General Control Scheme for Dual-Input Three-Level Inverter

Cheng Yan, Dehong Xu, Fellow IEEE, Wenjie Chen

Abstract—This paper proposes a general control scheme for the dual-input three-level inverter, which comes from Neutral Point Clamped (NPC) three-level inverter. It can be used for photovoltaic systems or battery storage systems with two DC sources. The dual-input three-level inverter can be connected with two PV arrays which are able to realize Maximum Power Point Tracking (MPPT) independently. Firstly, the dynamic model of dual-input three-level inverter is established, which describes the relationship between the dual-input voltages and the duty cycle. After discussing the control theory of the dual-input voltages, a typical control scheme is proposed. The design of control loop is introduced in details. Afterward, modulation and restriction of proposed method are discussed. Finally, experiment on 125kW dual-input three-level PV inverter is implemented to verify the validity and feasibility of proposed method.

Index Terms—Voltage control, Inverters, Power control, Pulse width modulation

I. INTRODUCTION

Currently three-level inverters have been widely used for PV generations [1]. With regards to PV inverter, If the PV array can be divided into two sub-arrays, which are connected to the upper and lower dc bus of the three-level inverter, then each sub-arrays can be controlled independently and work at its Maximum Power Point (MMP). Therefore independent control of the upper and lower dc bus of the three-level inverter is able to increase solar energy harvesting. This concept can be extended to battery energy storage system. In these cases, decoupling control of dual-input of the three-level inverter is needed.

Since the voltages of upper and lower half dc-bus in three-level inverter can be controlled independently, it is called dual-input three-level inverter in this paper. There have already been important developments with respect to control of dual-input three-level inverters.

Front-end dc-dc converter stages are added between the PV array and the three-level inverter [2]. The dc-dc converters are used to regulate the terminal voltage of two PV strings independently. Thus independent MPPT control is realized even for both PV strings with different output characteristics. Similarly, an auxiliary converter is used to dual-input three-level inverter in [3-5]. Compared to full-power capacity front-end dc-dc converter method, the auxiliary converter only needs to deal with the power deviation between the two inputs. Although both methods mentioned above can realize independent MPPT control of two PV strings, extra hardware are needed. It not only increases circuit complexity but also results in extra power conversion loss in the added DC/DC conversion stage. Therefore, dual-input voltage control methods without extra power stages are preferred.

Voltage control methods without extra additional power stages have been extensively investigated in literature [6-29]. Though most of them are concentrated on Neutral Point (NP) voltage balance for three-level inverter, it shares the similar control concepts for dual-input three-level inverter. These methods can be classified according to the pulse width modulation methods.

For dual-input three-level inverter control methods based on carrier-based PWM (CBPWM) schemes, positive or negative zero sequence voltage is injected according to the NP voltage and direction of instantaneous output three phase current [6-8]. If the accurate function between NP current and the added zero sequence voltage is revealed, the active control methods with linear model can be established. In [9-13], the accurate needed zero sequence voltage is derived online according to the deviation of dc-link voltage, the instantaneous current and the capacitance of dc-link. It can completely control the dc-link voltage of three-level inverter without any low-frequency NP voltage oscillations. Since the exact calculation of added zero sequence voltage in these methods is quite complicated, so the curve fitting is applied in [14] to simplify the calculation. Based on this control concept, an asymmetrical voltage control for dual-input three-level based on CBPWM is proposed in [15]. The NP current is indirectly controlled by the zero sequence voltage. Correlation between neutral point current and zero-sequence voltage is quite complicated, so the curve fitting is applied in [14] to simplify the calculation. The performance of all these methods depends on the accurate relationship between the zero sequence voltage and NP current. In [16-18], NP voltage control methods based on double-signal pulse width modulation (DSPWM) are able to completely remove low-frequency oscillation appears in NP. The relationship between changed modulation signal and the NP current is easy to be calculated. Besides, this method is suitable for any load over the full range of converter output voltage and for all load power. But the switching frequency of the power devices is higher than that with the standard CBPWM, and high-frequency harmonic component of the output voltages increases.
For dual-input three-level inverter control methods based on SVM, since one pair of redundant small vectors have opposite effect on the NP voltage, thus the NP voltage is controlled by selecting proper small vector or adjusting dwell time of redundant small vectors [19-21]. Independent voltage control methods based on SVM are proposed in [22-24]. The dwell time of two redundant vectors is rearranged according to instantaneous voltage deviation. Output voltage distortion due to the deviation of two capacitor voltages is taken into consideration. In [24], the influence of all active vectors in a switching sequence is taken into consideration before their activation. Similar control methods based on discontinuous PWM (DPWM) are realized by selecting small vector properly [25-27]. Methods based on the traditional SVM or DPWM are easy to be implemented. But the control performance has not been deeply investigated. Independent voltage control method based on virtue space vector pulse width modulation (VSVPWM) is proposed in [28]. This method is similar to DSPWM and can completely remove low-frequency oscillation. However, the switching loss and high-frequency harmonics of output voltage/current will increase.

All these methods mentioned above are all derived from specific PWM or SVM schemes. Up to now, we lack a general model to explicitly describe the relationship between the dual-input voltages and PWM duty cycles for the dual-input three-level inverter. Analysis of dual-input voltage control restriction has not been deeply investigated yet.

In this paper, we hope to generalize the basic concept of independent control beyond the specific PWM modulation. The control is based on power concept rather than the instantaneous output ac current. An independent control scheme of dual-input three-level inverter is proposed. The dual-input three-level inverter can be connected with two PV arrays which are able to realize Maximum Power Point Tracking (MPPT) independently. The paper is arranged as follows, in section II, the dynamic model of the dual-input three-level inverter is established. The relationship between the dual-input voltages and the duty cycle is revealed. After discussing the control theory of the dual-input voltages, a typical control scheme is proposed. In section III, The design of control loop is implemented in details. In section IV, modulation and restriction of the proposed method are discussed. The proposed method is verified via experimental results in section V, the conclusion is given in section VI.

II. MODELING OF DUAL-INPUT THREE-LEVEL INVERTER

A dual-input three-level inverter connected with two independent PV arrays is shown in Fig. 1. It is mainly composed of Neutral Point Clamped (NPC) or T-type three-level inverter which is connected to the grid with L filter and step up transformer.

It is assumed that power devices in Fig. 1 are ideal switches, and each arm of the bridge has three states (positive, negative and neutral). So each arm can be simplified by three switches (the upper, lower and neutral switches), shown in Fig. 2. PV1 and PV2 represent two independent PV arrays. \(i_{pv1}\) and \(i_{pv2}\) are the current of PV1 and PV2 respectively. \(i_p\) is the positive bus current between the dc capacitance and the three phase bridge. \(i_n\) is the negative bus current between the dc capacitance and the three phase bridge. \(v_{dc1}\) and \(v_{dc2}\) are the
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\[ L \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} d_{d1} & d_{d2} \\ d_{q1} & d_{q2} \end{bmatrix} \begin{bmatrix} v_{d1} - v_{d0} \\ v_{q1} - v_{q0} \end{bmatrix} - r \begin{bmatrix} i_d \\ i_q \end{bmatrix} - \omega L i_d \]

where \( v_{d0}, v_{q0} \) are the components of grid voltage in \( dq \) frame. \( i_d, i_q \) are the components of grid current in \( dq \) frame. \( d_{d1}, d_{d2}, d_{q1}, d_{q2} \) are the duty cycles for upper switches in \( dq \) frame, the \( d_{d0}, d_{q0} \) are the duty cycles of lower switches and the \( d_{d0}, d_{q0} \) are the switching duty cycles for neutral switches. The relationship between the duty cycles in \( dq \) frame and the duty cycles in the stationary coordinate frame is derived as,

\[ \begin{bmatrix} d_{d1} \\ d_{d2} \\ d_{q1} \\ d_{q2} \end{bmatrix} = T \begin{bmatrix} d_{d1} \\ d_{d2} \\ d_{d0} \\ d_{q2} \end{bmatrix} \]

where \( T \) is the matrix of park transformation,

\[ T = \frac{2}{\sqrt{3}} \begin{bmatrix} \cos \omega t & \cos (\omega t + \frac{\pi}{3}) & \cos (\omega t + \frac{2\pi}{3}) \\ -\sin \omega t & -\sin (\omega t + \frac{\pi}{3}) & -\sin (\omega t + \frac{2\pi}{3}) \end{bmatrix} \]

According to (3) and (6), duty cycles in \( dq \) frame satisfy the relationship,

\[ d_{d1} + d_{d2} + d_{d0} = 0 \]
\[ d_{q1} + d_{q2} + d_{q0} = 0 \]

The factor \( \omega L \) in (4) can be decoupled, so the model in each \( dq \) frame is composed of three decoupled parts. Among them, the zero-sequence equation can be ignored for three phase wire system.

Regulating q-axis voltage \( v_{q0} \) to be zero. If there are three-level PV inverter is controlled with unit power factor, i.e. \( i_q = 0 \). The power loss of the inverter is ignored, the grid power is equal to the sum of the dual-input power,

\[ P_{sum} = P_{d1} + P_{d2} = v_{p1} \cdot i_d \]

Therefore the total power \( P_{sum} \) can be controlled by regulating the d-axis grid current \( i_d \). The different power \( P_{d1} \) and \( P_{d2} \) from (5) and (8),

\[ P_{d1} = P_{d1} - P_{d2} = v_{d1} \cdot i_d \cdot d_{d1} + v_{d2} \cdot i_d \cdot d_{d2} \]
\[ P_{d2} = v_{q1} \cdot i_q \cdot d_{q1} + v_{q2} \cdot i_q \cdot d_{q2} \]

Diagram of dual-input three-level inverter is made as Fig. 3. The duty cycle in d-axis \( d_{d1} \) and \( d_{d2} \) can control the output power of three-level inverter. The duty cycle \( d_{q1} \) plays a more important role than \( d_{q2} \) in controlling the power deviation \( P_{d1} \) because \( v_{d1} \) and \( v_{d2} \) are approximately equal. In other words, the d-axis duty cycle of neutral switches \( d_{d0} \) determines the power deviation \( P_{d1} \). Therefore the duty cycle \( d_{dp} \) is used to control the d-axis current \( i_d \), i.e. total power. The rest duty cycle in d-axis \( d_{dq} \) can be decided by (8). For duty cycle in q-axis, \( d_{dq} \)

Fig. 3. Power dynamic model of dual-input three-level inverter

Fig. 4. Voltage control model of dual-input three-level inverter

B. Voltage control model

In PV application, the dc voltage is the controlled target. It is essentially controlled by the output power of each PV array. As the control relationship between power and duty cycle is established, the relationship between the voltage and its output power can be written as (11),

\[ C_1 \frac{dv_{p1}}{dt} = i_{p1} - i_{p1} = \frac{P_{d1}}{v_{p1}} \]
\[ C_2 \frac{dv_{p2}}{dt} = i_{p2} + i_{p2} = \frac{P_{d2}}{v_{p2}} \]

\[ (8) \]

The voltage of each PV array can be controlled by regulating its output power. So the dynamic model of dual-input three-level inverter for voltage control is shown in Fig. 4.

C. Voltage control scheme

Based on the model mentioned above, the voltage control scheme for dual-input three-level inverter is shown in Fig. 5. It is composed of outer dc voltage control loop and inner grid current control loop. Each voltage of dc bus is controlled by PI regulator with dc voltage feedback. The output of the voltage regulator is used as the power reference of the current inner loop. And the output of the current regulator is the duty cycle for three-level inverter. 
Besides, necessary decoupling between duty cycles with dc bus voltage is added. The factor $\alpha L$ between current $i_d$ and $i_q$ is also decoupled similar to the traditional dq dual controller [30]. The modulation is produced with the demand of certain duty cycle analyzed above.

### III. CONTROL LOOP DESIGNED AND ANALYSIS

From the analysis in the previous section, the power control can be divided into two parts: the total power is control by the d-axis current, which is determined by duty cycle $d_{dp}$, and the different power is mainly controlled by $d_{dq}$, the d-axis duty cycle of neutral switches. Replace the dual-input three-level inverter in Fig. 5 with mathematical module. The fundamental control loop is shown in Fig. 6.

#### A. Design of current inner control loop

The d-axis current $i_d$ is controlled by the duty cycle $d_{dp}$. The q-axis current $i_q$ is controlled by the duty cycle $d_{dq}$. There are several coupling factors between $d_{dp}$ and $d_{dq}$ in Fig. 6. The coupling is eliminated as (12). Besides, the inductor factor decoupling, DC voltage, and grid voltage feed forward are also implemented here [31][32]. So the duty cycle reference $d_{dp}^*$ can be designed as follow,

$$
\left.\begin{array}{l}
\frac{i_d^*}{i_d} = \left(\frac{i_d - i_d^*}{G_{Pl} (s)}\right) + v_{pd} - v_{pd2} \cdot d_{dp} - \alpha L \cdot i_q
\end{array}\right\}
$$

where $G_{Pl} (s)$ is the PI regulator for the current control loop.

So the inner control loop can be simplified as Fig. 7 without any coupling factors with the other loop. The $e^{\tau s}$ is the time delay of control loop. Besides, the disturbance of grid voltage are neglected. The transfer function of current control loop can be written as

$$
i_d = H_i (s) \cdot i_d^*,
$$

$$
H_i (s) = \frac{G_{Pl} (s) \cdot e^{-\tau s}}{sL + r + G_{Pl} (s) \cdot e^{-\tau s}}
$$

The inner control loop is similar to the traditional current control in d$q$ frame.

#### B. Design of voltage control loop

Similar to the d-axis duty cycle $d_{dp}$, The duty cycle reference $d_{dq}^*$ can be designed as follow,

$$
\left.\begin{array}{l}
d_{dq}^* = \left(\frac{P_1^* - P_2^*}{K} + \left(v_{dc1} - v_{dc2}\right) \cdot d_{dq}\right)/v_{dc2}
\end{array}\right\}
$$

$$
\left.\begin{array}{l}
P_1^* (s) = \left(v_{dc1} (s) - v_{dc2} (s)\right) G_{Pl} (s)
\end{array}\right\}

\left.\begin{array}{l}
P_2^* (s) = \left(v_{dc1} (s) - v_{dc2} (s)\right) G_{Pl} (s)
\end{array}\right\}
$$

where $K$ is the proportion coefficient. $P_1^*$ and $P_2^*$ are the output of the PV1 and PV2 voltage regulators respectively. $G_{Pl} (s)$ is the PI regulator for the voltage control loop.

According to Fig. 6, the sum of $P_1^*$ and $P_2^*$ is set as reference of duty cycle $i_d^*$. And the total output power $P_{sum}(s)$ and power deviation $P_{dev}(s)$ of inverter can be written,

$$
\left.\begin{array}{l}
P_{sum}(s) = \left(P_1^* (s) + P_2^* (s)\right) \cdot H_v (s) V_{pd}
\end{array}\right\}

\left.\begin{array}{l}
P_{dev}(s) = \left(P_1^* (s) - P_2^* (s)\right) \cdot K \cdot i_d
\end{array}\right\}
$$

According to (11) (17) and (18), the voltage of dc1 can be expressed,

$$
v_{dc1} (s) = \frac{A \cdot v_{dc2} (s) - B \left(v_{dc2} (s) - v_{dc2}^* (s)\right) + \frac{1}{sC_i} \cdot i_{pd1} (s)}{A + 1}
$$

$$
A = \frac{G_{Pl} (s) (K \cdot i_d + H_v (s) V_{pd})}{2 \cdot sC_i \cdot V_{dc1}}
$$

$$
B = \frac{G_{Pl} (s) (K \cdot i_d - H_v (s) V_{pd})}{2 \cdot sC_i \cdot V_{dc1}}
$$

The control performance of $v_{dc1}$ will be affected by $v_{dc2}$ due to the coefficient $B$, which will lead to unexpected disturbance and poor dynamic control performance. In order to control the voltage of dc1 and dc2 independently, the coefficient $B$ should be set approximately to be zero. So the
coefficient $K$ is designed:

$$K = H_i(s)v_{sd1}(s)/i_d$$  \hspace{1cm} (16)

As traditional control loop design, the inner loop is much faster than the outer loop \cite{33}, $H_i(s)$ can be regarded as one in designing the outer voltage loop. Then the voltage control of dc1 is only related to its voltage reference and disturbance of PV current,

$$v_{dc1}(s) = A v_{sd1}(s) + \frac{1}{sC_1 + A}i_{pv1}(s)$$  \hspace{1cm} (17)

It is similar to voltage control of dc2. As long as K is set as (19), the coupling between the voltage of dc1 and voltage of dc2 can be suppressed. The voltage of dc1 and dc2 can be controlled independently. The voltage control of dc2 is only related to its voltage reference and disturbance of PV current,

$$v_{dc2}(s) = \frac{A}{1 + A} v_{sd2}(s) + \frac{1}{sC_2 + A}i_{pv2}(s)$$  \hspace{1cm} (18)

C. Bode plot

The current control loop is designed to ensure that the output currents meet the grid code. The bandwidth of the current control loop should be high enough to deal with the dynamic situation such as LVRT. But the control bandwidth is limited by the switching frequency. In this paper, the switching frequency is 5kHz. The cross-over frequency of the current control loop is designed to 500Hz, which is much lower than the switching frequency to achieve quite good stability. The bode diagram before and after PI regulator are shown in Fig. 8. The cross-over frequency before control is 1000Hz. The zero-point frequency of the PI controller is designed to 50Hz. The cross-over frequency of control loop is 500Hz and phase margin is 49 degrees.

The voltage control loop is designed to control the DC/PV voltage. According to traditional control loop design, the outer voltage control loop should be much slower than inner current control loop. On the other hand, the voltage control speed should be faster than the MPPT speed. The MPPT interval in the inverter of this manuscript is 1s. So the bandwidth of the
voltage control loop is designed to 50Hz, which is much slower than the inner current control loop (500 Hz), and faster than the MPPT control speed (1Hz). The bode diagram before and after PI regulator are shown in Fig. 9. The cross-over frequency before control is 250Hz. The zero-point frequency of the PI controller is designed to 5Hz. The cross-over frequency is 50Hz and phase margin is 81 degrees.

Base on the analysis and design above, the inverter has enough dynamic performance. Meanwhile, the stability of the system is satisfactory.

IV. MODULATION AND RESTRICTION IN DUAL-INPUT THREE-LEVEL INVERTER

According to the analysis above, the basic control scheme has been established. Some duty cycles in dq frame (d_{ap}, d_{bp}, d_{an}, d_{bn}) have been determined by the control regulator, and the rest duty cycles bring free degree for modulation signal. In this section, the final modulation scheme will be discussed and the control restriction of dual-input three-level inverter will be revealed.

A. The PWM modulation generator

When four duty cycles d_{ap}, d_{bp}, d_{an}, d_{bn} are assigned by control scheme, the rest duty cycles in dq frame d_{dp}, d_{dq}, d_{dn}, d_{qn} can be derived by (8). The final modulation signal in stationary frame can be derived from the duty cycles in dq frame with inverse Park transformation T^2:

\[
\begin{bmatrix}
  d_{dp} \\
  d_{dq} \\
  d_{dn}
\end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix}
  \cos \theta & -\sin \theta & \frac{1}{\sqrt{2}} \\
  \cos (\theta - \frac{\pi}{2}) & -\sin (\theta - \frac{\pi}{2}) & \frac{1}{\sqrt{2}} \\
  \cos (\theta + \frac{\pi}{2}) & -\sin (\theta + \frac{\pi}{2}) & \frac{1}{\sqrt{2}}
\end{bmatrix}
\begin{bmatrix}
  d_{ap} \\
  d_{bp} \\
  d_{an}
\end{bmatrix}
\]

(19)

Similarly, the boundary of duty cycle d_{an}, d_{bn} in (23) represents the common-voltage components produced by the upper and lower bus respectively.

The modulation signal generated by (22) and (23) is called dual-input PWM in this paper. The dual-input PWM is more than a specific modulation scheme. The redundant duty cycles bring a free degree in generating modulation signal. So there are infinite kinds of modulation signal which can be used in dual-input three-level inverter. It provides the opportunity to choose best PWM scheme.

B. Control restriction for power deviation

Total power control restriction in dual-input three-level inverter is quite similar to that in conventional inverter. Modulation index is the basic restriction of total output power. We should pay more attention to control restriction of power deviation in dual-input three-level inverter. There must be a boundary for the power deviation of two dc input among all possible PWM modulation signals, which can be derived from the duty cycles of each switch.

Firstly, the duty cycle of upper three switches should be between 0 and 1,

\[ d_{ap}, d_{bp}, d_{an} \in [0, 1] \]

(21)

Substituting (22) into (24), the restriction of d_{dp} and d_{dq} is,

\[ \left| d_{dp} \right| \leq \frac{1}{\sqrt{2}} \]

\[ \left| d_{dq} \pm \frac{1}{\sqrt{3}} d_{dp} \right| < \frac{2}{\sqrt{3}} \]

(22)

It shows that the vector of d_{dp} and d_{dq} is located in a hexagon, which is similar to traditional SVM space vector hexagon diagram.

Similarly, the boundary of duty cycle d_{an} and d_{bn} is,

\[ \left| d_{an} \right| \leq \frac{1}{\sqrt{2}} \]

\[ \frac{\sqrt{3}}{2} d_{an} \pm \frac{1}{2} d_{an} \leq \frac{1}{\sqrt{2}} \]

(23)

Besides, there is another restriction for the duty cycles, the sum duty cycle of upper and bottom switches for every phase should be between 0 and 1

\[ d_{ap} + d_{an}, d_{bp} + d_{bn}, d_{dp} + d_{dn} \in [0, 1] \]

(24)

Equations (25)-(27) are the main restriction for duty cycles, in other words, the power control in dual-input three-level input is restricted by these equations. According to the boundary of the duty cycle in dq frame and the power deviation of the dual-input written as (10), the boundary of the power deviation is revealed.

Fig. 10 shows the maximum limit of the power deviation in 3D space based on two bus voltages (v_{dc1}, v_{dc2}), the y-axis is the voltage of the upper dc-bus voltage v_{dc1}, and x-axis is the voltage of the lower dc-bus voltage v_{dc2}. The value of v_{dc1} and v_{dc2} in Fig. 10 represents the ratio of dc-bus voltage to output line voltage. In other words, the v_{dc1} is equal to 1 in Fig. 10 means that the v_{dc1} is equal to the amplitude of output line voltage. As it is shown in X-Y view in Fig 10(b), when the sum of v_{dc1} and v_{dc2} is below one, the inverter cannot output essential grid voltage, so it has no ability to regulate the power deviation. When the v_{dc2} is fixed, the maximum power deviation is approximately proportional to v_{dc1}. And when v_{dc1} is fixed, v_{dc2} has little effect on the maximum power deviation.

Fig. 11 shows the minimum limit of the power deviation in 3D space based on two bus voltages (v_{dc1}, v_{dc2}), the y-axis is the voltage of the upper dc-bus voltage v_{dc1}, and x-axis is the voltage of the lower dc-bus voltage v_{dc2}. The value of v_{dc1} and v_{dc2} in Fig. 11 represents the ratio of dc-bus voltage to output line voltage. As it is shown in X-Y view in Fig 11(b), when the sum of v_{dc1} and v_{dc2} is below one, the inverter cannot output essential grid voltage, so it has no ability to regulate the power deviation. When the v_{dc1} is fixed, the minimum power deviation is approximately proportional to v_{dc2}. And when v_{dc2} is fixed, v_{dc1} has little effect on the minimum power deviation.
The PWM generator contains all possible PWM signals, including traditional PWM methods such as SPWM and SVM. For comparison, traditional PWM methods are taken into consideration, especially. There is an additional restriction for traditional SPWM or SVM. Only one pair of switches are operating in one switching period. In other words, during every switching period, there must be,

\[
\begin{align*}
&d_{ap} \cdot d_{an} = 0 \\
&d_{bp} \cdot d_{bn} = 0 \\
&d_{cp} \cdot d_{cn} = 0
\end{align*}
\]

(25)

To prevent complexity in viewing and analysis, Fig. 12 shows the comparison of dual-input PWM and traditional PWM under situation when \(v_{dc1}\) is equal to \(v_{dc2}\). The horizontal axis is the voltage of dc bus. The vertical axis is the power deviation of two inputs. The value of \(v_{dc1}\) and \(v_{dc2}\) represents the ratio of dc-bus voltage to output line voltage.

Fig. 12(a) is under situation when the power factor is one, i.e. the power factor angle \(\phi=0\). The red and blue lines represent the maximum power deviation of dual-input PWM and traditional PWM, respectively. Only the voltage of half bus is below 0.5, all PWM modulation cannot be able to work properly for three-level inverter. It is same to the conclusion from Fig. 10 and Fig. 11. With the increasing of the dc voltage, the power deviation capability is increasing proportionally. The relation between the dc voltage and maximum or minimum power deviation is approximately linear.

As shown in Fig. 12 (a), the traditional PWM method power deviation capability is slightly weaker than dual-input PWM method. One difference is that the lowest controllable dc voltage of dual-input PWM is smaller. The other difference is under the situation when dc voltage is high enough, the maximum power deviation of traditional PWM is equal to 100 percent. While the maximum power deviation of dual-input PWM can be larger than 100 percent.

Fig. 12 (b) shows the power deviation under situation when power factor angle \(\phi\) is 30 degrees. The controllable area of dual-input PWM method is much larger than that of traditional PWM. The lowest controllable dc voltage \(v_{dc1}\) and \(v_{dc2}\) in dual-input PWM is around 0.5, while the lowest voltage in traditional PWM is around 0.63. With the increasing of the dc voltage, dual-input PWM method always has wider controllable range.

Fig. 12 (c) shows the power deviation under situation when power factor angle \(\phi\) is 60 degrees. The controllable area of dual-input PWM method is significantly larger than that of traditional PWM. The lowest controllable dc voltage \(v_{dc1}\) and \(v_{dc2}\) in dual-input PWM is around 0.5, while the lowest voltage in traditional PWM is around 0.76. With the increasing of the dc voltage, dual-input PWM method always has wider controllable range.
Fig. 13 shows the comparison of dual-input PWM and traditional PWM under specific situation that \(v_{dc1}\) is 20% larger than \(v_{dc2}\). The horizontal axis is the \(v_{dc1}\), while \(v_{dc2}\) is 20% less than voltage of \(v_{dc1}\). The value of \(v_{dc1}\) and \(v_{dc2}\) represents the ratio of dc-bus voltage to output line voltage.

Fig. 13(a) is under the situation when the power factor is one, i.e. the power factor angle \(\phi=0\) degrees. The red and blue lines represent the maximum power deviation of dual-input PWM and traditional PWM, respectively. And the red and blue dash lines represent the minimum power deviation of dual-input PWM and traditional PWM, respectively. Similar to the situation when \(v_{dc1}\) is equal to \(v_{dc2}\), if \(v_{dc1}\) (horizontal axis) is below 0.55, all PWM modulation cannot be able to work properly for three-level inverter. With the increasing of the dc voltage, the control capability of power deviation is increasing proportionally. As the \(v_{dc1}\) is larger than \(v_{dc2}\), the control capability of positive power deviation is stronger than that of negative power deviation. For example, when the \(v_{dc1}\) reaches 1, maximum power deviation of traditional PWM is equal to 100 percent. On the other hand, minimum power deviation of traditional PWM reaches -100 percent until \(v_{dc1}\) is equal to 1.2 \((v_{dc2}\) is equal to 1). The relationship between the dc voltage and maximum or minimum power deviation is approximately linear. Besides, control capability of traditional PWM method power deviation is slightly weaker than that of dual-input PWM method.

Fig. 13(b) shows the power deviation under situation when power factor angle \(\phi=30\) degrees. The controllable area of dual-input PWM method is much larger than that of traditional PWM. The lowest controllable dc voltage \(V_{dc1}\) and \(V_{dc2}\) in dual-input PWM is around 0.55, while the lowest voltage in traditional PWM is around 0.69. With the increasing of the dc voltage, dual-input PWM method always has wider controllable range. Besides, as the \(v_{dc1}\) is larger than \(v_{dc2}\), the control capability of positive power deviation is stronger than that of negative power deviation.

Fig. 13(c) shows the power deviation under situation when power factor angle \(\phi=60\) degrees. The controllable area of dual-input PWM method is significantly larger than that of

![Fig. 12. Power deviation comparison when \(v_{dc1}\) is equal to \(v_{dc2}\): (a) \(\phi=0\) degrees. (b) \(\phi=30\) degrees. (c) \(\phi=60\) degrees](image1)

![Fig. 13. Power deviation comparison when \(v_{dc1}\) is 20% larger than \(v_{dc2}\): (a) \(\phi=0\) degrees. (b) \(\phi=30\) degrees. (c) \(\phi=60\) degrees](image2)
traditional PWM. With the increasing of the dc voltage, dual-input PWM method always has wider controllable range. Besides, as the $v_{dc1}$ is larger than $v_{dc2}$, the control capability of positive power deviation is stronger than that of negative power deviation.

One drawback of dual-input PWM method is that the number of turn-on and turn-off switching transient may slightly increase in every switching frequency period. But it is quite effective to enhance the control capability of power deviation. So in some extraordinary operation situation, such as PV application. When the PV panels are partially shadowed, large unbalance power deviation of two input arrays appears in dual-input PWM. Though the switching loss may increase, more PV energy can be harvested.

For practical application, when the inverter is operating under normal condition, the three level inverter can operate with PWM with less switching times which is similar to SPWM or SVM, when the required power deviation exceeds its controllable limit, the three level inverter can transit into dual-input PWM with more switching times to enhance the control capability of power deviation.

V. EXPERIMENTAL RESULTS

The implementation is carried out on a 125kW T-type three-level PV inverter to verify the proposed control method. Fig. 14 shows the experimental system and its main parameters are listed in the Table I.

The dual-input PV arrays of three-level inverter are produced by two Chroma dc power supply 62150H-1000s. Each one operates as PV array listed in the Table II.

Fig.15 shows the steady-state waveform with proposed method at 20kW. The DC voltage $v_{dc1}$, $v_{dc2}$ and current $i_{dc1}$, $i_{dc2}$ are constant without low-frequency fluctuation, while switching frequency of dc current exists, and $i_a$, $i_b$, $i_c$ are the grid current with low THD, so the power of the DC1 and DC2 are controlled to be constant with high output power quality.

Fig. 15(a) shows the steady waveform when voltages of $v_{dc1}$ and $v_{dc2}$ are same. The channel 1 and channel 2 are voltage of $v_{dc1}$ and $v_{dc2}$, channel 3, 4, and 5 are the three phase grid current. The voltages of $v_{dc1}$ and $v_{dc2}$ are both 320V. The three phase grid current are symmetrical, and the power quality is as good as that under traditional control with single PV input. Besides, there are nearly none of low-frequency oscillation on half bus voltage.

Fig. 15(b) shows the steady waveform when the voltage of $v_{dc1}$ is higher than voltage of $v_{dc2}$ by 20V. The three phase grid current are symmetrical, and the power quality is as good as that under traditional control with single PV input. Besides, there are nearly none of low-frequency oscillation on single $v_{dc1}$ or $v_{dc2}$ voltage. So the control method will not affect the steady performance of three-level inverter.
Fig. 16 shows the dynamic voltage control waveform when both voltages of dc1 and dc2 are changed. At time $t_0$ in Fig. 16, the voltages of dc1 and dc2 are controlled from 340V to 320V at same time. It can be seen that the control speed of $v_{dc1}$ and $v_{dc2}$ is almost same. The control time is around 100ms. When the voltages of dc1 and dc2 are controlled towards MPP. The grid current increases with voltage decreases, the output power increases. There is no surge in voltage and current. The total voltage control is implemented.

Fig. 17 shows the dynamic voltage control waveform when voltage of dc1 increases and dc2 decreases. The control performance is similar to that of total voltage control. The control speed of $v_{dc1}$ and $v_{dc2}$ is almost same. There is no surge on voltage and current. The different voltage control is implemented.

Fig. 18 shows the performance of single voltage control of PV1. At time $t_0$, the voltage of dc1 is reduced by 20V while the voltage of dc2 keeps constant. The working point of PV1 alters with voltage decreasing and current increasing. Meanwhile, the operation state of dc2 is keeping same. Both current and voltage of PV2 are not changed.

Fig. 19 shows the MPPT waveform of dual PV input. Both PV1 and PV2 are set as Table II. The maximum point power is 6kW. At time $t_1$, the three-level inverter is connected to the grid, the grid current increases. The voltage controller with MPPT is working properly. Both voltage of DC1 and DC2 can be tracked down to the maximum power point. At last time $t_2$ in the Fig. 19, each PV array works at its MPP. The bottom of Fig. 19 is the enlarged waveform of time $t_2$. The grid current is controlled with good quality.

Fig. 20 shows the tacking path of PV1 and PV2 with same PV array. The blue and red dots are the working state of PV1 and PV2 every 2 seconds. The slash lines are the P-V curve of dual PV input. Both PV1 and PV2 are set as Table II. The maximum point power is 6kW. At time $t_1$, the three-level inverter is connected to the grid, the grid current increases. The voltage controller with MPPT is working properly. Both voltage of DC1 and DC2 can be tracked down to the maximum power point. At last time $t_2$ in the Fig. 19, each PV array works at its MPP. The bottom of Fig. 19 is the enlarged waveform of time $t_2$. The grid current is controlled with good quality.

Fig. 20. Comparison of experiment curve and designed P-V curve with same dual PV array
This paper proposed general control scheme for dual-input three-level inverter. A dynamic model of dual-input three-level inverter is established, which represents the relationship between the voltage/power and specific duty cycle. With proposed method, dual-input voltages of three-level inverter can be controlled independently with good quality of grid current. Each PV array can achieve its maximum power when the PV arrays are operating under different circumstance. It increases energy harvesting for PV array. Besides, modulation and restriction of proposed method is discussed. The power deviation control capability of dual-input PWM is much stronger than that of traditional PWM.

VI. CONCLUSION

The proposed control scheme for dual-input three-level inverter is effective to achieve maximum power from two series PV array with power deviation. It can be controlled independently with good quality of grid current. Each PV array can achieve its maximum power when the PV arrays are operating under different circumstance. It increases energy harvesting for PV array. Besides, modulation and restriction of proposed method is discussed. The power deviation control capability of dual-input PWM is much stronger than that of traditional PWM.

REFERENCES

Cheng Yan was born in China, in 1987. He received the B.S. degree in Electronic and Information Engineering from the College of Electrical Engineering, Zhejiang University, Hangzhou, China, in 2010, where he is currently working toward the Ph.D. degree in electrical engineering. His research interests include power conversion, control and optimization for PV power generation systems.

Dehong Xu (M’94–SM’09–F’13) received the B.S., M.S., and Ph.D. degrees in power electronics from the Department of Electrical Engineering, Zhejiang University, Hangzhou, China, in 1983, 1986, and 1989, respectively.

He was a Visiting Scholar with the University of Tokyo, Japan, from June 1995 to May 1996. From June to December 2000, he was a Visiting Professor with CPES, Virginia Tech, USA. From February 2006 to April 2006, he was a Visiting Professor with ETH, Switzerland. Since 1996, he has been with the College of Electrical Engineering, Zhejiang University, as a Full Professor. He has authored or coauthored six books and more than 200 IEEE journal or conference papers. He owns more than 40 Chinese patents and three U.S. patents. His current research interests include power electronics topology and control, and applications for energy saving and renewable energy.

Dr. Xu is an At-Large Adcom Member of the IEEE Power Electronics Society from 2017 to 2019 and from 2006-2008. He is an Associate Editor of the IEEE TRANSACTIONS ON POWER ELECTRONICS. He is the IEEE PELS Distinguished Lecturer in 2015–2017. He received four IEEE journal or conference paper awards. In 2016, he received the IEEE PELS R. D. Middlebrook Achievement Award. He has been the President of the China Power Supply Society since 2013.

Wenjie Chen received the B.S. degree in Electrical and Information Engineering from Zhejiang University, Hangzhou, China, in 2009. He worked in Aalborg University as a visiting Ph.D. student in 2013. He received the Ph.D. degree in Power Electronics in the College of Electrical Engineering at Zhejiang University, Hangzhou, China, 2015.

Now he is a senior engineer working in SUNGROW POWER SUPPLY Co., Ltd.