Neutral Point Voltage Analysis for Three-Phase Four-Wire Three-Level Grid-Connected Converter Based on CBPWM Strategy

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This work was supported in part by the Fundamental Research Funds for the Central Universities of China under Grant JZ2019HGTB0074 and Grant PA2019GDJP0080, and in part by the Tianchang-HFUT Industrial Innovation Lead Key Funds Project under Grant JZ2019AHDS0002 and Grant JZ2020YDZJ0124.

ABSTRACT In order to ensure the safe and reliable operation of three-phase four-wire (3P4W) three-level grid-connected converter (TL-GCC) from the point of view of neutral point voltage (NPV) self-equilibrium, a sufficient condition based on carrier-based pulse width modulation (CBPWM) strategy is presented. The analysis of NPV self-equilibrium based on the sufficient condition is presented while different forms of current are outputted. Then, a novel active control method based on producing zero sequence direct current is proposed to balance NPV. The theoretical analysis of NPV self-equilibrium as well as the effectiveness of the proposed active NPV control method are verified by experimental results.

INDEX TERMS Three-phase four-wire three-level converter, NPV self-equilibrium, CBPWM strategy, active control of NPV.

I. INTRODUCTION
With the rapid development of new energy fields such as photovoltaic and wind power generation, grid-connected converter (GCC), as a core component of new energy generation, converts the generated electricity into appropriate electricity that can be fed into the grid [1]. Besides, GCC is also widely used in industrial fields, which can compensate for various nonlinear load currents and play a key role in energy saving of power resources.

According to the level of the dc bus, GCC can be divided into two-level converter and multi-level converter [2], [3]. Compared with two-level converter, three-level converter are now widely used because of low current harmonic components, low voltage stress and switching loss of power device [4], [5]. However, the characteristic of the three-level converter suffers from the problem of neutral point voltage (NPV) balance. The imbalanced NPV will result in the increment of output voltage harmonic components in the low and medium frequency bands. In severe cases, the imbalanced NPV may lead to the malfunction of the power device due to the increased voltage stress [6], [7].

The NPV self-equilibrium is a precondition for a three-level GCC (TL-GCC). In [8], the NPV self-equilibrium of TL-GCC has been proved under steady-state operation, but the analysis is applicable only to the three-phase three-wire (3P3W) system, rather than three-phase four-wire (3P4W) system. In fact, compared with 3P3W system, 3P4W system has the advantages of lightning protection, insulation, fault tolerant ability and electromagnetic compatibility improvement in many practical applications [9], [10]. Moreover, for a GCC, it is important not only to achieve reliable grid connection, but also to realize the transmission of various forms of three-phase current into the grid. Unfortunately, in the existing literatures, the NPV self-equilibrium characteristic of the 3P4W TL-GCC with various current forms has not been discussed before, which is a fundamental issue to be solved for practical applications.

For 3P4W TL-GCC, there are usually two topologies. One is three-leg topology and the other is four-leg topology. Considering the size and cost of the system, the three-leg topology is preferred in industrial application. Up to now, there is no literature on NPV self-equilibrium for 3P4W TL-GCC.
with three-leg. Moreover, considering the output current form in different applications, such as the grid-connected renewable energy generation (sine fundamental current) and active power filter (harmonics current), the NPV self-equilibrium becomes more complicated. So far, the sufficient condition of NPV self-equilibrium is not revealed for 3P4W TL-GCC with three-leg.

In practice, a certain offset will appear on NPV caused by inconsistent upper and lower capacitances or asymmetric rate of charge and discharge of the capacitors. Therefore, the active NPV control method is usually needed to achieve voltage balance between the upper and lower capacitors. At present, active NPV control methods are usually achieved by improving modulation algorithm. In [11]–[13], NPV balance is implemented by injecting zero sequence voltage (ZSV) into the modulated wave based on carrier-based pulse width modulation (CBPWM) strategy. For space vector PWM (SVPWM), NPV is regulated by adjusting the distribution of the redundant small vector pairs, because they have opposite effect on NPV [14]–[16]. In [17], a virtual SVPWM (VSVPWM) is proposed to effectively keep NPV balance under any operation conditions. Discontinuous PWM (DPWM) strategy that can eliminate dc offset on NPV is used in [18]. However, all the above strategies are only applicable to 3P3W system. In [19], [20], methods are proposed to decrease or eliminate ac ripples on NPV in 3P4W system, but there are few effective control methods focusing on eliminating dc offset.

In this article, a sufficient condition of NPV self-equilibrium is proposed based on CBPWM for 3P4W TL-GCC. Furthermore, an active NPV control method is obtained to effectively eliminate dc offset on NPV. The rest of this article is arranged as follows. Section 2 briefly reviews the topology of 3P4W TL-GCC including NPV characteristic. The NPV self-equilibrium is analyzed in Section 3 while different current forms are outputted. In Section 4, the corresponding experimental results about NPV self-equilibrium are presented. At present, active NPV control methods are usually used in [18]. However, all the above strategies are only applicable to 3P3W system. In [19], [20], methods are proposed to decrease or eliminate ac ripples on NPV in 3P4W system, but there are few effective control methods focusing on eliminating dc offset.

In this article, a sufficient condition of NPV self-equilibrium is proposed based on CBPWM for 3P4W TL-GCC. Furthermore, an active NPV control method is obtained to effectively eliminate dc offset on NPV. The rest of this article is arranged as follows. Section 2 briefly reviews the topology of 3P4W TL-GCC including NPV characteristic. The NPV self-equilibrium is analyzed in Section 3 while different current forms are outputted. In Section 4, the simulation results about NPV self-equilibrium are presented to verify the theoretical analysis. In Section 5, a novel active NPV control method based on adding zero sequence direct current to the reference is proposed, and the method is verified by simulation. In Section 6, the corresponding experimental results are provided, where the NPV self-equilibrium and the effectiveness of the proposed active NPV control method are verified. Finally, conclusion is drawn in Section 7.

II. TOPOLOGY OF 3P4W TL-GCC

The topology of 3P4W TL-GCC is shown in Fig. 1, where $e_z$ ($z = a, b, c$) is the grid voltage of phase $z$; $i_z$ is the output current of phase $z$, $u_z$ is the output voltage of phase $z$; $L_s$ and $R_s$ are the filter inductance and its parasitic resistance; $u_{dc}$ is the voltage of DC-link. $C_1$ and $C_2$ are the upper and lower capacitors. When NPV is balanced, the voltage of upper and lower capacitors satisfies with $u_{C1} = u_{C2} = u_{dc}/2$. For 3P4W TL-GCC with three-leg, it is worth noting that the neutral point of the grid is directly connected to the neutral point of the TL-GCC.

It can be seen from Fig. 1 that when only $S_{z1}$ and $S_{z2}$ are turned on, phase $z$ is connected to the positive bus and the output voltage is $u_{C1}$ labeled as level 1. When only $S_{z2}$ and $S_{z3}$ are turned on, phase $z$ is connected to the neutral point and the output voltage is 0 labeled as level 0. When only $S_{z3}$ and $S_{z4}$ are turned on, phase $z$ is connected to the negative bus and the output voltage is $-u_{C2}$ labeled as level $-1$.

Because there is no coupling relation among the three phases, the analysis of the three-phase system can be simplified into three single-phase systems and the three-phase current can be analyzed and controlled independently. For CBPWM strategy, the switching sequences are obtained by comparing modulation voltage $u_z$ with the carrier waves, which is shown in Fig. 2. In a switching cycle $T_s$, $u_z$ and $i_z$ are considered as constant.

According to the volt-second equilibrium principle, the duty cycle of each level of phase $z$ can be expressed as:

$$
\begin{align}
    d_{z1} &= \frac{u_z}{u_{dc}/2} = d_{z0} = 1 - \frac{u_z}{u_{dc}/2}, \quad d_{z-1} = 0 \quad (u_z > 0) \\
    d_{z1} &= 0, \quad d_{z0} = 1 - \frac{u_z}{u_{dc}/2}, \quad d_{z-1} = \frac{u_z}{u_{dc}/2} \quad (u_z < 0)
\end{align}
$$

where $d_{z}(x = 1, 0, -1)$ represents the duty cycle of level $x$ of phase $z$.

Controlling NPV into a proper range is a precondition to ensure the safe and reliable operation of TL-GCC. Therefore, it is necessary to analyze the NPV characteristic. Firstly, the

![FIGURE 1. Topology of 3P4W TL-GCC.](image1)

![FIGURE 2. The principle of CBPWM strategy for TL-GCC. (a) $u_z > 0$. (b) $u_z < 0$.](image2)
Taking Fig. 3 (a) and (b) as examples, when phase $z_i$ increases or decreases. So, $k_{NP}$ is defined as:

$$k_{NP} = \frac{u_{C1} - u_{C2}}{u_{C1} + u_{C2}}$$

(2)

The available current paths of phase $z$ are shown in Fig. 3. Taking Fig. 3 (a) and (b) as examples, when phase $z$ outputs level 1, the upper capacitor discharges if $i_z > 0$ or chargers $i_z < 0$. Due to the constant DC-link voltage, NPV thus increases or decreases. So, $k_{NP}$ decreases or increases according to eq. (2). The other cases can be similarly analyzed.

Table 1 summarizes the influence of $i_z$ and $u_z$ on $k_{NP}$. It can be seen that the increase or decrease of $k_{NP}$ is only related to the direction of the phase current except level 0 which makes NPV unchanged.

| Level of phase $z$ | $i_z$ | $u_{C1}$ | $u_{C2}$ | $k_{NP}$ |
|-------------------|------|---------|---------|---------|
| 1                 | $>0$ | decrease | increase | decrease |
| 0                 | $<0$ | increase | decrease | increase |
| -1                | $>0$ | decrease | increase | decrease |
| $<0$              | remain | remain | remain | |

Furthermore, the relationship between the increment of NPV $\Delta u_{NP}$ and $i_z$ in $[\theta_1, \theta_1 + T]$ can be expressed as:

$$\Delta u_{NP} = u_{NP} \left|^{\theta_1+T}_{\theta_1} \right. = \frac{\int_{\theta_1}^{\theta_1+T} i_{NP}(\theta)d\theta}{\omega C}$$

(5)

where $C$ denotes the capacitance of the upper and lower capacitors, and $\omega$ is the angular frequency of grid voltage.

If $\Delta u_{NP} = 0$ is always satisfied under arbitrary $\theta_1$ during the interval of $T$ without using any NPV balancing algorithm, $u_{NP}$ is unchanged and NPV achieves self-equilibrium, which is a sufficient condition for TL-GCC. Then according to eq. (5), the sufficient condition of NPV self-equilibrium can be simplified as:

$$\int_{\theta_1}^{\theta_1+T} i_{NP}(\theta)d\theta = 0$$

(6)

The smaller $T$ is, the higher the fluctuation frequency of NPV is. For worst case, $T$ equals to the period of the grid, i.e. $T = 2\pi/\omega$.

As mentioned before, for 3P4W topology, it can be simplified into three single-phase systems. So, a sufficient condition based on eq. (6) can be obtained as:

$$\int_{\theta_1}^{\theta_1+T} i_{NP}(\theta)d\theta = 0 \quad (z = a, b, c)$$

(7)

Based on CBPWM strategy, the NPV self-equilibrium characteristics under different current forms are discussed in the next section.

### III. NPV SELF-EQUILIBRIUM ANALYSIS OF 3P4W TL-GCC

The continuous time model of 3P4W TL-GCC in the stationary reference frame can be expressed as:

$$u_z = e_z + R_iZ + L_i \frac{di_z}{dt}$$

(8)

The grid voltage can be expressed as:

$$\begin{align*}
e_a &= E_m \cos(\omega t) \\
e_b &= E_m \cos(\omega t - 2\pi/3) \\
e_c &= E_m \cos(\omega t - 4\pi/3)
\end{align*}$$

(9)

where $\omega t = \theta$ represents the phase angle of grid voltage. In this section, the NPV self-equilibrium characteristics are analyzed while fundamental current, odd harmonic current and zero sequence direct current are respectively outputted.
A. FUNDAMENTAL CURRENT

For photovoltaic GCC, static var generator and so on, fundamental current is usually outputted. The three-phase current can be expressed as:

\[
\begin{aligned}
i_a &= I_{ma} \cos(\omega t + \varphi_a) \\
i_b &= I_{mb} \cos(\omega t + \varphi_b) \\
i_c &= I_{mc} \cos(\omega t + \varphi_c)
\end{aligned}
\] (10)

where \(I_{ma}\) and \(\varphi_c\) represent the amplitude and power factor angle of phase \(a\) current. For universality, the asymmetric three-phase currents are considered.

Taking phase \(a\) as an example, by substituting (9) and (10) into (8), \(u_a\) can be expressed as:

\[
u_a = E_m \cos(\omega t) + R_i I_{ma} \cos(\omega t + \varphi_a) - \omega L_i I_{ma} \sin(\omega t + \varphi_a)\] (11)

At \(\omega t = \theta_1\) and \(\theta_1 + \pi\), the phase current can be written as:

\[
\begin{aligned}
i_a (\theta_1) &= I_{ma} \cos(\theta_1 + \varphi_a) \\
i_a (\theta_1 + \pi) &= I_{ma} \cos(\theta_1 + \pi + \varphi_a)
\end{aligned}
\] (12)

Whatever the value of \(\theta_1\) is, from (12), it yields:

\[
i_a (\theta_1) = -i_a (\theta_1 + \pi)\] (13)

Similarly, it has:

\[
e_a (\theta_1) = -e_a (\theta_1 + \pi), \quad \frac{di_a}{dt} \bigg|_{\theta=\theta_1} = -\frac{di_a}{dt} \bigg|_{\theta=\theta_1+\pi}\] (14)

Substituting (13) and (14) into (11), it yields:

\[
u_a (\theta_1) = -u_a (\theta_1 + \pi)\] (15)

Combining (3), (13) and (15), it found:

\[
i_{aNP}(\theta_1) = -i_{aNP}(\theta_1 + \pi)\] (16)

By integrating \(i_{aNP}\) in the interval \([\theta_1, \theta_1+2\pi]\), the following equation is always satisfied:

\[
\int_{\theta_1}^{\theta_1+2\pi} i_{aNP}(\theta)d\theta = \int_{\theta_1}^{\theta_1+\pi} (i_{aNP}(\theta) + i_{aNP}(\theta + \pi))d\theta = 0\] (17)

The same results can be obtained for the other two phases:

\[
\int_{\theta_1}^{\theta_1+2\pi} i_{bNP}(\theta)d\theta = 0, \quad \int_{\theta_1}^{\theta_1+2\pi} i_{cNP}(\theta)d\theta = 0\] (18)

From the above analysis, it can be seen that the sufficient condition of NPV self-equilibrium given in (7) is always satisfied while outputting asymmetric fundamental current, and the NPV self-equilibrium period is \(2\pi\), which means that NPV fluctuates with fundamental frequency.

It is noted that when the three-phase currents are symmetric, the NPV self-equilibrium becomes a little different. The symmetric three-phase currents can be expressed as:

\[
\begin{aligned}
i_a &= I_m \cos(\omega t + \varphi) \\
i_b &= I_m \cos(\omega t + \varphi - 2\pi/3) \\
i_c &= I_m \cos(\omega t + \varphi - 4\pi/3)
\end{aligned}
\] (19)

Whatever the value of \(\theta_1\) is, when \(\omega t = \theta_1\) and \(\theta_1 + \pi/3\), the currents of phase \(a\) and phase \(c\) always satisfy with:

\[
i_a(\theta_1) = -i_c(\theta_1 + \pi/3)\] (20)

Then, it has

\[
e_a(\theta_1) = -e_c(\theta_1 + \pi/3), \quad \frac{di_a}{dt} \bigg|_{\theta=\theta_1} = -\frac{di_c}{dt} \bigg|_{\theta=\theta_1+\pi/3}\] (21)

Substituting (20) and (21) into (8), it yields:

\[
u_a(\theta_1) = -u_c(\theta_1 + \pi/3)\] (22)

Combining (3), (20) and (22), it has:

\[
i_{aNP}(\theta_1) = -i_{cNP}(\theta_1 + \pi/3)\] (23)

Similarly, it also has:

\[
i_{bNP}(\theta_1) = -i_{aNP}(\theta_1 + \pi/3), \quad i_{cNP}(\theta_1) = -i_{bNP}(\theta_1 + \pi/3)\] (24)

According to (23) and (24), the integral of \(i_{NP}\) in the interval \([\theta_1, \theta_1+2\pi]\) can be simplified as:

\[
\int_{\theta_1}^{\theta_1+\pi} i_{NP}(\theta)d\theta = \int_{\theta_1}^{\theta_1+\pi} (i_{aNP}(\theta) + i_{cNP}(\theta + \pi/3))d\theta + \int_{\theta_1}^{\theta_1+\pi} (i_{bNP}(\theta) + i_{aNP}(\theta + \pi/3))d\theta + \int_{\theta_1}^{\theta_1+\pi} (i_{cNP}(\theta) + i_{bNP}(\theta + \pi/3))d\theta = 0\] (25)

From eq. (25), it can be seen that the sufficient condition of NPV self-equilibrium given in eq. (6) is satisfied while outputting symmetric fundamental current, and the period of NPV self-equilibrium is \(2\pi/3\), which means that NPV fluctuates with triple fundamental frequency.

B. ODD HARMONIC CURRENT

For active power filter applications, odd harmonic current is usually outputted. In this case, the three-phase currents can be expressed as:

\[
\begin{aligned}
i_a &= \sum_{n=2k+1, k \in \mathbb{N}} I_{ma,n} \cos(n\omega t + \varphi_{a,n}) \\
i_b &= \sum_{n=2k+1, k \in \mathbb{N}} I_{mb,n} \cos(n\omega t + \varphi_{b,n}) \\
i_c &= \sum_{n=2k+1, k \in \mathbb{N}} I_{mc,n} \cos(n\omega t + \varphi_{c,n})
\end{aligned}\] (26)

Taking phase \(a\) as an example, when \(\omega t = \theta_1\) and \(\theta_1 + \pi\), it has:

\[
i_a(\theta_1) = -i_a(\theta_1 + \pi), \quad \frac{di_a}{dt} \bigg|_{\theta=\theta_1} = -\frac{di_a}{dt} \bigg|_{\theta=\theta_1+\pi}\] (27)

Since the form of grid voltage is unchanged, it yields:

\[
u_a(\theta_1) = -u_a(\theta_1 + \pi)\] (28)
Then, the integral of \( i_{NP} \) in the interval \([\theta_1, \theta_1 + 2\pi]\) can be calculated as:

\[
\int_{\theta_1}^{\theta_1+2\pi} i_{NP}(\theta)d\theta = \int_{\theta_1}^{\theta_1+2\pi} i_b(\theta)d\theta = 0
\]

From above analysis, it is found that while outputting odd harmonic current, the case is very similar to that outputting fundamental current.

### C. ZERO SEQUENCE DIRECT CURRENT

In some applications, TL-GCC is used to compensate the zero sequence direct current caused by asymmetric loads. In this case, the three-phase currents can be expressed as:

\[
i_a = i_b = i_c = I_0/3
\]

Substituting (9) and (30) into (8), the three-phase voltages can be obtained as:

\[
\begin{align*}
\theta & = E_m \cos(\omega t) + R_s I_0/3 \\
\theta_b & = E_m \cos(\omega t - 2\pi/3) + R_s I_0/3 \\
\theta_c & = E_m \cos(\omega t - 4\pi/3) + R_s I_0/3
\end{align*}
\]

Combining (4), (30) and (31), it is found that the integral of \( i_{NP} \) is always nonzero under arbitrary integral interval and \( I_0 \). So, the NPV self-equilibrium is not satisfied while outputting zero sequence direct current.

### IV. Simulation Results of NPV Self-Equilibrium

The NPV self-equilibrium under different current forms has been proved in Section 3. Based on MATLAB/Simulink simulation platform, \( \Delta u_{NP} \) will be calculated in a fundamental cycle when fundamental, odd harmonic and even harmonic current are respectively outputted. Because that even harmonic current is rarely used in practice, it is only discussed in the simulation.

\( \Delta u_{NP} \) with respect to \( L_s \) and \( \varphi \) is shown in Fig. 4. As shown in Fig. 4(a), for fundamental current and odd harmonic current, \( \Delta u_{NP} \) remains zero whatever the value of \( L_s \) and \( \varphi \) is. In Fig. 4(b), for even harmonic current, \( \Delta u_{NP} \) is nonzero except \( \varphi = 0 \) and \( \pi \) which indicates that the NPV self-equilibrium can hardly be achieved. For \( \varphi = \pi/2 \) or \( 3\pi/2 \), \( \Delta u_{NP} \) corresponds to extreme value, which means NPV increase or decrease with maximum rate.

In Fig. 5, the bar graph shows the value of \( \Delta u_{NP} \) while outputting current with different frequency under \( \varphi = \pi/2 \).

From Fig. 5, it can be seen that \( \Delta u_{NP} \) is always zero while outputting fundamental or odd harmonic current, but it is always nonzero while outputting even harmonic current. Moreover, \( \Delta u_{NP} \) will monotonically decrease with the increase of even harmonic current frequency. The results presented in Fig. 5 well verify the NPV self-equilibrium analysis discussed in Section 3.

\[
\int_{\theta_1}^{\theta_1+2\pi} E_m \cos(\omega t) + R_s I_0/3 \, d\theta = \frac{I_0}{3} \int_{\theta_1}^{\theta_1+2\pi} \! \! d\theta
\]

\[
\int_{\theta_1}^{\theta_1+2\pi} |E_m \cos(\omega t) + R_s I_0/3| \, d\theta
\]
where $R_s I_0/3$ is the voltage drop over $R_s$, which can be ignored. Eq. (32) can be simplified as:
\[
\Delta u_{NP} = \frac{2I_0}{\omega C_{dc}} \int_{\theta_1}^{\theta_1+2\pi} |E_m \cos \theta| \, d\theta = \frac{8E_m I_0}{\omega C_{dc}} \quad (33)
\]

Eq. (33) indicates that $\Delta u_{NP}$ is proportional to $I_0$. When $I_0 > 0$, $\Delta u_{NP} > 0$ is obtained to increase NPV. On the contrary, $I_0 < 0$ will decrease NPV.

When there is an offset on NPV, appropriate direct current can be used to realize NPV balance. In the integral interval, $\Delta u_{NP}$ and the derivative of $u_{NP}$ satisfy with:
\[
\frac{du_{NP}}{dt} = \frac{4E_m}{\pi C_{dc}} I_0 = K I_0 \quad (34)
\]

Then, a PI controller is adopted to obtain the target zero sequence direct current $I_0^*$. Finally, the proposed active NPV control is realized by superimposing $I_0^*$ on the three-phase currents of TL-GCC.

The circuit block diagram of the 3P4W TL-GCC system is presented in Fig. 6, where the voltage outer loop is not given.

In Fig. 6, $i_{a,b,c}(n+1)$ and $u_{a,b,c}(n+1)$ respectively denote the reference current and the modulation voltage in the next control cycle, $i_{a,b,c}(n-1)$ and $e_{a,b,c}(n-1)$ respectively denote the sampled phase current and grid voltage in the last control cycle. Moreover, deadbeat control (DBC) is adopted as the current controller, which has been widely used for its advantage of fast dynamic response [21], [22].

Based on the circuit block diagram shown in Fig. 6, the simulation model are built under the precondition of unbalanced NPV with key parameters listed in Table 2, where the single-phase and three-phase fundamental, second-harmonic and third-harmonic current are outputted respectively, and the proposed active NPV control method is involved at the moment marked by dotted line in Figs. 7-9.

| Parameter               | Value   |
|-------------------------|---------|
| DC bus voltage          | 750V    |
| Upper and lower capacitor | 2000μF  |
| Line voltage of grid    | 380V    |
| Filter inductor         | 3mH     |
| Switching frequency     | 16kHz   |
| Fundamental frequency   | 50Hz    |
| $K_p$ in PI controller  | 0.3     |
| $K_i$ in PI controller  | 0.5     |

It can be seen from Figs. 7-9 that the initial unbalanced NPV is quickly adjusted towards the balance state for all cases while the proposed active NPV control method is involved. And it is notable that the initial NPV is larger than $u_{dc}/2$, thus a negative zero sequence direct current is superimposed on the control current to decrease NPV, which is consistent with eq. (33).

Moreover, before involving active NPV control, the simulation results of Figs 7-9 also verify the theoretical analysis of NPV self-equilibrium. For Figs. 7 and 9, NPV self-equilibrium is satisfied and the dc offset on NPV is unchanged. But in Fig. 8, NPV self-equilibrium is lost and the voltage deviation of the upper and lower capacitors is gradually increased, which will finally trigger unbalance protection of the system in practice application.
While outputting single-phase fundamental current, Table 3 gives the FFT results of the output current with and without adopting the proposed active NPV method. It can be seen from Table 3 that the even-order harmonics are obviously reduced thanks to the balanced NPV by involving the proposed active NPV method.

### VI. EXPERIMENTS

To verify the theoretical analysis and the effectiveness of the proposed active NPV control method, a prototype of 3P4W TL-GCC is built in the lab. The main control chip is Freescale DSP MC56F84789 and the IGBT module is Infineon F3L300R07PE4. The key parameters for the experiments are consistent with that for simulations. In the experiments, reactive and harmonic current are respectively outputted to verify the theoretical analysis.

#### A. VERIFICATION OF THE SELF-EQUILIBRIUM CHARACTERISTIC

To verify the self-equilibrium characteristics discussed in Section 3, the prototype is controlled to respectively output single-phase and three-phase fundamental, second-harmonic and third-harmonic frequency current without active NPV control.

The experimental results are shown in Fig. 10 while outputting fundamental current. It can be seen from Fig. 10 that the NPV self-equilibrium is achieved for the both cases, but the NPV ripple are quite different. While outputting single-phase fundamental current, there are obvious ripples on NPV with fundamental frequency. While outputting three-phase fundamental current, the ripples with triple fundamental frequency become smaller.

While outputting third-harmonic current, the experimental results are shown in Fig. 11. From Fig. 11, it is found that similar conclusions with that described in Fig. 10 can be drawn.

While outputting second-harmonic current, the experimental results are shown in Fig. 12. It can be seen that for the both cases, the NPV self-equilibrium is lost, and NPV continuously increases. Finally, unbalance protection is triggered to shut down the system.

The experimental results shown in Figs. 10-12 well verify the theoretical analysis presented in Section 3.

#### B. VERIFICATION OF ACTIVE NPV CONTROL

To verify the effectiveness of the proposed active NPV control method, the experiments are executed under the precondition of unbalanced NPV, where a small capacitor is paralleled on the upper capacitor. Similarly, the converter is controlled to respectively output single-phase and three-phase fundamental.
It can be seen from Figs. 13-15 that the initial unbalanced NPV is quickly adjusted towards the balance state for all cases while the proposed active NPV control method is involved.
Especially for Fig. 14 while outputting second-harmonic current, NPV balance is achieved with the proposed active NPV control method, and the converter can thus work normally. Moreover, in Fig. 14, to avoid unbalance protection before involving the active NPV control, special $\varphi$ close to $\pi$ is selected to slow down the rate of NPV change, which also verifies the result shown in Fig. 4(b).

For all the cases, because the initial NPV is larger than $u_{dc}/2$, a negative zero sequence direct current is superimposed on the control current to quickly decrease NPV while the proposed active NPV control is involved, which is consistent with the theoretical analysis.

The experimental results of Figs. 13-15 verify that the proposed active control method can effectively ensure NPV balance for 3P4W TL-GCC.

VII. CONCLUSION

In this article, a sufficient condition of NPV self-equilibrium based on CBPWM strategy is presented for 3P4W TL-GCC with three-leg. Based on the sufficient condition, the NPV self-equilibrium characteristic is discussed while respectively outputting fundamental, odd harmonic and zero sequence direct current. Owing to the influence of direct current on NPV, an active control method is thus proposed. Simulation and experimental results verify the theoretical analysis.

REFERENCES

[1] Z. Xia, Z. Liu, and J. M. Guerrero, “Multi-objective optimal model predictive control for three-level ANPC grid-connected inverter,” IEEE Access, vol. 8, pp. 59590–59598, 2020.

[2] A. Taghvaie, M. E. Haque, S. Saha, and M. A. Mahmud, “A new step-up switched-capacitor voltage balancing converter for NPC multilevel inverter-based solar PV system,” IEEE Access, vol. 8, pp. 83940–83952, 2020.

[3] M. D. Siddique, B. Alamri, F. A. Salem, M. Orabi, S. Mekhilef, N. M. Shah, N. Sandeep, J. S. Mohamed Ali, A. Iqbal, M. Ahmed, S. S. M. Ghoneim, and M. M. Al-Harthi, “A single DC source nine-level switched-capacitor boost inverter topology with reduced switch count,” IEEE Access, vol. 8, pp. 5840–5851, 2020.

[4] W. Chen, H. Sun, X. Gu, and C. Xia, “Synchronized space-vector PWM for three-level VSI with lower harmonic distortion and switching frequency,” IEEE Trans. Power Electron., vol. 31, no. 9, pp. 6428–6441, Sep. 2016.

[5] W. Jiang, J. Li, J. Wang, J. Wang, and X. Huang, “An overall minimized switching loss discontinuous PWM strategy for neutral point clamped three level inverters,” IEEE Access, vol. 7, pp. 122387–122397, 2019.

[6] U.-M. Choi, J.-S. Lee, and K.-B. Lee, “New modulation strategy to balance the neutral-point voltage for three-level neutral-clamped inverter systems,” IEEE Trans. Energy Convers., vol. 29, no. 1, pp. 91–100, Mar. 2014.

[7] H. Peng, Z. Yuan, X. Zhao, B. Narayanasamy, A. Deshpande, A. I. Emon, F. Luo, and C. Chen, “Improved space vector modulation for neutral-point balancing control in hybrid-switch-based T-type neutral-point-clamped inverters with loss and common-mode voltage reduction,” CPSJ Trans. Power Electron. Appl., vol. 4, no. 4, pp. 328–338, Dec. 2019.

[8] J. Shen, S. Schröder, R. Rössner, and S. El-Barbari, “A comprehensive study of neutral-point self-balancing effect in neutral-point-clamped three-level inverters,” IEEE Trans. Power Electron., vol. 26, no. 11, pp. 3084–3095, Nov. 2011.

[9] H. Xiong and C. Wu, “Control strategy of three-phase four-wire three-leg inverters,” in Proc. IEEE 10th Int. Symp. Power Electron. for Distrib. Gener. Syst. (PEDG), Xi’an, China, Jun. 2019, pp. 75–78.

[10] S. Mohan, H. Guldner, R. Briest, and H. Wolf, “Analysis and control aspects of harmonic distortion in the front-end three-phase four-wire PWM boost rectifier,” in Proc. Eur. Conf. Power Electron. Appl., Sep. 2005, vol. 17, no. 4, p. 10.

[11] P. Chaturvedi, S. Jain, and P. Agarwal, “Carrier-based neutral point potential regulator with reduced switching losses for three-level diode-clamped inverter,” IEEE Trans. Ind. Electron., vol. 61, no. 2, pp. 613–624, Feb. 2014.

[12] J. Lyu, W. Hu, F. Wu, K. Yao, and J. Wu, “Variable modulation offset SPWM control to balance the neutral-point voltage for three-level inverters,” IEEE Trans. Power Electron., vol. 30, no. 12, pp. 7181–7192, Dec. 2015.

[13] C. Wang and Y. Li, “Analysis and calculation of zero-sequence voltage considering neutral-point potential balancing in three-level NPC converters,” IEEE Trans. Ind. Electron., vol. 57, no. 7, pp. 2262–2271, Jul. 2010.

[14] G. I. Orfanoudakis, M. A. Yaratich, and S. M. Sharkh, “Nearest-vector modulation strategies with minimum amplitude of low-frequency neutral-point voltage oscillations for the neutral-point-clamped converter,” IEEE Trans. Power Electron., vol. 28, no. 10, pp. 4485–4499, Oct. 2013.

[15] A. Lewicki, Z. Krzeminski, and H. Abu-Rub, “Space-vector pulsedwidth modulation for three-level NPC converter with the neutral point voltage control,” IEEE Trans. Ind. Electron., vol. 58, no. 11, pp. 5076–5086, Nov. 2011.

[16] T. Ghennam, E. M. Berkouk, and B. Francois, “A novel space-vector current control based on circular hysteresis areas of a three-phase neutral-point-clamped inverter,” IEEE Trans. Ind. Electron., vol. 57, no. 7, pp. 2669–2678, Aug. 2010.

[17] X. Wu, G. Tan, Z. Ye, G. Yao, Z. Liu, and G. Liu, “Virtual-space-vector PWM for a three-level neutral-point-clamped inverter with unbalanced DC-links,” IEEE Trans. Power Electron., vol. 33, no. 3, pp. 2630–2642, Feb. 2018.

[18] C. Xia, G. Zhang, Y. Yan, X. Gu, T. Shi, and X. He, “Discontinuous space vector PWM strategy of neutral-point-clamped three-level inverters for output current ripple reduction,” IEEE Trans. Power Electron., vol. 32, no. 7, pp. 5109–5121, Jul. 2017.

[19] F. Li, F. He, Z. Ye, T. Fernando, X. Wang, and X. Zhang, “A simplified PWM strategy for three-level converters on three-phase four-wire active power filter,” IEEE Trans. Power Electron., vol. 33, no. 5, pp. 4396–4406, May 2018.
[20] C. Wang, X. Si, and H. Xin, “Control of neutral-point voltage in three-phase four-wire three-level NPC inverter based on the disassembly of zero level,” in Proc. IEEE Energy Convers. Congr. Expo. (ECCE), Milwaukee, WI, USA, Sep. 2016, pp. 40–48.

[21] W. Jiang, X. Ding, Y. Ni, J. Wang, L. Wang, and W. Ma, “An improved deadbeat control for a three-phase three-line active power filter with current-tracking error compensation.” IEEE Trans. Power Electron., vol. 33, no. 3, pp. 2061–2072, Mar. 2018.

[22] H. Zhu, B. Qin, S. Gao, Z. Shu, and F. Gao, “Five-level diode-clamped active power filter using voltage space vector-based indirect current and predictive harmonic control.” IET Power Electron., vol. 7, no. 3, pp. 713–723, Mar. 2014.

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