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A Control Strategy for Dual-Input Neutral-Point-Clamped Inverter-Based Grid-Connected Photovoltaic System

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Abstract—This paper presents a control strategy for a dual-input neutral-point-clamped (NPC) inverter-based grid-connected photovoltaic (PV) system to asymmetrically control the PV arrays without incorporating any additional external circuit. This is achieved by employing an analytically developed linearization block, which helps in generating the required neutral point (NP) current to counter for the difference in the PV currents. The analysis also provides the maximum NP current compensation limits of the NPC inverter. If the required NP current reference is less than the maximum limit, both PV arrays operate at their maximum power points. However, if the required current exceeds the limit, one of the PV arrays operates at its maximum power point (MPP) while the output power of the other PV array is reduced to satisfy the NP current limit. Experimental tests are conducted on a laboratory prototype to validate the performance of the proposed control strategy.

Index Terms—Carrier-based pulsewidth modulation, feed-forward compensation, neutral-point-clamped (NPC) converter, neutral-point current, partial shading, photovoltaic (PV) arrays.

NOMENCLATURE

v_{ga}, v_{gb}, v_{gc}	Grid phase voltages
f	Grid frequency
θ_g	Grid voltage angle
v_d^*, v_q^*	AC-side voltage references of the neutral-point-clamped (NPC) converter in dq frame
v_a^*, v_b^*, v_c^*	Normalized ac-side phase voltage references of the NPC converter in abc frame
v_a, v_b, v_c	Normalized ac-side phase voltage references with zero-sequence injection of the NPC converter in abc frame
δ	Phase angle difference between the converter's ac-side voltage and the ac-side current
m	Modulation index
i_a, i_b, i_c	AC-side currents in abc frame
i_d, i_q	AC-side currents in dq frame
I_m	Maximum value of phase current
i_d^*, i_q^*	AC-side current references in dq frame
p_g	Grid power
L	Grid filter inductor
f_s	Carrier frequency
i_{NP}	Neutral-point current

$\bar{i}_{NP}$

i_{NPref}

$\bar{i}_{NPmax}$

i_z

$d_{NP_a}, d_{NP_b}, d_{NP_c}$

$d_{l_a}, d_{l_b}, d_{l_c}$

$d_{h_a}, d_{h_b}, d_{h_c}$

$d'_{NP_a}, d'_{NP_b}, d'_{NP_c}$

$d'_{l_a}, d'_{l_b}, d'_{l_c}$

$d'_{h_a}, d'_{h_b}, d'_{h_c}$

v_{dc}

v_{PV1}, v_{PV2}

i_{PV1}, i_{PV2}

p_{PV1}, p_{PV2}

Irr_{PV1}, Irr_{PV2}

Neutral-point current averaged over a fundamental period of the grid voltage
Neutral-point current reference
Maximum average neutral-point current compensation capability of the NPC inverter

Average neutral-point current generated due to zero-sequence voltage

Duty cycles for connecting the three phases to the neutral-point

Duty cycles for connecting the three phases to the negative dc-rail

Duty cycles for connecting the three phases to the positive dc-rail

Feedforward compensated duty cycles for connecting the three phases to the neutral-point

Feedforward compensated duty cycles for connecting the three phases to the negative dc-rail

Feedforward compensated duty cycles for connecting the three phases to the positive dc-rail

DC-link voltage

PV arrays voltage

PV arrays current

PV arrays power

Irradiance levels for PV arrays

I. INTRODUCTION

In recent years, solar energy has become one of the prominent sources for electricity generation [1]. According to the International Energy Agency on Photovoltaic Power Systems (IEA PVPS) report for 2019, the global cumulative photovoltaic (PV) installations have crossed 620 GW [2]. Most of the PV systems are grid-connected, which accounts for more than 99% of the total installed PV capacity as compared to the stand-alone PV systems [3].

For grid-integration of high power PV systems, either multistring or centralized configuration is employed [3]–[7]. In the multistring configuration, each PV string is connected to a dc-dc converter (commonly a boost converter), which helps in tracking individual maximum power point (MPP) of the

Fig. 1. Circuit diagram of a dual-input (PV1, PV2) three-phase NPC inverter-based grid-connected PV system.

strings. These converters are connected to the grid using a central dc-ac converter. While in the centralized configuration, the PV strings are connected directly in parallel to the dc-bus of one common central dc-ac converter. The MPP tracking for all the strings is achieved using the central converter. As the centralized configuration employs single-stage power conversion, the initial installation cost and the implementation complexity is lower as compared to the multistring configuration, which has a two-stage power conversion. However, due to the single MPP tracking operation, the power conversion efficiency reduces under partial shading and panel mismatch for such a configuration.

In the literature, many researchers have employed multilevel converters to improve the MPP tracking performance of the strings [7]–[12]. One of the widely employed multilevel converters is the neutral-point-clamped (NPC) converter, shown in Fig. 1 [13]. In [7], the PV array is directly connected to the dc-link of the NPC converter. In this topology, under any mismatch between the PV panels or partial shading conditions, the converter is unable to extract the maximum available power from the PV array. In order to increase the power extraction, the PV panels can be divided between the dc-link capacitors of the NPC converter, as shown in Fig. 1. The split dc-link capacitors of an NPC converter can be independently controlled in order to achieve separate MPPs for the PV strings. Due to this advantage, a dual-input three-phase NPC inverter-based grid-connected PV system (Fig. 1) is considered in this paper. This converter topology is intended for medium-power PV systems, in the range of tens to hundreds of kW.

In Fig. 1, the PV arrays are connected to the bipolar dc-bus of the NPC inverter. When both the PV arrays operate under the same irradiance levels ($I_{PV1} = I_{PV2}$), no average current flows through the neutral point (NP) and both the PV arrays operate at their corresponding MPPs. Contrarily, under partial shading or array mismatch, both the PV arrays need to operate at different MPPs to extract maximum power, resulting in $I_{PV1} \neq I_{PV2}$. If the difference between I_{PV1} and I_{PV2} is not compensated by the NP current, the capacitor voltages start diverging and the power conversion efficiency decreases

due to the inability of PV arrays to achieve their corresponding MPPs. Each phase of the NPC converter behaves as a single-pole triple-throw switch and can be connected to either positive dc-rail (+1), negative dc-rail (-1) or NP (0) [13]. Therefore, the NP current is contributed by all the phases and is determined by using the phase currents and the duty cycles connecting the phases to the NP. As the values of the NP duty cycles are in the range [0, 1], the maximum average NP current that can be supplied is restricted. Thus, it is important to design a control strategy that is able to extract the maximum power from the solar PV arrays for the whole range of operating conditions.

Many attempts have been made in the literature to address the abovementioned issue regarding the dual-input NPC inverter-based grid-connected PV systems. Naik *et al.* [14] employed an additional auxiliary converter at the dc-link of the NPC inverter in order to achieve independent MPP tracking of the split sections. The auxiliary converter helps in generating an average NP current to compensate the difference of the two PV array currents. It is constituted by four additional switches, two inductors and one capacitor, increasing the complexity of the system. A similar approach is presented in [15], wherein an auxiliary converter constituted by four switches and one inductor is incorporated to the dc-link of the NPC inverter. However, the auxiliary converter only operates under partial shading (when the power difference between the two PV arrays exceed 20%). An MPP tracking for both the PV arrays together, i.e., considering them as one unit, is achieved when the power difference is small. This implies that the inherent capability of the NPC inverter to compensate the NP current reference is unused. Moreover, the additional cost of such auxiliary converters could partially overshadow the power generation gain during partial shading in large central inverter-based PV systems.

Park *et al.* [16] proposed a new carrier-based pulsewidth modulation (CBPWM) method to control the dc-link voltages asymmetrically without using any additional hardware. A zero-sequence voltage is utilized to achieve the asymmetric control. In addition, the shape of the carrier waveform is modified according to the instantaneous capacitor voltages, which becomes difficult to implement in real-time. Another solution is presented in [17], wherein the two PV array voltages are controlled asymmetrically by modifying the three-phase turn-on times. The reference voltages are also modified to reduce the effect of asymmetric capacitor voltages on the ac-side output voltage. However, no comprehensive analysis to determine the maximum NP current compensation capability of the NPC inverter is provided under this method. In [18], a PWM technique based on virtual-space vectors is presented in order to independently control the PV array voltages for a multilevel diode-clamped converter. The authors have also discussed how the voltage control is limited by the operating modulation index and irradiance difference between the PV arrays. However, again no quantitative analysis to determine the maximum NP current compensation capability of the NPC converter is provided. Moreover, the paper did not demonstrate the maximum power extraction capability of the proposed methodology when the NP current limits are exceeded.

In this paper, a control strategy is presented for a dual-

input NPC inverter-based grid-connected PV system that is able to asymmetrically control the two PV arrays and extract maximum possible power for the whole range of operating conditions. This is achieved by using a linearization block that takes actions directly proportional to the required NP current. The proposed linearization block also quantifies the maximum NP current compensation capability of the NPC converter using the converter's ac-side voltages and currents. The proposed control strategy ensures that both PV arrays operate at their respective MPPs under partial shading and panel mismatch if the required NP current reference is less than the maximum NP current compensation capability of the NPC converter. However, if the required NP current exceeds this limit, one of the PV arrays is operated at its MPP while the operating point of the other PV array is chosen so as to extract maximum possible power without incorporating any additional hardware. The advantages of the proposed control strategy are:

- It enables asymmetrical control of the PV arrays.
- It takes into account all the possible operating conditions without incorporating any auxiliary hardware.
- A feedforward compensation is incorporated in order to neutralize the effect of asymmetric PV array voltages on the ac-side voltages.
- In the proposed control strategy, the difference between the two PV currents, i.e., the NP current reference, is translated to duty cycles using a linearization block. The calculated duty cycles are compared to a carrier signal to generate the switching pulses of the NPC inverter.
- The proposed linearization block is developed analytically by integrating the NP current contribution of each phase.
- The average NP current is controlled linearly using the proposed linearization block.
- The proposed block also gives the maximum average NP current compensation capability of the NPC inverter.

The paper is organized as follows. Section II introduces the average NP current generation mechanism and the proposed linearization block. Section III provides the operating principles and the overview of an overall control system. Section IV provides the experimental validation of the proposed control strategy. Section V presents simulation results to analyze the performance of the proposed control strategy further, and Section VI summarizes the conclusions of this work.

II. PROPOSED AVERAGE NP CURRENT REGULATION STRATEGY

As discussed under Section-I, for the dual-input three-phase NPC inverter-based grid-connected PV system (Fig. 1), the difference between I_{PV1} and I_{PV2} needs to be compensated in order to obtain a stable operation of the PV system. This difference in the current determines the required NP current reference (i_{NPref}). Thus, the main aim of the proposed control strategy is to switch the NPC inverter in such a way that the generated nonzero average NP current ($\bar{i}_{NP}$) compensates the i_{NPref} .

A. Average NP Current Generation Mechanism

This subsection discusses the basic concept of generating a nonzero average NP current in NPC inverter to compensate the i_{NPref} . In order to achieve this, it is important to analyze the factors affecting the NP current. The NP current (i_{NP}) over a switching period is given as [19]:

$$i_{NP} = \sum d_{NPj} i_j, j \in \{a, b, c\}, \quad (1)$$

where d_{NPj} represents the duty cycle connecting phase j to the NP and i_j represents the current of phase j . The average NP current ($\bar{i}_{NP}$) is calculated by averaging i_{NP} over the fundamental grid voltage period. From (1), it is clear that the NP duty cycle of each phase directly affects the generated $\bar{i}_{NP}$.

Different modulation strategies have been presented in the literature to calculate these duty cycles. One of the commonly employed carrier-based pulsewidth modulation (CBPWM) technique is the two-level modulation [20]. In this modulation technique, all the three phases switch between consecutive voltage levels, i.e., either between the positive dc-rail and the NP or between the negative dc-rail and the NP, which is called as two-level modulation in this paper and the NP duty cycle is given as [20]:

$$d_{NPj} = 1 - |v_j^*| \quad (2)$$

where, v_j^* represents the normalized ac-side voltage reference of phase j in abc frame with respect to half of the dc-link voltage. A zero-sequence voltage (v_z) based on the difference in the PV voltages, is added to the normalized ac-side voltage reference as follows [19]:

$$v_j = v_j^* + v_z, \text{ where } v_z = \frac{v_{PV2} - v_{PV1}}{v_{PV2} + v_{PV1}}. \quad (3)$$

The added zero-sequence shifts the position of the ac-side references in accordance to the imbalance in the capacitor voltages. This zero-sequence voltage does not appear in the line-to-line ac-side voltages and its effect on the NP current can be easily accounted for as discussed in the next subsection. Thus, the NP duty cycle for the two-level modulation based on the normalized ac-side voltage with zero-sequence injection is given as:

$$d_{NPj} = 1 - |v_j| \quad (4)$$

The rest of the duty cycles are given as [19]:

$$d_{hj} = \frac{|v_j| + v_j}{2}; d_{lj} = \frac{|v_j| - v_j}{2}, \quad (5)$$

where d_{hj} and d_{lj} are the duty cycles for connecting phase j to the positive and negative dc-rails, respectively. Since the PV voltages are variable, it is important to incorporate feedforward compensation to the duty cycles to avoid low-frequency distortion in the ac-side voltages. The feedforward compensated duty-cycles are calculated as [19],

$$d'_{hj} = d_{hj} \frac{v_{dc}}{2v_{PV2}}; d'_{lj} = d_{lj} \frac{v_{dc}}{2v_{PV1}}; d'_{NPj} = 1 - d'_{hj} - d'_{lj}, \quad (6)$$

where $v_{dc} = v_{PV1} + v_{PV2}$ and d'_{hj} , d'_{lj} and d'_{NPj} are the feedforward compensated duty cycles for connecting phase j

Fig. 2. Waveforms of normalized ac-side voltages, current and feedforward compensated duty cycles of phase a , i_{NP} and $\bar{i}_{NP}$ when the solar PV arrays are operating at different voltages generating: (a) Appropriately zero i_{NP} , (b) positive i_{NP} and (c) negative i_{NP} .

to the positive, negative and NP dc-rails, respectively. The updated NP current is calculated as,

$$i_{NP} = \sum d'_{NPj} i_j. \quad (7)$$

Fig. 2(a) shows the waveforms of normalized ac-side voltage, current, feedforward compensated duty cycle of phase a , i_{NP} and $\bar{i}_{NP}$ when the PV arrays are operating at different voltages ($v_{PV1}=0.8$ pu and $v_{PV2}=1.2$ pu). These waveforms are obtained using (7) and assuming sinusoidal ac-side voltage and current, i.e., $v_a^* = m\cos(\theta_g + \delta)$ and $i_a = I_m\cos(\theta_g)$. As the resultant v_z is positive, the v_a obtained is greater than v_a^* . From Fig. 2(a), it is clear that under the two-level modulation, the average NP current contribution of phase a is very small, arising from the imbalance in the capacitor voltages. The remaining phases can also be analyzed in the same manner. Therefore, the obtained $\bar{i}_{NP}$ is very small over a fundamental period when all the phases switch in two consecutive voltage levels. However, if the dc-link capacitor voltages are balanced ($v_z = 0$), the average NP current contribution will be, in turn, zero under two-level modulation. A higher magnitude of zero-sequence voltage (v_z) leads to a larger nonzero average NP current (i_z), however, this provides limited flexibility to control the generated current and to operate the PV arrays at their respective MPPs. Thus, the two-level modulation does not provide the freedom to inject the required average NP current (i_{NPref}) for obtaining stable operation of the PV system.

In [21], the authors presented ‘three-level modulation’ technique with the aim of completely eliminating the NP voltage ripples. In this technique, one of the phases is chosen to switch in three voltage levels in one switching period, i.e., positive, NP and negative dc-rails, while the other two phases switch only in two consecutive voltage levels (similar to the

two-level modulation). This study also showed that the NP current can be controlled within the NP current limits by switching one or more phases in three voltage levels. In other words, if phase j switches between the positive and negative dc-rails, i.e., $d_{NPj} = 0$, this phase does not contribute to the NP current. Using this feature, the current can be injected/withdrawn in/from the NP in order to generate the required $\bar{i}_{NP}$. The feedforward compensated duty cycles for phase j when switching between the positive and negative dc-rails are given as,

$$d'_{NPj} = 0; d'_{hj} = \frac{v_j}{2} + \frac{v_{PV1}}{v_{dc}}; d'_{lj} = 1 - d'_{hj}. \quad (8)$$

When the NP duty cycle for each phase is kept zero for a span of α radians within a fundamental period (the phase switches between the positive and negative dc-rails), and is calculated using the two-level modulation for the rest of the period, a nonzero average NP current is generated, as depicted in Figs. 2(b) and (c). Disregarding i_z , the generated $\bar{i}_{NP}$ is positive when the α span coincides with the negative phase current (Fig. 2(b)) and is negative if the α span coincides with the positive phase current (Fig. 2(c)). The α span is placed symmetrically on the peak of the phase current, as shown in Fig. 3. For $\alpha \leq 2\pi/3$, only one of the three phases switches between the positive and negative dc-rails. However, for $2\pi/3 < \alpha \leq \pi$, two phases switch between the positive and negative dc-rails simultaneously. The maximum average NP current compensation capability of the NPC inverter is obtained when $\alpha = \pi$.

B. Effect of Zero-Sequence Voltage on Average NP Current

This subsection shows the calculation of average NP current generated due to zero-sequence voltage.

Fig. 3. Operating principle of the linearization block.

Using (5) and (6), the feedforward compensated duty cycle for connecting phase j to the NP for positive normalized modulation signal ($v_j \geq 0$) is given as,

$$d'_{NPj} = \frac{v_{dc}}{2v_{PV2}}(1 - v_j). \quad (9)$$

Similarly, the d'_{NPj} for negative normalized modulation signal ($v_j < 0$) is given as,

$$d'_{NPj} = \frac{v_{dc}}{2v_{PV1}}(1 + v_j). \quad (10)$$

The effect of zero-sequence voltage on the average NP current is easily determined by assuming all the phases are switching under two-level modulation. Considering each phase contributes equally to i_z ,

$$\frac{i_z}{3} = \frac{1}{2\pi} \int_0^{2\pi} d'_{NPj} i_a d\theta_g, \quad (11)$$

$$\begin{aligned} \frac{i_z}{3} = \frac{1}{2\pi} & \left[\int_{-\pi/2-\beta-\delta}^{\pi/2+\beta-\delta} \frac{v_{dc}}{2v_{PV2}}(1 - m\cos(\theta_g + \delta)) \right. \\ & I_m \cos(\theta_g) d\theta_g \\ & + \left. \int_{\pi/2+\beta-\delta}^{3\pi/2-\beta-\delta} \frac{v_{dc}}{2v_{PV1}}(1 + m\cos(\theta_g + \delta)) \right. \\ & \left. I_m \cos(\theta_g) d\theta_g \right]. \end{aligned} \quad (12)$$

Here (Fig. 3),

$$\beta = \left| \cos^{-1} \left(\frac{v_{PV1} - v_{PV2}}{mv_{dc}} \right) - \frac{\pi}{2} \right|. \quad (13)$$

For ease of understanding and representation, a function $F(\theta_g, r, k)$ is defined as,

$$F(\theta_g, r, k) = \frac{-1}{2\pi} \int r(1 - m\cos(\theta_g + \delta + k)) I_m \cos(\theta_g) d\theta_g. \quad (14)$$

Integrating with respect to θ_g , function F is obtained as,

$$F(\theta_g, r, k) = \frac{rI_m}{8\pi} (m\sin(\delta + k + 2\theta_g) - 4\sin(\theta_g) + 2m\theta_g \cos(\delta + k)). \quad (15)$$

Eq. (12) in terms of function F is written as,

$$\frac{i_z}{3} = -F(\theta_g, r_p, 0) \Big|_{-\pi/2-\beta-\delta}^{\pi/2+\beta-\delta} - F(\theta_g, r_n, \pi) \Big|_{\pi/2+\beta-\delta}^{3\pi/2-\beta-\delta}, \quad (16)$$

$$\text{where } r_p = \frac{v_{dc}}{2v_{PV2}} \text{ and } r_n = \frac{v_{dc}}{2v_{PV1}}. \quad (17)$$

Using (15), (16) and (17), i_z is given as,

$$i_z = \frac{3I_m}{4\pi} \cos(\delta) [m(r_p + r_n)(-2\beta + \sin(2\beta)) - m\pi(r_p - r_n) + 4(r_p - r_n)\cos(\beta)]. \quad (18)$$

From (18), it is clear that $i_z=0$ when the dc-link capacitor voltages are balanced as $r_p = r_n$ and $\beta=0$.

C. Proposed Linearization Block

In this paper, the required difference between the two PV currents (i_{NPref}) is translated into α . The area integrated over the α span under two-level modulation is proportional to the difference between the required NP current (i_{NPref}) and the average NP current generated by the zero-sequence voltage (i_z), as it can be seen from Fig. 2. Considering all the phases contribute equally to i'_{NPref} , wherein $i'_{NPref} = i_{NPref} - i_z$, the contribution of each phase is equal to one-third of the required current. Thus,

$$\frac{i'_{NPref}}{3} = \frac{-1}{2\pi} \int_{-\alpha/2}^{\alpha/2} d'_{NPj} i_a d\theta_g. \quad (19)$$

The negative sign ahead of area integrated over the α span denotes that the average NP current generated is in the opposite direction (Figs. 2(b) and (c)). Using (9), (10) and (19), α is calculated to generate the required i_{NPref} .

If $i'_{NPref} \leq 0$ and $v_{PV1} \leq v_{PV2}$, such that $\pi/2 + \beta - |\delta| \geq 0$, (19) can be written as,

$$\begin{aligned} \frac{i'_{NPref}}{3} = \frac{-1}{2\pi} \int_{-\alpha/2}^{\alpha/2} \frac{v_{dc}}{2v_{PV2}}(1 - m\cos(\theta_g + \delta)) \\ I_m \cos(\theta_g) d\theta_g, \end{aligned} \quad (20)$$

$$\alpha \leq 2\alpha_1, \text{ where } \alpha_1 = |\pi/2 + \beta - |\delta||.$$

Thus, (20) in terms of function $F(\theta_g, r, k)$ is given as,

$$\frac{i'_{NPref}}{3} = F(\theta_g, r_p, 0) \Big|_{-\alpha/2}^{\alpha/2}. \quad (21)$$

Using (15), (21) is calculated as,

$$\frac{i'_{NPref}}{3} = \frac{r_p I_m}{4\pi} \left[m\cos(\delta)\sin\alpha + \alpha m\cos(\delta) - 4\sin\left(\frac{\alpha}{2}\right) \right]. \quad (22)$$

In order to obtain an analytic solution, the sine functions are approximated as quadratic functions by using the MATLAB Curve Fitting tool. The approximations for $\sin\alpha$ and $\sin(\alpha/2)$ are given in (23).

$$\begin{aligned} \sin\alpha &= -0.4162\alpha^2 + 1.308\alpha - 0.0475, \\ \sin\left(\frac{\alpha}{2}\right) &= -0.08449\alpha^2 + 0.5972\alpha - 0.02353. \end{aligned} \quad (23)$$

Accuracy of these approximated functions are validated by the root mean square error of less than 0.02 and 0.01 for $\sin\alpha$ and $\sin(\alpha/2)$, respectively. Substituting (23) in (22) and rearranging, a quadratic equation in terms of α is obtained as,

$$\begin{aligned} (0.4162m\cos(\delta) - 0.33796)\alpha^2 \\ + (-2.308m\cos(\delta) + 2.3888)\alpha \\ + \left(0.0475m\cos(\delta) - 0.09412 + \frac{4\pi i'_{NPref}}{3r_p I_m} \right) = 0. \end{aligned} \quad (24)$$

Solving (24) for α :

$$\alpha = \frac{28850m\cos(\delta) - 29860 + 12500\sqrt{q}}{10405m\cos(\delta) - 8449}, \quad (25)$$

where,

$$q = 5.2477m^2\cos^2(\delta) - 10.805m\cos(\delta) - 6.9699m\frac{i'_{NPref}}{r_p I_m}\cos(\delta) + 5.6597\frac{i'_{NPref}}{r_p I_m} + 5.5791. \quad (26)$$

If the solution of α obtained under (25) is greater than $2\alpha_1$, (21) can be written as,

$$\frac{i'_{NPref}}{3} = \begin{cases} F(\theta_g, r_p, 0) \Big|_{-\alpha/2}^{\alpha_1} + F(\theta_g, r_n, \pi) \Big|_{\alpha_1}^{\alpha/2}, & \delta \geq 0 \\ F(\theta_g, r_n, \pi) \Big|_{-\alpha/2}^{-\alpha_1} + F(\theta_g, r_p, 0) \Big|_{-\alpha_1}^{\alpha/2}, & \delta < 0. \end{cases} \quad (27)$$

Taking the case of $\delta \geq 0$, (27) upon solving yields (similar procedure applies to $\delta < 0$ case),

$$\begin{aligned} \frac{i'_{NPref}}{3} = \frac{I_m}{8\pi} & \left[m(r_p + r_n)\sin(2\alpha_1 + \delta) - mr_n\sin(\delta + \alpha) \right. \\ & - 4(r_p + r_n)\sin\left(\frac{\alpha}{2}\right) + m\alpha(r_p - r_n)\cos(\delta) \\ & + 2m\alpha_1(r_p + r_n)\cos(\delta) - mr_p\sin(\delta - \alpha) \\ & \left. + 4(-r_p + r_n)\sin(\alpha_1) \right]. \end{aligned} \quad (28)$$

Rearranging (28),

$$\begin{aligned} & m(r_p + r_n)\sin(2\alpha_1 + \delta) - mr_n\sin(\delta + \alpha) \\ & - 4(r_p + r_n)\sin\left(\frac{\alpha}{2}\right) + m\alpha(r_p - r_n)\cos(\delta) \\ & + 2m\alpha_1(r_p + r_n)\cos(\delta) - mr_p\sin(\delta - \alpha) \\ & + 4(-r_p + r_n)\sin(\alpha_1) - \frac{8\pi i'_{NPref}}{3I_m} = 0. \end{aligned} \quad (29)$$

To solve (29), α is calculated as a linear function of Δv using Taylor series as,

$$\alpha = \alpha_o + \frac{\partial \alpha}{\partial \Delta v} \Big|_{\Delta v=0} \Delta v, \quad (30)$$

where $\Delta v = v_{PV1} - v_{PV2}$ and α_o is the solution of (29) when $\Delta v = 0$ (implying $\beta = 0$, $i_z = 0$ and $r_p = r_n = 1$). α_o is obtained as,

$$\alpha_o = 2\sin^{-1}\left(\frac{2 - \sqrt{p}}{2m\sin(\delta)}\right), \quad (31)$$

where,

$$\begin{aligned} p = 4 - (2m\sin(\delta)) & \left(m\sin(2\alpha_1 + \delta) - m\sin(\delta) \right. \\ & \left. + 2\alpha_1 m\cos(\delta) - \frac{4\pi}{3} \frac{i_{NPref}}{I_m} \right) \end{aligned} \quad (32)$$

and $\frac{\partial \alpha}{\partial \Delta v}$ at $\alpha = \alpha_o$ is calculated as,

$$\frac{\partial \alpha}{\partial \Delta v} = \left[\frac{8\cos(\delta) - 4\sin(\alpha_1) + m\cos(\delta)(\alpha_o + \sin(\alpha_o) - 2\pi) + 2mv_{dc}(\cos(\delta) + \cos(2\alpha_1 + \delta))\frac{\partial \alpha_1}{\partial \Delta v}}{-mv_{dc}\sin(\delta)\sin\alpha_o + 2v_{dc}\cos(\frac{\alpha_o}{2})} \right] \quad (33)$$

Using (30), (31) and (33), the complete solution for α is obtained. The solution set for calculating α under different cases has been summarized in Table I when $i'_{NPref} \leq 0$ and $v_{PV1} \leq v_{PV2}$. Due to the periodic nature of the reference ac-side voltages and the ac-side currents, the solution of α can be easily extended to other cases by using symmetrical modifications, as shown in Table II.

D. Calculation of Maximum Average NP Current Compensation Capacity

As discussed earlier, it is important to quantize the maximum average NP current that can be compensated by the NPC inverter. This limit is needed for the stable operation of the PV system, as discussed in the next section. The maximum average NP current compensation capacity of the NPC inverter ($|\bar{i}_{NPmax}|$) is obtained when $\alpha = \pi$ and is shown in Table III for each case. Using Tables II and III, the value of $|\bar{i}_{NPmax}|$ is easily calculated under all the operating cases.

III. PROPOSED CONTROL STRATEGY

This section provides the details of the operating principles of the proposed control strategy and also presents the overview of the overall control system.

A. Operating Principle

The proposed control strategy aims to asymmetrically control the solar PV arrays and extract maximum possible power. The basic operating principle of the proposed control strategy is explained as follows. Fig. 4 presents current-voltage ($I - V$) and power-voltage ($P - V$) curves for different possible operating conditions for the two solar PV arrays. In Fig. 4(a), both PV arrays operate at the same irradiance levels (no partial shading). In this case, a zero or a small current (due to panel mismatch) flows through the NP, which can be easily compensated by the proposed control strategy. Thus, both PV arrays operate at their respective MPPs (operating points A and B) in this case. Fig. 4(b) shows the case when the PV arrays operate at different irradiance levels, such that the difference between the currents at points A and B is less than the maximum average NP current compensation capability of the NPC inverter ($\bar{i}_{NPmax}$). Under this case, the proposed control strategy ensures that both PV arrays operate at their respective MPPs. In Fig. 4(c), the difference in the irradiance levels increases further such that the difference between the currents at A and B is higher than $\bar{i}_{NPmax}$. As the required NP current cannot be compensated, both PV arrays cannot operate at their respective MPPs simultaneously. In this case, to obtain the maximum possible power extraction, the PV array

TABLE I
FUNCTION $F(\theta, r, k)$ AND SOLUTION OF α WHEN $i'_{NPref} \leq 0$ AND $v_{PV1} \leq v_{PV2}$

CASE-I. $\pi/2 + \beta - |\delta| \geq 0$

$$\frac{i'_{NPref}}{3} = F(\theta_g, r_p, 0) \Big|_{-\alpha/2}^{\alpha/2} \text{ only if } \alpha \leq 2\alpha_1, \text{ where } \alpha_1 = |\pi/2 + \beta - |\delta||.$$

$$\alpha = \frac{28850m\cos(\delta) - 29860 + 12500\sqrt{q}}{10405m\cos(\delta) - 8449}, \text{ where } q = 5.2477m^2\cos^2(\delta) - 10.805m\cos(\delta) - 6.9699m \frac{i'_{NPref}}{r_p I_m} \cos(\delta) + 5.6597 \frac{i'_{NPref}}{r_p I_m} + 5.5791.$$

$$\frac{i'_{NPref}}{3} = \begin{cases} F(\theta_g, r_p, 0) \Big|_{-\alpha/2}^{\alpha_1} + F(\theta_g, r_n, \pi) \Big|_{-\alpha_1}^{\alpha/2}, & \delta \geq 0 \\ F(\theta_g, r_n, \pi) \Big|_{-\alpha/2}^{-\alpha_1} + F(\theta_g, r_p, 0) \Big|_{-\alpha_1}^{\alpha/2}, & \delta < 0 \end{cases} \text{ only if } \alpha > 2\alpha_1, \text{ where } \alpha_1 = |\pi/2 + \beta - |\delta||.$$

$$\alpha = \alpha_o + \frac{\partial \alpha}{\partial \Delta v} \Big|_{\Delta v=0} \Delta v, \text{ where } \alpha_o = 2\sin^{-1}\left(\frac{2 - \sqrt{p}}{2m\sin(|\delta|)}\right) \text{ and } \frac{\partial \alpha}{\partial \Delta v} = \left[\frac{8\cos(\delta) - 4\sin(\alpha_1) + m\cos(\delta)(\alpha_o + \sin(\alpha_o) - 2\pi) + 2mv_{dc}(\cos(\delta) + \cos(2\alpha_1 + |\delta|)) \frac{\partial \alpha_1}{\partial \Delta v}}{-mv_{dc}\sin(|\delta|)\sin\alpha_o + 2v_{dc}\cos(\frac{\alpha_o}{2})} \right]$$

$$\text{here, } p = 4 - (2m\sin(|\delta|)) \left(m\sin(2\alpha_1 + |\delta|) - m\sin(|\delta|) + 2\alpha_1 m\cos(\delta) - \frac{4\pi}{3} \frac{i'_{NPref}}{I_m} \right).$$

CASE-II. $\pi/2 + \beta - |\delta| < 0$

$$\frac{i'_{NPref}}{3} = F(\theta_g, r_n, \pi) \Big|_{-\alpha/2}^{\alpha/2} \text{ only if } \alpha \leq 2\alpha_2, \text{ where } \alpha_2 = |\pi/2 - \beta - ||\delta| - \pi||.$$

$$\alpha = \frac{28850m\cos(\delta) + 29860 - 12500\sqrt{q}}{10405m\cos(\delta) + 8449}, \text{ where } q = 5.2477m^2\cos^2(\delta) + 10.805m\cos(\delta) + 6.9699m \frac{i'_{NPref}}{r_n I_m} \cos(\delta) + 5.6597 \frac{i'_{NPref}}{r_n I_m} + 5.5791.$$

$$\frac{i'_{NPref}}{3} = \begin{cases} F(\theta_g, r_p, 0) \Big|_{-\alpha/2}^{-\alpha_2} + F(\theta_g, r_n, \pi) \Big|_{-\alpha_2}^{\alpha/2}, & \delta \geq 0 \\ F(\theta_g, r_n, \pi) \Big|_{-\alpha/2}^{\alpha_2} + F(\theta_g, r_p, 0) \Big|_{\alpha_2}^{\alpha/2}, & \delta < 0 \end{cases} \text{ only if } 2\alpha_3 \geq \alpha > 2\alpha_2, \text{ where } \alpha_2 = |\pi/2 - \beta - ||\delta| - \pi|| \text{ and } \alpha_3 = |\pi/2 - \beta + ||\delta| - \pi||.$$

$$\alpha = \alpha_o + \frac{\partial \alpha}{\partial \Delta v} \Big|_{\Delta v=0} \Delta v, \text{ where } \alpha_o = 2\sin^{-1}\left(\frac{2 - \sqrt{p}}{2m\sin(|\delta|)}\right) \text{ and } \frac{\partial \alpha}{\partial \Delta v} = \left[\frac{8\cos(\delta) + 4\sin(\alpha_2) + m\cos(\delta)(\alpha_o + \sin(\alpha_o) - 2\pi) - 2mv_{dc}(\cos(\delta) + \cos(2\alpha_2 - |\delta|)) \frac{\partial \alpha_2}{\partial \Delta v}}{-mv_{dc}\sin(|\delta|)\sin\alpha_o + 2v_{dc}\cos(\frac{\alpha_o}{2})} \right]$$

$$\text{here, } p = 4 + (2m\sin(|\delta|)) \left(m\sin(2\alpha_2 - |\delta|) + m\sin(|\delta|) + 2\alpha_2 m\cos(\delta) + \frac{4\pi}{3} \frac{i'_{NPref}}{I_m} \right).$$

$$\frac{i'_{NPref}}{3} = \begin{cases} F(\theta_g, r_p, 0) \Big|_{-\alpha/2}^{-\alpha_2} + F(\theta_g, r_n, \pi) \Big|_{-\alpha_2}^{\alpha_3} + F(\theta_g, r_p, 0) \Big|_{\alpha_3}^{\alpha/2}, & \delta \geq 0 \\ F(\theta_g, r_p, 0) \Big|_{-\alpha/2}^{-\alpha_3} + F(\theta_g, r_n, \pi) \Big|_{-\alpha_3}^{\alpha_2} + F(\theta_g, r_p, 0) \Big|_{\alpha_2}^{\alpha/2}, & \delta < 0 \end{cases} \text{ only if } \alpha > 2\alpha_3, \text{ where } \alpha_3 = |\pi/2 - \beta + ||\delta| - \pi||.$$

$$\alpha = \frac{-2.308r_p m\cos(\delta) + 2.3888r_p - \sqrt{(2.308r_p m\cos(\delta) - 2.3888r_p)^2 - q}}{0.67592r_p - 0.8324r_p m\cos(\delta)}, \text{ where}$$

$$q = 4(0.3379r_p - 0.4162r_p m\cos(\delta)) \left[2(r_p - r_n)(\sin(\alpha_2) + \sin(\alpha_3)) - m \left(\frac{r_p + r_n}{2} \right) (\sin(2\alpha_3 + |\delta|) + \sin(2\alpha_2 - |\delta|)) \right. \\ \left. - (\alpha_2 + \alpha_3)(r_p + r_n)m\cos(\delta) + 0.09412r_p - 0.0475r_p m\cos(\delta) - \frac{4\pi}{3} \frac{i'_{NPref}}{I_m} \right].$$

$$\text{Here, } \frac{\partial \alpha_1}{\partial \Delta v} = \frac{-\text{sign}\left(\cos^{-1}\left(\frac{\Delta v}{mv_{dc}}\right) - \frac{\pi}{2}\right) \text{sign}\left(\frac{\pi}{2} + \beta - |\delta|\right)}{\sqrt{m^2 v_{dc}^2 - \Delta v^2}} \text{ and } \frac{\partial \alpha_2}{\partial \Delta v} = \frac{-\text{sign}\left(\cos^{-1}\left(\frac{\Delta v}{mv_{dc}}\right) - \frac{\pi}{2}\right) \text{sign}\left(\beta - \frac{\pi}{2} + ||\delta| - \pi|\right)}{\sqrt{m^2 v_{dc}^2 - \Delta v^2}}$$

Fig. 4. $I - V$ and $P - V$ curves for the two solar PV arrays operating at: (a) Same irradiance levels, (b) small difference in irradiance levels, and (c) large difference in irradiance levels.

Fig. 5. Proposed control strategy.

TABLE II
SYMMETRICAL MODIFICATIONS TO CALCULATE α

Conditions	Change of variables in Table I
$v_{PV1} \leq v_{PV2}$ $i'_{NPref} \leq 0$	No change
$v_{PV1} \leq v_{PV2}$ $i'_{NPref} > 0$	$\delta \rightarrow \delta + \pi$ $i'_{NPref} \rightarrow -i'_{NPref}$
$v_{PV1} > v_{PV2}$ $i'_{NPref} \leq 0$	$\delta \rightarrow \delta + \pi$ $v_{PV1} \rightarrow v_{PV2}$ $v_{PV2} \rightarrow v_{PV1}$
$v_{PV1} > v_{PV2}$ $i'_{NPref} > 0$	$i'_{NPref} \rightarrow -i'_{NPref}$ $v_{PV1} \rightarrow v_{PV2}$ $v_{PV2} \rightarrow v_{PV1}$

Fig. 6. Calculation of the duty cycles using a linearization block.

with lower power operates at its MPP ((B) in Fig. 4(c)) while the other array operates at the right side of its MPP (A'), in such a way that the difference between their currents matches the maximum available NP current (i_{NPmax}) provided by the NPC converter.

Therefore, the operating principle of the proposed control strategy revolves around the NP current required and the maximum average NP current compensation capability of the NPC inverter.

B. Control System

An overview of the proposed control strategy is shown in Fig. 5. Different components of the control system are explained below:

1) DC-link voltage management

Firstly, the PV array voltages and currents are utilized to determine the PV array powers. The PV array with lower power is named as PV-l and is utilized to generate the d -component of the ac-side current reference (i_d^*), while the array operating with higher power named as PV-h is employed to generate the NP current reference (i_{NPref}). This is done to ensure that the array with a lower irradiance operates at its MPP and the other array operates at the right side of its MPP (if operation on MPP is not feasible). A perturbation and observation (P&O) MPP tracking technique is employed to generate the voltage references (V_{PV-l}^* and V_{PV-h}^*) [22]. v_{PV-l}^* and v_{PV-h}^* are compared to v_{PV-l} and v_{PV-h} (measured voltages) and fed to proportional-integral (PI) controllers to generate i_d^* and i_{NPref} , respectively.

2) Current controller

The ac-side voltage references in dq frame (v_d^* and v_q^*)

TABLE III
CALCULATION OF $|\bar{i}_{NPmax}|$ WHEN $i'_{NPref} \leq 0$ AND $v_{PV1} \leq v_{PV2}$

CASE-I. $\pi/2 + \beta - |\delta| \geq 0$

$$|\bar{i}_{NPmax}| = \begin{cases} \frac{3r_p I_m}{4\pi} (m\pi \cos(\delta) - 4) + i_z, & \text{if } \alpha \leq 2\alpha_1, \\ \frac{3I_m}{8\pi} \left(m(r_p + r_n) \sin(2\alpha_1 + |\delta|) - 4(r_p - r_n) \sin(\alpha_1) + 2\alpha_1 m(r_p + r_n) \cos(\delta) \right. \\ \quad \left. + m(r_p + r_n) \sin(|\delta|) + \pi m(r_p - r_n) \cos(\delta) - 4(r_p + r_n) \right) + i_z, & \text{if } \alpha > 2\alpha_1. \end{cases}$$

CASE-II. $\pi/2 + \beta - |\delta| < 0$

$$|\bar{i}_{NPmax}| = \begin{cases} \frac{3r_n I_m}{4\pi} (-m\pi \cos(\delta) - 4) + i_z, & \text{if } \alpha \leq 2\alpha_2, \\ \frac{3I_m}{8\pi} \left(-m(r_p + r_n) \sin(2\alpha_2 - |\delta|) + 4(r_p - r_n) \sin(\alpha_2) - 2\alpha_2 m(r_p + r_n) \cos(\delta) \right. \\ \quad \left. + m(r_p + r_n) \sin(|\delta|) + \pi m(r_p - r_n) \cos(\delta) - 4(r_p + r_n) \right) + i_z, & \text{if } 2\alpha_3 \geq \alpha > 2\alpha_2, \\ \frac{3I_m}{8\pi} \left(4(r_p - r_n)(\sin(\alpha_2) + \sin(\alpha_3)) - m(r_p + r_n)(\sin(2\alpha_2 - |\delta|) + \sin(2\alpha_3 + |\delta|)) \right. \\ \quad \left. - 2(\alpha_2 + \alpha_3)(r_p + r_n)m \cos(\delta) - 8r_p + 2\pi r_p m \cos(\delta) \right) + i_z, & \text{if } \alpha > 2\alpha_3. \end{cases}$$

are generated using a typical dq -based current controller, as shown in Fig. 5.

3) *Generation of converter voltage references*

The v_d^* and v_q^* are transformed into abc frame (v_a^* , v_b^* and v_c^*) using the dq -to- abc transformation.

4) *Calculation of duty cycles using the linearization block*

In the proposed control strategy, for the required i_{NPref} , a value of α is obtained, which is then translated to duty cycles. During the α span, the NP duty cycle for the phase switching between positive and negative dc-rails is zero and the duty cycles for connecting the respective phase to the positive and negative dc-rails are calculated using (8), as shown in Fig. 6. For the remaining time period, the duty cycles are calculated like the two-level modulation, by using (6).

The obtained duty cycles are compared to the carrier signal to generate the switching pulses of the NPC inverter.

IV. EXPERIMENTAL RESULTS

In order to validate the performance of the proposed control strategy, experimental tests have been performed on a laboratory prototype, shown in Fig. 7. The parameters of the prototype are listed in Table IV.

Moreover, the computation complexity of the proposed linearization block is determined by measuring its execution time in the ControlDesk of dSPACE 1007. The obtained execution time for the calculation of the linearization block was $4.92 \mu s$ while operating at a carrier frequency $f_s = 2$ kHz. Thus, the obtained time is very small as compared to the carrier period $T_s = 500 \mu s$. This is due to the fact that no numerical iterative solvers are required, hence, the proposed control is suitable for practical systems.

Fig. 7. Picture of the hardware prototype.

TABLE IV
EXPERIMENTAL AND SIMULATION PARAMETERS

Parameter	Value
Grid phase voltage (rms)	110 V
Grid frequency, f	50 Hz
Grid filter inductor, L	10 mH
Carrier frequency, f_s	2 kHz
DC-link capacitors (each), $C1, C2$	2.2 mF
Open-circuit PV voltages, $V_{OC_{PV1}}, V_{OC_{PV2}}$	224.59 V
Short-circuit PV currents, $I_{SC_{PV1}}, I_{SC_{PV2}}$	5.146 A
MPP PV voltage (1000 W/m ² , 50° C), $V_{MPP_{PV1}}, V_{MPP_{PV2}}$	175 V
MPP PV power (1000 W/m ² , 50° C), $P_{MPP_{PV1}}, P_{MPP_{PV2}}$	800 W

Fig. 8. Performance of the proposed control strategy when solar array PV2 operates under step change in irradiance: (a) Waveforms of Irr_{PV1} and Irr_{PV2} , v_{PV1} and v_{PV2} , i_{PV1} , i_{PV2} , i_{NPref} and $\bar{i}_{NP}$, p_{PV1} , p_{PV2} and p_g , α (in rad), (b) PV1 operating points and (c) PV2 operating points.

A. Performance under Step Change of Irradiance

Fig. 8 shows the performance of the proposed control strategy when PV2 undergoes a step change in irradiance, while PV1 operates at a constant irradiance. Fig. 8(a) shows various waveforms of the experimental setup under the mentioned step

change of irradiance. Figs. 8(b) and (c) tracks the operating points of the PV arrays on the PV curve with respect to time. The operating points of PV1 are denoted by ‘o’ while PV2 are represented by ‘+’.

During Interval 1 of Fig. 8(a), both PV arrays operate at the same irradiance level, i.e., $Irr_{PV1} = Irr_{PV2} = 1000 \text{ W/m}^2$, hence, the required i_{NPref} is very close to zero and the required α is very small in this case. From Fig. 8, it is clear that both PV arrays operate at their MPPs under this condition with $v_{PV1} = v_{PV2} = 175 \text{ V}$ and $p_{PV1} = p_{PV2} = 800 \text{ W}$. This result validates the operating condition discussed under Fig. 4(a), i.e., MPP is achieved by both PV arrays while operating with the same irradiance levels.

During Interval 2, Irr_{PV2} changes to 800 W/m^2 with PV1 operating at 1000 W/m^2 , hence, the required i_{NPref} increases. As a result, α also increases in order to generate an average NP current equal to the required i_{NPref} . The solar array PV2 tracks its new MPP ($v_{PV2} = 169 \text{ V}$ and $p_{PV2} = 640 \text{ W}$), while array PV1 remains at the same operating point ($v_{PV1} = 175 \text{ V}$ and $p_{PV1} = 800 \text{ W}$). This interval shows the condition discussed under Fig. 4(b) when the required i_{NPref} is less than $\bar{i}_{NPmax}$. During this interval, the required i_{NPref} is generated by switching a phase in three voltage levels for α duration. Moreover, both PV arrays still track their respective MPPs.

During Interval 3, the required i_{NPref} exceeds the maximum NP current compensation capability of the NPC inverter when Irr_{PV2} changes to 600 W/m^2 with $Irr_{PV1} = 1000 \text{ W/m}^2$. Under this condition, the solar array PV2 tracks its new MPP ($v_{PV2} = 162 \text{ V}$ and $p_{PV2} = 480 \text{ W}$) and α saturates at π radians in order to generate the maximum $\bar{i}_{NP}$. Under this condition, the solar array PV1 operates at the right side of its MPP so that the difference between the PV currents equals $\bar{i}_{NPmax}$. This helps in achieving stable operation of the grid-connected PV system without incorporating any additional auxiliary converter. This result validates the condition discussed under Fig. 4(c) wherein the required i_{NPref} is greater than $\bar{i}_{NPmax}$.

Therefore, from Fig. 8, it is clear that the proposed control strategy effectively extracts the maximum possible power under all operating conditions. Fig. 9 shows the harmonic spectra of v_{ab} and Fig. 10 depicts the harmonic spectra of i_a under different irradiance levels of PV2. As the irradiance difference increases, α increases in order to provide the required average NP current. The increase in α implies that the chosen phase is switching for longer duration in three voltage levels. When $2\pi/3 < \alpha \leq \pi$, two phases switch in three voltage levels simultaneously. The increase in α results in more harmonic components at high frequencies, thereby increasing the THD of line-to-line voltage and grid current as visible from Figs. 9 and 10.

B. Performance under Linear Change of Irradiance

Fig. 11 shows the same waveforms when solar array PV2 is subjected to a linear change of irradiance while PV1 operates at a constant irradiance of 1000 W/m^2 .

Initially, $Irr_{PV1} = 1000 \text{ W/m}^2$ and $Irr_{PV2} = 500 \text{ W/m}^2$, which results in an i_{NPref} larger than the maximum NP

Fig. 9. Harmonic spectra of v_{ab} when Irr_{PV1} is 1000 W/m^2 and Irr_{PV2} is: (a) 1000 W/m^2 , (b) 800 W/m^2 and (c) 600 W/m^2 .

Fig. 10. Harmonic spectra of i_a when Irr_{PV1} is 1000 W/m^2 and Irr_{PV2} is: (a) 1000 W/m^2 , (b) 800 W/m^2 and (c) 600 W/m^2 .

current compensation capability of the NPC inverter. Under this case, solar array PV2 tracks its MPP, while solar array PV1 operates at the right side of its MPP. The α is saturated at π radians, such that $\bar{i}_{NP} = \bar{i}_{NPmax}$.

As the irradiance of solar array PV2 increases, its current and power increase as it tracks its MPP. Besides, initially the required i_{NPref} is greater than $\bar{i}_{NPmax}$ and α is saturated at π radians. Consequently, as i_{PV2} increases, i_{PV1} increases as well and PV1 starts moving towards its MPP. After the required i_{NPref} becomes equal to $\bar{i}_{NPmax}$, α starts decreasing. At this point the converter is able to compensate for the difference in PV currents and PV1 reaches its MPP. When $Irr_{PV1} = Irr_{PV2} = 1000 \text{ W/m}^2$, both the solar arrays operate at their respective MPPs and the obtained α is small. The required i_{NPref} is also close to zero in this operating condition.

A vice-versa operation is observed when the irradiance of solar array PV2 starts decreasing. With decreasing Irr_{PV2} , α increases when the required NP current reference is lower than $\bar{i}_{NPmax}$. During this time, both solar PV arrays operate at their respective MPPs. When $i_{NPref} > \bar{i}_{NPmax}$, α becomes saturated at π radians. The solar array PV2 tracks its MPP while the solar array PV1 operating point shifts to the right-side of its MPP in order to generate an $\bar{i}_{NP}$ equal to $\bar{i}_{NPmax}$.

As can be seen from this figure, the dynamic of v_{PV1} is synchronized with the saturation of α . This indicates that the proposed control strategy can control the two PV arrays independently as long as the maximum NP current limit is not reached ($\alpha < \pi$). Hence, while $\alpha < \pi$, v_{PV1} can remain at its MPP irrespective of Irr_{PV2} dynamic. For $\alpha = \pi$ radians, the condition is the same as in Fig. 4(c) and PV1 operates at the right side of its MPP. The results shown in Fig. 12 verify the effectiveness of the proposed control strategy for extracting the maximum possible power from PV arrays under linear increase/decrease of irradiance.

C. Performance with Asymmetrical PV Arrays

In order to validate the performance of the proposed control strategy for asymmetrical PV arrays, two PV arrays with different open-circuit voltages and short-circuit currents ($V_{OC_{PV1}} = 224.59 \text{ V}$, $I_{SC_{PV1}} = 5.146 \text{ A}$, $V_{OC_{PV2}} = 192.5 \text{ V}$ and $I_{SC_{PV2}} = 4.8 \text{ A}$) are used. Fig. 12(a) shows the waveforms when PV2 is subjected to a step change in irradiance, while PV1 operates at a constant irradiance. Figs. 12(b) and (c) track the operating points of the PV arrays on the PV curve with respect to time. The operating points of PV1 are denoted by 'o' while PV2 are represented by '+'.

Fig. 11. Performance of the proposed control strategy when solar array PV2 operates with linear change in irradiance: Waveforms of Irr_{PV1} and Irr_{PV2} , v_{PV1} and v_{PV2} , i_{PV1} , i_{PV2} , i_{NPref} and $\bar{i}_{NP}$, p_{PV1} , p_{PV2} and p_g , and α (in rad).

During Interval 1 of Fig. 12(a), both PV arrays operate at the same irradiance level, i.e., $Irr_{PV1} = Irr_{PV2} = 1000 \text{ W/m}^2$, the required i_{NPref} is very small in this case. From Figs. 12, it is clear that both PV arrays operate at their MPPs under this condition with $v_{PV1} = 175 \text{ V}$, $p_{PV1} = 800 \text{ W}$ and $v_{PV2} = 150 \text{ V}$, $p_{PV2} = 640 \text{ W}$. During Interval 2, Irr_{PV2} changes to 800 W/m^2 with PV1 operating at 1000 W/m^2 , hence, the required i_{NPref} increases. As a result, α also increases in order to generate an average NP current equal to the required i_{NPref} . The solar array PV2 tracks its new MPP ($v_{PV2} = 145 \text{ V}$ and $p_{PV2} = 512 \text{ W}$), while array PV1 remains at the same operating point ($v_{PV1} = 175 \text{ V}$ and $p_{PV1} = 800 \text{ W}$). During Interval 3, the required i_{NPref} exceeds the maximum NP current compensation capability of the NPC inverter when Irr_{PV2} changes to 600 W/m^2 with $Irr_{PV1} = 1000 \text{ W/m}^2$. Under this condition, the solar array PV2 tracks its new MPP ($v_{PV2} = 139 \text{ V}$ and $p_{PV2} = 384 \text{ W}$) and α saturates at π radians in order to generate the maximum $\bar{i}_{NP}$. Under this condition, the solar array PV1 operates at the right side of its MPP so that the difference between the PV currents equals $\bar{i}_{NPmax}$. Therefore, it is clear that both PV arrays operate at their respective MPPs when the required NP current reference is lower than $\bar{i}_{NPmax}$, even with asymmetrical PV arrays. When i_{NPref} is larger than $\bar{i}_{NPmax}$, α saturates at π radians and, as desired, solar array PV2 tracks

Fig. 12. Performance of the proposed control strategy with asymmetrical PV arrays: Waveforms of Irr_{PV1} and Irr_{PV2} , v_{PV1} and v_{PV2} , i_{PV1} , i_{PV2} , i_{NPref} and $\bar{i}_{NP}$, p_{PV1} , p_{PV2} and p_g , and α (in rad), (b) PV1 operating points and (c) PV2 operating points.

its MPP while PV1 operates at the right side of its MPP.

V. COMPARATIVE ANALYSIS

Simulation tests are performed to compare the performance of the proposed control strategy employing the dual-inputs of

Fig. 13. Circuit diagram of a conventional three-phase NPC inverter-based grid-connected PV system without NP connection [7], [23].

Fig. 14. Performance comparison between the proposed control strategy employing dual-inputs of the NPC inverter and a conventional PV system without using NP connection.

the NPC inverter (Fig. 1) to a conventional PV system without NP connection by using the parameters provided in Table IV. In the conventional system, both PV1 and PV2 are connected in series between the positive and the negative dc-rails of the NPC inverter, as shown in Fig. 13 [7], [23]. Therefore, a single MPP tracking for both PVs is used in the conventional system. However, the configuration employed in this paper employs the dual-inputs of the NPC inverter to independently control the solar PV arrays to achieve separate MPPs. The total PV power extracted from the two PV arrays under different cases of irradiance differences is shown in Fig. 14. The irradiance of PV1 array is kept at 1000 W/m², while the irradiance of PV2 array is decreased from 1000 W/m² in steps of 50 W/m² at intervals of one second. From this figure, it is clear that with the proposed solution, the power extracted from the solar PV arrays under all the cases of partial shading is higher compared to the conventional PV system.

VI. CONCLUSION

In this paper, a control strategy for dual-input neutral-point-clamped inverters-based grid-connected PV systems has been

presented. The strategy has been designed to extract maximum possible power from the PV arrays under all operating conditions without incorporating any additional auxiliary converter. A feedforward compensation has also been incorporated to compensate the effect of asymmetric PV array voltages on the grid-side voltages. In addition, a linearization block has been analytically developed, which helps in translating the required NP current reference to duty cycles. The maximum average NP current compensation capability of the NPC inverter has also been quantified using the proposed linearization block, which gives a freedom to operate both solar PV arrays at MPP until the converter becomes saturated. Once the required NP current reference is higher than the maximum average NP current compensation limit, the converter saturates and the developed control strategy allows to operate the PV array with lower irradiance at its MPP, while the other PV array is operated at the maximum possible power under saturated conditions. In this way, the efficiency of the whole system is optimized. Experimental results verify the effectiveness of the proposed strategy in extracting the maximum possible power under all operating conditions.

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