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An Optimized Control Method for Four-leg Inverter

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Abstract: This paper studies three-phase four-leg inverterand conduct the system analysis under the situations of balanced and unbalanced load. Based on existing decoupling control method, this paper analyses the principle of decoupling control method and presents a new optimized digital control method. This optimized method uses the last calculation result to compensate the error and simplifies the control. It only needs to sample the neutral line current and the voltage sampling of load is not necessary. This paper conducts simulation and experiment to verify the control method, and the performance is perfect.

Key words: Four-leg Inverter; Unbalanced load; decoupling control

1. INTRODUCTION

In the design schemeofthe three-phase four-wire systemoutput inverter, the structure of four-leg has been widely used forthe advantages of the low utilization of direct voltage, the strong ability with unbalanced load, the flexible methods of control and the number of power devices used less etc. The structure has been widely used in asymmetrical three-phase load or the nonlinear load, the three-phase current is thereforeunbalance and it will generate the unbalanced three-phase voltage[1]. In this system structure, the function of the fourth bridge is to make the midpoint voltage of three-phase load to zero by controlling the neutral line current, so as to make the voltage of three-phase load equilibrium [2]. We have to series line inductance in the midline for controlling the neutral current, but the control of the three-phase four-wire system became very complicated, as the neutral current is the sum of three-phase current and the midline inductor will be coupledwith three-phase filter inductor [3]. At present, there are mainly four kinds control methods: decoupling control, the SVM control, carrier PWM control, error judgment control method. Aiming at decoupling

control method, this paper puts forward an optimized control strategy which improves the control effect of four-leg [4-9].

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1. Three-phase equilibriumsystem analysis

Fig. 1 is the schematic diagram of three-phase four-leg inverter. The circuit is composed of three-phase bridge arms A, B, C and neutral line bridge arm. The capacity values of the two capacitances on the DC bus are equal and halfway point of them is choseas reference ground. Three-phase outputsusethe LC smoothing, and the filter inductorsare,, respectively,the midline inductor isL_N, the voltage of the midpoint load M is ,the voltages of the three-phase loadsare,, respectively.

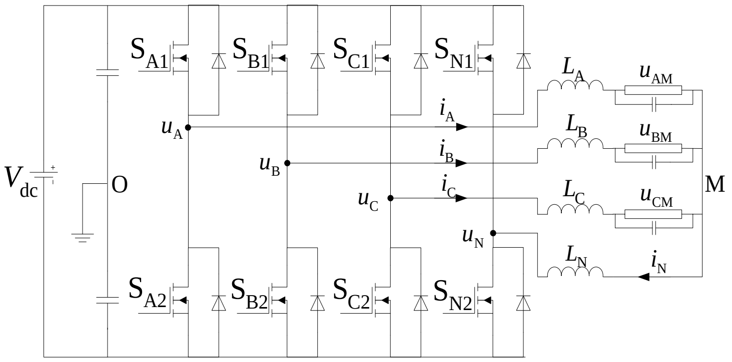

Fig.1: Diagram of Four-Leg Inverter

The switch state function is defined as Eq. (1).

$$S_i = \begin{cases} 1 & \mathrm{S}_{i1}\mathrm{ON}, \mathrm{S}_{i2}\mathrm{OFF} \\ 0 & \mathrm{S}_{i1}\mathrm{OFF}, \mathrm{S}_{i2}\mathrm{ON} \end{cases} \qquad i = \mathrm{A,B,C,N} \tag{1}$$

When is zero, the output of i bridge arm is 0.5, when is one, the output of i bridge arm is-0.5. Therefore, the difference values of the each bridge armoutput voltage and neutral line bridge arm is Eq. (2).

$$u_{i\mathrm{N}} = \left(S_i - S_\mathrm{N}\right)V_\mathrm{dc} \qquad i = \mathrm{A,B,C} \tag{2}$$

According toKVL law we can get Eq. (3).

$$\begin{cases} u_\mathrm{AN} = u_\mathrm{A} - u_\mathrm{N} = L_\mathrm{A}\dfrac{di_\mathrm{A}}{dt} + u_\mathrm{AM} + L_\mathrm{N}\dfrac{di_\mathrm{N}}{dt} \\ u_\mathrm{BN} = u_\mathrm{B} - u_\mathrm{N} = L_\mathrm{B}\dfrac{di_\mathrm{B}}{dt} + u_\mathrm{BM} + L_\mathrm{N}\dfrac{di_\mathrm{N}}{dt} \\ u_\mathrm{CN} = u_\mathrm{C} - u_\mathrm{N} = L_\mathrm{C}\dfrac{di_\mathrm{C}}{dt} + u_\mathrm{CM} + L_\mathrm{N}\dfrac{di_\mathrm{N}}{dt} \end{cases} \tag{3}$$

Under the stable state, the voltage of the three-phaseload is balance. If the output of the neutral linebridge arm,then the midpoint of the load voltage,As the Eq. (4) shows.

$$\begin{cases} u_{\mathrm{AM}} = U_{\max} \sin(\omega \mathrm{t}) \\ u_{\mathrm{BM}} = U_{\max} \sin(\omega \mathrm{t} - \dfrac{2\pi}{3}) \\ u_{\mathrm{CM}} = U_{\max} \sin(\omega \mathrm{t} + \dfrac{2\pi}{3}) \end{cases} \tag{4}$$

Now the output voltages of the three-phase bridge armsare Eq. (5).

$$\begin{cases} u_{\mathrm{A}} = L_{\mathrm{A}} \dfrac{di_{\mathrm{A}}}{dt} + u_{\mathrm{AM}} \\ u_{\mathrm{B}} = L_{\mathrm{B}} \dfrac{di_{\mathrm{B}}}{dt} + u_{\mathrm{BM}} \\ u_{\mathrm{C}} = L_{\mathrm{C}} \dfrac{di_{\mathrm{C}}}{dt} + u_{\mathrm{CM}} \end{cases} \tag{5}$$

For the unbalance load, , andis symmetrical, andthree-phase currentsare also symmetrical. Therefore, three phase modulation waves , and are also symmetricalwhen the PWM waveform is produced to control the three-phase bridge arm, and the vectorsynthesis is a circle. But when the three-phase is asymmetric,the three-phase load voltage and current are no longer symmetrical;the synthesis of three phase modulation wave vector becomes the oval. Thus it is unable to realize three-phase independent control by controlling the neutral line bridge arm .

2. System analysis of three-phase imbalance state

When the three-phase is imbalance, the midpoint of three-phase load M's potential is not zero, then the Eq.(5)turns into Eq. (6).

$$\begin{cases} u_{\mathrm{A}} = L_{\mathrm{A}} \dfrac{di_{\mathrm{A}}}{dt} + u_{\mathrm{AM}} + u_{\mathrm{M}} \\ u_{\mathrm{B}} = L_{\mathrm{B}} \dfrac{di_{\mathrm{B}}}{dt} + u_{\mathrm{BM}} + u_{\mathrm{M}} \\ u_{\mathrm{C}} = L_{\mathrm{C}} \dfrac{di_{\mathrm{C}}}{dt} + u_{\mathrm{CM}} + u_{\mathrm{M}} \end{cases} \tag{6}$$

In order to meet=0, we get Eq. (7).

$$u_{\mathrm{N}} = u_{\mathrm{M}} - L_{\mathrm{N}} \frac{di_{\mathrm{N}}}{dt} \tag{7}$$

Assuming that three-phase filtering inductance is equal, we get Eq. (8).

$$L_{\mathrm{A}} = L_{\mathrm{B}} = L_{\mathrm{C}} = L \tag{8}$$

FromEq.(6), we get Eq. (9).

$$u_{\mathrm{A}}+u_{\mathrm{B}}+u_{\mathrm{C}}=u_{\mathrm{AM}}+u_{\mathrm{BM}}+u_{\mathrm{CM}}+3\left(L\frac{d\left(i_{\mathrm{A}}+i_{\mathrm{B}}+i_{\mathrm{C}}\right)}{dt}+u_{\mathrm{M}}\right) \tag{9}$$

If the three phase control is independent, the three-phase modulation waves will reach three phase equilibrium, so,at the same time it satisfies the, by the Eq.(7)and Eq. (9), we get the Eq. (10)

$$u_{\mathrm{N}}=-\frac{1}{3}\left(u_{\mathrm{AM}}+u_{\mathrm{BM}}+u_{\mathrm{CM}}\right)-\left(\frac{L}{3}+L_{\mathrm{N}}\right)\frac{di_{\mathrm{N}}}{dt} \tag{10}$$

The Eq.(10)is the output voltage of the neutrallinebridge arm when the three-phase load is imbalance.

3. The Optimized Digital Control Method

In the last section, we have discussed the output voltage of the neutral line bridge arm under the imbalance load. FromEq.(10) we can see that the control of neutral line voltage is complex as it involves differential operation so we choose a digital control method to control. At the same time, considered of the Eq. (10) contains differential operation, when faced with a phase change in load, $\frac{di_{\mathrm{N}}}{dt}$ will became bigger; It will affect the stability of the system, so we need to transform differential operation into integral operation. Because the result of the integral operation lags 180°than differential operation, and the amplitude is of differential operation, so we use the in placeof ,and we can obtain Eq. (11).

$$u_{\mathrm{N}}=-\frac{1}{3}\left(u_{\mathrm{AM}}+u_{\mathrm{BM}}+u_{\mathrm{CM}}\right)+\left(\frac{L}{3}+L_{\mathrm{N}}\right)\omega^{2}\int i_{\mathrm{N}}dt \tag{11}$$

Let $\frac{L}{3}+L_{\mathrm{N}}=\alpha$,and put Eq.(11)discretization is Eq. (12).

$$u_{\mathrm{N}}(k)=-\frac{1}{3}\left[u_{\mathrm{AM}}(k)+u_{\mathrm{BM}}(k)+u_{\mathrm{CM}}(k)\right]+\alpha\omega^{2}\sum T_{s}i_{\mathrm{N}}(k) \tag{12}$$

Under the actual situation, there will always be errors between differential and integral calculations, in order to compensate the error, we optimizeEq.(12) and get Eq. (13)

$$u_{\mathrm{N}}(k)=\beta(k)\left[u_{\mathrm{AM}}(k)+u_{\mathrm{BM}}(k)+u_{\mathrm{CM}}(k)\right]+\alpha\omega^{2}\sum T_{s}i_{\mathrm{N}}(k) \tag{13}$$

The Eq.(13)compensates the errors by multiply a coefficienton the sum of three-phase voltages. We make the real optimization to improve the accuracy of the compensation. Assuming is continuous, that the last calculation of $u_{\mathrm{N}}(k-1)$ and $u_{\mathrm{N}}(k)$ is not mutated, then we can use the last calculation results to optimize, just like the Eq. (14) shows.

$$\beta(k)=\frac{u_{\mathrm{N}}(k-1)-\alpha\omega^{2}\sum T_{s}i_{\mathrm{N}}(k)+\alpha\left[\frac{i_{\mathrm{N}}(k)-i_{\mathrm{N}}(k-1)}{Ts}-\omega^{2}\sum T_{s}i_{\mathrm{N}}(k)\right]}{\left[u_{\mathrm{AM}}(k)+u_{\mathrm{BM}}(k)+u_{\mathrm{CM}}(k)\right]} \tag{14}$$

The Eq.(14)use the previous calculations to optimize the coefficient, and compensate the error of differential and integral calculations. We can get Eq. (15) by arranging Eq. (14).

$$\beta(k)=\frac{u_{\mathrm{N}}(k-1)-\alpha\left[2\omega^{2}\sum T_{s}i_{\mathrm{N}}(k)-\frac{i_{\mathrm{N}}(k)-i_{\mathrm{N}}(k-1)}{T_{s}}\right]}{u_{\mathrm{AM}}(k)+u_{\mathrm{BM}}(k)+u_{\mathrm{CM}}(k)} \tag{15}$$

Then we take Eq.(15) to Eq. (13) for substitution.

$$u_{\mathrm{N}}(k)=u_{\mathrm{N}}(k-1)+\alpha\left[\frac{i_{\mathrm{N}}(k)-i_{\mathrm{N}}(k-1)}{T_{s}}-\omega^{2}\sum T_{s}i_{\mathrm{N}}(k)\right] \tag{16}$$

The Eq.(16)is the final output voltage of neutral line bridge arm, from the Eq.(16),we can see that this method can control the output voltage of the neutral line bridge arm though sampling the current on the center line. It greatly simplifies thecontrol algorithm and has nothing to do with the voltage of load,and realizes the decoupling control.

5. Simulation and experiment

5.1 The Result of Simulation

We set up the simulation model, simulation parameter is DC 600V, the output filter inductance is 3Mh, the filter capacitor is 10uF, the switching frequency is 10 KHz.

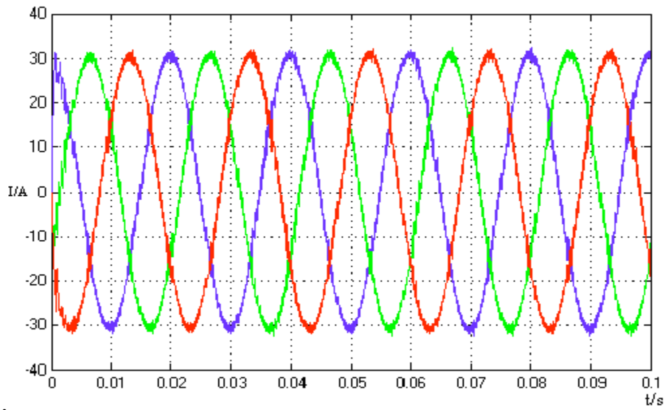

Fig.2:The output current waveforms of inductance when three-phase loadsarebalance

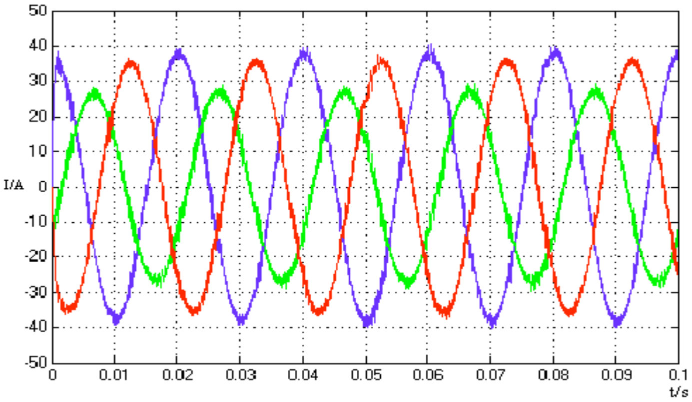

Fig.3:The output current waveforms of inductance when three-phase loadsare imbalance

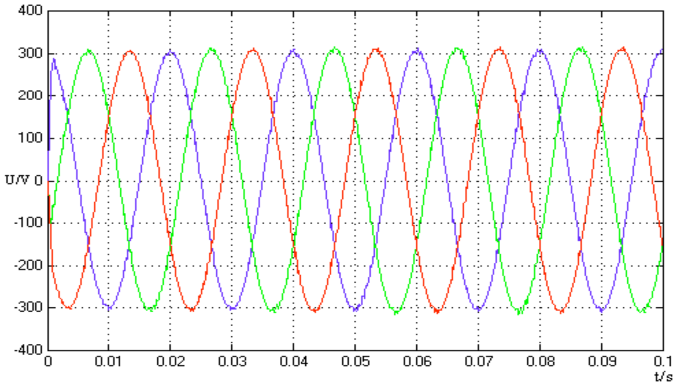

Fig.4:The output voltage waveforms of inductance when three-phase loadsare imbalance

When the load is unbalanced the imbalance rate is: phase A is 20%, phase B is 30%. From the waveform analysis of Fig. 2, Fig. 3 and Fig. 4 we can know that the output voltagesare always maintaining symmetry when the loads are imbalance,and it shows that the simulation algorithm is feasible.

3.2 Experimentresult

In order to further verify this control methodproposed, we set up an off-grid three-phase four-leg inverter experiment platform on the basis ofTMS320F28335. The parameter of this50kw three-phase four-leg inverter is:WPAP330150 AC network AVDD and 150kwDC AVDD, its maximum DC power and AC power are both150kw,DC open-circuit voltage is 1000v. YOKOGAWADL850 oscillographic recorder has100MS/s speed, high resolution of 16 bits and isolation of 1kV.

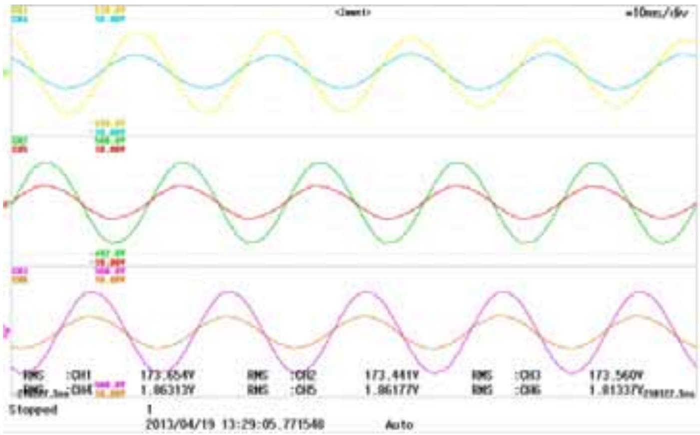

Fig.5: The output voltage and current waveforms of the loads when the threephasesare balance

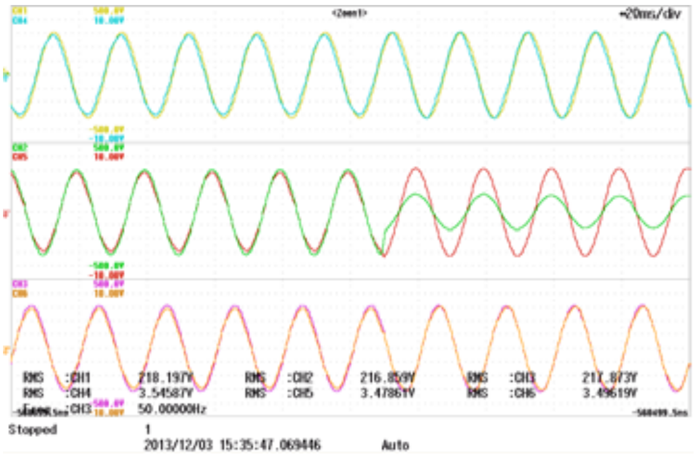

Fig.6:The output voltage and current waveforms of the loads when the threephases are imbalance

Fig.5shows the output waveforms of the three-phase voltages and currents when each phase of three-phase loads is 15KW. It obviously that three-phase voltage and currentmaintain symmetry and each phase has 120^{o}difference with the other. The Fig.6shows the waveforms of voltages and currents for unbalanced loads, at the beginning,A, B and C threephases loads are all 15KW, and then A and Cremain unchanged, the load of phase B is changed from the original 15 kw to 6 kw, the current of phase Bis changed from the original 68A to 27.3A. Can be seen from the diagram, the three-phase voltage amplitudes and phases remain unchanged when the loads switchover. From the analysis, we can know that when the three-phase is imbalance, the three-phase output inductor currents will be asymmetrical, and there will be a current flowing through the fourth bridge arm.So we achieve the expected control effect. Through the analysis of experimentresults, we verified that the three-phase four-leg inverter has the ability to carry unbalanced loads. To put it another way,the three-phase four-leg inverteris stronger in stability that it canstill output symmetrical three-phase voltages under the condition of unbalanced loads.

5. Conclusions

This paper analyzes the decoupling control algorithm of the three-phase four-leg, and optimizes the decoupling algorithm. The optimized method uses the last result to compensate the error of current calculation. This method only needs to sample the neutral line current and the voltage sampling of load is not necessary, and simplifies the control. This paper also conducts simulation and experiment to verify the control method, and the performance is perfect.

4. References

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6.Vitae

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