Identification of a permanent magnet synchronous motor system with dead-zone characteristics

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Abstract: - An off-line identification method based on the least-squares approximation technique is applied for identifying electric parameters of a servo drive model and PWM inverter. Because of the nonlinearity introduced by the dead time, turn-on/off delay, snubber circuit and voltage drop across power devices, the output voltage of voltage-source inverters is distorted seriously in the low output voltage region. This distortion seriously influences identification results. In this paper, the proposed identification method takes into account the influence of “dead time”. Also, permanent magnet synchronous motor (PMSM) model with PWM inverter is proposed. It allows estimating the effect of nonlinearities on the servo drive accuracy features, and is important for the synthesis of parameter identification algorithms and for the fault diagnosis. The paper provides experimental results of identification algorithm work.

Key-Words: - Identification; Servo Drive; “Dead Time” Effect; Voltage Drop of Power Devices, PWM inverter; Least-Squares Approximation.

1 Introduction

In recent years, due to the development of high speed switching devices such as power transistors and insulated gate bipolar transistors (IGBTs), pulse width modulated (PWM) voltage source inverters (VSIs) are widely used in adjustable speed motor drives.

In a PWM VSI, since a switching device has finite switching times—turn-on time and turn-off time, a dead time should be considered in a PWM gate signal in order to prevent the simultaneous conduction of two switching devices in each leg of the inverter. Since both switching devices in each leg are off during the dead time and the output voltage is dependent on the direction of an output current, these cause a distortion of the inverter output voltage, which is called as “dead-time effects” [1]. The distortion of the inverter output voltage affects machine currents, which results in a...
phase current distortion, torque pulsations, and degradations of control performance [2]–[8].

Several methods have been presented to deal with the dead-time issue. These methods include dead-time compensation [9]–[16] and dead-time minimization [17]–[20]. Most of the dead-time compensation methods are developed based upon the knowledge of current polarities. The key challenges of these methods are the correct calculation of the compensation voltage and the accurate detection of the zero current crossing, based on accurate estimation of “dead time”.

For the dead-time minimization method, dead time is still required when the current is around zero-crossing points in which current polarity detection is difficult and not accurate. Therefore, the dead-time effect cannot be completely removed under this circumstance. So in this case, the problem of estimation of “dead time” remains relevant.

In the articles, however, the problem of identification of the delay and electrical parameters of the motor with influence “dead time effect” is not considered. In this paper, we propose a motor model with an inverter and “dead time effect”, which allows investigating the influence of the “dead time” not only on the accuracy of management [21], but also on the accuracy of parameter identification and diagnosis [22]. Algorithms of delay identification and motor parameters identification with the influence of “dead time” are proposed.

2 Problem Formulation

2.1 Analysis of dead time effect

Fig. 1 shows a diagram of a three-phase inverter with pulse-width modulation (PWM), widely used to control AC machine drive. As is well known, because of the finite turn-off time of the switching devices, a time delay has to be imposed between the turn-off command of a switching device in a leg of an inverter, and the corresponding turn-on command of the other switching device in the same leg. This delay time is denoted as “dead time”.

During the "dead time" output voltage is determined by the direction of current flow (Fig. 2).

\[
U_{\text{mean}} = \left( \gamma_h - \frac{1}{2} - \tau \cdot \text{sign}(i) \right) U_{DC},
\]

where

\[
\text{sign}(i) = \begin{cases} 
1, & \text{if } i > 0 \\
-1, & \text{if } i < 0
\end{cases}
\]

\( \gamma_h \) – relative turn-on time of top side switch of the inverter leg excluding the "dead time" (Fig. 2), \( \tau \) – relative time delay, \( i \) - phase current, \( U_{DC} \) - DC voltage.

Output voltage of the inverter can also be distorted by the voltage drop across power switches,
which exists during the entire PWM cycle. It is determined by the current-voltage characteristic of
the switch, where direct branch of characteristic is defined by transistor and reverse branch is defined
by antiparallel diode. Thus, the voltage drop across power switches according to the direction of switch
current flow $i_{sw}$ can be written as
$$
\Delta u_{\text{sw,dir}} = \begin{cases} 
\Delta u_{\text{sw,dir, const}}, & \text{if } i_{sw} > 0 \\
\Delta u_{\text{sw,rev, const}}, & \text{if } i_{sw} < 0
\end{cases},
$$
(2)
where $\Delta u_{\text{sw,dir}}$ – voltage drop across power switch during direct current flow, and $\Delta u_{\text{sw,rev}}$ – voltage drop across power switch during reverse current flow.

The current-voltage characteristics of semiconductor switches are essentially nonlinear. So, it is widely used a piecewise linear approximation of the forward and backward branches of the current-voltage characteristic of the switch to simplify the analysis:
$$
\Delta u_{\text{sw,dir}} = \Delta u_{\text{sw,dir, const}} + r_{\text{diff, dir}} \cdot i_{sw},
$$
(3)
$$
\Delta u_{\text{sw,rev}} = \Delta u_{\text{sw,rev, const}} + r_{\text{diff, rev}} \cdot i_{sw},
$$
where $\Delta u_{\text{sw,dir, const}} > 0$ and $\Delta u_{\text{sw,rev, const}} < 0$ are the constant parts of voltage for direct and reverse current flows; $r_{\text{diff, dir}} > 0$ and $r_{\text{diff, rev}} > 0$ are the differential switch resistances for direct and reverse current flows. In the general case:
$$
\Delta u_{\text{sw,dir}} = \delta\Delta u_{\text{sw,dir, const}} + r_{\text{diff, dir}} \cdot i_{sw},
$$
where $\Delta u_{\text{sw,dir}} \neq \Delta u_{\text{sw,dir, const}}$, $r_{\text{diff, dir}} \neq r_{\text{diff, rev}}$. Then the output voltage average value of the inverter leg can be rewritten as:
$$
U_{\text{mean}} = \gamma_s - \tau \cdot \text{sign}(i) \cdot U_{DC} - \Delta u_{\text{sw,dir}},
$$
(4)
where
$$
\Delta u_{\text{sw,dir}} = \begin{cases} 
(\gamma_s - \tau)\Delta u_{\text{sw,dir}}, & \text{if } i > 0 \\
-(1 - \gamma_s + \tau)\Delta u_{\text{sw,rev}}, & \text{if } i > 0 \\
(\gamma_s + \tau)\Delta u_{\text{sw,dir}}, & \text{if } i < 0 \\
-(1 - \gamma_s - \tau)\Delta u_{\text{sw,rev}}, & \text{if } i < 0
\end{cases}.
$$
(5)

The voltage drop across the power switch causes additional vertical offset of the inverter regulating characteristic. In the case where the differential resistance of semiconductor switches can be neglected and the difference absolute values of direct and reverse constant part of voltage drop across the power switches can be neglected (i.e. $r_{\text{diff, dir}} = r_{\text{diff, rev}} = 0$ and $|\Delta u_{\text{const, dir}}| = |\Delta u_{\text{const, rev}}| = |\Delta u_{\text{const}}|$) expression (5) is greatly simplified:
$$
\Delta u_{\text{sw}} = 2\Delta u_{\text{const}}(\gamma_s - \tau \cdot \text{sign}(i) - \frac{1}{2}),
$$
(6)
and equation (4) becomes:
$$
U_{\text{mean}} = \left(\gamma_s - \frac{1}{2} - \tau \cdot \text{sign}(i)\right)U_{DC} - 2\Delta u_{\text{const}}.
$$
(7)

PWM inverter sinusoidal algorithm with double sided ramp voltage reference is selected as the base control algorithm. It is implemented in analog form or digitally using microprocessor technology. Relative turn-on time of top side switch of the inverter leg for each of the motor phases is calculated as follows:
$$
\gamma_{s,a}(t) = 0.5 \cdot (1 + u_{e}(t) \sin(\varphi(t))),
$$
$$
\gamma_{s,b}(t) = 0.5 \cdot (1 + u_{e}(t) \sin(\varphi(t) + 120^\circ)),
$$
$$
\gamma_{s,c}(t) = 0.5 \cdot (1 + u_{e}(t) \sin(\varphi(t) - 120^\circ)),
$$
(8)
where $u_e(t)$ is a control signal for the three-phase system, that assumes the values from the interval $[-1;1]$; $\varphi(t)$ – electric rotation angle of the motor.

Output voltage of the inverter leg without “dead time” is calculated as follows:
$$
U_{a}(t) = u_{e}(t) \cdot \frac{U_{DC}}{2} \cdot \sin(\varphi(t)),
$$
$$
U_{b}(t) = u_{e}(t) \cdot \frac{U_{DC}}{2} \cdot \sin(\varphi(t) + 120^\circ),
$$
$$
U_{c}(t) = u_{e}(t) \cdot \frac{U_{DC}}{2} \cdot \sin(\varphi(t) - 120^\circ),
$$
(9)
where $U_{a}(t), U_{b}(t)$ и $U_{c}(t)$ are the mean values of output voltages of A, B and C phase legs during the switching period. The inverter output phase voltage distortion can be written as
$$
\Delta U_a = (2\gamma_{s,a} - 1)\Delta u_{\text{const}} + \tau \cdot (U_{DC} - 2\Delta u_{\text{const}}) \cdot \text{sign}(i_a),
$$
$$
\Delta U_b = (2\gamma_{s,b} - 1)\Delta u_{\text{const}} + \tau \cdot (U_{DC} - 2\Delta u_{\text{const}}) \cdot \text{sign}(i_b),
$$
$$
\Delta U_c = (2\gamma_{s,c} - 1)\Delta u_{\text{const}} + \tau \cdot (U_{DC} - 2\Delta u_{\text{const}}) \cdot \text{sign}(i_c),
$$
(10)
Thus, the system of equations for PMSM currents (Fig. 1) can be written as:
$$
\begin{cases}
(U_a(t) - \Delta U_a(t)) - (U_c(t) - \Delta U_c(t)) = \\
= (2i_a(t) + i_b(t))R - (e_a(t) - e_b(t)) + L \frac{d(2i_a(t) + i_b(t))}{dt},
\end{cases}
$$
(11)
$$
\begin{cases}
(U_b(t) - \Delta U_b(t)) - (U_c(t) - \Delta U_c(t)) = \\
= (2i_b(t) + i_a(t))R - (e_a(t) - e_b(t)) + L \frac{d(2i_b(t) + i_a(t))}{dt},
\end{cases}
$$
$$
i_a(t) + i_b(t) + i_c(t) = 0,
$$
where $e_a, e_b, e_c$ are back-EMF for each motor phase, $R$ and $L$ are resistance and inductance of the motor phases. Fig. 3 shows graphs of current distortion with and without voltage distortion for $\tau = 0.03$ and $\Delta u_{\text{sw}} = 0.02 \cdot U_{DC}$.
2.2 Dead time effect influence on identification results

Equation for PMSM currents considering the influence of “dead time” are as follows:

$$\begin{align*}
\left\{ \begin{array}{l}
R + L \frac{d}{dt} I_a(t) = U_a(t) - \frac{1}{3} (2 \Delta U_a(t) - \Delta U_b(t) - \Delta U_c(t)) + e_a(t), \\
R + L \frac{d}{dt} I_b(t) = U_b(t) - \frac{1}{3} (2 \Delta U_b(t) - \Delta U_c(t) - \Delta U_a(t)) + e_b(t), \\
R + L \frac{d}{dt} I_c(t) = U_c(t) - \frac{1}{3} (2 \Delta U_c(t) - \Delta U_a(t) - \Delta U_b(t)) + e_c(t).
\end{array} \right.
\end{align*}$$

Usually the parameters of the object ($R$ and $L$) can be determined from the step response control (Fig. 4). Identification is performed with locked rotor of PMSM to eliminate the influence of back-EMF. Fig. 5-6 shows the graph of identification results with different step amplitude (different curves correspond to different electrical angles). Dispersion of results caused by the change of the electric angle is a few percent of the measured value, so it can be neglected.

Identification result error is caused by “dead time”. Change of control signal leads to a change of the disturbance generated by "dead time", so this also leads to a change of current in the circuit. This is especially noticeable when control signal is crossing zero because disturbance in this zone varies widely.
3 Problem Solution

3.1 Identification of delay

Relative delay $\tau$ is composed of hardware and software delays. Software delay is defined by the developer of control system, and the hardware exists in any PWM inverter, but its value is not reported by manufacturers. As a result, the relative delay $\tau$ is not known beforehand, so there is the problem of identification of this parameter for successful identification of other parameters.

Identification of parameter $\tau$ is worth doing with locked PMSM rotor to eliminate the influence of back-EMF. In this experiment, a control signal for each leg of the inverter is calculated as follows:

$$
\gamma_a^*(t) = u_0 \sin(\omega t), \\
\gamma_b^*(t) = u_0 \sin(\omega t + 120^\circ), \\
\gamma_c^*(t) = u_0 \sin(\omega t - 120^\circ),
$$

where the parameter $\omega$ is selected from the conditions $e_T << 1$ to eliminate the influence of phase inductance on the shape of the phase currents, and parameter $u_0$ is selected as close to 1. If it is impossible to immobilize the rotor, then must be performed the following condition:

$$
\omega \ll \frac{U_{\text{DC}} - \Delta U_{\text{const}}}{c_p e_T}
$$

In this case, formula (12) can be simplified:

$$
R_i(t) = U_i(t) - \frac{1}{3} (2\Delta U_i(t) - \Delta U_a(t) - \Delta U_c(t)), \\
R_i(t) = U_i(t) - \frac{1}{3} (2\Delta U_i(t) - \Delta U_a(t) - \Delta U_c(t))
$$

Data sets for the three currents are formed using the result of the experiment:

$$
I_a = [i_{a1}, i_{a2}, \ldots, i_{a_n}], \\
I_b = [i_{b1}, i_{b2}, \ldots, i_{b_n}], \\
I_c = [i_{c1}, i_{c2}, \ldots, i_{c_n}],
$$

where $i_{a_n}$, $i_{b_n}$ and $i_{c_n}$ are currents in phases A, B and C at the time $t_n$. Suppose that:

$$
H = \begin{bmatrix}
    h_{11} & h_{12} \\
    h_{21} & h_{22} \\
    \vdots & \vdots \\
    h_{n1} & h_{n2}
\end{bmatrix},
$$

where

$$
h_{ia} = u_0 \sin(\omega t_a), \\
h_{ib} = \frac{1}{3} \left(2\text{sign}(i_{a_1}) - \text{sign}(i_{b_1}) - \text{sign}(i_{c_1})\right),
$$

and vector of unknown parameters is as follows:

$$
X = \begin{bmatrix}
    U_{\text{DC}} - \Delta U_{\text{const}} \\
    \frac{1}{R} \\
    U_{\text{DC}} - \Delta U_{\text{const}} \\
    \frac{1}{R}
\end{bmatrix}
$$

Then the current in phase A can be found:

$$
I_a = H \cdot X.
$$

We use the method of least squares and find the vector of unknown parameters $X$:

$$
X = (H^T H)^{-1} H^T I_a.
$$

In this case, the relative delay can be found as:

$$
\tau = \frac{X_2}{X_1}
$$

Data sets should include currents not close to zero to improve the accuracy of identification. This is due to the fact that in this area the formula (7) is not always valid because of the "zero current clamping phenomenon" [23, 24].

3.2 Identification of electric parameters of a servo drive

Parameters determined by the step response in each leg of the inverter, formed as follows:

$$
\gamma_a^*(t) = \begin{cases} 
  u_{01} & \text{при } t<0, \\
  u_{02} & \text{при } t>0,
\end{cases} \\
\gamma_b^*(t) = 0, \\
\gamma_c^*(t) = \begin{cases} 
  -u_{01} & \text{при } t<0, \\
  -u_{02} & \text{при } t>0,
\end{cases}
$$

where

$$
u_{01} \in (2\tau; 1), \quad u_{02} \in (2\tau; 1), \quad u_{01} \neq u_{02}.
$$

This experiment should be carried out carefully with locked rotor, otherwise whole object may be damaged as a result of breakthrough moment.
According to formula (11) during the experiment currents in the phases will vary as follows:

\[
i_s(t) = -i_s(t) = \frac{(u_{q1} - 2\tau)U_{DC} + \left(\left(\frac{u_{q2} - u_{q0}}{2R}\right) - \left(\frac{u_{q0} - 2\tau}{2R}\right)\right)U_{DC}}{1 - e^{-\frac{t}{\tau}}},
\]

\[
i_s(t) = 0.
\]

Due to the condition (7), the voltage distortion caused by the presence of "dead time", does not change during the experiment. Then:

\[
T_e = \frac{T_p}{3},
\]

where \(T_p\) is the transient time (time of entry into five percent area). Then:

\[
i_s(x) - i_s(0) = \frac{(u_{q2} - u_{q0})U_{DC}}{2R},
\]

i.e. change of currents in the phases will not depend on the presence of "dead time", which means:

\[
K_{ob} = \frac{i_s(x) - i_s(0)}{u_{q2} - u_{q0}}.
\]

The results of this method of identification does not depend on the "dead time" due to the features of the experiment.

### 3.3 Experimental results

We used the stand for research (Fig. 7). PMSM has the following parameters according to nameplate data: \(c_r = 6.2 \text{ V} \cdot \text{s/rad}, \ R = 1.2 \Omega, \ T_e = 8 \text{ ms}\).

The relative delay \(\tau\) is determined according to the procedure described above. The experiment was carried with locked rotor. Phase current, resulting from the experiment, is illustrated in Fig. 8.

Matching of the simulated and experimental data is good enough to justify the applicability of the proposed identification method. Following value was obtained according to the data: \(\tau = 0.03\) .

![Fig. 8. PMSM phase current (1) and the current estimated by the results of identification of the relative delay (2).](image)

Fig. 8. PMSM phase current (1) and the current estimated by the results of identification of the relative delay (2). (3.72)

Electrical resistance \(R\) and electromagnetic time constant \(T_e\) are identified according to the procedure described above. Identification results without model nonlinearities are:

\(R = 1.88 \Omega, \ T_e = 5.1 \text{ ms}\),

and the results of algorithm of identification tacking into account the model nonlinearities are:

\(R = 1.28 \Omega, \ T_e = 7.3 \text{ ms}\).

### 4 Conclusion

The model of the drive, which takes into account the nonlinearity of inverter semiconductor power switches, is considered in paper. The model allows analyzing the influence of nonlinearities of the inverter on the final positioning accuracy. The resulting voltage distortion model of the inverter can be used in determining the drive parameters experimentally to improve the accuracy of the identification results. Fault simulation of servo drive on this model will facilitate technical diagnostics of faults in real systems management.

Designed offline identification algorithm allows estimating the electromechanical parameters of the electric drive taking into account “dead time effect”. The applicability of this system was validated by experiments on the test stand.
References:
