Research Article

Efficiency Improvement of Three-Phase Cascaded H-Bridge Multilevel Inverters for Photovoltaic Systems

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Medium-scale photovoltaic (PV) systems using cascaded H-bridge multilevel inverters have a capability to perform individual maximum power point tracking (MPPT) for each PV panel or each small group of panels, resulting in minimization of both power losses from panel mismatch and effect of partial shading. They also provide high power quality, modularity, and possibility of eliminating dc-dc boost stage and line-frequency transformer. However, each PV panel in the system is subjected to a double-line-frequency voltage ripple at the dc-link which reduces the MPPT efficiency. This paper proposes a dc-link voltage ripple reduction by third-harmonic zero-sequence voltage injection for improving the MPPT efficiency. Moreover, a control method to achieve individual MPPT control of each inverter cell is also presented. The validity and effectiveness of the proposed methods were verified by computer simulation.

1. Introduction

Renewable energy technology has undergone a substantial development in the last three decades. Photovoltaic (PV) system is promising and one of the fastest growing renewable energy sources. The worldwide cumulative installed capacity of PV systems has been increasing exponentially in the last decade and recently has reached a level of 178 GW at the end of 2014 [1] due to the decreasing price per PV panel and government policies in many countries.

Generally, the PV system topologies can be categorized into four groups: (1) central inverter, (2) module-integrated inverter, (3) string inverter, and (4) multistring inverter [2–5]. In the central inverter topology, several PV strings (PV panels connected in series) are connected in parallel with one blocking diode per string to form a single dc-link and are connected to the grid via a central inverter. This topology has a simple structure, a reliable control, and a low initial cost. However, with only one centralized maximum power point tracking (MPPT) control, the energy yield can be easily reduced by the effects of panel mismatch and partial shading. Dividing PV panels into smaller groups with

individual MPPT control can mitigate the problem [6, 7]. The module-integrated inverter topology is another side of the spectrum. In this topology, one converter operates with only one or a few PV panels. Thus, the power loss from panel mismatch can be minimized and the effect of partial shading can be mitigated. However, the voltage amplification by either dc-dc boost stage or transformer is required. The module-integrated inverter topology is intended for small PV systems lower than 500 W. For the string inverter topology, one PV string is connected to the grid via one inverter. Therefore, the benefit of this topology is a trade-off between central inverter and module-integrated inverter topologies. Finally, the multistring inverter topology combines higher energy yield of the string inverter with low initial cost of the central inverter topology. Several PV strings, each with one dedicated dc-dc converter, are connected to a central inverter. Moreover, in addition to the traditional two-level inverters, the use of neutral-point-clamped (NPC) inverter for either central inverter, string inverter, or multistring inverter topologies has also been reported [8, 9].

Recently, cascaded H-bridge multilevel inverter topology has gained interest from many researchers for PV system

FIGURE 1: Topology of the grid-connected cascaded H-bridge PV system. (a) Single-phase system. (b) Three-phase system. (c) H-bridge inverter.

applications [10–20]. It is characterized by a cascade connection of several H-bridge inverters per one phase. The system topology is depicted in Figure 1 which can be either a single-phase system in Figure 1(a) or a three-phase system in Figure 1(b), depending on the system power rating. A single PV panel can be directly connected to the dc side of each H-bridge inverter to implement the concept of one converter per one PV panel. This is similar to that of the module-integrated inverter topology. In this case, it is possible to achieve the distributed MPPT control by each H-bridge inverter individually [10, 11] that greatly optimizes the energy yield from the PV panels. The advantages of this system can be summarized as follows:

- (i) The MPPT can be performed individually for each PV panel to eliminate the effects of panel mismatch and partial shading, thus maximizing the energy production in contrast to the system utilizing the centralized MPPT.
- (ii) Due to the voltage scalability of the cascaded multilevel converter, it is possible to eliminate the dc-dc boost converter stage and line-frequency transformer for voltage elevation. This can reduce the weight and cost of the PV system.
- (iii) The cascaded multilevel converter produces multilevel PWM output voltage waveform which has low voltage THD (Total Harmonic Distortion) and low

current THD. Therefore, EMI emission and harmonic filter are minimized.

- (iv) Due to multiplicative effect of switching frequency, the system can achieve high output switching frequency while the device switching frequency is low. Thus, the switching power loss is low.
- (v) The modularity of the system enables the reduction of manufacturing cost and easy maintenance operation.

On the other hand, the system can be extended to a large-capacity PV system in which the dc-link of each H-bridge inverter can be connected to several PV strings with one dedicated dc-dc converter per string that is similar to the concept of multistring inverter topology [12, 13]. This kind of system can achieve a power rating of a few megawatts with the voltage rating in the medium-voltage level. However, this paper focuses on a smaller PV system with one PV panel per one H-bridge inverter for simplifying the analysis to be presented in this paper.

Since each PV panel is directly connected to a single-phase dc-ac inverter, it is subjected to power fluctuation of an angular frequency of 2ω produced by the ac side of the H-bridge inverter. The power fluctuation causes voltage ripple at the terminal of the PV panel connected to the dc-link capacitor. The low-frequency ripple of the dc-link voltage is significant in this topology because each cell is a single-phase inverter. This is unlike in a three-phase inverter such as NPC or conventional two-level inverter where the three phase

FIGURE 2: Effect of dc-link voltage ripple on the MPPT [3].

legs share a common dc-link in which the ripple frequency is higher (3ω) but much smaller in amplitude. The voltage ripple causes an output power ripple from the PV panel because the terminal voltage swings around the voltage at MPP. This power ripple makes the average output power somewhat lower than the power at MPP, thus reducing the MPPT efficiency, as described in Figure 2 [3]. Since the MPPT algorithm always drives the operating point to the MPP and the center of voltage swing is always the voltage at MPP, reducing the dc-link voltage ripple in each cell can increase the average output power and the MPPT efficiency.

The dc-link voltage (or current) ripple reduction methods have been proposed for some systems and applications; for example, [21] proposed a dc-link ripple current reduction for paralleled three-phase voltage-source converter (VSC) with interleaving (this method requires two VSCs connected in paralleled), [22] proposed a dc-link voltage ripple reduction for a transformerless modular wind generator system, and [23] proposed a dc-link voltage ripple minimization method for a modular VSC for HVDC power transmission. This paper presents a dc-link voltage ripple reduction in each cell of the three-phase cascaded H-bridge multilevel PV system by injecting the third-harmonic zero-sequence voltage to improve the MPPT efficiency. The objective of the third-harmonic zero-sequence voltage injection in this paper is different from that in [24] where it is used to increase the dc-link utilization and obtain higher number of voltage levels. The method proposed in this paper does not introduce any additional circuit component. In addition, this paper also describes a control method to achieve individual MPPT control in each converter cell. The validity and effectiveness of the methods presented in this paper are verified by computer simulation.

2. Circuit Configuration of the PV System

According to Figure 1, each phase of the system is a series connection of multiple converter cells. Each converter cell consists of an H-bridge inverter and a PV panel as an isolated dc source. The dc-link capacitor is installed in parallel with each PV panel as a power decoupling element for absorbing the PWM switching current produced at the dc side of each

FIGURE 3: Circuit diagram of cell a1.

H-bridge inverter. The system is connected to the grid via ac-link inductor(s) L . Each H-bridge inverter is modulated with a unipolar PWM technique and produces three-level PWM voltage. The frequency of triangular carrier signal for each cell is f_c . When several cells are connected in series, a phase-shift PWM (PS-PWM) modulation strategy is used to generate multilevel PWM voltage waveform. In this case, the number of output voltage levels becomes $2n+1$ levels (line-to-neutral), where n is the number of cells per phase. The phase shift of carrier signals of the adjacent cells is π/n [25]. Due to the multiplicative effect of switching frequency of the PS-PWM, the system then achieves an output switching frequency of $2nf_c$, while the device switching frequency is only at f_c . This has a positive effect on the system efficiency. Moreover, both the multilevel PWM and high switching frequency characteristics have a positive effect on the harmonic performance of the system.

3. Principle of dc-Link Voltage Ripple Reduction

This paper proposes the dc-link voltage ripple reduction by injecting the third-harmonic zero-sequence voltage component which can reduce the dc-link voltage ripple without introducing any additional circuit component. Since the third-harmonic zero-sequence voltage injection technique can be used only for three-phase three-wire systems, this paper focuses on the three-phase cascaded H-bridge PV system as shown in Figure 1(b) only.

Considering cell a1 depicted in Figure 3 in steady-state condition, the instantaneous power of capacitor p_C has only ac component. Hence, by neglecting power losses of the H-bridge inverter, the instantaneous power balance can be expressed as

$$p_C = (p_{PV})_{ac} - (p_H)_{ac} = (v_{PV}i_{PV})_{ac} - (v_Hi_a)_{ac}, \quad (1)$$

where p_{PV} is the power flowing from the PV panel, p_H is the power flowing to the dc side of H-bridge inverter, and $(y)_{ac}$ is the ac component of y . In this case, $(v_Hi_a)_{ac}$ is much larger than $(v_{PV}i_{PV})_{ac}$ because v_H and i_a are both ac quantities while v_{PV} and i_{PV} are both dc quantities. Hence, the instantaneous power of capacitor p_C at the steady-state can be approximated as

$$p_C \approx -(v_Hi_a)_{ac}. \quad (2)$$

An approximated expression of the ac ripple component $\tilde{v}_C$ of capacitor voltage can be calculated from the dc-link capacitor power p_C as (see Appendix)

$$\tilde{v}_C = \frac{\int p_C dt}{CV_C}. \quad (3)$$

Hence, from (2) and (3), the ac ripple component of dc-link voltage can be expressed as

$$\tilde{v}_{PV} = \frac{-\int (v_H i_a)_{ac} dt}{CV_{PV}}, \quad (4)$$

where C is the capacitance of the dc-link capacitor and V_C is the nominal capacitor voltage. It should be noted that V_{PV} and V_C are equal.

Voltage v_H without the third-harmonic zero-sequence voltage injection is expressed as

$$v_H = V_H \sin \omega t, \quad (5)$$

while v_H with the third-harmonic zero-sequence voltage injection is expressed as

$$v_H = V_H (\sin \omega t + A_3 \sin 3\omega t), \quad (6)$$

where A_3 is the relative amplitude of the third-harmonic voltage. By assuming that the system operates with power factor close to unity, the grid current i_a is expressed as

$$i_a = I_a \sin \omega t. \quad (7)$$

Substituting (5), (6), and (7) into (4), the dc-link voltage ripple component without the third-harmonic zero-sequence voltage injection is expressed as

$$\tilde{v}_{PV_{org}} = \frac{V_H I_a}{4\omega CV_{PV}} \sin 2\omega t, \quad (8)$$

while the dc-link voltage ripple with the third-harmonic zero-sequence voltage injection is expressed as

$$\tilde{v}_{PV_{inj}} = \frac{V_H I_a}{4\omega CV_{PV}} (1 - A_3) \sin 2\omega t + \frac{V_H A_3 I_a}{8\omega CV_{PV}} \sin 4\omega t. \quad (9)$$

Figure 4 shows the plots of the estimated waveforms of dc-link voltage ripple $\tilde{v}_{PV_{org}}$ and that of the dc-link voltage ripple with the third-harmonic zero-sequence voltage injection $\tilde{v}_{PV_{inj}}$ when $A_3 = 0.4$. It can be seen that injecting the third-harmonic zero-sequence voltage can reduce the amplitude of the dc-link voltage ripple. Figure 5 shows the percentage of the dc-link voltage ripple reduction versus A_3 obtained from the theoretical calculation using (8) and (9), for $A_3 = 0$ to 0.8. It shows that as A_3 increases more ripple amplitude reduction can be achieved. However, Figure 6 shows that the amplitude of v_H is higher than 100% when A_3 is larger than 0.4 (amplitude is equal to 100% when $A_3 = 0$). Hence, the relative amplitude A_3 cannot be increased arbitrarily without bound in order to prevent the overmodulation of H-bridge inverter. The maximum possible value of A_3 depends on

FIGURE 4: Estimation of dc-link voltage ripple without and with the third-harmonic zero-sequence voltage injection.

FIGURE 5: Amplitude reduction of dc-link voltage ripple versus A_3 when injecting third-harmonic zero-sequence voltage.

the modulation index of the H-bridge inverter which is a ratio between the voltage amplitude V_H and the PV panel voltage at maximum power point V_{mpp} . For example, when the modulation index is equal to 0.85, the amplitude of v_H can be increased by the third-harmonic zero-sequence voltage injection up to 117% ($=1/0.85 \times 100$) before overmodulation occurs. Thus, the maximum possible value of A_3 is 0.6 according to Figure 6. Hence, the dc-link voltage ripple amplitude reduction can be achieved up to 39% according to Figure 5.

4. Method for Individual MPPT Control

The principle of individual MPPT control is based on the individual control of the dc-link voltage of each converter cell. By considering Figure 3, the following relation can be obtained:

$$i_H = i_{PV} - C \frac{dv_{PV}}{dt}. \quad (10)$$

Hence, the dc-link voltage v_{PV} can be controlled by controlling i_H using the proportional-integral (PI) controller as shown in Figure 7, considering i_{PV} as a disturbance. In this case, i_H is related to i_a as

$$i_H = d \cdot i_a, \quad (11)$$

where d is the duty cycle of the H-bridge inverter. This means that the H-bridge inverter works as a current-source

FIGURE 6: Amplitude of v_H versus A_3 with the third-harmonic zero-sequence voltage injection (100% when $A_3 = 0$).

FIGURE 7: dc-link voltage controller (output is i_H^*).

converter when seen from the dc side, where i_H can be made proportional to i_a by adjusting the duty cycle. Note that d is an ac signal because i_a is an ac signal while i_H is a dc signal. Therefore, the product of d and i_a becomes a dc signal. Assuming that i_a has a constant amplitude, the output of PI controller in Figure 7 is changed to D in Figure 8, where D is rms value of d . This means that the dc-link voltage can be controlled by adjusting the duty cycle of the H-bridge inverter. However, adjusting duty cycle will also affect the H-bridge inverter output voltage v_H because

$$v_H = d \cdot v_{PV}. \quad (12)$$

Thus, the duty cycle of each inverter in phase x (where $x = a, b, c$) cannot be adjusted arbitrarily; otherwise the summation of v_H in phase x may not be equal to v_x^* , where v_x^* is the voltage command for phase x obtained from the grid current control. In order to simultaneously control the grid current and the individual dc-link voltage, the output voltage command of each inverter must be a weighted proportion of v_x^* calculated by

$$v_H^{xj*} = v_x^* \frac{D_{xj} v_{PV}^{xj}}{\sum_{j=1}^n (D_{xj} v_{PV}^{xj})}, \quad (13)$$

where $j = 1 - n$ and D_{xj} is the rms value of the duty cycle of cell xj obtained from the PI controller as shown in Figure 8.

The calculation of the voltage command v_x^* for each phase is based on the grid current control using the conventional voltage-oriented control with dq -current decoupling [26]. The d -axis current command i_d^* is calculated from the summation of error signals of all cells passing through the PI controller as shown in Figure 9, while the q -axis current command i_q^* is set to zero.

FIGURE 8: dc-link voltage controller (output is D).

FIGURE 9: Calculation of i_d^* .

The calculation of the dc-link voltage command for each cell v_{PV}^{xj*} to achieve MPPT can be done by the conventional Perturb and Observe (P&O) method, the PI-based Incremental Conductance method, or others as described in [27].

5. Simulation Results

The simulation model of the three-phase cascaded H-bridge PV system in Figure 1(b) was created with four cells per phase. In this model, it is assumed that each H-bridge inverter is connected to a PV panel and a dc-link capacitor at the dc-link network. The parameters of the PV panel are based on the PV panel model CHSM6610P-250 from Astronergy with the nominal output power of 250 W. Table 1 summarizes the parameters used in the simulation model.

5.1. Simulation Results without the Third-Harmonic Zero-Sequence Voltage Injection. Figure 10 shows the steady-state simulation results of the system in Figure 1(b) without the third-harmonic zero-sequence voltage injection. Figure 10 shows that the waveforms of the three-phase voltage command (v_a^* and v_b^*) are sinusoidal with only fundamental component. The waveforms of the line-to-line output voltages (v_{ab} and v_{bc}) are multilevel PWM voltage waveforms with 17 voltage levels. Therefore, the waveforms of the grid currents (i_a and i_b) are close to sinusoidal with small ripples and low THD. The peak amplitude of the grid current in this case is

FIGURE 10: Simulation results without the third-harmonic zero-sequence voltage injection.

TABLE 1: Parameters used in the simulation model.

PV panel open circuit voltage	38 V
PV panel short circuit current	9.1 A
PV panel maximum power voltage	30 V
PV panel maximum power current	8.3 A
PV panel nominal output power	250 W
Number of cells per phase	4
DC capacitor	3,300 μ F
AC inductor	1 mH
Grid voltage	122.5 V _{L-L}
Grid frequency	50 Hz
System power rating	3 kW
PWM carrier frequency	2 kHz
Output switching frequency	16 kHz

19.2 A. The dc-link voltage waveform of cell c1 v_{dc1} contains a 100 Hz ripple of $8.2 V_{p-p}$ and a small switching-frequency

ripple. The output power of PV panel of cell c1 P_{PV1} contains a 200 Hz ripple of $25.7 W_{p-p}$ and a small switching-frequency ripple with an average output power and peak output power of 238 W and 249 W, respectively. The peak output power is the power at MPP which is equal to a product of maximum power voltage and maximum power current in Table 1 ($30 V \times 8.3 A$). The total power produced by this system is calculated as

$$P_{total} = v_{sa}i_a + v_{sb}i_b + v_{sc}i_c, \quad (14)$$

where v_{sa} , v_{sb} , and v_{sc} are the line-to-neutral grid voltages. In this case, the calculated total power is 2,856 W. Note that the converter power loss is neglected in this simulation.

5.2. Simulation Results with the Third-Harmonic Zero-Sequence Voltage Injection. Figure 11 shows the steady-state simulation results of the system in Figure 1(b) with the third-harmonic zero-sequence voltage injection ($A_3 = 0.4$). The waveforms of three-phase voltage command (v_a^* and v_b^*) are

FIGURE 11: Simulation results with the third-harmonic zero-sequence voltage injection ($A_3 = 0.4$).

the combinations of the fundamental component and the third-harmonic components. The waveforms of the line-to-line output voltages (v_{ab} and v_{bc}) are multilevel PWM voltage waveforms similar to those in Figure 10. These waveforms do not contain the third-harmonic component because the system is the three-phase three-wire system which cancels the zero-sequence third-harmonic components out at the

output. As a result, the waveforms of the grid currents (i_a and i_b) are still close to sinusoidal with only fundamental component. The peak amplitude of the grid current in this case is increased to 19.7 A. The waveform of the dc-link voltage of cell c1 v_{dc1} contains 100 Hz and 200 Hz ripple components as predicted by (9). The amplitude of the dc-link voltage ripple is decreased to 5.6 V_{p-p}. It can be seen that the

TABLE 2: Comparison of the results.

	w/o third-harmonic injection	w/third-harmonic injection	% of change
Grid current peak amplitude	19.2 A	19.7 A	+2.6%
dc-link voltage ripple amplitude	8.2 V _{p-p}	5.6 V _{p-p}	-32%
PV panel power ripple amplitude	25.7 W _{p-p}	13.6 W _{p-p}	-47%
PV panel power at MPP	249 W	249 W	
PV panel average output power	238 W	244.3 W	+2.6%
Output power of the system	2,856 W	2,932 W	+2.6%

dc-link voltage waveform in Figure 11 and that in Figure 4 are similar. This confirms the validity of dc-link voltage ripple estimation presented in Section 3.

In Figure 11, the ripple output power waveform of PV panel of cell c1 is a multifrequency waveform. The amplitude of the power ripple is decreased to 13.6 W_{p-p} with an average output power increased to 244.3 W. The peak power waveform remains 249 W. In this case, the total power produced by this system is 2,932 W (calculated by (14)) which is increased about 2.6% from the previous case.

5.3. Comparison of the Results. Table 2 shows the comparison of the simulation results of the two cases. It can be seen that injecting the third-harmonic zero-sequence voltages with $A_3 = 0.4$ can reduce the amplitudes of the dc-link voltage ripple by 32%. The PV panel power ripple is also decreased, while the peak of power ripple remains unchanged (equal to the power at MPP). As a result, the average output power of each PV panel is increased and the total output power is also increased for the same amount. According to the simulation results, the total output power is increased about 2.6% without any additional circuit component. However, it should be noted that the percentage of the increased power also depends on the accuracy of the current-voltage characteristics of the PV panel used in the simulation.

It should also be noted that the value of the dc-link voltage ripple reduction of 32% in Table 2 is consistent with the value of about 30% in Figure 5. This means that the theoretical estimation of the dc-link voltage ripple presented in Section 3 is accurate.

6. Conclusion

This paper presents a dc-link voltage ripple reduction of the three-phase cascaded H-bridge multilevel PV system using the third-harmonic zero-sequence voltage injection. Therefore, this method is valid only for three-phase three-wire systems. The injection of third-harmonic zero-sequence voltage can reduce the amplitudes of the voltage ripple and power ripple of each PV panel. As a result, the average output power of each PV panel and the total output power are

increased. According to the simulation results, the dc-link voltage ripple reduction is 32% when the relative amplitude of the third-harmonic voltage is 0.4, resulting in the total power increase of 2.6% without any additional circuit component. This paper also presents a control method to achieve an individual MPPT control of each converter cell.

Appendix

Derivation of dc-Link Voltage Ripple Equation

The derivation presented in this section is the same as [28] and is repeated here for completeness. The dc-link voltage $v_{PV}(t)$ of each cell is equal to the dc-link capacitor voltage $v_C(t)$. Denote the dc-link capacitor instantaneous power by $p_C(t)$ and the dc-link capacitor instantaneous energy by $W_C(t)$. $v_C(t)$, $p_C(t)$, and $W_C(t)$ can be related as

$$W_C(t) = \int p_C(t) dt = \frac{1}{2} C (v_C(t))^2 = W_0 + \tilde{W}_C(t). \quad (A.1)$$

Equation (A.1) shows that $W_C(t)$ can be expressed as a summation of the dc component W_0 and the ac component $\tilde{W}_C(t)$. From (A.1), the dc-link capacitor voltage $v_C(t)$ can be expressed as

$$v_C(t) = \sqrt{\frac{2}{C} W_C(t)} = V_C + \tilde{v}_C(t). \quad (A.2)$$

Equation (A.2) shows that $v_C(t)$ can be expressed as a summation of dc mean voltage V_C and the ac ripple component $\tilde{v}_C(t)$. The objective of the following section is to find $\tilde{v}_C(t)$.

Define $v_C(t) = f(x)$ and $x = (2/C)W_C(t)$. Hence, from (A.2), the following equations are obtained:

$$\begin{aligned} f(x) &= \sqrt{x}, \\ f'(x) &= \frac{1}{2\sqrt{x}}. \end{aligned} \quad (A.3)$$

Next, choose a point $t = a$ for Taylor series expansion of $f(x)$ which makes $W_C(a) = W_0$ ($\tilde{W}_C(a) = 0$). Then, the following equations are obtained:

$$\begin{aligned} x|_{t=a} &= x_0 = \frac{2W_0}{C}, \\ f(x_0) &= \sqrt{\frac{2W_0}{C}}, \\ f'(x_0) &= \frac{1}{2\sqrt{2W_0/C}}. \end{aligned} \quad (A.4)$$

The function $f(x)$ can be approximated by Taylor series expansion around the point x_0 as

$$f(x) \approx f(x_0) + f'(x_0)(x - x_0). \quad (A.5)$$

By substituting (A.4) into (A.5), the following equation is obtained:

$$\begin{aligned} f(x) &= \sqrt{\frac{2W_0}{C}} + \frac{(2/C)W_C(t) - 2W_0/C}{2\sqrt{2W_0/C}} \\ &= \sqrt{\frac{2W_0}{C}} + \frac{\bar{W}_C(t)}{\sqrt{2CW_0}}. \end{aligned} \quad (\text{A.6})$$

By comparing (A.6) with (A.2), the terms V_C and $\bar{v}_C(t)$ can be expressed as

$$\begin{aligned} V_C &= \sqrt{\frac{2W_0}{C}}, \\ \bar{v}_C(t) &= \frac{\bar{W}_C(t)}{\sqrt{2CW_0}} = \frac{\bar{W}_C(t)}{CV_C} = \frac{\int_0^t (p_C(\tau))_{ac} d\tau}{CV_C}. \end{aligned} \quad (\text{A.7})$$

Therefore, the ac ripple component $\bar{v}_C(t)$ can be calculated from the ac component of the dc-link capacitor power $(p_C(t))_{ac}$.

Nomenclature

$(y)_{ac}$:	ac component of y
A_3 :	Relative amplitude of third-harmonic voltage
C :	Capacitance of dc-link capacitor
d :	Duty cycle signal of bridge cell
D :	rms value of d
D_{xj} :	rms duty cycle of j th cell of phase x
i_a :	Grid current of phase a
I_a :	Amplitude of i_a
i_d^* :	d -axis current reference of the system
i_q^* :	q -axis current reference of the system
i_H :	Current of bridge cell at the dc side
i_{PV} :	Current of PV panel
p_C :	Instantaneous power of dc-link capacitor
p_H :	Instantaneous power of bridge cell at the ac side
p_{PV} :	Instantaneous power of PV panel
v_C :	dc-link capacitor voltage
$\bar{v}_C$:	ac ripple component of dc-link capacitor voltage
V_C :	dc mean value of dc-link capacitor voltage
v_H :	Output voltage of bridge cell at the ac side
V_H :	Amplitude of v_H
v_{PV} :	Voltage of PV panel
$\bar{v}_{PV}$:	ac ripple component of PV panel voltage
V_{PV} :	dc mean value of PV panel voltage
$\bar{v}_{PV_{org}}$:	Ripple component of PV panel voltage without third-harmonic injection
$\bar{v}_{PV_{inj}}$:	Ripple component of PV panel voltage with third-harmonic injection
v_x^* :	Voltage reference of phase x
v_H^{xj*} :	Reference of v_H for j th cell of phase x
v_{PV}^{xj} :	PV panel voltage of j th cell of phase x
v_{sa}, v_{sb}, v_{sc} :	Line-to-neutral grid voltages
W_C :	Instantaneous energy of dc-link capacitor
W_0 :	dc component of W_C
$\bar{W}_C$:	ac component of W_C
ω :	Fundamental angular frequency of the system.

Competing Interests

The authors declare that they have no competing interests.

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