Research on Decomposition Sequence Feedforward Decoupling Control of Four-leg Inverter

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Abstract. Three-phase four-leg inverter is currently the most efficient inversion for three-phase unbalanced and nonlinear load, this paper adopts the method of sequential feedforward decoupling control to decompose the asymmetric three-phase voltage and current into three-phase symmetrical positive, negative and zero-sequence components by symmetrical component method, each component is converted into DC variables in both positive and negative dq synchronous rotating coordinate, the voltage and current double closed PI control loop without static deviation is realized. The simulation and experiment results show that the inverter has a strong load capacity under three phase unbalanced load conditions, and the total harmonic distortion (THD) rate of each phase voltage is less than 3%, which meets the power standards and has a great value of application.

Introduction

With the continuous development of power electronics technology, three-phase inverter is widely used in industry, rail transit, electric vehicles and military fields. At the same time, the application of various unbalanced and nonlinear loads in various fields of power system is becoming increasingly prominent, which requires three-phase inverter with strong unbalanced and nonlinear load performance [1]. Especially in the field of military micro-grid, the main load object of power supply is nonlinear load of motor, and most of them are working in unbalanced state. The traditional three-phase inverter can not guarantee the symmetrical output of three-phase voltage. Therefore, it has important value in military and civilian field to study the inverter control methods under the unbalanced load condition [2]. In order to make the inverter have outstanding ability with unbalanced load, the three-phase four-leg inverter topology is adopted. Compared with the traditional three-phase combined, capacitor splitting and connected transformer inverter topology, it has the advantages of flexible control, high bus voltage utilization, avoiding the use of formation transformer at the connection midpoint, greatly reducing the volume weight of the inverter, reducing the occupancy of the limited volume of various weapon systems, so it has been widely studied [3].

The control strategy determines the output performance and load capacity of the three-phase four-leg inverter. In this paper, the output voltage and the filter inductance current of the inverter are decomposed into positive sequence, negative sequence and zero sequence components respectively by using the sequencing decomposition algorithm, and the coupling terms in the dq rotating coordinate system are decoupled by the feedforward decoupling method, and the components are transformed into DC variables, double closed-loop PI control without static error is realized [4]. The inverter can output symmetrical three-phase voltage stably under various load conditions, and the THD of each phase load voltage is small, which is verified by simulation and experiment.

Mathematical Model of Three-phase Four leg Inverter Topology

As shown in Figure 1, the three-phase four-leg inverter topology adds a leg to the traditional three-phase three-leg topology, which connects the neutral point of the three-phase load with the middle point of the fourth leg through the inductance $L_n$, providing a path for zero-sequence current.
under unbalanced load. DC bus voltage is $U_{dc}$, $L$ and $C$ are filter inductance and capacitance, $R$ is equivalent resistance load, $u_a$, $u_b$, $u_c$ are three-phase load voltage, $i_{La}$, $i_{Lb}$, $i_{Lc}$ are three-phase filter inductance current[5].

According to Kirchhoff's law, the analytical model of three-phase four-leg inverter topology in abc natural coordinate is established, then it is transformed into dq synchronous rotating coordinate. The new mathematical model is as follows:

$$
\begin{align}
    L \frac{di_d}{dt} &= u_a \cdot d_a - u_r + \omega L i_q \\
    L \frac{di_q}{dt} &= u_a \cdot d_q - u_r - \omega L i_d \\
    C \frac{du_d}{dt} &= i_a - i_d + \omega Cu_q \\
    C \frac{du_q}{dt} &= i_a - i_q - \omega Cu_d \\
    (L + 3L_n) \frac{di_0}{dt} &= U_{dc} - u_0 - u_r,
\end{align}
$$

In Eq. 1, $d$, $i_d$, $i_q$, $u$ denote the conduction ratio, inductance current, load current and load voltage respectively, subscript $d$, $q$, 0 denote the components of each physical quantity on the $d$, $q$, and 0 axes. According to the model established in the dq synchronous rotating coordinate, the equivalent circuit model of the three-phase four-leg inverter topology can be obtained as is shown in Figure 2. It can be found that the physical quantities of $d$ and $q$ axes are coupled, which is not conducive to the design and implementation of the control system, and the control effect is poor [6].
Sequence Decomposition Algorithm and Feedforward Decoupling Control Method

Symmetrical Component Method

According to the principle of symmetrical component method, any set of asymmetric vectors (such as three-phase voltage and three-phase current) can be decomposed into the sum of positive, negative and zero sequence components. The most common algorithm of symmetric component method is:

\[ x_{ik} = C_k \cdot \bar{x}_i \ (k=p,n,0; \ i=a,b,c) \]  

(2)

In Eq. 2, \( C_k \) represents the transformation matrix, all the transformation matrix can be obtained:

\[ C_p = \frac{1}{3} \begin{bmatrix} 1 & \alpha & \alpha^2 \\ \alpha^2 & 1 & \alpha \\ \alpha & \alpha^2 & 1 \end{bmatrix}, \quad C_n = \frac{1}{3} \begin{bmatrix} 1 & \alpha^2 & \alpha \\ \alpha & 1 & \alpha^2 \\ \alpha^2 & \alpha & 1 \end{bmatrix}, \quad C_0 = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}, \quad \alpha = e^{j\frac{2\pi}{3}}. \]

Because the zero sequence component is transformed into a set of vector with the same frequency, phase and amplitude by the transformation matrix, the vector can not be substituted into the synchronous rotating coordinate for transformation, which is not conducive to the design of the control system. Therefore, it is necessary to deal with the zero-sequence component specially. The vector \( \bar{x}_{bo} \) rotates clockwise 120 degrees and the vector \( \bar{x}_{o} \) rotates counterclockwise 120 degrees. That is to say, a set of three-phase symmetrical zero sequence components is constructed, which can be converted into the dq synchronous rotating coordinate. The new zero sequence component can be obtained by matrix \( C'_0 \) transformation:

\[ C'_0 = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ \alpha^2 & \alpha & \alpha^2 \\ \alpha & \alpha^2 & \alpha \end{bmatrix} \]

(3)

By substituting the formula \( \alpha = e^{j\frac{2\pi}{3}} \) into the transformation matrix \( C_p \), we can get:

\[ \begin{bmatrix} x_{op} \\ x_{on} \\ x_{on} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ -\frac{1}{2} & 1 & -\frac{1}{2} \\ -\frac{1}{2} & -\frac{1}{2} & 1 \end{bmatrix} \begin{bmatrix} 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ \frac{\sqrt{3}}{2} & 0 & -\frac{\sqrt{3}}{2} \\ -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & 0 \end{bmatrix} \begin{bmatrix} x_b \\ x_c \\ x_a \end{bmatrix} \]

(4)

The positive sequence component can be obtained by the sequencing module constructed according to Eq. 4. The physical meaning of \( -j \) is 90 degrees lag. It can be realized by saving the value of the first quarter period to participate in the subsequent operation. In digital signal processor, the lag of 90 degrees can be achieved by digital bandpass filter. The 3-phase symmetric negative sequence and zero sequence component can be obtained according to the same principle based on the transformation matrix.

Feedforward Decoupling Control Method

Taking the three-phase asymmetric load voltage of the inverter as an example, the sequence algorithm can decompose it into three-phase symmetrical positive, negative and zero sequence components:

\[ u = u_p + u_n + u_0 \]

\[ u_p = U_{mi} \begin{bmatrix} \sin(\omega t + \varphi_p) \\ \sin(\omega t - 2\pi/3 + \varphi_p) \\ \sin(\omega t + 2\pi/3 + \varphi_p) \end{bmatrix}, \quad u_n = U_{mi} \begin{bmatrix} \sin(\omega t + \varphi_n) \\ \sin(\omega t + 2\pi/3 + \varphi_n) \\ \sin(\omega t - 2\pi/3 + \varphi_n) \end{bmatrix}, \quad u_0 = U_{mi} \begin{bmatrix} \sin(\omega t + \varphi_0) \\ \sin(\omega t + 2\pi/3 + \varphi_0) \\ \sin(\omega t - 2\pi/3 + \varphi_0) \end{bmatrix} \]

\( U_{mi}, \ \varphi_i (i=p,n,0) \) represent the voltage amplitude and initial phase of positive, negative sequence and zero sequence component respectively.
The transformation matrix of the abc static coordinate to the forward dq rotation coordinate is $T_p$. The rotation angular velocity of $\omega t$ for forward dq coordinate corresponds to the fundamental frequency of the positive voltage sequence component. The positive and negative sequence components in forward dq coordinate system can be obtained through coordinate transformation:

$$T_p = \frac{2}{3} \begin{bmatrix} \cos \omega t & \cos(\omega t - 2\pi/3) & \cos(\omega t + 2\pi/3) \\ -\sin \omega t & -\sin(\omega t - 2\pi/3) & -\sin(\omega t + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} u_{dP} \\ u_{oP} \\ u_{nP} \end{bmatrix} = U_{mP} \begin{bmatrix} \sin \varphi_p \\ -\cos \varphi_p \end{bmatrix}$$

(6)

From the analysis of Eq. 6, the positive sequence becomes a DC variable, the PI controller can be adjusted without static error, while the negative sequence component becomes an AC variable with a frequency of $2\omega t$, which is not conducive to the realization of the PI control without static error.

In order to adjust the negative sequence without static error, a negative dq rotating coordinate is established, and the transformation matrix is $T_n$. The positive and negative sequence are as follows:

$$T_n = \frac{2}{3} \begin{bmatrix} \cos \omega t & \cos(\omega t + 2\pi/3) & \cos(\omega t - 2\pi/3) \\ -\sin \omega t & -\sin(\omega t + 2\pi/3) & -\sin(\omega t - 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} u_{dN} \\ u_{oN} \\ u_{nN} \end{bmatrix} = U_{mN} \begin{bmatrix} \sin(2\omega t + \varphi_n) \\ \cos(2\omega t + \varphi_n) \end{bmatrix}$$

(7)

From the analysis of Eq. 7, the negative sequence component becomes an AC variable in the negative dq rotating coordinate, it can be adjusted without static error by PI controller.

The zero sequence component is transformed by the same method as the positive sequence component, and the positive, negative and zero sequence components of the inductance current can be transformed by the same method as above. It is easier to realize the double closed loop PI control of the voltage outer loop and the current inner loop by converting the voltage and current into the DC variables, which makes the output response of the control system more rapid and accurate.

The control equations of positive sequence’s voltage outer loop and current inner loop are:

$$\begin{align*}
\dot{i}_{dP} &= \left( k_{sp} + k_{su} \right) (u_{d, ref} - u_d) - \omega C u_q \\
\dot{i}_{oP} &= \left( k_{sp} + k_{su} \right) (u_{o, ref} - u_o) + \omega C u_d \\
u_{dP} &= \left( k_{sp} + k_{su} \right) (i_{dP} - i_d) - \omega L i_{eq} + u_d \\
u_{oP} &= \left( k_{sp} + k_{su} \right) (i_{oP} - i_o) + \omega L i_{eq} + u_q
\end{align*}$$

(8)

The control methods of negative and zero sequence component are similar to those of positive sequence component. The decoupling control block diagram of the system is shown in Figure 3.

![Figure 3. The block diagram of control system.](image-url)
Simulation Analysis
To verify the feasibility of the control system, MATLAB/Simulink simulation software is used to simulate and analyze the control scheme. The specific simulation parameters are as follows:

The rated power of the inverter is 18kW, the rated output voltage and frequency is 220V/50Hz, the DC bus voltage is 650V, the switching frequency of the power transistor is 10kHz, the filter inductance is 8mH, the filter capacitance is 15 μF, and the middle line inductance is 5mH.

Figure 4 shows the simulation waveforms of three-phase load voltage, current and midline current under unbalanced load conditions (A-phase 10Ω pure resistance, B-phase 20Ω+10mH resistance inductive load, C-phase 10Ω+50 μF resistance-capacitive load):

![Figure 4. The simulation waveform of three-phase load voltage, current and midline inductance current.](image)

It can be seen clearly that the voltage symmetry of the three-phase load is good, and the THD is 1.32%. The waveform distortion is obvious only at the beginning of the system, but the duration is less than 5 ms. The system responds quickly. At the same time, the neutral current produced by the unbalanced load is not zero through the middle line. It is proved that the fourth leg has a control effect on the neutral current produced by the unbalanced load. The effectiveness of the algorithm for three-phase four leg inverter is verified.

Experimental Verification
In order to verify the feasibility of the algorithm, DSP is used to realize the decoupling algorithm, PI control without static error and space vector pulse width modulation strategy. The main parameters of the experimental prototype are: rated output power 18kW, the DC bus voltage is 650V, the rated value and frequency of the output voltage are 220V/50Hz, the switching frequency of the power transistor switching frequency is 15kHz, the inductance and capacitance of the output filter are 10mH and 20μF respectively, and the inductance of the middle line is 5mH.

The load capability of the inverter under unbalanced load is tested, and the waveforms of the three-phase load voltage and current and the middle line current of the prototype are recorded. Figure 5 shows the waveforms of three-phase load voltage, current and midline current recorded by oscilloscope under the unbalanced load of resistance, inductance and capacitance respectively.

![Figure 5. The waveform of three-phase load voltage, current and midline inductance.](image)

According to the waveform analysis of Figure 5, under three-phase unbalanced resistance-inductance and capacitance load, the three-phase load voltage is symmetrical, the load current and the middle line current pulsate slightly due to the influence of inductance, but the total harmonic distortion rate of the output voltage waveform is still less than 3%, which meets the military power standards.
Conclusion

In this paper, the method of sequence decomposition and feedforward decoupling control is applied to load voltage and inductance current control of three-phase four-leg inverter. The double closed-loop PI control with no static error is realized, and the load-carrying capacity of the inverter is verified by simulation and experiment under three-phase unbalanced load. Simulation and experimental data show that the inverter has a strong unbalanced load capacity, and the THD of each phase voltage is less than 3%, meeting the military power standards, it has a great practical value.

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