A New Dead-time Compensation Method Based on LMS Algorithm for PMSM

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Abstract. This paper presents a new dead-time compensation method for permanent-magnet synchronous motor (PMSM) at low speed. Based on least-mean-square (LMS) algorithm and combined with the traditional average voltage compensation method, the proposed method can determine the current polarity through extracting the fundamental current. Compared with traditional compensation methods, the proposed method can detect current polarity more accurately at low speed due to the narrower notch bandwidth. Moreover, this method is robust to motor parameters and easy to implement. The proposed method is simulated in a voltage-source inverter PMSM drive controlled by I/F and the results show that it meets the requirement of dead-time compensation and eliminates the influence of dead-time effect.

1. Introduction
Pulse width modulation (PWM) type converters are widely used in various motor control applications. To prevent short-circuits between the upper and lower switches of power converters from over-current protection, the dead time is mandatory in the switching gating signal for voltage source converters. Dead-time and on/off delay introduce output voltage and current distortions, zero-current-clamping phenomenon, and output fundamental-frequency voltage reduction [1].

The existence of dead time has an impact on voltage, current and torque, especially at low frequency, because there are more switching times in a cycle at low frequency under the same carrier wave. In the literature, compensation based on the average voltage theory is widely analyzed and applied, which need to calculate the effective voltage loss of each switching cycle and compensate according to the polarity of the current [2]. As a matter of fact, many literatures use a lot of complex algorithms or improve the performance of hardware to get accurate current polarity [3]. Kalman filter is used to reconstruct the base phase current, which improves the accuracy of polarity detection, and requires additional circuits to measure the output voltage of the inverter [4].

In this paper, a new dead-time compensation method based on the least-mean-square (LMS) algorithm is proposed. The polarity of the current is determined by extracting the fundamental wave of the feedback current, so as to accurately compensate the dead-time loss voltage. Compared with the compensation method based on average theory and disturbance observer, LMS algorithm has online adaptive ability and strong robustness to parameter changes.

2. Dead-time effects analysis
For the three-phase voltage source inverter circuit connected with the motor using the driving power semiconductor device, the current direction is defined as positive if the current flows from inverter to motor shown in Figure 1. In addition, the waveform of output voltage changing with the switch signal is shown in the figure. shown in Figure 2.
The voltage error $\Delta V_{dt}$ caused by dead time and switch delay in a switching cycle can be expressed as in (1). It can be seen that the positive and negative values are determined by the current direction.

$$\Delta V_{dt} = V_{\text{dead}} \text{sign}(i_a)$$  \hspace{1cm} (1)

$V_{\text{dead}}$ is defined as

$$V_{\text{dead}} = -\frac{T_{\text{dead}} + T_{\text{on}} - T_{\text{off}}}{T_{\text{pwm}}} (V_d - V_{\text{sat}} + V_{\text{Diode}}) - \frac{V_{\text{sat}} + V_{\text{Diode}}}{2}$$  \hspace{1cm} (2)

Where $T_{\text{dead}}$, $T_{\text{on}}$, $T_{\text{off}}$, $T_{\text{pwm}}$, and $V_d$ are dead-time, turn-on time, turn-off time, switching period, and dc bus voltage, respectively. $V_d$ is the dc bus voltage. $V_{\text{sat}}$ and $V_{\text{Diode}}$ denote switch saturation voltage and diode forward voltage. The sign function can be expressed as

$$\text{sign}(i_a) = \begin{cases} -1 & i_a < 0 \\ +1 & i_a > 0 \end{cases}$$  \hspace{1cm} (3)

From the previous derivation, it can be known that the voltage loss is theoretically a certain value. The polarity of error voltage depends on the polarity of the current. Therefore, it is very important to determine the current polarity accurately for dead time compensation.

The dead-time can also cause zero-current-clamping phenomenon. Zero current clamping effect refers that when the absolute value of current is close to zero, the current will be forced to stay at zero for a period of time, whether from positive to negative or from negative to positive. This phenomenon is due to the reverse voltage of semiconductor switching devices [5]. Therefore, the voltage source converter must be compensated for eliminating the negative effect by dead time especially at low frequency.
3. Proposed dead-time compensation method

3.1. LMS Algorithm

The purpose of the LMS algorithm is to obtain the computational coefficients for the next iteration from the error returned by the feedback. After enough iterations, the LMS algorithm can extract or eliminate signals of a given frequency from the input signal.

As shown in Fig. 4, a single-frequency signal extraction method is constituted by using the LMS algorithm. K is the number of iterations and T is the sampling time. \( x_1 \) and \( x_2 \) are given reference inputs which are sinusoidal with the certain frequency of \( \omega \). And \( \omega \) represents the center frequency of the eliminator or extractor. It can be seen that \( x_1 \) and \( x_2 \) have a \( \pi/2 \) phase shift. As a result, through \( x_1 \) and \( x_2 \) times respective corresponding weight factors \( w_1 \) and \( w_2 \), all sinusoidal signal \( y \) with the certain frequency of \( \omega \) can be synthesized. This algorithm is generally implemented in digital software after discretization.

\[
\begin{align*}
\cos(\omega kT) & \quad \text{d}(k) \\
x_1(k) & \quad w_1(k) \\
x_2(k) & \quad w_2(k) \\
y(k) & \quad \text{LMS} \\
\end{align*}
\]

**Figure 4.** Schematic structure of the certain frequency LMS algorithm

The LMS algorithm can be expressed as in (4) ~ (6). In (6), \( \mu \) is the iteration rate, which refers to the convergence rate and the notch width. Figure 5 shows that the smaller \( \mu \) means slower convergence speed but narrower notch width. Based on the control block diagram, the transfer function from \( \varepsilon \) to \( y \) can be derived in z-domain as shown in (7).

\[
\begin{align*}
x_1(k) &= \cos(\omega_0 k T) \\
x_2(k) &= \sin(\omega_0 k T + \pi / 2) \\
y(k) &= w_1(k) x_1(k) + w_2(k) x_2(k) \\
w_1(k+1) &= w_1(k) + 2 \mu \varepsilon(k) x_1(k) \\
w_2(k+1) &= w_2(k) + 2 \mu \varepsilon(k) x_2(k) \\
G(z) &= \frac{2 \mu (z \cos \omega_0 T - 1)}{z^2 - 2z \cos \omega_0 T + 1}
\end{align*}
\]
3.1.1. Theory of the Proposed Method

The schematic structure of the proposed compensation method is shown in the figure 6. The LMS algorithm extracts the fundamental wave of the three-phase feedback current as shown in Figure 7, which is a smooth sinusoidal wave without harmonic distortion and zero-crossing clamping effect. Therefore, the extracted fundamental wave can be used to accurately judge the current polarity. Combined with polarity, the calculated compensation voltage is added to the modulated sine wave. After the compensated modulation wave and the triangular carrier pass through the comparator, the switching signal is obtained and input to the inverter.

3.2. Considerations of Learning Rate $\mu$

In the LMS algorithm, the choice of learning rate $\mu$ is critical to the extraction effect especially at low speeds. The determination of the learning rate must ensure a certain convergence speed and a sufficiently small bandwidth to allow only the fundamental wave to pass. If $\mu$ is set too high, the extracted
fundamental current contains harmonics such as the fifth harmonic and the seventh harmonic as shown in Figure 8. If $\mu$ is set too low, the convergence speed is too slow to track the waveform in time as shown in Figure 9.

![Figure 8. Extracted current with high $\mu$](image)

![Figure 9. Extracted current with low $\mu$](image)

### 4. Simulation results

In order to verify the effectiveness of the method proposed in this paper, a surface-mounted PMSM vector control model was built in MATLAB/Simulink. The control method adopts I/F control, and then the LMS algorithm and average voltage compensation module are added to the simulation. The given speed is 1Hz, and the dead time is set to 2us.

In the simulation, the phase current waveform without dead-time compensation is shown in the Figure 10. The current waveform has obvious distortion, especially when the current crosses the zero point, there is a serious current clamping effect. The phase current waveform with dead-time compensation is shown in the Figure 11.

![Figure 10. Phase current waveform without dead-time compensation](image)

![Figure 11. Phase current waveform with dead-time compensation](image)
The current waveform before and after compensation is analyzed by FFT as shown in Figure 12 and Figure 13. It can be clearly seen that the current harmonics are fully suppressed, and the total harmonic distortion is reduced from 11.95% to 0.40%.

5. Conclusions
In this paper, a new dead-time compensation method based on the least-mean-square (LMS) algorithm is presented for PMSM at low speed. The polarity of the current is determined by extracting the fundamental wave of the feedback current, so as to accurately compensate the dead-time loss voltage due to the narrower notch bandwidth. The proposed method is simulated in a voltage-source inverter PMSM drive controlled by I/F and the results show that the total harmonic distortion is reduced from 11.95% to 0.40% and it meets the requirement of dead-time compensation.

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