Capacitor Voltage Balancing Control of Four-Leg Inverter for Two Vector-Controlled Induction Motor Drives

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Recently, the four-leg inverter and the four switch inverter, which have fewer of switches, have been studied for their advantages of low cost and compactness(1)–(12). In particular, the four-leg inverter(13)–(15) can drive two motors independently. Applications of the four-leg inverter are factory automation, electric vehicles and crane trucks. The inverter consists of four legs and two capacitors connected in a series. However, many of conventional studies on the four-leg inverter and the four switch inverter have used open-loop control systems such as the volts per hertz (V/f) control system. This paper proposes capacitor voltage balancing control of the four-leg inverter for two vector-controlled induction motor drives. In this a study, the source of the capacitor voltage fluctuation caused by the current flow through the capacitors is analyzed by using the space vector and a compensation method is described. The capacitor voltage fluctuation compensation method and the independent drives of the two induction motors fed by the four-leg inverter with the vector control method are demonstrated with experimental results.

Keywords: four-leg inverter, two three-phase induction motors, independent drives, vector control method

1. Introduction

Dual three-phase voltage source inverter (three-VSI) systems are generally used to drive two three-phase AC motors independently. The system connects one motor to one three-VSI and requires dual three-VSIs. Recently, a four-switch inverter(1)–(12), a four-leg inverter(13)–(15), and six-switch inverter(16), which have fewer switches, have been studied. Reduction of the number of switches is attractive for reducing the cost and saving space. The four-leg inverter consists of four legs and two capacitors connected in series. One phase of both motors is shared and connected to the neutral point of two-spirit capacitors in common. The four-leg inverter requires eight-switching devices. In brief, it can eliminate four switches compared with dual three-VSI systems. We believe that the four-leg inverter can be applied to factory automations and a crane trucks.

However, the four-leg inverter and four switch inverter have several weaknesses. One of them is the capacitor voltage fluctuation. This problem causes unbalanced three-phase motor current and an unstable motor drive. Jaehong Kim, Jinseok Hong, and Kwaghee Nam(7) analyzed the capacitive source impedance and fluctuation of two capacitor voltages by utilizing space vectors.

Many conventional studies of four-leg inverter and four-switch inverter, used open-loop control systems such as the volts per hertz (V/f) control system. However, very few studies have used closed-loop systems. This study presents a closed-loop control systems, namely the vector control method.

First, this paper shows the main circuit architecture of the four-leg inverter. Next, a PWM technique different from the normal three-VSI is illustrated. Then, this paper shows that balanced three-phase current can be automatically obtained with the vector control method. Subsequently, the cause of capacitor voltage fluctuation is investigated using space vectors, and the compensation terms and compensation method applicable to the vector control method are shown. Finally, the characteristics of capacitor voltage balancing control of the four-leg inverter for vector-controlled two Induction motor drives, and the load characteristics of the four-leg inverter are demonstrated by the experimental results.

2. Main Circuit Structure of Four-Leg Inverter

Figure 1 shows the structure of a four-leg inverter to supply two three-phase AC motors(13)–(15). The inverter consists of four legs and two capacitors connected in-a series. The U1 and V1 phases of the inverter are connected to the U and V phases of IM1 respectively, and the U2 and V2 phases are

![Fig. 1. Main circuit of a four-leg inverter](image-url)
connected to the U and V phases of IM2 respectively. The W phase of both IM1 and IM2 is shared and connected to the neutral point of the two-sprit capacitors in common. In the four-leg inverter, $v_{UNi}$, $v_{VNi}$ and $v_{WNi}$ are the phase voltages in IM-$i$ ($i = 1, 2$), $v_{WO}$ ($x = U1, V1, U2, V2, W$) is the $x$-phase voltage of the inverter. $v_{WO}$ indicates the neutral-point potential of the two-sprit capacitors. $i_{UNi}$, $i_{VNi}$, $i_{WNi}$ are the phase currents in the IM$i$ and $i_{W}$ is the phase current of the inverter. $E$ expresses the magnitude of the DC-bus voltage. $C$ is the capacitance of the two-sprit capacitors. In this work, a based-point is chosen on the negative side of the DC-bus for simplifying the analysis.

3. PWM Technique of Four-Leg Inverter

Because the W phase of the inverter is connected to the neutral point of the two-sprit capacitors, modulation in this phase is impossible. The four-leg inverter must be modulated in only two phases, U and V. Therefore, the PWM technique in the three-phase VSI (three-VSI) is not directly applicable to the four-leg inverter. Figure 2 shows the block diagram of the PWM technique in the four-leg inverter. To obtain a balanced three-phase AC voltage, the phase difference between the U-W and V-W line voltages needs to be controlled to $2\pi/3$. Then, the command signal of the U (V) phase voltage in IM$i$ compared with the carrier signal is obtained by subtracting the W-phase voltage command from the U (V)-phase voltage command. The command signal of the U (V)-phase voltage is as follows

$$\begin{align*}
e_{Us} &= \frac{v_{UNi}^* - v_{WNi}^*}{E/2} \quad \text{................. (1)} \\
e_{Vs} &= \frac{v_{VNi}^* - v_{WNi}^*}{E/2}
\end{align*}$$

where, $v_{UNi}^*$ is the actual $k$ phase voltage command in motor $i$ and “*” is the command value. $v_{WNi}^*$ can be defined as follows:

$$\begin{align*}
v_{UNi} &= \frac{1}{2}M_i E \sin(\omega_i t - \phi_i^*) \\
v_{VNi} &= \frac{1}{2}M_i E \sin(\omega_i t - \frac{2}{3}\pi - \phi_i^*) \quad \text{................. (2)} \\
v_{WNi} &= \frac{1}{2}M_i E \sin(\omega_i t - \frac{4}{3}\pi - \phi_i^*)
\end{align*}$$

where, $M_i$ and $\omega_i$ are the modulation index and fundamental angular frequency in IM-$i$ respectively. $\phi_i^*$ is the initial phase angle of the phase voltage in IM-$i$.

4. Unbalanced Current Compensation

The neutral point potential ($v_{WO}$) of the two-sprit capacitors is given by the following equation:

$$v_{WO} = \frac{1}{2}E - \frac{1}{2C} \int (i_{W1} + i_{W2}) \, dt = \frac{1}{2}E + \Delta v_{WO} \quad \text{........................ (3)}$$

where, $\Delta v_{WO}$ represents the fluctuating components of $v_{WO}$.

From (3), $v_{WO}$ changes around $E/2$ because W phase currents of each motors flow through capacitors. The voltage fluctuation affects motor phase currents and makes it unbalanced. The fluctuated component $\Delta v_{WO}$ depends on the fundamental wave frequency and peak value of the both motor currents. In other words, it will be able to decrease when the motors are driven at lighter load and higher speed condition, and be also decreased by the capacitor with larger capacitance. However, the too large capacitor is undesirable because one of the merits of the four-leg inverter is saving space. Therefore, it needs to consider the compensation method that keeps three-phase current balancing.

Under open-loop control such as V/f control system, $\Delta v_{WO}$ must be added to command signals in each phase to obtain balanced three-phase current [21]. So, the command signal of U (V) phase voltage is as follows

$$\begin{align*}
v_{UO} &= v_{UNi}^* - v_{WNi}^* + \Delta v_{WO} \quad \text{................. (4)} \\
v_{VO} &= v_{VNi}^* - v_{WNi}^* + \Delta v_{WO}
\end{align*}$$

However, under vector control, the command values to be balanced three-phase current are automatically obtained even if $\Delta v_{WO}$ is not added. We think that is because the vector control performs the feedback and dq axis control. So the equation of command signal of U (V) phase voltage is (1) under vector control.

5. Compensation Method of The Drift

A. The drift phenomenon of two capacitors

Since capacitance of two capacitors of the four-leg inverter is equal, the voltage of each capacitor should be equal to $E/2$. However, at the time of starting of a motor and speed change, the voltage of each capacitor becomes imbalance. We define this thing as drift phenomenon. If a drift phenomenon happens, it causes the reduction of DC voltage utility factor. Moreover, motors cannot be driven stably. Therefore the compensation to restrain the drift phenomenon needs to be added.

Figure 3 shows one of the switching modes in one motor. The four-leg inverter can regard two motors as independence. Therefore, in order to analyze easily, circuit analysis can be conducted only by one motor. The number of switching pattern is four in one motor. Where, $V_{ij}$ in Fig. 4(a) shows the switching state when $S_j$ is OFF, $S_i$ is ON, $S_1$ is OFF, and $S_4$ is ON in Fig. 3. At this time, two current loops are made. Applying Kirchhoff’s voltage and current law to the circuit, it follows that

$$\begin{align*}
Z_i i_{W1} - Z_i i_{V1} &= \frac{E}{2} + \Delta v_{WO} \\
Z_i i_{W1} - Z_i i_{W1} &= \frac{E}{2} + \Delta v_{WO} \\
i_{U1} + i_{V1} + i_{W1} &= 0
\end{align*}$$

Solving about $Z_i i_{U1}$, $Z_i i_{V1}$, and $Z_i i_{W1}$, the phase voltage are obtained such that
This equation shows the relation of each phase voltage and ΔvWO. Transforming the phase voltages according to space vector $V_{1i} = (2/3)(Z_{iU}i + Z_{iV}e^{j\theta} + Z_{iW}e^{j3\theta})$, it follows that

$$V_{1i} = \begin{pmatrix} 0 \\ -1 \\ 0 \end{pmatrix} + \frac{2}{3} j \Delta v_{WO} e^{j\theta}$$

$$= \begin{pmatrix} 1/6 - j\sqrt{3}/6 \\ \sqrt{3}/2 \\ 1/6 + j\sqrt{3}/6 \end{pmatrix} + \frac{2}{3} j \Delta v_{WO} e^{j\theta}$$

Where,

$$\Delta V = \frac{2}{3} j \Delta v_{WO} e^{j\theta}$$

In the same way, the other switching mode $V_{12}(S_1$ is OFF, $S_2$ is ON, $S_3$ is ON, and $S_4$ is OFF), $V_{13}(S_1$ is ON, $S_2$ is OFF, $S_3$ is ON, and $S_4$ is OFF) and $V_{14}(S_1$ is ON, $S_2$ is OFF, $S_3$ is ON, and $S_4$ is ON) are obtained such that

$$V_{12} = \begin{pmatrix} 1/2 + j\sqrt{3}/6 \\ \sqrt{3}/2 \\ 1/2 - j\sqrt{3}/6 \end{pmatrix} + \Delta V$$

$$V_{13} = \begin{pmatrix} 1/2 + j\sqrt{3}/6 \\ \sqrt{3}/2 \\ 1/2 - j\sqrt{3}/6 \end{pmatrix} + \Delta V$$

It shows that the same term $\Delta V$ affects all the switching modes. So, $\Delta V$ causes drift phenomenon. Therefore, it should be considered how the term affects the stable drive.

Then, according to the direction and magnitudes of current vector, the space vectors are drawn in Fig. 4(a). Figure 4(a) shows the case when the neutral point potential of two capacitors $v_{WO} = E/2$, namely $\Delta v_{WO}$ is zero. But if $\Delta v_{WO}$ is not zero, $\Delta v_{WO}$ causes shifting of parallelogram of the space vector like Fig. 4(b) and (c). Figure 4(b) shows when $\Delta v_{WO}$ is positive, and (c) shows negative. Moreover, since the drift phenomenon term $\Delta V$ is $(2/3)\Delta v_{WO} e^{j\theta}$, the center of the parallelogram fluctuates along $60^\circ$ line. At the same time, as $\Delta V$ increases, the voltage contours appear as ellipses and the usable voltage range of the parallelogram decreases. In conclusion, the neutral point potential of two capacitors $v_{WO}$ must be maintained to $E/2$. At the same time, the drift phenomenon term $\Delta V$ also must be restrained.

B. Compensation method of the drift

As previously mentioned, the capacitors voltage fluctuations must be eliminated. In order to restrain the drift, it is necessary to add the compensation terms to the command signal. The relation between the command signal of U (V) phase voltage and $\Delta V$ are shown in Fig. 5. The vector of the drift phenomenon term $\Delta V$ can be decomposed into the command signal of U and V phase voltage commands vectors. The inverse vector of these vectors must be added to restrain the drift. From Fig. 5, the compensation terms $\delta v_{UO}$ and $\delta v_{VO}$ follow that

$$\delta v_{UO} = -\frac{2}{3} \Delta v_{WO}$$

$$\delta v_{VO} = -\frac{2}{3} \Delta v_{WO}$$

Adding (12) to (4), the command signals of U and V phase voltage are obtained as

$$v_{UO} = v_{U}^{NI} + \Delta v_{WO} + \delta v_{UO}$$

$$v_{VO} = v_{V}^{NI} - \Delta v_{WO} + \delta v_{VO}$$

Fig. 3. The current pass of switching mode $V_{1i}(0, 0)$. (a) $\Delta v_{WO} = 0$

Fig. 4. The space vector of four-leg inverter

$$(b) \Delta v_{WO} > 0$$

$$(c) \Delta v_{WO} < 0$$
Note that (13) is effective under V/f control system, whereas vector control method is not effective. Under vector control method, even if these compensation terms are added to the voltage command signals of U, V phase just before compared with the carrier signal, it is meaningless since the response of Automatic Current Regulator (ACR) in vector control system is very quickly. Therefore, in order to use the compensation terms (12) effectively under vector control method, it must be added before PI controller, not behind PI controller. So, it is necessary to transform (12) into d, q axis coordinate and current compensation terms.

In the four-leg inverter, transformation from d, q command voltages to U, V phase command voltage is

\[
\begin{bmatrix}
v_{UO} \\
v_{VO}
\end{bmatrix} = \sqrt{2} \begin{bmatrix}
\cos \theta & -\sin \theta \\
\cos \left(\theta - \frac{2\pi}{3}\right) & -\sin \left(\theta - \frac{2\pi}{3}\right) \\
\cos \left(\theta - \frac{4\pi}{3}\right) & -\sin \left(\theta - \frac{4\pi}{3}\right)
\end{bmatrix} \begin{bmatrix}
v_d \\
v_q
\end{bmatrix} = \sqrt{2} \begin{bmatrix}
\cos \left(\theta - \frac{\pi}{6}\right) & -\sin \left(\theta - \frac{\pi}{6}\right) \\
\sin \left(\theta - \frac{\pi}{6}\right) & \cos \left(\theta - \frac{\pi}{6}\right)
\end{bmatrix} \begin{bmatrix}
v_d \\
v_q
\end{bmatrix}
\]

Also, inverse transformation is from (14) such as

\[
\begin{bmatrix}
v_d \\
v_q
\end{bmatrix} = \sqrt{2} \begin{bmatrix}
\cos \theta & \sin \left(\theta - \frac{\pi}{6}\right) \\
-\sin \theta & \cos \left(\theta - \frac{\pi}{6}\right)
\end{bmatrix} \begin{bmatrix}
v_{UO} \\
v_{VO}
\end{bmatrix}
\]

Substituting \(\delta v_{UO}, \delta v_{VO}\) of (12) into \(v_{UO}, v_{VO}\) of (15), it follows that

\[
\begin{bmatrix}
\delta v_d \\
\delta v_q
\end{bmatrix} = \sqrt{2} \begin{bmatrix}
\cos \theta & \sin \left(\theta - \frac{\pi}{6}\right) \\
-\sin \theta & \cos \left(\theta - \frac{\pi}{6}\right)
\end{bmatrix} \begin{bmatrix}
\frac{2}{3\sqrt{3}} \Delta v_{WO} \\
\frac{2}{3\sqrt{3}} \Delta v_{WO}
\end{bmatrix}
\]

Then, dividing (16) by the impedance of stator winding, \(\delta R + 2\delta Ls\), d, q axis current compensation terms \(\delta i_d, \delta i_q\) can be obtained. d, q axis current commands of four-leg inverter are got by adding the compensation current \(\delta i_d, \delta i_q\) to the usually d, q axis current command of vector control. Figure 6 shows the block diagram which is applicable to the vector control. Where, \(i^*d, i^*q\) denote d, q axis current commands, and \(i_d, i_q\) denote d, q axis actual values. \(L\) denote the stator inductance.

Figure 7 shows the entire block diagram of four-leg inverter. \(v_{WO}\) is detected with voltage sensor. From (3), \(\Delta v_{WO}\) is obtained by subtracting \(E/2\) from \(v_{WO}\). Provided separate commands for each motor, each motor can drive independently.

6. Experimental Results

In order to demonstrate the independent drives of two IMs, and the usefulness of the compensation method for the drift phenomenon, a four-leg inverter experimental prototype to supply two three-phase squirrel-cage IMs has been implemented. The system configuration of the prototype is shown in Fig. 8. The main circuit consists of four IGBT-modules and two-spirit capacitor. PE-Expert3 is used as the control system. The PE-Expert3 is the digital control system equipping a DSP, which also has an Analog-Digital (AD) Converter, digital input-output and PWM function. A program written by user is implemented with transmitting the program from a host computer to the DSP on the PE-Expert3. Figure 9 depicts the photo of experimental prototype. Table 1 shows the ratings and parameters of tested IMs. Both IMs are driven by vector control. The ratings and parameters of both IMs are identical. The DC bus voltage is 282 V. A slider is used to boost-up three-phase input voltage. The inverter DC-bus voltage can be obtained by adjusting the input voltage of a three-phase diode-rectifier with the slider. C is 9900 \(\mu\)F and carrier frequency is 10 kHz.

A. Characteristics of Four-Leg Inverter

In this experiment, to demonstrate the independent driving of both IMs, the commands of the rotation direction of IM1 and IM2 was given opposite direction and both IMs are driven under no load operation. Figures 10 and 11 show the rotor speed of the IM1 and IM2. The speed commands in the IM1 is accelerated up to 700 rpm in the direction of order rotation in zero second and 700 rpm in the direction of order rotation from 1.0 seconds. The speed commands in the IM2 is accelerated up to 700 rpm in the direction of reverse rotation in zero second and 700 rpm
in the direction of reverse rotation from 1.0 seconds. As can be seen from these figures, two three-phase IMs can be independently driven with the four-leg inverter.

Figures 12 and 13 show the neutral point potential of two capacitors. Experimental conditions of the speed of two IMs are the same as Figs. 10 and 11. Figure 12 shows the neutral point potential not adding the compensation terms $\delta i_{id}$, $\delta i_{iq}$. The drift phenomenon of $v_{WO}$ can be observed about at starting time and speed change. And there is stationary error about 10 V(7%) in steady state. In this case, two IMs cannot
drive stably.

Figure 13 shows the neutral point potential with compensation. The drift phenomenon of $v_{WO}$ cannot be almost observed at starting time and speed change compared with no compensation. Moreover, there is stationary error about 4 V(3%) in steady state. In this case, two IMs can be driven stably.

As can be seen from Figs. 12 and 13, the validity of the compensation method was shown.

Figure 14 and 15 show the three-phase current waveforms of the IM1 and IM2. It can be confirmed that the balanced three-phase current can be obtained in both IMs.

B. Load characteristics of Four-Leg Inverter

In this experiment, it is purpose to examine the load characteristics of the four-leg inverter.

Figures 16 and 17 show the rotor speed of the IM1 and IM2. The speed commands in the IM1 is accelerated up to 650 rpm in the direction of order rotation in zero seconds, 650 rpm in the direction of order rotation from 1.0 seconds to 2.0 seconds, slowed down to 400 rpm in the direction of order rotation in 2.0 seconds and 400 rpm in the direction of order rotation from 3.0 seconds. The speed commands in the IM2 is accelerated up to 300 rpm in the direction of reverse rotation in zero seconds, 300 rpm in the direction of reverse rotation from 1.0 seconds to 3.0 seconds, accelerated up to 600 rpm in the direction of reverse rotation in 3.0 seconds and 600 rpm in the direction of reverse rotation from 4.0 seconds. IM1 is added 100% load and IM2 is added 50% load. From the both figures, it is shown that the speed control of two IMs with vector control is possible even if the load is 100%.

Figure 18 shows the load characteristics of the neutral point potential of two capacitors. The commands of the speed are
Induction motor drives fed by the four-leg inverter (Haruki Tanaka et al.)

Fig. 16. Speed of IM1 (100% load) (Experimental result)

Fig. 17. Speed of IM2 (100% load) (Experimental result)

Fig. 18. The neutral point potential of two capacitors (Experimental result)

Figures 19 and 20 show the current wave forms of two IMs in steady state. As can be seen from these figures, the peak currents increase by adding the load. The peak currents of two IMs giving load are settled within the rated current respectively.

7. Conclusion

This paper proposed independent drives of two induction motors fed by a four-leg inverter with vector control method. Up to now, the four switch inverter and four-leg inverter were researched only open-loop control. This paper was described about vector control method. This paper analyzed that the balanced three-phase current was derived with vector control method. The compensation method of the neutral point potential fluctuation also was proposed under the vector control. Moreover, the effectiveness of the compensation method and the independent drives of two motors fed by a four-leg inverter and the load characteristics of four-leg inverter were verified by the experimental results.

The research for transient state of motor driving fed by four-leg inverter, compensation method at the high frequency driving mode, etc, will be topics for future studies.

the same as Figs. 16 and 17. As can be seen from the figure, there is stationary error about 12 V(9%) in steady state. In the future, we must solve this problem.
References


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