Inverter Dead Time Compensation Method using On-Line tuning

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In this paper, a method for dead time voltage compensation is proposed. The dead time is a period for preventing short circuits in the semiconductor power devices incorporated in inverters. Owing to this dead time, an error occurs in the output voltage of the inverter with respect to the voltage command. To suppress this error, a dead time compensation signal is generally added to the voltage command. However, the accuracy of the above-mentioned compensation control may be reduced because of the switching characteristics of the power device, transmission delay of the switching command, and so on. In the proposed method, to achieve highly accurate dead time compensation, the waveform of the compensation signal is formed based on a circuit model that assumes a virtual capacitor is connected to the semiconductor power device in parallel. In addition, an automatic adjustment method was proposed for parameters such as the capacitance of the virtual capacitor. The proposed method is validated experimentally.

Keywords: inverter, dead time voltage, compensation, control

1. Introduction

This paper reports on how to improve the compensation accuracy of dead time compensation for PWM inverters.

When controlling a PWM inverter, the dead time inserted to prevent cross-conduction of the power element causes a disturbance in the inverter output voltage. It is known that when this disturbance voltage is time-averaged with a period approximately equal to the carrier frequency, its voltage shape is a square wave with a polarity opposite to the polarity of the motor current, and its amplitude is the product of the dead time length T_d , the carrier frequency f_c , and the inverter DC voltage V_{dc} . Henceforth, we will refer to this disturbance voltage caused by dead time as “dead time voltage”. As a countermeasure against this dead time voltage, a process called “dead time compensation”, in which a square-wave compensation voltage of the opposite polarity to the dead-time voltage is added in advance to the voltage command, is widely used⁽¹⁾.

Although the theory of dead-time compensation is well-established, it is built on the premise that the power device operates instantaneously without delay in response to a switching command. However, in some cases, the compensation accuracy can be reduced due to factors such as the switching characteristics of the power element or transmission delays in the insulating element when transmitting a

switching command to the power element, which can cause changes in the dead time voltage shape generated by the inverter. Specifically, a change in amplitude occurs in the dead time voltage square wave. Furthermore, even for the same voltage, the shape of the end of the square wave may vary, resulting in a trapezoidal shape with a certain slope. In addition, the current zero clamping phenomenon⁽²⁾⁽³⁾, which is generated by a principle different from the above phenomenon, is also known. Under this phenomenon, the current is clamped near zero by a combination of current ripple caused by PWM and the nonlinear behavior of the reflux diodes connected in parallel to the power element. This changes the shape of the end of the dead time voltage, reducing the accuracy of the dead time compensation.

There have been various studies of countermeasures against this decrease in dead time compensation accuracy. As noted above, the dead time voltage is based on a square wave, but the shape can change due to various factors. Therefore, many methods have been proposed to adjust the shape of the waveform while assuming a square wave shape for the dead-time compensation voltage. Specifically, there have been proposals to adjust the dead time amplitude^{(4)–(7)} and to adjust the shape of the end of the dead time compensation voltage⁽⁸⁾⁽⁹⁾. In addition, a method to extract the dead time voltage shape directly using a disturbance observer has been proposed. With respect to the former adjustment approach, an off-line pre-tuning technique has been proposed that simultaneously adjusts both the amplitude and the shape of the end of the dead time compensation voltage⁽¹⁰⁾. However, as far as we can tell, the method was not fully developed, and more study is required. The latter approach, based on the disturbance observer, does not require determining the shape (structure) of the dead time voltage in advance, but it does require precise motor parameters, and the design of the control system is complicated.

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Given the above considerations, this paper also adopts a dead time voltage model that allows parameter representation of both the amplitude and end shape of the dead time voltage while assuming that the dead time voltage has a square wave shape as an average value for each carrier period. Furthermore, our proposed method builds a dead time compensation voltage model that changes the structure slightly from the dead time voltage model described above, taking into account the ease of parameter tuning and implementation.

In addition, we investigate how to carry out simultaneous on-line tuning of the parameters representing the amplitude and end shape while performing dead time compensation based on the dead time compensation voltage model. Finally, we report the results of validation of the method on actual equipment.

The structure of this paper is described below. In Section 2, we analyze the actual measured waveform of the inverter output voltage to derive a dead time voltage model. Next, Section 3 describes the dead time compensation voltage model and our parameter tuning method, which focuses on the distortion of the motor current caused by dead time compensation errors. Section 4 reports the results of validation of our method on actual equipment, and Section 5 summarizes our results.

2. Dead Time Voltage Model

This section describes the dead time voltage model used in this paper. Figure 1 shows the terminal voltage waveforms (U-N, positive output current polarity) of a 200 V inverter measured at different current magnitudes. The shape of the voltage waveform on the fall side, where the terminal voltage decreases, changes in a complicated manner. Figure 2 shows the average voltage error values in the waveform shown in Fig. 1 calculated with respect to the ideal output voltage, excluding the delay in transmission of the switching command. Although the terminal voltage shape changes over time in complex ways, it can be seen that the smaller the current, the greater the voltage error, especially on the fall side where the terminal voltage drops. This phenomenon, which has been observed in the literature⁽¹¹⁾, is presumably caused by the switching characteristics of the power element. Another phenomenon that has been reported to cause similar changes in the shape of the inverter output terminal voltage waveform is the charging and discharging activity of parasitic capacitors connected in parallel to the power element⁽¹²⁾. Although these two phenomena are generated by different principles, what they have in common is they both cause a deviation from the theoretical square wave dead-time voltage when averaged over the carrier period, and the smaller the current at the moment of switching, the greater the deviation.

One proposed method uses a sigmoid function as a model for expressing dead time voltage waveforms at small currents such as those in Fig. 2⁽⁹⁾. However, the calculation of the sigmoid function itself is somewhat complicated in practice. Therefore, in this paper, we adopt the parasitic capacitance model mentioned above. This is a simple mathematical model that comprehensively captures the changes in the shape of the inverter output terminal voltage waveform caused not only by the charging and discharging activity of parasitic capacitors but also by the switching characteristics

Fig. 1. Measurement result of inverter output voltage waveform

Fig. 2. Measurement result of inverter voltage error

Fig. 3. Pattern diagram of output voltage error

of the power element. In this paper, the parasitic capacitance in the model is treated as a virtual element. The value of this virtual parasitic capacitance is a parameter for controlling the end shape in the dead time voltage model.

Figure 1 also shows a delay in the start of the terminal voltage in response to the logic signal switching command. Figure 3 is a schematic diagram that includes the switching signal delay described above. Figure 3(b) shows the ideal

Fig. 4. Parasitic capacitance circuit model

output voltage assuming that the pin voltage changes instantaneously in response to the logic signal P/N switching command shown in Fig. 3(a) and assuming that there is no dead time. The voltage shape shown in Fig. 3(c) reflects the dead time, signal delay, switching characteristics, and so on. The delay on the rise side of the terminal voltage is labeled T_{dr} , and the delay on the fall side is labeled T_{df} . As a result, the voltage error shown in Fig. 3(d) is generated with respect to the ideal voltage shape in Fig. 3(b). In Fig. 3(d), five regions in the error voltage waveform are identified and labeled 1 to 5. The area S_1 to S_5 of each region is the product of the corresponding time and the inverter DC voltage V_{dc} , except in the case of S_3 and S_5 .

Here, S_3 and S_5 , which depend on the switching characteristics of the power element, are collectively represented in the aforementioned parasitic capacitance model. Figure 4(a) illustrates the parasitic capacitance model for one phase. For example, when the capacitor on the lower arm is charged and the current starts as positive, the terminal voltage changes as shown in Fig. 4(b), and the area S_6 is given by Equation (1). Here, C is the virtual parasitic capacitance value, V_{dc} is the DC voltage of the inverter, and i is the current. As we discuss below, Equation (1) assumes that termination occurs within the charge/discharge dead time section of the parasitic capacitor.

$$S_6 = \frac{C \cdot V_{dc}^2}{i} \dots \dots \dots (1)$$

Using this method, the error voltage waveform areas S_3 and S_5 in Fig. 3(d) are collectively represented by Equation (2), taking into account the sign (positive or negative).

$$S_5 - S_3 = \frac{C \cdot V_{dc}^2}{i} \dots \dots \dots (2)$$

The area S_7 defined in Equation (3) is the sum of the areas S_1 , S_2 , S_3 , S_4 , and S_5 of the error voltage waveforms described in Fig. 3(d) above, taking into account their polarities.

$$S_7 = -S_1 - S_2 - S_3 + S_4 + S_5 \\ = -(T_d + T_{dr} - T_{df}) \cdot V_{dc} + \frac{C \cdot V_{dc}^2}{i} \dots \dots \dots (3)$$

The dead time voltage is obtained by dividing this area S_7 by the carrier section as shown in Equation (4). Here, f_c is the carrier frequency.

$$V_{td} = -(T_d + T_{dr} - T_{df}) \cdot f_c \cdot V_{dc} + \frac{C \cdot f_c \cdot V_{dc}^2}{i} \dots \dots \dots (4)$$

The first term of Equation (4), which is equivalent to the

change in dead time, can be represented by a single coefficient α . This is shown in Equation (5).

$$V_{td} = -\alpha \cdot T_d \cdot f_c \cdot V_{dc} + \frac{C \cdot f_c \cdot V_{dc}^2}{i} \dots \dots \dots (5)$$

Equation (5) above serves as the dead time voltage model. In Equation (5), α is the parameter for amplitude adjustment, and the parasitic capacitance C is the parameter for edge shape adjustment.

3. Dead Time Compensation Method

3.1 Dead Time Compensation Voltage Model Dead time compensation can be performed by calculating the dead-time voltage using Equation (5) from the preceding section and adding it in reverse polarity to the voltage command. However, the second term of Equation (5) contains the reciprocal of the current, which may become excessive or discontinuous near a current of zero, making it difficult to implement. A method proposed to address this problem is to switch equations based on a threshold current to ensure that the maximum charge-discharge section of the parasitic capacitance never exceeds the dead time section⁽¹²⁾. However, it is also necessary to consider the ease of on-line tuning of the parameters of the dead-time voltage model, as we discuss later in Section 3.3. Based on these considerations, in the proposed method, we use the dead time compensation voltage model defined in Equations (6) and (7) based on the dead time voltage model in Equation (5). This is equivalent to shifting the second term of Equation (5) relative to the current i as illustrated in Fig. 5.

$$V_{td} = -\alpha \cdot T_d \cdot f_c \cdot V_{dc} + \frac{C \cdot f_c \cdot V_{dc}^2}{i + i_x} \dots \dots \dots (6)$$

$$i_x = \frac{C \cdot V_{dc}}{\alpha \cdot T_d} \dots \dots \dots (7)$$

By rearranging Equation (6) according to the polarity of current, we obtain Equation (8), which is a relatively simple equation to calculate.

$$V_{tdcomp} = \begin{cases} \alpha \cdot T_d \cdot f_c \cdot V_{dc} - \frac{C \cdot f_c \cdot V_{dc}^2}{i + i_x} & (i \geq 0) \\ -\alpha \cdot T_d \cdot f_c \cdot V_{dc} - \frac{C \cdot f_c \cdot V_{dc}^2}{i - i_x} & (i < 0) \end{cases} \dots \dots \dots (8)$$

In this paper, dead time compensation is carried out using this equation. Examples of dead time compensation voltage waveforms based on Equation (8) are shown in the middle parts of Figs. 6(a) and (b). The amplitude of the compensation voltage increases or decreases as Parameter α increases or decreases. As Parameter C decreases, the shape of the wave is closer to a square wave, but as C increases, the shape

Fig. 5. Transformation of exp. (5)

Fig. 6. Example of dead time compensation voltage using exp. (8)

Fig. 7. Control block diagram and signal waveform

of the wave becomes more rounded at the edges. As mentioned above, the value of α is mainly due to the transmission delay time of the insulating element. In general, we assume that an element with a certain degree of dead time is selected, so the value of α will be close to 1. The value of C is difficult to state in a general way, since it is affected by the characteristics of the power module and the current zero clamp phenomenon. However, in the experimental validation on actual equipment described in this paper, it was a value on the order of nF.

3.2 Basic Principles of Parameter Tuning This section describes our method of tuning the parameters of the dead time compensation voltage expressed in Equation (8). Both the dead time compensation voltage and the dead time voltage are composed of fundamental wave components synchronized with the phase current and harmonic components. The parameters α and C of the dead time compensation voltage change the magnitude of the harmonic components as well as the fundamental wave components in the compensation voltage.

Unless both parameters are properly tuned, the dead time compensation error voltage will also contain harmonic components, causing pulsations in the current. The proposed

method takes advantage of this by feeding back the current and tuning the parameters so that these current pulsations are minimized.

However, noise in the detected current interferes with the tuning of the parameters. Therefore, we take the following measures. As mentioned above, the dead time compensation voltage and dead time voltage are synchronized to the phase current, so the current pulsations mentioned above are most prominent in directions orthogonal to the current vector on the dq axis rotation coordinates. The proposed method takes advantage of this to tune the parameters of components orthogonal to the current vector. In addition, the dead-time compensation voltage waveform itself is used as a reference signal for the detection processing to identify when the parameters are too high or too low. This arrangement is depicted in the block diagram in Fig. 7. Components orthogonal to the current vector are obtained by applying a low-pass filter to the dq axis current on the rotational coordinates, converting it to current phase θ_i , and using θ_i to performing the coordinate conversion. As a result, the dead time compensation voltage becomes a sawtooth wave signal as shown in the lower part of Figs. 6(a) and (b), and this is used as the reference signal. Integrator 1 shown in Fig. 7, which is used to

Fig. 8. Timing chart of integrator 2 in Fig. 7

tune Parameter α , operates at all times. On the other hand, Integrator 2, which is used to tune Parameter C, which controls the end shape and is sensitive near the current zero crossing, has the limited operating section shown in Fig. 8.

As the figure shows, Integrator 2 is operated when the absolute value of the phase current is within the threshold value, which is set to 4 times the value of i_x in Equation (7). Details on the operating section of integrator 2 are given in the appendix. In order to extract the current pulsation components in the orthogonal direction of the current vector, it is necessary to eliminate the effects of the components in the calculation of the current phase θ_i . Since the current pulsation caused by the dead time voltage has 6 times the fundamental frequency component on the rotational coordinates, we set the cut-off frequency fLPF of the low-pass filter for the dq-axis current to 3 times the frequency command f^* . Here we further describe the initial values of the parameters α and C. We set the value of α to 1 since it is expected to converge to a value close to 1 as described in Section 3.1. Since C is affected by the terminal voltage waveform of the inverter, we calculated C based on the waveform data from the inverter, which we set to 0.5 [nF] in the actual test described in Chapter 4. Details are also provided in the appendix.

3.3 Interference During Parameter Tuning This section discusses interference during parameter tuning. Since the reference signal for the detection processing during parameter tuning is calculated based on the dead-time compensation voltage signal, the amplitude of the sawtooth reference signal increases or decreases along with the increase or decrease of Parameter α , as shown in Fig. 6(a). On the other hand, as shown in the lower parts of Fig. 6(b), modifying Parameter C changes the sharpness of the saw shape of the reference signal as desired, but also changes to the amplitude of the reference signal, which is undesirable. In other words, there can be interference between the tuning of Parameter C and the tuning of Parameter α in our proposed method. As noted in Section 3.1, the value of Parameter C varies greatly depending on the system to which it is applied, so fluctuations from the initial value are expected in the process of on-line tuning. What we need, therefore, is a way to minimize the influence of Parameter C on the tuning of Parameter α and its results.

Based on this perspective, we compared the degree of interference between the parameters α and C in our proposed method and in another dead time compensation voltage model described in Ref. (13). Since Ref. (13) did not use the concept of amplitude adjustment, here we adopt Parameter α

 Fig. 9. Tuning interference between α and C

as the coefficient for the entire dead time compensation equation.

Reference (13) provides dead time voltage models for each commutation mode. However, we can express the dead time compensation voltage models in Ref. (13) in Equation (9) and (10) by taking their sum and convert them to a voltage error for each carrier period. Examples of dead time compensation voltage waveforms using both equations are shown in Figs. 6(c) and (d).

$$V_{dcmp} = \begin{cases} \alpha \left(T_d \cdot f_c \cdot V_{dc} - \frac{C \cdot f_c \cdot V_{dc}^2}{i} \right) & (i \geq i_{th}) \\ \alpha \left(\frac{T_d^2 \cdot f_c}{4C} \right) i & (|i| < i_{th}) \\ \alpha \left(-T_d \cdot f_c \cdot V_{dc} + \frac{C \cdot f_c \cdot V_{dc}^2}{i} \right) & (i \leq -i_{th}) \end{cases} \quad \dots \dots \dots (9)$$

$$i_{th} = \frac{2C \cdot V_{dc}}{T_d} \quad \dots \dots \dots (10)$$

The lower part of Fig. 9 shows the results of calculating the values of Parameter α that generate the same fluctuations in amplitude as Parameter C when the reference signal for detection is generated using the conventional method in Ref. (13) and our proposed method. Figure 9 shows that compared to the conventional method, our proposed method minimizes the change in Parameter α relative to Parameter C. As an example, the upper part of Fig. 9 shows the waveform when C changes from 1.0 [nF] to 2.5 [nF]. The original reference signal has an α of 1.0, but in the conventional method, α equals 0.59. On the other hand, in our proposed method, it is around

Fig. 10. Experimental results using the proposed method during V/f control operation

0.79. This suggests that our proposed dead time compensation voltage model is more suitable for simultaneous tuning of amplitude and end shape, since it minimizes the interference when tuning both parameters simultaneously.

4. Experiment

4.1 Experimental Conditions This section describes the experimental conditions under which we validated our proposed method on actual equipment. To validate our proposed method, we added it to the V/F control system of an induction machine. If the parameters of the dead time compensation voltage model are poorly tuned, the current will contain pulsation, and if this current is used to calculate the dead time compensation voltage, the reference signal used in the detection processing for on-line parameter tuning will also contain distortion, and the parameter tuning will not work well. We therefore calculate the dead time compensation voltage using a reconstructed current after suppressing the pulsation by applying LPF processing on the rotation coordinates^{(13)–(15)}. Details on this processing and automatic parameter tuning are shown in Fig. 7. Other experimental conditions are listed in Table 1. The values of adjustment gains K_1 and K_2 were set by preliminary tests and simulations to determine the values that eliminated oscillations in the current and the signal in the control system.

4.2 Experimental Results Figure 10 shows the experimental results of the application of the proposed method. In order to verify the effect of dead time voltage compensation under the proposed method, we compensated the ON-state voltage separately. As the figure shows, we were able to obtain convergence of both α and C by running the on-line tuning mechanism shown in Fig. 7 starting at time 7 [sec] with the initial values set to $\alpha = 1.0$ and $C = 0.5$ [nF]. Further,

Table 1. Experimental sonditions

Parameter	Value	Unit
Carrier Frequency(f_c)	10	[kHz]
DC Bus Voltage(V_{dc})	301	[V]
Dead Time(T_d)	3	[μ sec]
Motor rated power	3.7	[kW]
Motor pole number	4	[-]
Adjustment gain K_1	-0.31	[-]
Adjustment gain K_2	3.1×10^{-8}	[-]

when the parameters converge, the pulsations in the detected speed are significantly suppressed. There is also a decrease in the error in the U-phase output voltage of the inverter as the parameters converge, but a slight sinusoidal error remains. This voltage error, which will be addressed below, is the result of the proposed algorithm detecting the characteristic shape of the square wave dead time voltage error and implementing the adjustment.

Figure 11 shows the results obtained when varying the frequency command, including the convergence of the two parameters and the suppression of the pulsations in the detected speed. The figure also shows the results of analyzing the error components of the U-phase voltage before and after the on-line tuning of the parameters, starting with the first-order fundamental frequency component (plotted at 0.1x). The 5th and 7th order frequency components in particular, which are often included in the dead time voltage, are significantly suppressed. On the other hand, the 13th order component shows a slight increase after on-line tuning. This is presumably one of the dead time voltage components generated by the inverter that cannot be expressed in our proposed dead time compensation voltage model. Figure 11 also shows the harmonic RMS values up to the 50th order (plotted at 0.25x),

Fig. 11. Experimental results using the proposed method during V/f control operation and Analysis result of U-Phase voltage error

which are also suppressed by the parameter tuning. Taken together, these results show that we were able to validate the operation of the proposed system, although under limited conditions.

5. Summary

In this paper, a dead time compensation method is proposed using a dead time compensation voltage model with parameters to represent amplitude and slope, which can be represented by relatively simple equations. The proposed model is based on the parasitic capacitance model, which is able to capture the phenomenon that the dead time voltage becomes smaller as the current becomes smaller due to the switching characteristics of the power element near the current zero crossing, although we introduced certain modifications to avoid zero division and facilitate parameter tuning. We proposed an automatic adjustment method that performs on-line tuning of the two parameters simultaneously from the current pulsation information and validated the method experimentally. In the future, we plan to investigate further improvement of the inverter voltage accuracy, establish a design method for the integrator gain for parameter tuning, confirm its stability, and improve the reliability of the algorithm by applying it to drive systems consisting of other inverters and motors.

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Appendix

1. Operation of Integrator 2 for Tuning Parameter C

Integrator 2 needs to operate near the end of the dead time compensation voltage (that is, near the current zero crossing) for Parameter C adjustment, but it is difficult to identify the end based on the geometry of the compensation voltage. Accordingly, for this paper, we define the end as the section in which the instantaneous signal of the dead-time compensation signal is within a given range of amplitude equivalents. This makes it possible to expand and contract the section over which Integrator 2 operates depending on the C -value held by the controller at that moment. In this paper, this is achieved by setting the aforementioned range to 80[%] and the threshold of operation to $4 \cdot i_x$.

Modifying the dead time compensation voltage Equation (8) from Section 3.1, we obtain Equation (A1).

$$V_{idcmp} = \begin{cases} \alpha \cdot T_d \cdot f_c \cdot V_{dc} \cdot \left(\frac{i}{i + i_x} \right) & (i \geq 0) \\ -\alpha \cdot T_d \cdot f_c \cdot V_{dc} \cdot \left(\frac{i}{i - i_x} \right) & (i < 0) \end{cases} \dots\dots\dots (A1)$$

where (A1) is the product of two parts: $\alpha \cdot T_d \cdot f_c \cdot V_{dc}$, which represents the amplitude, and $i/(i \pm i_x)$, which represents the shape. Here, we denote the latter signal Y . We can be set 80[%] as the threshold by substituting $\pm 4 \cdot i_x$ for the variable i in the current in this signal Y , yielding $\pm 4/5$. An example of calculating the signal Y is shown in app. Fig. 1. The operating section of Integrator 2 can be specified according to the change in the end shape due to Parameter C .

2. ON-state Voltage Compensation

During the validation on actual equipment described in Section 4, we carried out the ON-state voltage compensation separately using the table depicted in app. Fig. 2 in order to improve the verification accuracy of the proposed dead time compensation signal structure and parameter tuning method. The data is read by performing linear interpolation with the phase current value as an argument, and a sign corresponding to the polarity of the phase current is added to the voltage command.

3. Initial Setting of Parameter C

Here we explain how we set the initial value of Parameter C in the validation on actual equipment described in Section 4. This parameter expresses the voltage error that accompanies the changes in the inverter terminal voltage waveform shown in Fig. 2 in Section 2, so the initial value is converted from the data shown in Fig. 2. Let V_e denote the voltage error data shown in the figure (gray plot). V_e can be calculated as shown in Equation (A2), which is obtained by multiplying the carrier frequency f_c by the equation indicating the area of the error voltage waveform in Equation (1).

$$V_e = f_c \cdot \frac{C \cdot V_{dc}^2}{i} \dots\dots\dots (A2)$$

The reverse calculation value of C using Equation (A2) is

app. Fig. 1. Calculation result signal Y

app. Fig. 2. On-drop Voltage [V]

app. Fig. 3. Reverse calculation result of C

shown in app. Fig. 3. In the figure, the values range from 0 to 2 [nF] depending on the phase current value at the moment of switching. In light of the above results, the initial value of Parameter C was set to 0.5 [nF] for the validation on actual equipment described in Section 4.

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