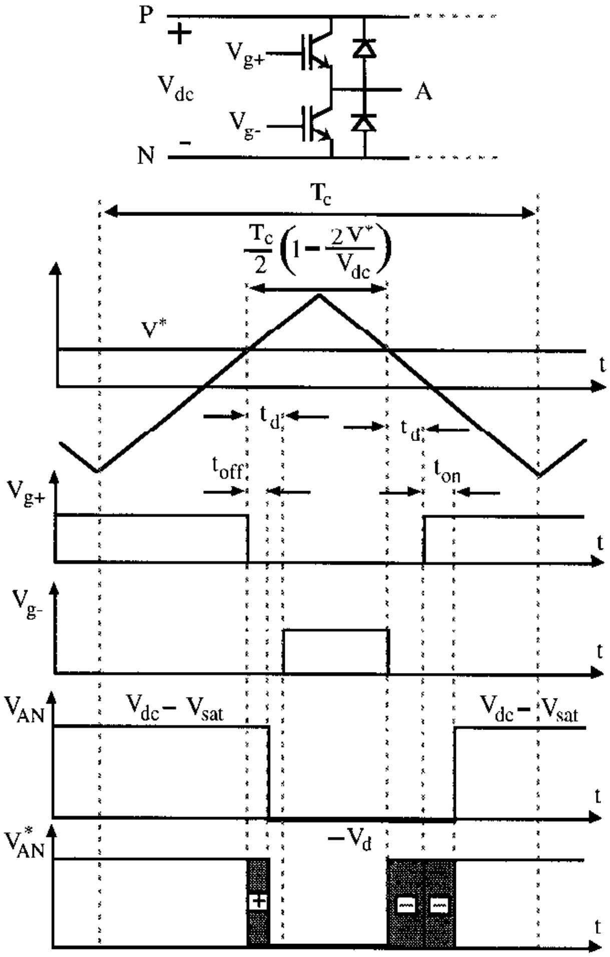

Fig. 1: PWM voltage waveforms for positive current From the top: gate signal to top device, gate signal to bottom device, actual pole voltage and commanded pole voltage.

TABLE I

VOLTAGE ERROR DUE TO NON-IDEAL SWITCHING

Current (A) (rms)	V_{AN} (V) (rms)	ΔV (V) (rms)
0	25.0	0
0.5	10.7	14.3
1.16	10.4	14.6
1.87	10.0	15.0
2.30	9.7	15.3
9.40	9.1	15.9

In general it is very expensive and not practical to measure each one of the terms in (3). Instead they are normally obtained through off-line experimental measurements [5]. The main difficulty here are changes in device's on-state voltages with load current and frequency [13]. An exact compensation would require either a precise model of each switch or direct voltage measurements. Since both techniques are expensive a much simpler approach was used.

The method consisted in using (3) to compute ΔV for nominal values and applying a second order correction for different load currents. This is done by building a table that uses the current magnitude as input and produces a correction factor as output. The complete table is built in RAM as a look-up table.

The current-direction determination on the other hand must be done on-line. The main problem here occurs around the zero crossings where it is very difficult to achieve a reliable measurement due to the PWM noise and the clamping of the current [9].

B. Current polarity determination

As mentioned in the introduction average dead time compensation techniques rely on direct current measurements to determine the sign of the compensation needed. Because of PWM noise and current clamping around the zero crossing, accurate measurement of the current polarity is very challenging. In the past several solutions have been proposed, however they require either a high bandwidth current sensor [2, 11] or are computation intensive making these solutions not suitable for low cost applications [7-9].

The main objective here is to be able to obtain reliable current polarity information using a low cost implementation. In general only the polarity of the current is needed to apply the compensation, however because of the change in the switching times with load changes, its magnitude is also required. To overcome this difficulty a d-q synchronous frame transformation of the current is used. Assuming a sinusoidal current in phase a and multiplying it by cos ωt and sin ωt yields

$$\begin{aligned} i_q &= I_{pk}\cos(\omega t - \phi)\cos(\omega t) \\ &= \frac{I_{pk}}{2}\left[\cos(2\omega t - \phi) + \cos(\phi)\right] \qquad (4) \end{aligned}$$

and

$$\begin{aligned} i_d &= I_{pk}\cos(\omega t - \phi)\sin(\omega t) \\ &= \frac{I_{pk}}{2}\left[\sin(2\omega t - \phi) + \sin(\phi)\right] \qquad (5) \end{aligned}$$

where I_{pk} is the peak value of the current and ϕ is the phase angle with respect to the voltage.

The d and q-axis current components contain, ideally, both a double frequency term and the wanted dc component. To eliminate the double frequency term a notch type filter is used. In addition, to eliminate the high frequency components, a low-pass filter is added. The notch filter is tuned at twice the excitation frequency.

After eliminating the AC components from (4) and (5) a simple trigonometric relation yields both the magnitude and the phase angle of the current. Once the phase angle is known the instant of zero crossing can be determined simply by counting from the instant of the zero crossing of the reference voltages. A block diagram of the magnitude and phase angle measurements is shown in Fig. 2. Experimental results of the phase angle measurement for a fundamental frequency of 3 Hz are presented in Fig. 3.

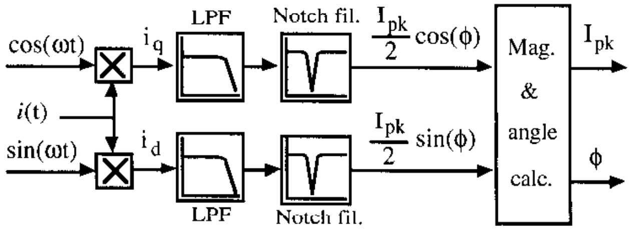

Fig. 2: Current measurement and decomposition into magnitude and phase angle.

Once the magnitude and phase angle of the measured current is determined by this means, an ideal current waveform is reconstructed. This reconstructed current is then used in the dead time compensation algorithm, which proceeds as follows: if the reconstructed current is positive the magnitude ΔV (computed from (3) and corrected by the load current) is added to the commanded voltage and if the current is negative ΔV is subtracted from the commanded voltage. A block diagram showing the implementation is presented in Fig. 4.

III. INFLUENCE OF VOLTAGE ACCURACY ON V/f DRIVES

The importance of a correct synthesis of the output voltage in V/f drives goes beyond the harmonic distortion introduced by the dead time but, because of the loss of fundamental voltage, also affects the output torque and speed. For this type of drives it is known that the torque is proportional to the square of the voltage [12]. Assuming that the output voltage has an error ΔV with respect to the commanded value V^* then

$$T \propto \left(V^* + \Delta V\right)^2 \qquad (6)$$

which can be approximated to

$$T \approx T_o\left(1 + \frac{2\Delta V}{V^*}\right) \qquad (7)$$

and the error in the torque is

$$\Delta T = T - T_o = \frac{2\Delta V}{V^*}T_o \qquad (8)$$

At high speeds the commanded voltage V^* is large and the ratio $\Delta V/V^*$ becomes negligible, however, at low speeds V^* is small and even small errors in the voltage will yield large torque and speed errors. Figs. 5 and 6 show the torque and speed errors for 3 stator frequencies: 60, 6 and 3 Hz. As expected the errors are negligible for high output voltages (60 Hz) but they become very large for small output voltages (3 Hz). Therefore it is evident that to achieve a good speed accuracy in a V/f drive it is essential to have an even better

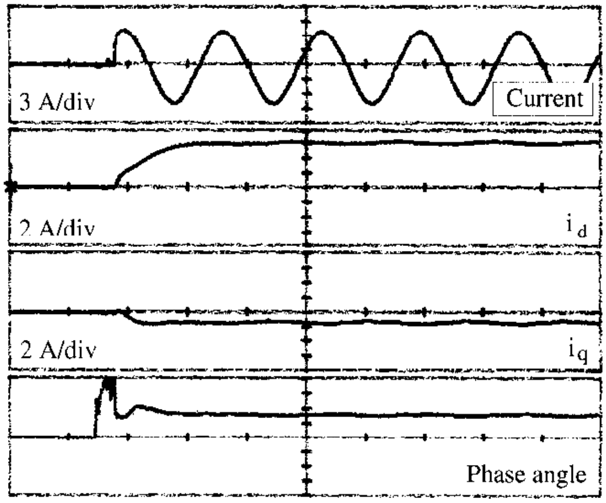

Fig. 3: Current phase angle measurement. From top to bottom: phase current, d-axis current component, q-axis current component and derived phase angle. Time scale is 0.2 sec/div.

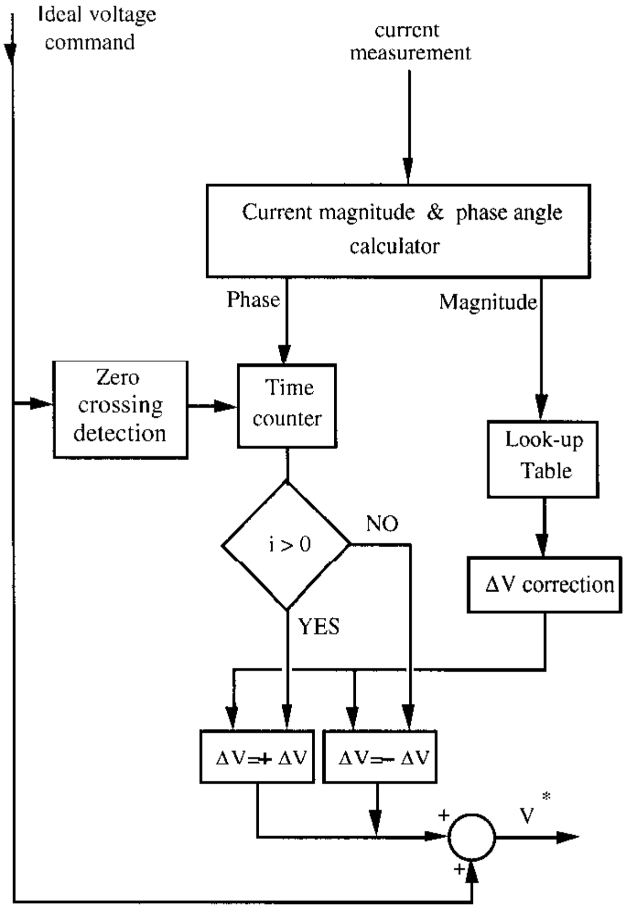

Fig. 4: Block diagram of the proposed dead time compensation algorithm.

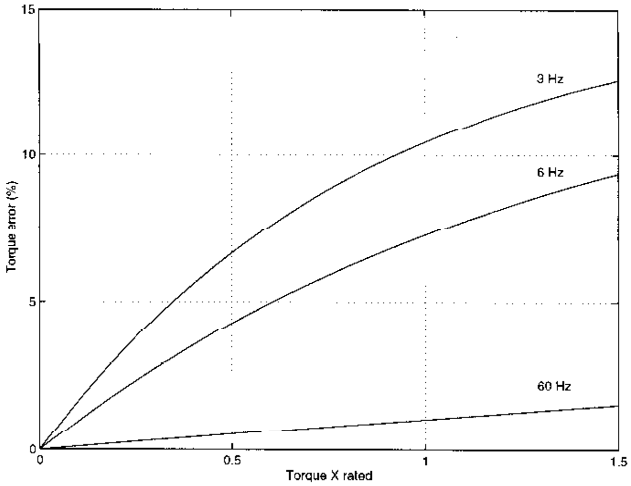

Fig. 5: Torque error due to 1 volt peak error in output voltage. The machine parameters used in the simulation are given in Table II.

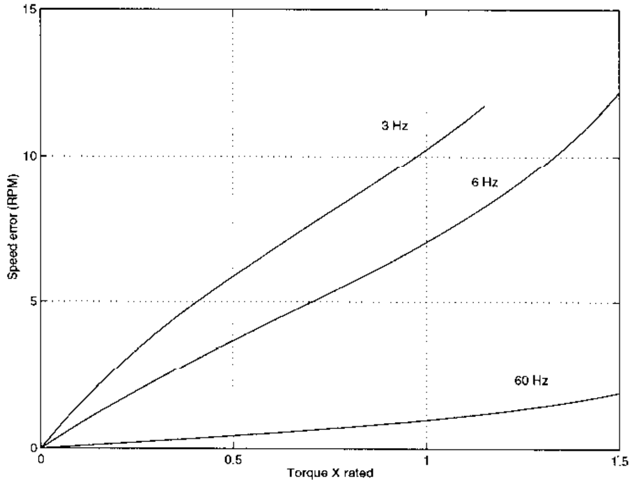

Fig. 6: Speed error due to 1 volt peak error in output voltage. The machine parameters used in the simulation are given in Table II.

accuracy in the synthesized output voltage. For example for the machine used in the experiment, to obtain a 0.3% speed accuracy it is necessary to synthesize the PWM output voltage to better than 0.4 volts, which represents a 0.2% accuracy.

IV. EXPERIMENTAL RESULTS

The proposed compensation method has been implemented as a part of a low cost constant V/f drive using a 3 Hp induction motor whose parameters are given in the Appendix. Two phase currents were measured using open-loop type current sensors with asynchronous sampling. The sampling time was 1 ms. Fig. 7 shows the phase current when the actual measured current or the reconstructed waveform is used in the dead time compensation algorithm. In the first case the clamping of the current around the zero crossing is quite clear. This result is similar to the one reported in [5] but the technique used here is simpler. The second waveform corresponds to the case where the reconstructed current is used. The improvement achieved by the proposed method is self evident with the current showing almost no distortion.

Fig. 8 shows the measured and reconstructed current along with a x-y plot indicating an almost perfect match. The phase-a current (raw and filtered) is shown in Fig. 9, also shown here are the actual commanded voltage (including the compensation ΔV) and the ideal commanded voltage. Results for 1 Hz operation are shown in Fig. 10. The line currents show almost no distortion thus indicating a correct compensation.

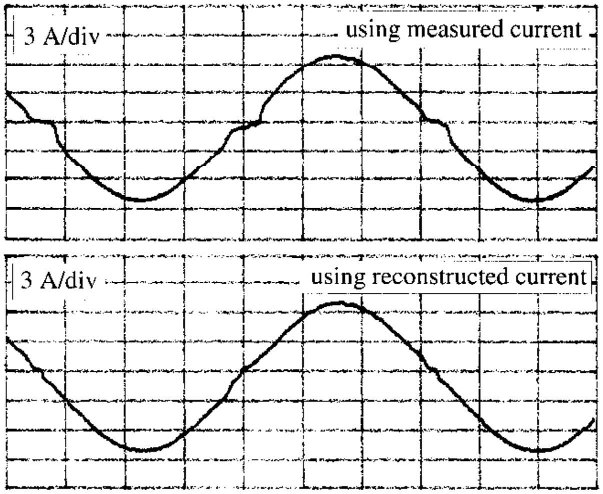

Fig. 7: Phase current. Top: using measured current to compensate for dead time. Bottom: using reconstructed current to compensate for dead time. Time scale 50 ms/div. (f= 3 Hz)

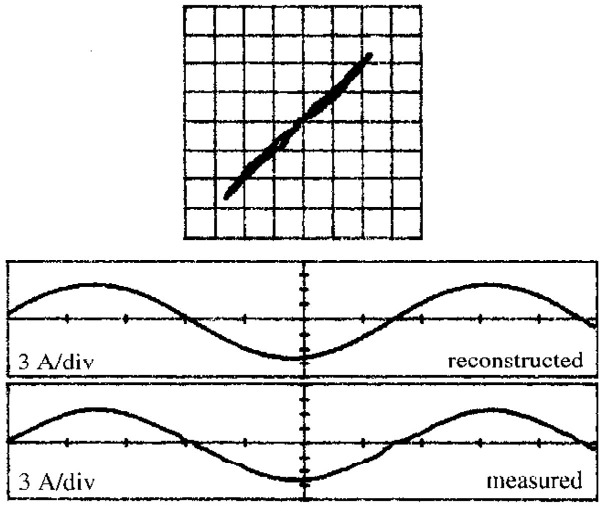

Fig. 8: Measured current at 3 Hz. Top trace: reconstructed current, bottom trace: measured current. Time scale is 50 ms/div.

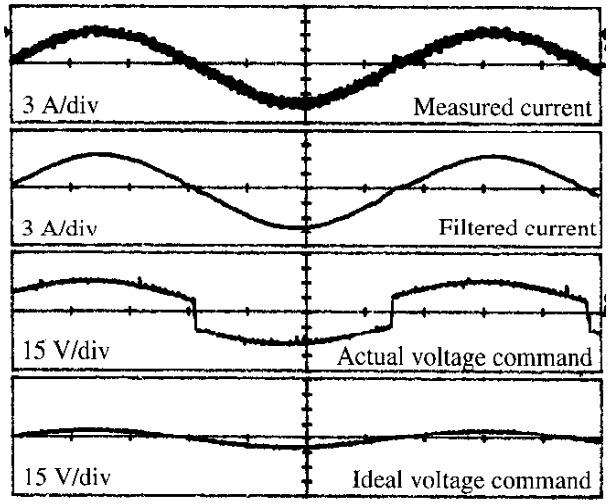

Fig. 9: Measured currents at 3 Hz.. From top: phase-a current, filtered phase a current, commanded voltage including compensation and ideal commanded voltage. Time scale is 50 ms/div.

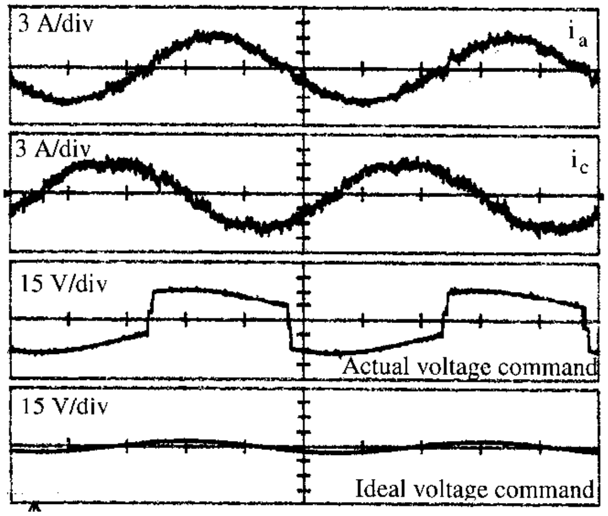

Fig. 10: Measured currents at 1 Hz.. From top: phase-a current, phase-c current, commanded voltage compensated by dead time and ideal commanded voltage. Time scale is 0.2 s/div.

V CONCLUSIONS

The dead time compensation method proposed in this paper provides a low cost and efficient means to reduce current distortion in open loop PWM-VSI drives. The output voltage error produced by the dead time and its influence on the torque output for constant V/f drives has been presented in some detail and a compensation method based on an average technique using a feed forward and a feedback loop has been implemented. The main problem, current detection around the zero crossings, has been solved by using an instantaneous back calculation of the current phase angle.

The calculated phase angle is then used in the feed forward compensation loop and the current magnitude is used in the feedback loop. Given the closed loop nature of this calculation the zero crossing of the current is accurately obtained. Experimental results validating the proposed method are presented.

APPENDIX

PARAMETERS OF THE MACHINE USED IN THE STUDY

TABLE II

INDUCTION MACHINE DATA

3 Hp	$r_s = 0.89\ \Omega$
230 V	$r_r = 0.73\ \Omega$
9 A (rms)	$L_s = 0.065$ H
60 Hz	$L_r = 0.065$ H
1740 rpm	$L_m = 0.062$ H

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