Compensation for Neutral Point Potential in Three-Level Inverter by using Motor Currents

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Abstract— The three-level inverter has several advantages of large capacity, large voltage and low current waveform distortion. However, there is an important problem of neutral point potential variation in three-level inverter. The variation causes an unbalance in the DC link voltage levels and current waveform distortion.

In this paper, we propose a new method to control the neutral point potential. The neutral point potential in three-level inverter is analyzed by state variable. The proposed method uses the estimated value of the neutral point potential, which is calculated by motor currents. The proposed method can be applied at various speeds and regenerating operation. The validity of the proposed method is proved by experimental results and simulation.

1. Introduction

Three-level inverter [1] offer low harmonic output, but variation of the neutral point potential in the DC link is a problem. As the neutral point potential fluctuations, the voltage applied to switching elements becomes unbalanced, so that the output current waveform may become distorted, creating a need to control the neutral point potential in three-level inverters.

For this purpose, the ramp comparison control method is proposed: a zero-sequence component is superimposed on the voltage command [2]. There are also other techniques, such as the spatial voltage vector command [3], in which voltage vectors with different switching states are applied at the ends of the switching period, while the output time ratio is controlled, and the method of Ref. [4], in which the sum of the electric charges flowing in and out of the neutral point via the output time [5]. In the conventional algorithm based on space voltage vectors, the ratio of the positive-mode (when the neutral point potential is rising) output time and the negative-mode output time is controlled; however, the neutral point potential must be detected [3], [5].

This paper proposes a control method using the detected value of the motor current rather than the potential or current at the neutral point [6]. The basic principle is that with three-level inverters, the motor currents flow through the neutral point in the zero switching state. Therefore, the output time ratio can be controlled by using such a switching state and the motor current to represent the neutral point current, and estimating the neutral point potential by integrating the current. In the proposed compensation method, the neutral point potential for the next control cycle is estimated by using the current detected at each sampling point, so that feedforward-like compensation for the neutral point potential is possible. The effectiveness of the proposed method is evaluated by analysis and experiments.

2. Circuit configuration

The system configuration of a permanent magnet synchronous motor drive using a three-level inverter is shown in Fig.1. The main circuit is built on an IGBT module; the permanent magnet synchronous motor is a 6-pole 771-W machine, and the DC link has a capacity of 330µF. The neutral point potential is measured with a 22-kΩ resistance inserted in the DC link. The control circuit is essentially based on a DSP (TMS320C32). The three phase currents are transformed into and in the rotating reference frame, and and voltage commands are produced via speed PI control and current PI control. After that, and in the stationary reference frame are obtained, and the PWM pattern is obtained by space vector selection. Finally, the output PWM pulse is provided with 6-µs dead time, and the IGBT gates are driven.
3. Method of analysis

In order to acquire the neutral point potential, analysis is performed on every switching mode of the voltage vector using the state variable. Regard is paid to variation of the neutral point in the state equation of the permanent magnet synchronous motor. The assumptions for the analysis are as follows.

1. Both capacitors have same rating
2. Power devices are considered to be ideal elements, that is switching time lags and forward drops are ignored.

A. Analytical model

PWM waveforms in the analysis space are given in Fig.2. The diagram shows waveforms in the range of 60 degrees for a permanent magnet synchronous motor driven at an inverter frequency of 60 Hz, with a sampling period of 252 µs (carrier frequency 1980 Hz). The voltage vectors extracted in this space are positive/negative mode small vectors and zero vectors. In this study, V0 is defined as the zero vector, V1-V6 as small voltage vectors, V7-V12 as medium voltage vectors, and V13-V18 as large voltage vectors (see Fig.4 (a)). The switching states for small vectors are shown in Fig.3.

The neutral point potential is rising in the positive mode, and falling in the negative mode; hence the variation of the potential can be expressed in terms of the phase voltage as follows:

\[ V_{n}^{+}(1,0,0) : V_{1}^{+}(E_{d}/2,v_{n},v_{n}) \] \hspace{1cm} (1)
\[ V_{n}^{-}(0,-1,-1) : V_{1}^{-}(v_{n},E_{d}/2,E_{d}/2) \] \hspace{1cm} (2)

The potential variation and current at the neutral point are:

\[ v_{n} = \frac{1}{2C} \int i_{n} \, dt \] \hspace{1cm} (3)
\[ i_{n} = -(S_{u}i_{u} + S_{v}i_{v} + S_{w}i_{w}) \] \hspace{1cm} (4)
Here $S_a$, $S_v$, $S_w$ are the switching functions of the neutral point clamp, taking the value of 1 at clamp, and 0 otherwise. For example, in Fig.3 (a), $i_v$, $i_w$ flow through the neutral point, and $i_n=-(i_v+i_w)$, while in Fig.3 (b), $i_n$ flows through the neutral point, and $i_n=-i_n$. Since the analysis is preformed in the stationary reference frame, $i_n$, $i_v$, $i_w$ are transformed into $i_\alpha$, $i_\beta$, and $S_a$, $S_v$, $S_w$ are transformed into $S_\alpha$, $S_\beta$, so that the following differential equation is derived:

\[
pv_n = -\frac{1}{2C} \sqrt{\frac{2}{3}} \left( S_\alpha i_\alpha + S_\beta i_\beta \right)
\]

Thus, the state equation of permanent magnet synchronous motor may be written as follows:

\[
\begin{bmatrix}
    v_{\alpha 0} - S_\alpha v_n \\
    v_{\beta 0} - S_\beta v_n
\end{bmatrix} =
\begin{bmatrix}
    R + pL_\alpha & 0 \\
    0 & R + pL_\beta
\end{bmatrix}
\begin{bmatrix}
    i_\alpha \\
    i_\beta
\end{bmatrix} +
\begin{bmatrix}
    -\omega_e \phi_\beta \\
    \omega_e \phi_\alpha
\end{bmatrix}
\]

(6)

B. Compensation for neutral point potential using motor current

When voltage command vector is extracted in area ○ in Fig.4 (a) or (b), the positive and negative modes of $V_1$ are applied at both ends of control period, and $T_1=T_3=T_2/2$ in Fig.4(c). In this paper, the output time ratio of $T_1$ to $T_4$ is denoted by $K_1$, and compensation is not applied when $K_1=0.5$. In typical neutral point potential control, both output times are adjusted in combination with the detected neutral point potential [3]. In proposed compensation algorithm, the neutral point current is expressed via the motor current in order to calculate the neutral point potential; the estimated potential is then used to control the output time ratio $K_1$. In Fig.4(c), $l$ stands for the sampling point, and $T_1$~$T_4$ are the output times for the respective voltage vectors; supposing that the neutral point currents are $i_{n1}$~$i_{n4}$ as in Eq. (4), the estimated neutral point potential at the moment ($l+1$) is

\[
\hat{v}_n(l+1) = \hat{v}_n(l) + (i_{n1}T_1 + i_{n2}T_2 + i_{n3}T_3 + i_{n4}T_4)/2C
\]

(7)

Here $\hat{v}_n(l+1)$ is the estimate for the next control period. Using this estimated value, feed back compensation is provided. The output time ratio $K_1$ is defined in the following way:

\[
K_1 = 0.5 \mp K_2 \times \hat{v}_n(l+1)
\]

(8)

Here $K_1$ is assumed to be within 0.1~0.9
In addition, $K_2$ is the gain for the neutral point potential variation; the gain should be chosen appropriately because with $K_2$ set too high, the current waveform becomes distorted.

And in motoring operation, sign in equation (8) takes negative and in regenerating operation, takes positive.

4. Analysis and experiments

In our analysis, Newton's method is used to solve 44-dimensional nonlinear simultaneous equations including the expressions for the initial values of the state variables and for the switching time; the initial values are then employed in the Runge-Kutta method.

The waveforms at rotational speed of 1,200 rpm and a current command of 3 A are shown in Fig.5, which corresponds to the $120^\circ$ range in Fig.2. The waveforms pertain (from top to bottom) to the u-phase current, the neutral point current, the neutral point potential, and its estimate. The neutral point potential estimate in Fig.5 (a) corresponds to

![Fig.5. Calculated waveforms in various parts (1200 rpm, 3 A, 120°)](image)

Fig.6. Experimental waveforms at various rotational speeds (under load 3 A)
(a) without compensation, (b) current feed back compensation, (c) feedforward compensation
the theoretical average pattern. On the other hand, Fig.5 (b) presents the results of compensation using this estimate; as is evident from the diagram, variation of the neutral point potential is reduced.

Experimental under-load waveforms at varied speed are shown in Fig.6, namely, (a) without compensation, (b) with current feedback compensation, and (c) with feedforward compensation (app.Fig.1). Without compensation, the neutral point potential at 1,200 rpm is steady on the whole, but sharp fluctuations occur due to imbalance at inflow and outflow. This effect becomes even more pronounced and shifts to the negative side at 100 rpm. At 1,800 rpm, the voltage command is on the border of the voltage vector, so that the switching pattern shows strong fluctuations; in this case, the neutral point potential shifts significantly to the negative side, and the current waveform becomes distorted. With feedforward compensation, the neutral point potential is kept stable at 100 rpm and 1,200 rpm, but at 1,800 rpm, the motor current becomes distorted because compensation is no longer possible for the above reasons. On the other hand, in the proposed method, steady operation at a fixed potential is ensured for any speed.

Fig.7 shows the u-phase current waveform and neutral point potential, together with the calculated and experimental waveforms of the potential estimate; the experimental waveforms are enlarged diagram of A, B and C in Fig.6 (ii). As is evident from the diagrams, the calculated waveforms agree well with experimental results.

Fig.8 illustrates simulation results of regenerating operation. The road is changed from no load to −1.11N·m at 200 ms. Compared with without
compensation, the stability of neutral point potential with compensation is maintained.

5. Conclusions

This paper has dealt with compensation for the neutral point potential in a permanent motor synchronous motor driven by a three-level inverter.

The following conclusions were drawn:

(1) Conventional control techniques involve detection of the neutral point potential to adjust the output time ratio of the voltage vectors. In this paper, the neutral point potential is not detected; instead, using the motor current performs compensation for the neutral point potential.

(2) The proposed method was compared to non-compensation operation and feedforward compensation, and stable operation was confirmed even under severe conditions with sharp variation of the switching pattern.

(3) The proposed compensation algorithm provided stabilization of neutral point potential variation, and improvement of the motor current waveform, at various rotational speeds.

(4) The calculation results verified that the proposed method could be applied in regenerating operation.

References


Appendix

Feedforward compensation for neutral point potential

This algorithm involves control over the output time ratio without using the detected or estimated value of the neutral point potential. The voltage vectors and their output intervals during two control periods are shown in app.Fig.1.

Diagram (a) corresponds to Fig.4 (c) (case of no compensation). Here, since the voltage vectors are extracted in the middle of control period, the output times are different for positive and negative modes, and an inflow-outflow current unbalance occurs at the neutral point. As shown in diagram (b), compensation ensures that the output times for the positive and negative modes are kept equal for every control period, and hence no current unbalance occurs at the neutral point.