Pulse Based Dead Time Compensator for PWM Voltage Inverters

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Abstract - The dead time necessary to prevent the short circuit of the power supply in pulse width modulated (PWM) voltage inverters results in output voltage deviations. Although individually small, when accumulated over an operating cycle, the voltage deviations are sufficient to distort the applied PWM signal. This paper presents a new method to correct for the dead time deviations. The *Pulse Based Compensator* is less hardware and software intensive than other dead time compensation methods providing a low cost solution. The pulse based technique is developed by analyzing the effects of dead time on a pulse by pulse basis and correcting each pulse accordingly. The technique is evaluated through simulation and experimental results. Other compensation methods are evaluated and the results compared with the pulse based technique. This comparison indicates previous methods can produce magnitude and phase errors in the applied terminal voltage, whereas the proposed method compensates for the dead time without significant magnitude and phase errors in the terminal voltage of PWM voltage source inverters.

I. Introduction

The state of the art in motor control provides an adjustable voltage and frequency to the terminals of the motor through a pulse width modulated (PWM) voltage source inverter drive. As the power devices change switching states, a dead time exists. Although the dead time is short, it causes deviations from the desired fundamental output voltage. While each deviation does not appreciably affect the fundamental voltage, the accumulated deviations result in reduced fundamental output voltage, distorted machine currents, and torque pulsations. To compensate for the dead time in PWM signals, the industry has investigated this problem [1-3], and has tried various methods of correction [4-10].

Applications will expose the inadequacies of a particular compensation technique. Fractional horsepower drives exhibit dead time induced instabilities to a lesser extent than integral horsepower drives. Consequently this can lead to a masking of the inherent problems associated with the dead time effect. For example, a dead time compensated ac drive may perform well on a fan or pump application with an induction motor, but inadequately on a fiber application with a synchronous reluctance motor.

Most dead time compensation techniques are based on an average value theory; the lost voltage is averaged over an operating cycle and added vectorially to the command voltage [4-7]. One technique uses a method of adjusting the compensation time using a PI controller [7]; while another approach corrects by detecting the direction of power flow [9]; and another uses a feedforward method for high performance current regulated drives [10].

This paper proposes a pulse by pulse compensation technique that adjusts the symmetric PWM pulses to correct for the voltage distortion due to the dead time effect. The proposed method compensates for the dead time without significant magnitude and phase errors in the terminal voltage of the PWM voltage source inverters. The technique is evaluated through simulation and experimental results. Other techniques are evaluated and the results are compared with the pulse based technique.

II. Voltage Deviations due to the Dead Time Effect.

A: Dead Time Effects

When ac induction, synchronous reluctance, or synchronous pm motors are operated using open-loop adjustable-frequency drives, system instabilities may occur for certain frequency ranges and loading conditions. The cause of these instabilities can be inherent low-frequency motor instabilities, instability due to the interaction between the motor and the PWM inverter, or the choice of PWM strategy.

When the ac induction motor is fed by the voltage source inverter, the applied stator voltage waveforms contain harmonics generated by the PWM algorithm. The system stability will be affected by these harmonics, especially at low frequencies and no load conditions, causing additional mach- ine losses and reduced efficiency. The magnitude of these losses will depend on the magnitude of the harmonic content in the applied voltage and are compounded by induced harmonics. Excessive harmonics will increase motor heating and torque pulsations. Even the smallest of harmonics as a percent of the fundamental, when coupled with the motor, can result in unstable operation. The choice of the PWM strategy is then important to minimize the voltage and current harmonics. Defects in the PWM strategy will result in voltage deviations at the motor terminals and will be intensified by the addition of the inverter dead time.

The use of fast switching devices in the inverter such as IGBTs or MOSFETs, which use high carrier frequencies (5K to 15K hertz) with lower dead time values (in the area of 2 to 5 microseconds), will not rid the system of instability prob- lems. Higher carrier frequencies improve waveform quality by raising the order of principle harmonics; but low frequency subharmonics may persist in the output voltage due to the dead time, thus producing beat components and oscillations.

Fig. 1 shows the current waveform of a 10 HP high efficiency induction motor rated at 18 amps peak, 460 vac, and 40 N-m, operated by a 10 HP general purpose volts-per-hertz controller operating at 15 Hz with a 4K Hz carrier frequency, and no compensation for the dead time. At no load, the motor currents exhibit distortion with peak currents of 13 amps producing severe torque pulsations. These unstable regions vary over machine frame size and operating points.

In general most ac motors do not run in a continuous no load condition, but many applications require periods of light load or no load as part of the process. It is during these periods, that instabilities in the system can deteriorate the process reliability. Stability can improve as load is applied to the machine, but may require full load to stabilize. Output voltage will be low increasing current draw to supply the load resulting in reduced efficiencies. In the case of Fig. 1, a two-thirds load (26 N-m) applied to the machine provides stable operation.

B: Pulse Deviations

The effects of the dead time on the output voltage can best be examined from one phase of the PWM inverter. The basic configuration shown in Fig. 2 consists of upper and lower power devices T1 and T2, and reverse recovery diodes D1 and D2, connected between the positive and negative rails of the power supply. Commutation of the power devices comes from the PWM generator which creates the Swu and Swunot base drive signals. Output terminal U is connected to motor phase U and the current iu is positive with respect to the motor.

Examining the power device switching sequence as T1 is turning OFF and T2 turning ON, or T2 is turning OFF and T1 turning ON, there exists a time when both power devices cease to conduct. During the dead time output U appears to be floating, but the current iu must conduct through

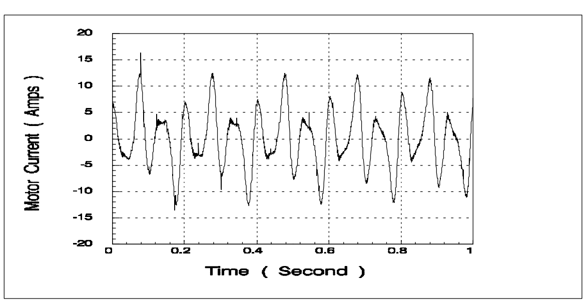


Fig. 1. Motor Instability: 10 HP ac Induction Motor Without Dead Time Compensation.

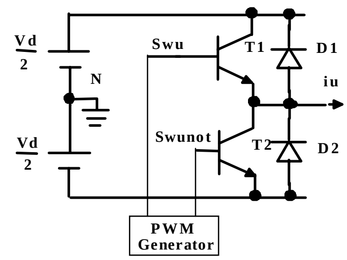


Fig. 2. Single Phase Configuration of PWM Inverter.

reverse recovery diodes D1 and D2. Depending on the current polarity, the reference voltage may be delayed by the dead time.

Consider the four possible commutation sequences. In the first condition, the current iu is positive. T1 transitions from ON to OFF and T2 from OFF to ON. During the dead zone, D2 conducts and D1 blocks the flow of current to the positive rail. This condition results in the correct voltage applied to the motor terminals.

In the second condition, the current iu is positive. T1 transitions from OFF to ON and T2 from ON to OFF. During the dead zone, D2 continues conduction and D1 blocks the flow of current to the positive rail. Current conducts in D2 until the dead time elapses, then T1 turns ON. This condition results in a <u>loss</u> of voltage at the motor terminals.

In the third condition, the current iu is negative. T1 transitions from OFF to ON and T2 from ON to OFF. During the dead zone, D1 conducts and D2 blocks the current flow to the negative rail. This condition results in the correct voltage applied to the motor terminals.

For the fourth condition, the current iu is negative. T1 transitions from ON to OFF and T2 from OFF to ON. During the dead zone, D1 continues conduction and D2 blocks the flow of current to the negative rail. Current conducts in D1 until the dead time elapses, then T2 turns ON. This condition results in a <u>gain</u> in voltage at the motor terminals.

Fig. 3 shows the effect of dead time on hypothetical pulse times Swu and Swunot for power devices T1 and T2. Trace 3a and 3b are the ideal pulse times; if applied, the resulting fundamental voltage would be of the correct magnitude and phase. In trace 3c, T1 transitions from ON to OFF, but there must be a delay time before T2 in trace 3d can turn from OFF to ON. Likewise as T2 in trace 3d transitions from ON to OFF, T1 in trace 3c must delay before it can turn on.

Consider iu positive in trace 3e, as T1 transitions from ON to OFF, there is no reduction or gain to the pulse time as compared to the ideal pulse time. As T1 transitions from OFF to ON, the pulse time decreases from the ideal resulting in a deviation to the pulse time and an incorrect fundamental voltage to the load.

When iu is negative as in trace 3f, T1 is held on longer than the ideal, resulting in an increase in pulse time, and an incorrect fundamental voltage applied to the load. As T1

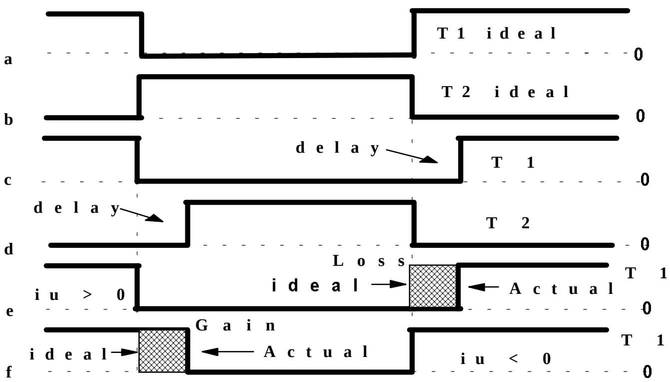


Fig. 3. Ideal and Corrupted Pulse Patterns for Power Devices T1 and T2.

transitions from OFF to ON, there is no reduction or gain to the pulse as compared to the ideal pulse.

To compensate for the dead time effect, a **Pulse Based Dead Time Compensator** method has been developed. The Pulse Based Dead Time Compensator method compensates for the pulse deviations due to the dead time effect on a pulse by pulse basis. By modifying the switching times to compensate for the dead time effect, the output voltage can be properly controlled in magnitude and phase.

III. Pulse Based Method of Correction

The Pulse Based Dead Time Compensator updates the turn-on time of the power device at the beginning of a PWM cycle and the turn-off time of the device at the midpoint of the PWM cycle by software correction. Correction is based on the polarity of the currents, independent of operating or carrier frequencies. The method does not need current phase detection, thus eliminating the a/d converters and software overhead of other methods. Simple current polarity detectors interfaced to the data bus make it compatible with microprocessor or DSP I/O architecture's, which yields an inexpensive dead time compensator.

Fig. 4 shows the pulse time correction using the Pulse Based Dead Time Compensator for iu > 0. Trace 4a is the ideal pulse time for T1 as T1 transitions from OFF to ON and from ON to OFF. Trace 4b shows the pulse after the dead time counter if allowed to be processed by the PWM waveform generator without correction. Trace 4c shows the error pulse (4a - 4b) due to the dead time.

To correct the error, the software algorithm adjusts the pulse time width. For iu > 0, time is added to the pulse before the dead time generator creating an unsymmetrical pulse. The increased pulse time (4d), is processed through the dead time counter. The actual pulse (4e) is identical to the ideal pulse time (4a) in width and position.

Fig. 5 shows the operation of the Pulse Based Dead Time Compensator for iu < 0. The correction is similar to iu > 0 in Fig. 4, except time is subtracted from the pulse. Trace 5a is the ideal pulse time. Trace 5b shows the ideal

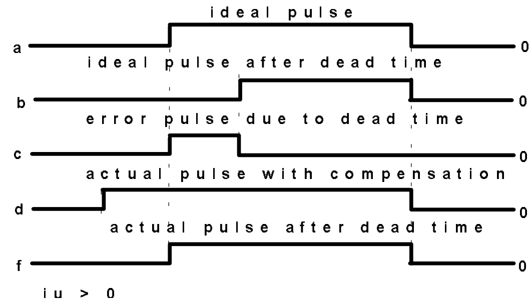


Fig. 4. Pulse Based Dead Time Compensator for iu > 0.

pulse time after the dead time. Trace 5c shows the error pulse (5a - 5b) due to the dead time. The reduced pulse time (5d) is processed through the dead time counter. The actual pulse (5e) is identical to the ideal pulse time (5a) in width and position.

The Pulse Based Dead Time Compensator uses a minimal amount of software code space as compared to other techniques, which require angle calculations to determine the proper magnitude and phase of the corrected voltage command [5-8]. This advantage allows the user more processor power for other control functions. The Pulse Based Method offers the ability to modify the switching dead times to account for dissimilar turn-on and turn-off characteristics of the power devices, thus eliminating the need for power device measurements.

IV. Comparison of Compensation Methods

Most dead time compensation methods are either voltage compensation or current feedback types. Waveform correction for the dead time effect is attained by returning the lost volt-seconds to the applied PWM pulse pattern.

A: Voltage Compensation Types.

From the work by Murai, et al. [4], a hardware compensator measures the phase voltage changes at the inverter output based on the current polarity. Logic signals are used to measure the positive and negative phase voltage times for

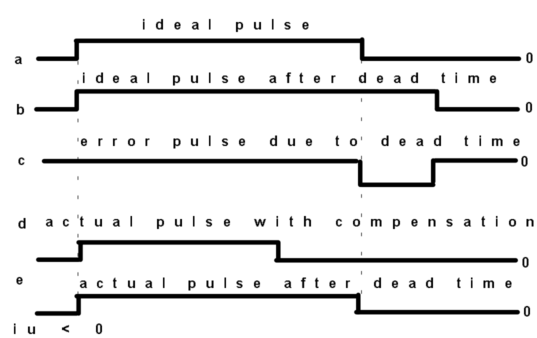


Fig. 5. Pulse Based Dead Time Compensator for iu < 0.

the previous commutation and are stored in a counter. The stored
times are fed back, and with closed loop control, compensates next switching of the phase leg. Although the actual delay time is measured, this method compensates on the next pulse basis resulting in a phase shift in the applied voltage.

The method proposed by Choi, et al. [7] compensates for the dead time effects and voltage drops of the power devices with a Strategy of Adjusting the Compensation Time. First the electrical characteristics of the power devices are modeled as linear functions of the device currents and compensated for in a feedback loop. This is combined with the turn-on and turn-off characteristics of the devices to produce a voltage feedback signal that is compared with a voltage reference through a PI controller to adjust the compensation time, hence producing the same inverter output voltage as the reference voltage. The technique requires the currents to be "well regulated", implying a current regulator is employed.

Fig. 6 shows the pulse times for the Strategy of Adjusting the Compensation Time for iu > 0. Trace 6a is the ideal pulse time for T1 as T1 transitions from OFF to ON and ON to OFF. Trace 6b displays T1 after the guaranteed dead time (Td). Trace 6c displays T2 with correction (Tc), and the guaranteed dead time (Td). Trace 6d shows the line to neutral voltage applied to the motor. This method produces the same pulse time as the ideal condition, but results in a position shift from the ideal pulse time.

B: Current Feedback Compensation Types.

Current feedback compensators use current feedback information to create an error voltage vector which is summed with the reference voltage. The error voltage equals the fundamental component of a square wave signal, the amplitude of which compensates for the volt-seconds lost. One method, the Square Wave Voltage or Average Value (AV), calculates the magnitude of the error voltage as a function of the carrier period (tc), dead time (Td), and bus voltage (vbus). The phase angle alpha (α) of the error voltage vector equals the phase angle of the feedback currents. The addition of a compensating voltage vector to the reference voltage vector produces 3-phase symmetrical reference voltage signals [8].

If the volt-seconds of the error pulses in one cycle of operating frequency (fe), is represented by an equivalent square wave, the fundamental component of the resulting six-step signal can be added to the reference as shown in (1):

$$Vas^* = Vas + Vafund. \qquad (1)$$

Fig. 7 displays the sequence of signals comprising the corrected modulating signal. Trace 7a is the reference wave. Trace 7b shows the equivalent six-step phase voltage representing the lost voltage due to the dead time. Trace 7c is the fundamental component of the error voltage. Trace 7d shows the modified and original reference signals clearly depicting the resultant phase shift in the modulating signal. This techniques compensates for the effect of dead time on an average value basis through modifications of the reference signal; this approach has an inherent delay.

Fig. 8 shows the pulse times for the AV method of iu > 0. Trace 8a is the ideal pulse time for T1 as T1 transitions OFF to ON and ON to OFF. Trace 8b shows the pulse time without compensation after the dead time counter. Trace 8c shows the pulse time with compensation using the AV method. The added compensation increases the pulse time width based on the operating frequency, carrier frequency, dead time, and the gain adjustment.

Trace 8d shows the corrected pulse time after the dead time counter. The actual pulse (8d) is identical to the ideal pulse (8a), but note the position shift. This position shift results in deviations in the applied fundamental voltage. The time width of the error pulses shown in trace 8e, (8a-8d), varies with Vafund.

A more accurate method of dead time correction is the Vector Summation (VS) method. This method is similar to the AV method, but requires more computations to determine the fundamental component of the lost volt-seconds.

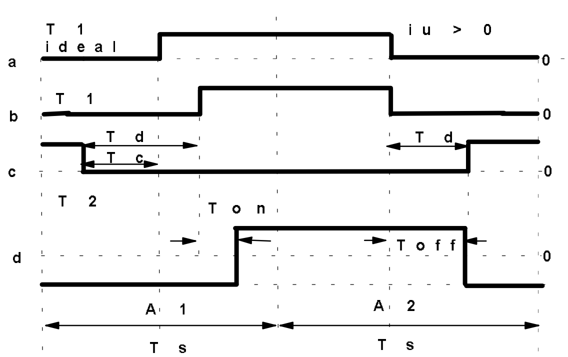


Fig. 6. Voltage Feedback Compensation Type - Strategy of Adjusting the Compensation Time.

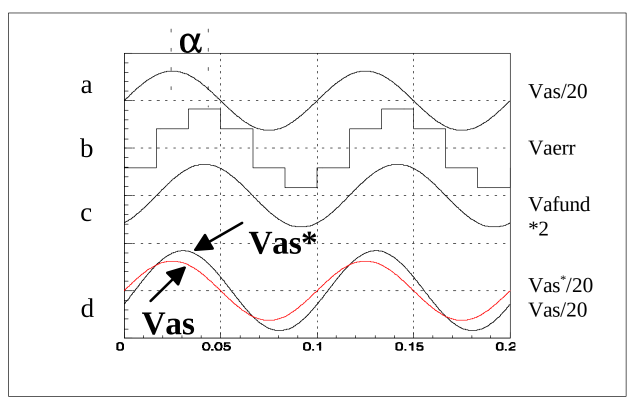


Fig. 7 Average Value Dead Time Compensator.

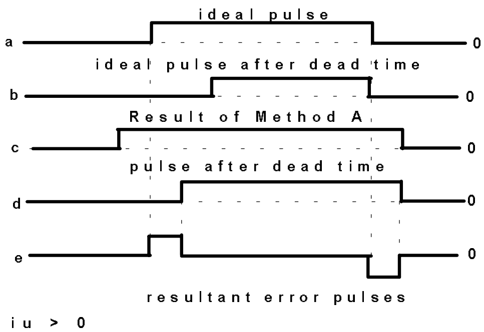


Fig. 8. Pulse Patterns for the Average Value Compensation Method.

The equations for magnitude and phase to create the error voltage vector are shown in Table 1.

The above mentioned dead time compensation methods provide acceptable correction for output waveform distortion due to the dead time effects on ac induction motors. Some of these solutions are costly requiring dedicated hardware and considerable computing time. The voltage compensating and current feedback techniques apply pulse width correction, but with a phase shift in the fundamental voltage component.

V. Implementation of Pulse Based Dead Time Compensation Methods

The Pulse Based Dead Time Compensator was implemented in a INTEL 80C196MC microcontroller which includ- es an internal PWM waveform generator [11]. Compensation for the dead time effects is accomplished by adjusting the pulse times of the waveform generator to correct for the gain or loss of pulse time. The method is independent of operating and carrier frequency, but dependent on current polarity. There are two modes of operation within the INTEL 80C196MC waveform generator to generate center type PWM [11]. In mode 0, the counter control is down/up, and reloaded at the beginning of every PWM period. Correction can only be made at the beginning of each PWM cycle. In mode 1, the counter control is down/up, and reloaded at every half PWM cycle. Corrections can be made each half PWM cycle.

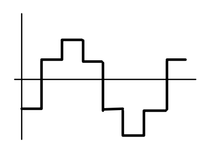
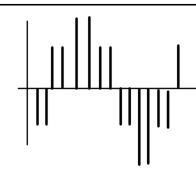
A: Twice Carrier Rate Pulse Based Dead Time compensation.

Fig. 9 shows the block diagram of the Twice Carrier Rate (TCR) Pulse Based Dead Time Compensation in Mode 1. For simplicity, discussion will be limited to the u_phase switching signal generation. Decisions for correction are based on the down/up counter status and the current polarity. From these conditionals corrections are made to add, subtract, or leave the switching time unchanged.

The software algorithm generates the ideal u_phase pulse times, u_on and u_off, for the desired operating point. U_on and u_off are stored in the compensation software routine. The predetermined dead time value is loaded into the dead time control register of the waveform generator. The u_phase current detector continuously updates current polarity information via the microcontroller data bus. An interrupt signal from the waveform generator updates the counter status bit, (CNT STATUS).

If iu > 0 and CNT STATUS is down, the compensation software adds the dead time value to u_on and stores the cor-

Table 1
Dead Time Error Correction Formulas and Approximate Error Waveshape.

Method	AV	VS
Magnitude	$\frac{2}{\pi} * [\frac{Vbus*Td}{tc}]$ $Td(\text{sec}),\quad tc(\text{sec}) = (\frac{1}{fc})$	$\frac{4}{\pi} * [\sin \pi a \sum_{\frac{-n}{2}}^{\frac{n}{2}} \cos \frac{\pi}{n} * Vbus]$ $a = \frac{Td*fe}{2} \quad n = \frac{fc(\text{carrier frequency,Hz})}{fe(\text{operating frequency,Hz})}$
Phase	$\angle\alpha$ *phase angle of current*	$\angle\alpha$ *phase angle of current*
Waveshape		

rected value in u_on. The corrected u_on is sent to the wave- form generator. The corrected u_on is processed through the dead time counter. The dead time counter

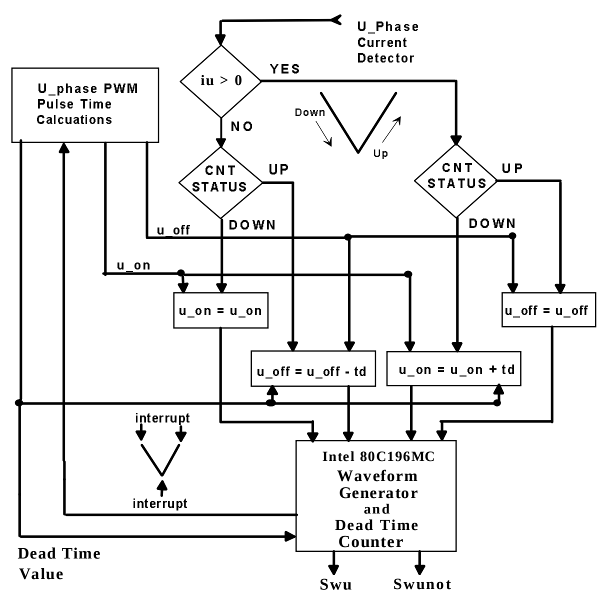


Fig. 9. Block Diagram of Twice Carrier Rate Pulse Based Dead Time.

provides the non-overlapping signals for the PWM output pair Swu and Swunot. The u_on pulse pattern is identical to the ideal pulse pattern.

If iu > 0 and CNT STATUS is up, no correction is made to u_off. U_off is sent to the waveform generator and processed through the dead time counter.

If iu < 0 and CNT STATUS is down, no correction is made to u_on. U_on is sent to the waveform generator and processed through the dead time counter.

If iu < 0 and CNT STATUS is up, the compensation software subtracts the dead time value from u_off and stores the corrected value in u_off. The corrected u_off is sent to the waveform generator and processed to yield the correct pulse width to the machine terminals. Repeating this process over a period of time corresponding to the fundamental frequency of operation yields the correct phase voltage applied to the machine terminals.

B: Carrier Rate Pulse Based Dead Time Compensation.

The Carrier Rate (CR) Pulse Based method requires less software than the TCR Pulse Based method, but provides less than optimum correction. Fig. 10 shows the reduced block diagram of the CR Pulse Based Dead Time Compensation in Mode 0. For simplicity, discussion will be limited to the u_phase switching signal generation. Decisions for correction are based on current polarity at the beginning of each PWM period.

The software algorithm generates the ideal u_phase pulse times, u_on and u_off, for the desired operating point. U_on and u_off are stored in the compensation software routine. The predetermined dead time value is loaded into the dead time control register of the waveform generator. Because Mode 0 restricts pulse times to symmetrical center aligned methods, only one-half the dead time value is stored in the compensation software routine. The u_phase current detector continuously updates current polarity information via the microcontroller data bus. An interrupt signal is sent to the compensation software at the beginning of each PWM period.

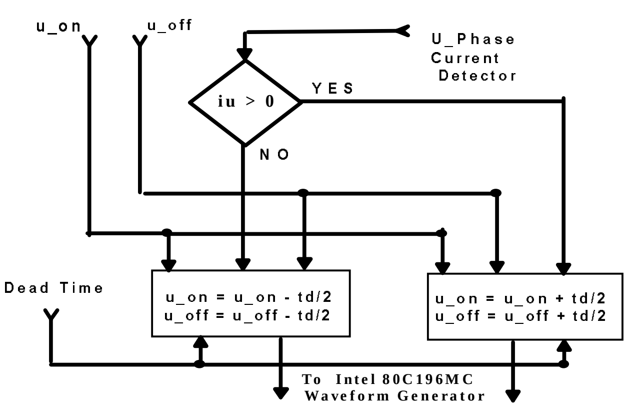


Fig. 10. Block Diagram of Carrier Rate Pulse Based Dead Time Compensation using INTEL 80C196MC in Mode 0.

If iu > 0, the compensation software adds one-half the dead time to u_on and u_off increasing the pulse time, and the corrected value is stored in u_on and u_off. The corrected u_on and u_off are sent to the waveform generator and the dead time counter. The corrected pulse time is processed through the dead time counter, but the resultant pulse position is shifted by one-half the dead time.

If iu < 0, the compensation software subtracts one-half the dead time from u_on and u_off decreasing the pulse time. The correction is then the same as for iu > 0. The position shift in the CR Pulse Based method is enough to reduce the applied fundamental voltage and induce instabilities in low impedance and high voltage motors.

VI. Experimental Results

The TCR Pulse Based Dead Time Compensation method applies the correct fundamental voltage to the motor terminals. Fig. 11 shows the waveform correction that occurs when the TCR Pulse Based Compensation method is applied to the same motor used in Fig. 1. The motor current is stable with the correct no load flux current for the 10 HP 460 vac high efficiency induction machine. The steady state waveform is excellent and a frequency spectrum of the current and line-line voltage showed a 12 fold reduction in subharmonics.

Fig. 12 demonstrates the dynamic performance of the TCR Pulse Based method transitioning from an unstable operating mode to a stable operating mode. The TCR compensation method has a high bandwidth, one capable of correcting the applied voltage in a dead beat fashion with excellent transient characteristics.

The voltage and current feedback type methods provide good waveform correction on ac induction machines, but the weakness of these methods becomes apparent when using motors other than the standard ac induction motor. The synchronous reluctance or synchronous pm motor used widely in the fiber industry can become unstable using an AV method. Fig. 13 shows the current waveform of a synchronous reluctance motor controlled by a general purpose

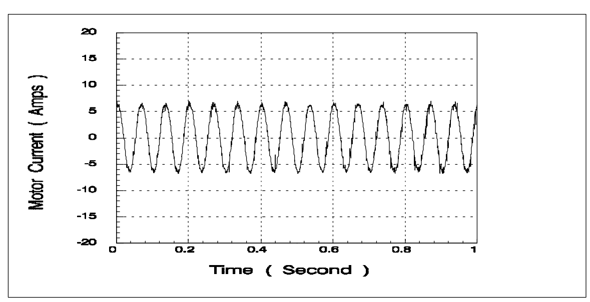


Fig. 11. Stable Operation: 10 HP ac Induction Motor with TCR Pulse Based Dead Time Compensation.

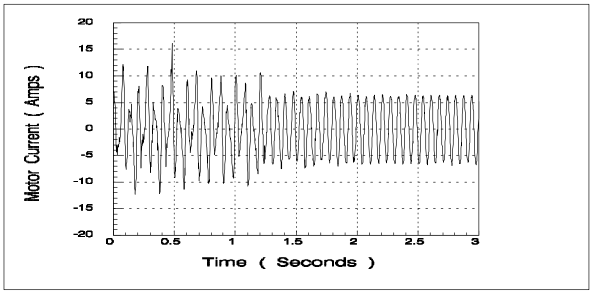


Fig. 12. Dynamic Performance: 10 HP ac Induction Motor using TCR Pulse Based Dead Time compensation.

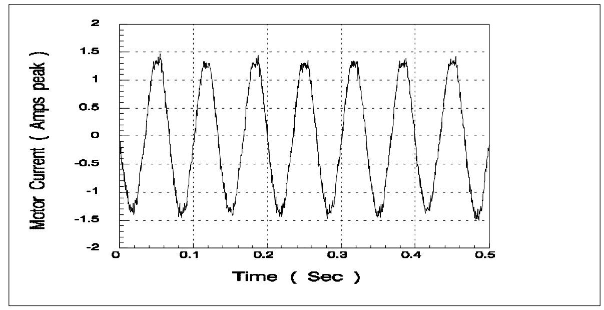


Fig. 14. TCR Pulse Based Compensation Method Controlling a Synchronous Reluctance Motor.

volts-per-hertz controller using a voltage feedback dead time compensation method at 15 Hz. The result of an inadequate dead time compensation method is exhibited by low frequency subharmonics which cause excessive motor heating and loss of synchronization. Neither is an acceptable case for fiber applications.

The TCR Pulse Based Dead Time Compensation method reduces the low frequency subharmonic content by applying the correct voltage pulse pattern to the motor terminals. Fig. 14 displays the current waveform of the same synchronous reluctance motor controlled by a general purpose volts-per-hertz controller at 15 Hz. Voltage reference, dead time, and carrier frequency are the same for the Average Value and TCR Pulse Based results displayed above.

VII. Pulse Pattern Comparisons

A vector analysis of the pulse patterns examines the fundamental voltage vectors for no compensation, AV, and the Pulse Based (TCR and CR) methods. Simulations were performed with an inverter dead time of 2 microseconds, carrier frequency 4K Hz, operating frequency 10 Hz, with the speed fixed to eliminate any mechanical instabilities. The load is a 10 Hp 460 vac high efficiency induction motor rated at 18 amps peak.

Fig. 15 compares the fundamental voltage vectors in the q-d reference frame. The q-axis is displayed on the horizontal axis and the d-axis on the vertical axis. The magnitude and phase relationships in per unit quantities are displayed for each method.

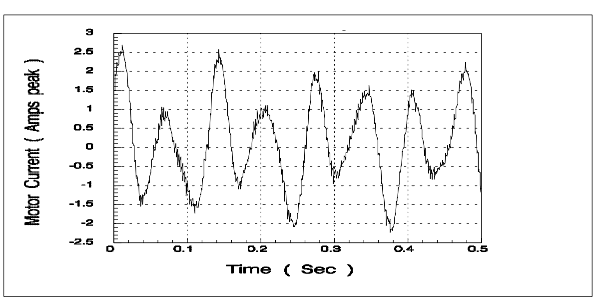


Fig. 13. Voltage Feedback Type Compensation Method Controlling a Synchronous Reluctance Motor.

Examining the voltage vector for no compensation shows decreased fundamental voltage and a phase shift toward the d-axis. The resultant phase shift and loss of magnitude is directly related to the loss or gain in pulse time of the applied voltage.

The AV method applies the largest voltage magnitude, but the phase shift is greater than with no compensation. The increased voltage magnitude does not guarantee stable operation as explained above. Waveform correction is achieved by gain and phase adjustment of the reference wave based on the carrier period, dead time, and bus voltage. Due to the approximation inherent in this method, an error occurs in the applied voltage as shown. The inability to apply the voltage vector to the q-axis and the resulting phase shift in the applied voltage is the reason this and other types of next pulse based methods have difficulty in providing stable operation to low impedance or high voltage motors. In addition, the larger voltage applied increases the flux and losses within the machine.

The CR Pulse Based method provides good waveform correction, but due to the delay in the pulse position of one-half the dead time value, results a magnitude error and phase shift in the applied fundamental voltage. Even this small pulse position shift can result in unstable operation with low impedance or higher voltage motors.

Finally, the TCR Pulse Based method applies all the voltage in the q-axis with no phase shift. The unique

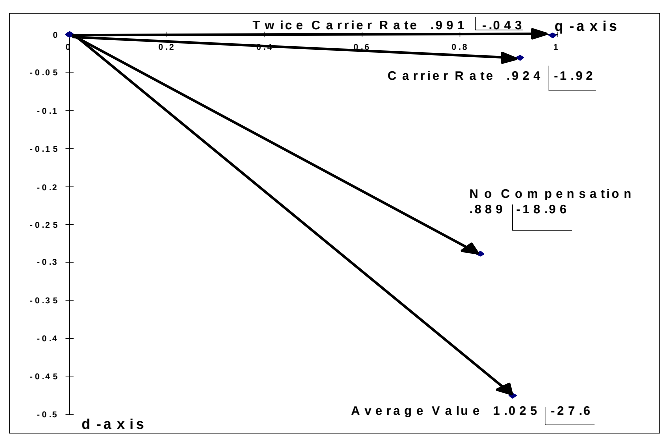


Fig. 15. Fundamental Voltage Vector Comparison of Compensation Methods.

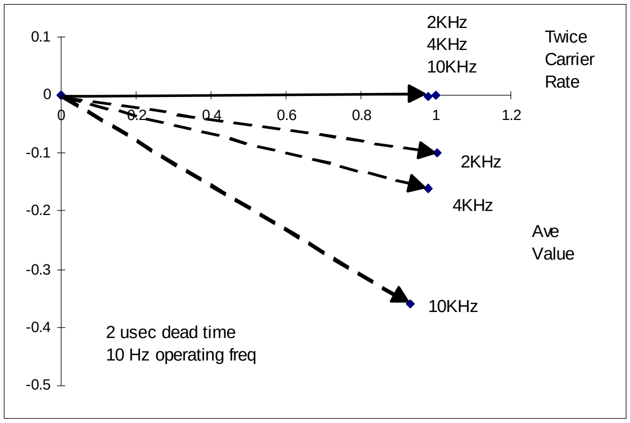


Fig 16. Comparison of Pulse Based and Average Value methods for varied carrier frequencies.

characteristic of the pulse by pulse correction insures the correct voltage is applied. Stable operation is then achieved with both the ac induction and low impedance ac machines.

Fig. 16 compares the fundamental output voltage vectors for the TCR Pulse Based and AV methods at varied frequencies of 2K, 4K, and 10K Hz. Dead time, reference voltage, and operating frequency are fixed for each carrier frequency. The TCR Pulse Based method shows the fundamental voltage is applied to the q-axis without phase shift for each carrier frequency. The AV method shows the fundamental voltage with the correct magnitude, but has increasing phase shift toward the d-axis for each carrier frequency.

VIII. Conclusions

The results presented in this paper demonstrate the ability of the Pulse Based Dead Time Compensation Method to provide stable operation for ac induction, synchronous reluctance, or other low impedance motors. Correction on a pulse by pulse bases provides the most optimum correction and corrects each pulse accordingly. Simulation and experimental results demonstrate the proposed method's accuracy and ability to maintain the correct magnitude and phase for the applied fundamental voltage. The method is independent of operating frequency, carrier frequencies, and the load. Furthermore, the technique is compatible with digital open or closed loop control and is independent of the ac machine and PWM modulator.

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