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EDITED BY

Wenping Zhang,
Tianjin University, China

REVIEWED BY

Qinglei Bu,
Xi'an Jiaotong-Liverpool University, China
Lunbo Deng,
Southwest Jiaotong University, China

*CORRESPONDENCE

Yinxiao Zhu,
✉ yinxiao.zhu@zju.edu.cn

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Unit power rating balancing for differential-power-processing-based distributed photovoltaic systems

Jiahua Ni¹, Zhixing Zhao¹ and Yinxiao Zhu^{2*}

¹PowerChina Huadong Engineering Cooperation Limited, Hangzhou, China, ²College of Electrical Engineering, Zhejiang University, Hangzhou, China

Differential power processing (DPP) architectures are effective solutions for photovoltaic (PV) systems experiencing uncertainties in environmental conditions, such as non-uniform irradiation, which can significantly degrade electricity production efficiency and operating safety. Among the different architectures available, the PV-to-bus DPP configuration has shown excellent performances for control flexibility and galvanic isolation capability. However, recent control schemes for PV-to-bus architectures offer lower-than-desirable efficiency enhancements, such as those involving implementation complexities and unit power distributions. Hence, a unit power rating balancing (UPRB) scheme is proposed in this work to reconfigure the distribution of differential power among the unit converters with the aim of ensuring submodule-level optimization and enhanced performance of the entire PV system. The proposed UPRB scheme integrates perturbation-and-observation-based maximum power-point tracking units to maximize the energy harvested from PV modules, and the unit balance-point tracking unit is employed to determine the optimal string current reference directly for mitigating the unbalanced differential power in the DPP units. By suppressing the maximum processed power in each DPP unit, the capital cost and system size can be reduced. Simulation and experimental studies were conducted, whose evaluation results support the applicability of the proposed control scheme.

KEYWORDS

differential power processing, photovoltaic system, energy harvesting, unit power rating balancing, efficiency

1 Introduction

Recently, solar power generation programs have gained widespread acceptance globally given the advancements in photovoltaic (PV) technology (Blaabjerg et al., 2023). In typical solar farms and distributed PV systems, the PV panels are first connected in series to enhance the voltage for achieving the required value and then connected in parallel for construction of the PV generation grid (Zhu et al., 2024b). However, the uncertainties associated with environmental conditions, such as partial shading, dust deposition, and cell aging, can easily cause series string mismatches between the panels and reduce the total power generated by the distributed PV system (Aifan et al., 2024; Zhu et al., 2024a). Typically, bypass diodes are used to protect a PV substring with 20–24 cells. However,

the power generated still exhibits a significant reduction trend under various mismatch conditions owing to the occurrence of multiple maximum power points (MPPs) on the power–voltage curve (Nunes et al., 2022; Ali et al., 2023; Zhu et al., 2022). To mitigate the power losses caused by multiple MPP scenarios, various advanced maximum power-point tracking (MPPT) solutions have been proposed for partially shaded PV systems, such as the reference-voltage-line-aided method (Li et al., 2022), particle swarm optimization algorithm (Refaat et al., 2023), peafowl optimization algorithm (Li et al., 2021), and machine-learning-based method (Yilmaz et al., 2023). However, these methods have mostly increased the implementation complexity and computational requirements of the control units. Furthermore, a portion of the available power from the PV string is dissipated by implementing such MPPT methods, which reduces the overall energy efficiency of the system (Chu et al., 2024).

To address these issues, new architectures like full power processing (FPP) and differential power processing (DPP) have been proposed to enhance power generation under PV mismatch conditions. As shown in Figure 1, DC power optimizers (DCPOs) and microinverters are the widely adopted power interfaces in the FPP architecture for distributed PV systems (Celik et al., 2018; Ramli and Salam, 2019). Here, each DCPO or microinverter is connected in series and includes an MPPT unit to maximize the power extracted from the corresponding PV module, thereby guaranteeing the efficiency of the system. However, a certain level of power loss is unavoidable in this architecture as the PV power production is fully processed, degrading both the energy production and system reliability (Shenoy et al., 2013). Compared to FPP, the DPP architecture reduces power losses by processing only a portion of the total PV power through the DPP converter units while the main power is fed to the centralized converter directly (Jeong et al., 2019). This means that only a fraction of the total power is processed by the DPP converter and that the power rating specified for each DPP converter is relatively low; further, this architecture requires a small-sized and low-cost design (Amaral da Luz et al., 2023). Notably, under consideration of similar converter efficiencies, the total power loss of the DPP architecture is lower than that of the DCPO on average. Meanwhile, if a low-level or no-mismatch condition occurs, none of the power passes through the DPP converter, which further improves the power transmission efficiency. A comparison between FPP and DPP showed that the system could achieve higher efficiency under the DPP architecture owing to contribution from the fraction of output power processing capability (Olalla et al., 2015).

The DPP architecture can be broadly divided into two types, namely PV element to PV element (PV-PV) architecture and PV element to bus architectures, according to the port connection conditions of the DPP converter. For the PV-PV architecture shown in Figure 2a, the number of DPP converter units is always one less than the number of PV modules; here, the proposed topologies include switched-capacitor converter (SCC) (Uno et al., 2022) and switched-inductor converter (SLC) (Shenoy et al., 2013). The SCC system is based on the principle of voltage equalization among all submodules but cannot achieve an accurate MPP for each submodule when a mismatch occurs (Dong et al., 2019). The synchronous bidirectional buck-boost topology is used as the DPP converter in the SLC configuration, which provides bidirectional

transition of power flow between the relative submodules. However, the PV-PV architecture requires connections between adjacent PV elements, which increases the system complexity and necessitates coordinated control. The PV element to bus DPP architecture topologies can be divided into PV element to isolated port (PV-IP) and PV element to non-isolated port (PV-NIP) bus architectures, as demonstrated in Figures 2b–d. In the PV-IP architecture illustrated in Figure 2b, the secondary sides of the DPP converters are parallel, establishing an isolated port bus; accordingly, selection of the secondary-side voltage of each DPP converter unit can be decoupled from the PV voltage. The PV-IP DPP architecture provides high flexibility of hardware design and reliable voltage equalization capability without an additional communication network for the DPP and central converters (Chu et al., 2017). In the type I PV-NIP bus architecture shown in Figure 2c, the secondary sides of the DPP converters are connected in parallel and share the same input voltage as the central converter; the switching components on the secondary side experience higher voltage stresses than those on the primary side as they share the same voltage (i.e., the sum of the PV module output voltage), which increases the power loss and implementation cost. Moreover, both the submodule and central converter require MPPT control and parameter sensors (Khan and Xiao, 2017). In this case, the string current cannot be regulated, and the power rating limitation of each DPP converter becomes invalid. Furthermore, given the high voltage stresses on the secondary side of the PV-NIP architecture, the system flexibility is further increased and power loss is reduced. By utilizing this topology, the differential power processed by the DPP and string converters increases the system power loss (Chu et al., 2022). To address these limitations, the type II PV-NIP bus architecture implementation is shown in Figure 2d; the secondary sides in this topology are directly connected to the bus, and the central converter can control the string current directly. Thus, the currents in both the DPP and central converters can be decoupled to improve and the reliability and control flexibility of the system. The important features of different control schemes for the PV-NIP DPP architectures are compared in Table 1.

To achieve balanced distribution of the differential power and simple extraction of the maximum power, a unit power rating balancing (UPRB) scheme with DPP-converter-unit-level-independent MPPT control is proposed herein for the PV-NIP DPP architectures. To ensure bidirectional power transfer capability, various bidirectional DC-DC converters may be employed as the DPP units, e.g., dual active bridge (DAB) converters (Wang et al., 2021; Bu et al., 2022; Shi et al., 2022; Feng et al., 2025) and quasi-Z-source-based isolated

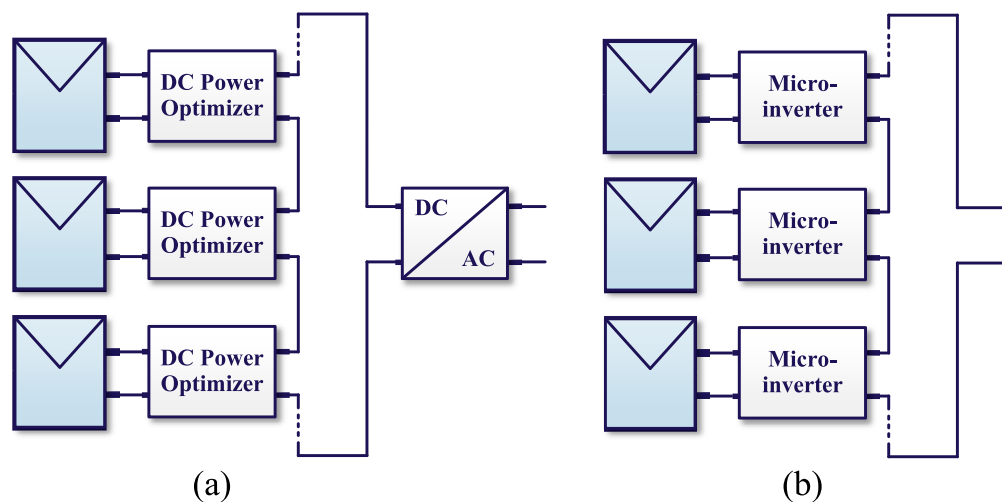


FIGURE 1
Typical full power processing architectures for distributed photovoltaic (PV) systems: (a) DC power optimizer; (b) microinverter.

is employed to determine the optimal string current reference adaptively to mitigate the unbalanced differential power in the DPP units. Notably, the MPPT control at the DPP converter unit level is decoupled from the string-level current optimization. The implementation of the widely adopted P&O-based MPPT method herein aims to reduce control complexity. For better maximum energy yield, the P&O method may be replaced with any other advanced MPPT method. Both simulations and experiments were carried out in this work to validate the effectiveness of the proposed UPRB scheme. The remainder of this paper is organized as follows. Section 2 presents an analysis of the theoretical differential power distributions in the PV-NIP bus DPP architectures. The technical details of the proposed UPRB scheme are introduced in Section 3. The simulations and experimental validations are presented in Section 4 and Section 5, respectively, and the conclusions of the study are summarized in Section 6.

2 Theoretical power distribution in the PV-NIP DPP architecture

Compared to other DPP architectures, the type II PV-NIP bus DPP architecture offers better system efficiency and control flexibility; here, the DPP converter only transfers energy between its relative series-connected elements and the entire string, which offers the benefits of modularity and independent converter operating state. Accordingly, the type II PV-NIP bus DPP architecture shown in Figure 2d is employed in this work.

2.1 Generalized power distribution model

In a PV-NIP bus architecture with bidirectional DPP converter units, the direction of differential current flow according to

Kirchhoff's current law (KCL) depends on the differences between the string current and currents in the corresponding PV elements. As demonstrated in Figure 3a, when the current of the i^{th} PV element $I_{pv,i}$ is greater than the string current I_{string} ($I_{pv,i} > I_{\text{string}}$), the DPP converter will remove the current from the PV element and feed the bus for approaching the MPP of the relative element, thereby creating the differential current $I_{dpp,i} = I_{pv,i} - I_{\text{string}}$ such that the power flows into the DPP converter from the PV element. When the PV element current is equal to the string current ($I_{pv,i} = I_{\text{string}}$), as shown in Figure 3b, no power will be injected or removed between the PV element and PV string; this means that the differential current $I_{dpp,i}$ is equal to zero. When the PV element current is less than the string current ($I_{pv,i} < I_{\text{string}}$), the power in the string will feed the PV element via injected differential current from the bus through the DPP converter unit to achieve the MPP, as demonstrated in Figure 3c; here, the differential current flow through the i^{th} DPP converter unit $I_{dpp,i} = I_{pv,i} - I_{\text{string}}$.

Accordingly, the system can be configured using a mathematical model to explain the relationships between the PV element current, string current, and differential current through basic ascension of each PV element with the operating current $I_{pv,i}$ and voltage $V_{pv,i}$ as well as a known string current I_{string} . According to KCL, the differential current of the i^{th} DPP converter unit can be expressed as $I_{dpp,i} = I_{pv,i} - I_{\text{string}}$ and given in matrix form as Equation 1:

$$\begin{bmatrix} 1 & -1 & 0 & \cdots & 0 \\ 0 & 1 & -1 & \ddots & \vdots \\ 0 & \ddots & \ddots & \ddots & 0 \\ \vdots & \ddots & 0 & 1 & -1 \\ 0 & \cdots & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_{dpp,1} \\ I_{dpp,2} \\ \vdots \\ I_{dpp,n-1} \\ I_{dpp,n} \end{bmatrix} = \begin{bmatrix} I_{pv,2} - I_{pv,1} \\ I_{pv,3} - I_{pv,2} \\ \vdots \\ I_{pv,n} - I_{pv,n-1} \\ I_{\text{string}} - I_{pv,n} \end{bmatrix}. \quad (1)$$

Here, the conditions of the i^{th} PV element are known but the operating condition of the central converter is unknown.

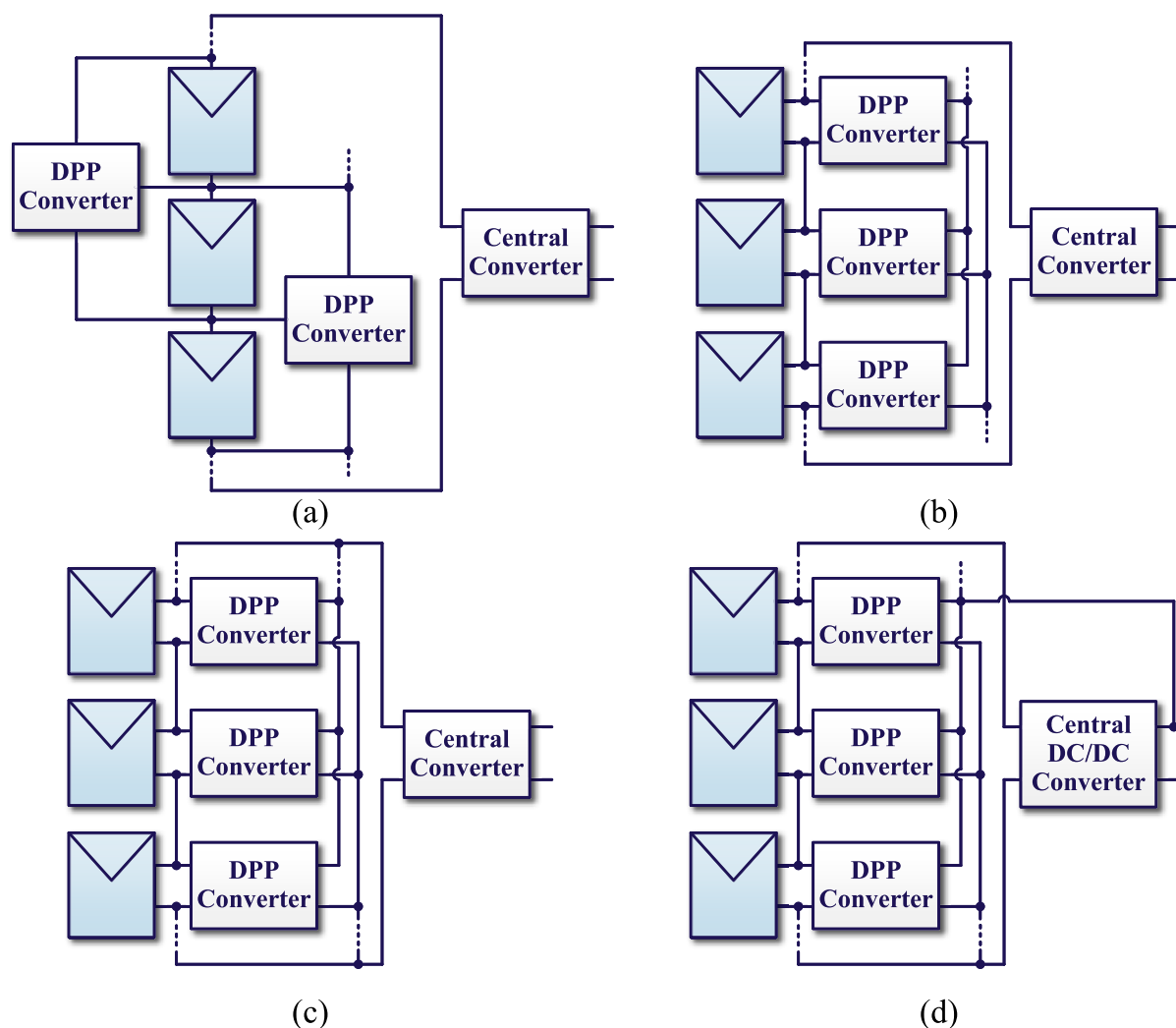


FIGURE 2 Typical differential power processing (DPP) architectures for distributed PV systems: (a) PV element to PV element architecture; (b) PV element to isolated port bus architecture; (c) PV element to non-isolated port (PV-NIP) bus architecture type I; (d) PV-NIP bus architecture type II.

TABLE 1 Key features of different control schemes for the PV-NIP DPP architectures.

Reference	Objective	MPPT	String control	Complexity	Tracking speed	Oscillations
Jeon et al. (2017)	Total minimum	P&O	P&O	Moderate	Low	High
Jeon and Park (2019)	Unit balance	P&O	P&O	Moderate	Low	High
Chu et al. (2019)	Total minimum	Modified P&O	Direct	Moderate	High	Moderate
Chu et al. (2020)	Adaptive	Direct	Direct	Simple	High	Low
Zhu et al. (2022)	Unit balance	Modified P&O	Direct	High	Moderate	Low
This work	Unit balance	P&O	Direct	Moderate	Moderate	Moderate

The central converter determines the conditions of the string current I_{string} . Hence, the condition of the i^{th} DPP converter unit is unknown, which offers a range of control freedom for this codetermined system.

The ideal differential power flowing through the i^{th} DPP converter unit $P_{\text{dpp},i}$ is expressed as in Equation 2:

$$P_{\text{dpp},i} = V_{\text{pv},i} |I_{\text{dpp},i}| = V_{\text{pv},i} |I_{\text{pv},i} - I_{\text{string}}|. \quad (2)$$

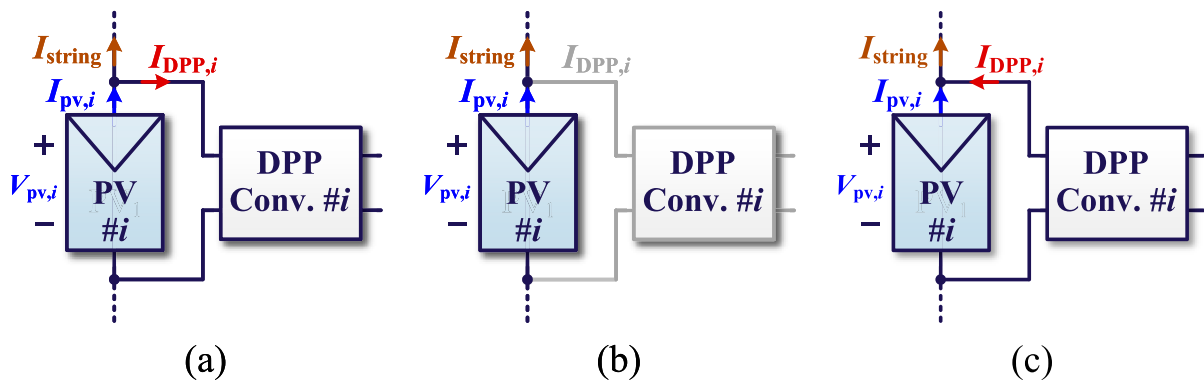


FIGURE 3

Differential current paths of the i^{th} DPP converter unit in the type II PV-NIP bus DPP architecture: (a) differential current path when $I_{pv,j} > I_{\text{string}}$; (b) differential current path when $I_{pv,j} = I_{\text{string}}$; (c) differential power path when $I_{pv,j} < I_{\text{string}}$. Here, $I_{pv,j}$ is the current of the i^{th} PV element, $V_{pv,j}$ is the voltage of the i^{th} PV element, $I_{dpp,i}$ is the differential current flowing through the i^{th} DPP converter unit, and I_{string} is the current of the PV string.

Then, the ideal total differential power P_{DPP} of a DPP system with n PV elements and n DPP converter units can be expressed as in Equation 3:

$$P_{\text{DPP}} = \sum_{i=1}^n P_{\text{dpp},i} = \sum_{i=1}^n V_{pv,i} |I_{dpp,i}| \quad (3)$$

$$= V_{pv,1} |I_{pv,1} - I_{\text{string}}| + V_{pv,2} |I_{pv,2} - I_{\text{string}}| + \dots + V_{pv,n} |I_{pv,n} - I_{\text{string}}|$$

Considering the power rating, P_{DPP} can be regulated to a specific value by changing the string current, as mentioned before. In reality, the voltage variation is far lower than the current changes at different irradiation levels. Therefore, the power rating of each DPP converter is affected by the string current resulting from different DPP currents as well as the approximate PV voltage. In a system with n PV elements, assuming that the PV voltage and current match the conditions $V_{pv,1} \cong V_{pv,2} \cong \dots \cong V_{pv,n}$ and $I_{pv,1} < I_{pv,2} < \dots < I_{pv,n}$, a maximum differential power rating $P_{\text{dpp,max}}$ will exist among the DPP converter units whose particular values would follow the string current changes.

When the string current I_{string} is less than the minimum PV current $I_{pv,1}$ ($I_{\text{string}} < I_{pv,1}$), the unit processing the greatest power under this assumption will be the i^{th} DPP converter whose power rating is expressed by Equation 4:

$$P_{\text{dpp,max}} = V_{pv,n} (I_{pv,n} - I_{\text{string}}), \text{ when } I_{\text{string}} < I_{pv,1} \quad (4)$$

As the string current increases, in the region of between $I_{pv,1}$ and average of $I_{pv,1}$ and $I_{pv,n}$ ($I_{pv,1} < I_{\text{string}} < \frac{I_{pv,1} + I_{pv,n}}{2}$), the largest differential power rating still occurs at the i^{th} DPP converter whose value is given by Equation 5:

$$P_{\text{dpp,max}} = V_{pv,n} (I_{pv,n} - I_{\text{string}}), \text{ when } I_{pv,1} < I_{\text{string}} < \frac{I_{pv,1} + I_{pv,n}}{2} \quad (5)$$

With continued increase of the string current, the DPP converter with the most stressed differential power rating will change to the first converter unit whose string current is in the range of average

of $I_{pv,1}$ and $I_{pv,n}$ to less than $I_{pv,n}$, namely $\frac{I_{pv,1} + I_{pv,n}}{2} < I_{\text{string}} < I_{pv,n}$, as given by Equation 6:

$$P_{\text{dpp,max}} = V_{pv,1} (I_{pv,1} - I_{\text{string}}), \text{ when } \frac{I_{pv,1$$

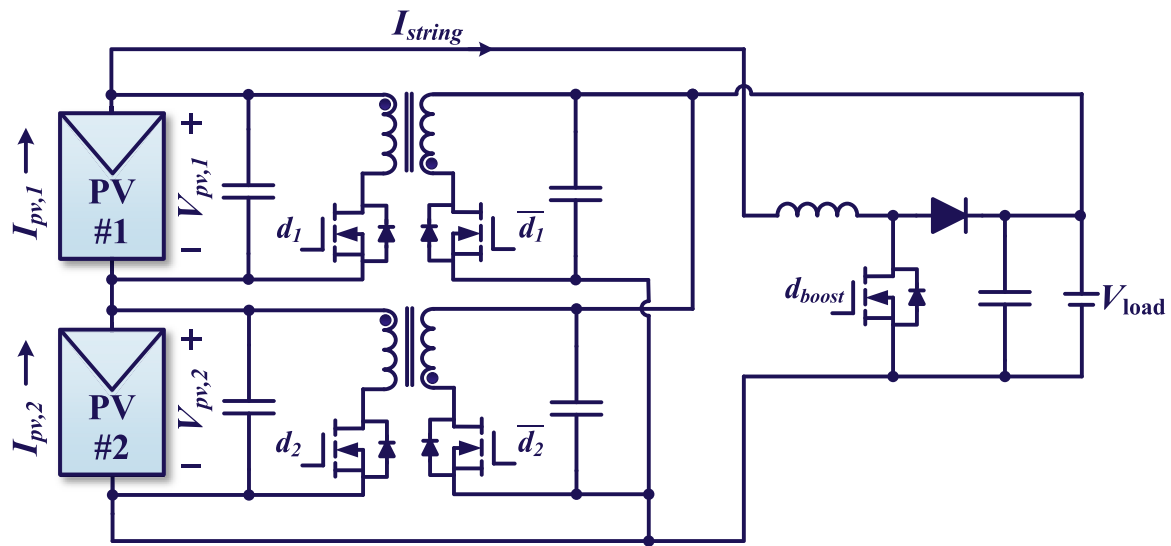


FIGURE 4
PV-NIP bus DPP architecture with even numbers (two) of PV elements and bidirectional flyback-based DPP converter units.

respectively, the differential power stress on each DPP converter can be calculated using the above approach. Assuming that there is no power loss during power transfer and that each PV element operates at its MPP with a very close MPP voltage, the theoretical differential power analysis can be carried out for the example architecture.

2.2.1 Example of a system with two PV elements

According to Equation 3, the total differential power for the DPP architecture with three PV elements shown in Figure 4 is given by Equation 9:

$$P_{DPP} = |P_{dpp,1}| + |P_{dpp,2}| = V_{pv,1} |I_{pv,1} - I_{string}| + V_{pv,2} |I_{pv,2} - I_{string}| \quad (9)$$

Assuming $I_{pv,1} < I_{pv,2}$, the string current I_{string} is swept from zero to a value exceeding $I_{pv,2}$, and the largest differential power among the DPP converters can be expressed as Equations 10a–c according to the different values of I_{string} :

$$P_{dpp,max} = V_{pv,2} (I_{pv,2} - I_{string}), \text{ when } I_{string} < \frac{(I_{pv,1} + I_{pv,2})}{2} \quad (10a)$$

$$P_{dpp,max} = V_{pv,1} (I_{pv,1} - I_{string}) = V_{pv,n} (I_{pv,n} - I_{string}), \text{ when } I_{string} = \frac{(I_{pv,1} + I_{pv,2})}{2} \quad (10b)$$

$$P_{dpp,max} = V_{pv,1} (I_{pv,1} - I_{string}), \text{ when } I_{string} > \frac{(I_{pv,1} + I_{pv,2})}{2} \quad (10c)$$

To illustrate the differences in differential power obtained, a case study was conducted using the MSX-60 PV module, which has an MPP voltage of 17 V and MPP current of 3.5 A under standard test conditions. In the case study, the example is assumed under the mismatching condition, where the two PV elements are operated at unique MPPs with MPP currents of 1.4 A and 3.5 A for PV elements 1 and 2, respectively.

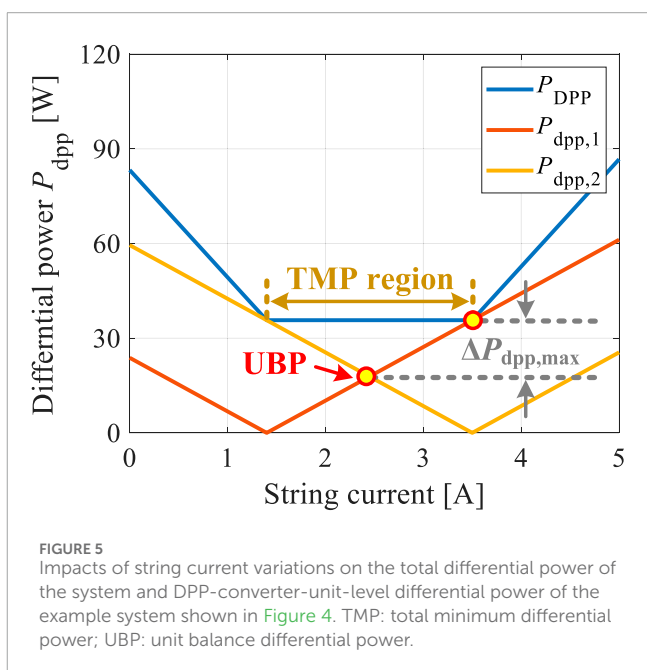


FIGURE 5
Impacts of string current variations on the total differential power of the system and DPP-converter-unit-level differential power of the example system shown in Figure 4. TMP: total minimum differential power; UB: unit balance differential power.

As demonstrated in Figure 5, the impacts of string current variations on the total differential power P_{DPP} and DPP-converter-unit-level differential power values ($P_{dpp,1}$ and $P_{dpp,2}$) were investigated. The total minimum differential power (TMP) P_{DPP} can be obtained by restricting the string current to the range between 1.4 A and 3.5 A. The extreme power stresses of the two DPP converter units within the region of the TMP are 35.7 W and 0 W. Thus, the differential power stresses on the DPP converter units can be balanced using an operating string current of 2.45 A, which may be considered the unit balance differential power

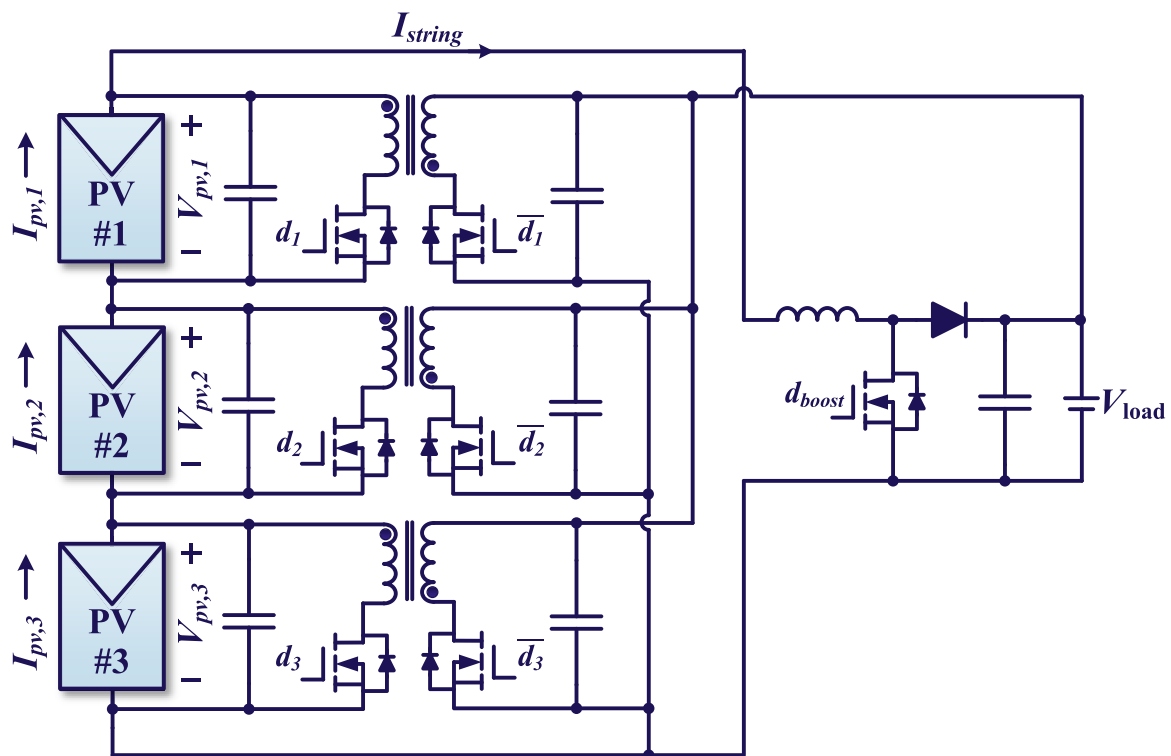


FIGURE 6
PV-NIP bus DPP architecture with odd numbers (three) of PV elements and bidirectional flyback-based DPP converter units.

2.2.2 Example of a system with three PV elements

The total differential power for a DPP architecture with three PV elements shown in Figure 6 is given by Equation 11:

$$P_{DPP} = |P_{dpp,1}| + |P_{dpp,2}| + |P_{dpp,3}|$$

$$= V_{pv,1} |I_{pv,1} - I_{string}| + V_{pv,2} |I_{pv,2} - I_{string}| + V_{pv,3} |I_{pv,3} - I_{string}| \quad (11)$$

Assuming $I_{pv,1} < I_{pv,2} < I_{pv,3}$, the string current I_{string} is swept from zero to a value exceeding $I_{pv,3}$, and the largest differential power among the DPP converters can be expressed by Equations 12a–c according to the different values of I_{string} :

$$P_{dpp,max} = V_{pv,3} (I_{pv,3} - I_{string}), \text{ when } I_{string} < \frac{(I_{pv,1} + I_{pv,3})}{2} \quad (12a)$$

$$P_{dpp,max} = V_{pv,1} (I_{pv,1} - I_{string}) = V_{pv,n} (I_{pv,n} - I_{string}),$$

$$\text{when } I_{string} = \frac{(I_{pv,1} + I_{pv,3})}{2} \quad (12b)$$

$$P_{dpp,max} = V_{pv,1} (I_{pv,1} - I_{string}), \text{ when } I_{string} > \frac{(I_{pv,1} + I_{pv,3})}{2} \quad (12c)$$

In this case, the example mismatches of the MPP currents in the three-element DPP system are 0.7 A, 2.8 A, and 3.5 A for PV elements 1, 2, and 3, respectively. As demonstrated in Figure 7, the impacts of string current variations on the total differential power P_{DPP} and DPP-converter-unit-level differential power values ($P_{dpp,1}$,

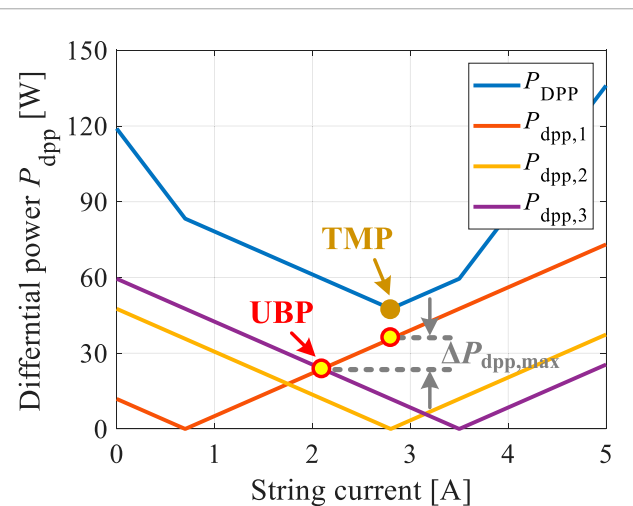


FIGURE 7
Impacts of string current variations on the total differential power of the system and DPP-converter-unit-level differential power of the example system shown in Figure 6. TMP: total minimum differential power; UBP: unit balance differential power.

$P_{dpp,2}$, and $P_{dpp,3}$) were analyzed. Unlike Figure 5, the TMP P_{DPP} was obtained only at the string current of 2.8 A, its maximum unit-level differential power was 35.7 W. Thus, the maximum differential power stresses at the DPP converter unit level can be balanced using a string current of 2.8 A, which is determined using Equation 12b.

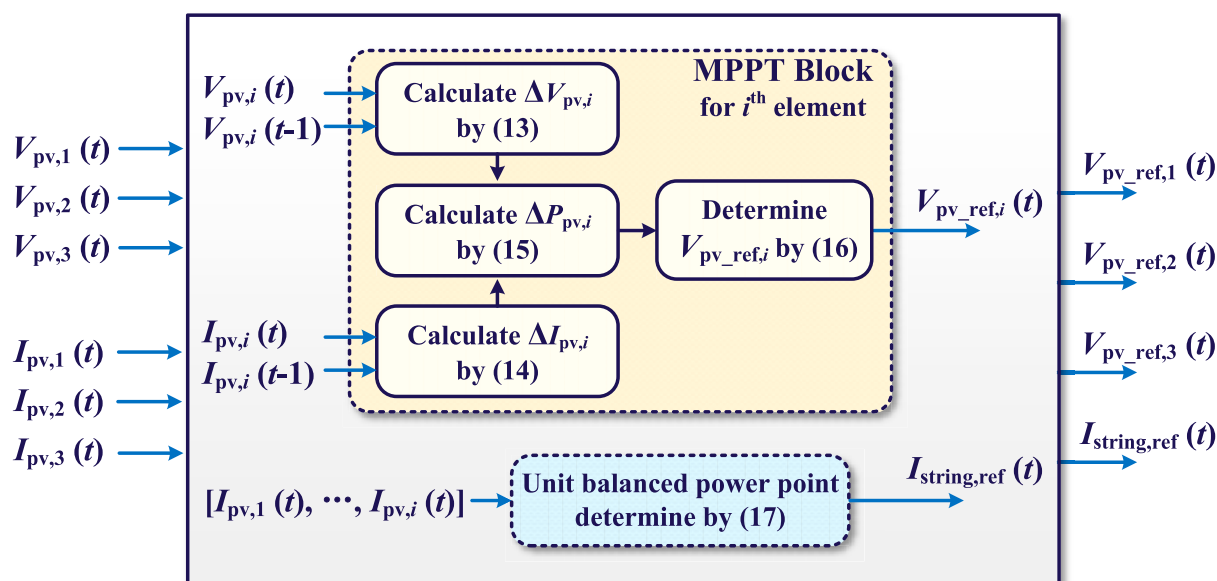


FIGURE 8
Control diagram of the proposed unit power rating balancing (UPRB) scheme.

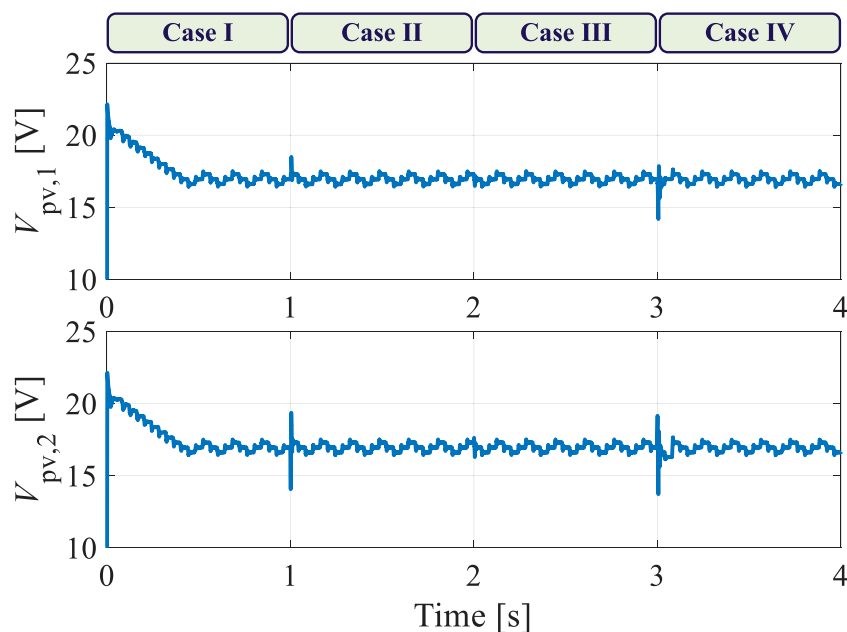


FIGURE 9
Simulation results of the PV element voltages under various shading scenarios.

In summary, the tracking for the TMP may induce a significant unbalancing in the unit differential power distribution in the PV-NIP DPP system. It should be noted that UBP distribution can be achieved by regulating the string current. In a DPP system with even number of elements, the tracking for UBP could also ensure minimization of the total differential power in some cases.

3 Proposed UPRB scheme

Notably, the mitigation of unbalanced differential power can reduce uneven thermal distribution as well as the aging effect in relative converters, improving the lifetime of the DPP system (Zhu et al., 2022). In accordance with the above analysis, the unit-level differential power can be optimized sufficiently with minimal

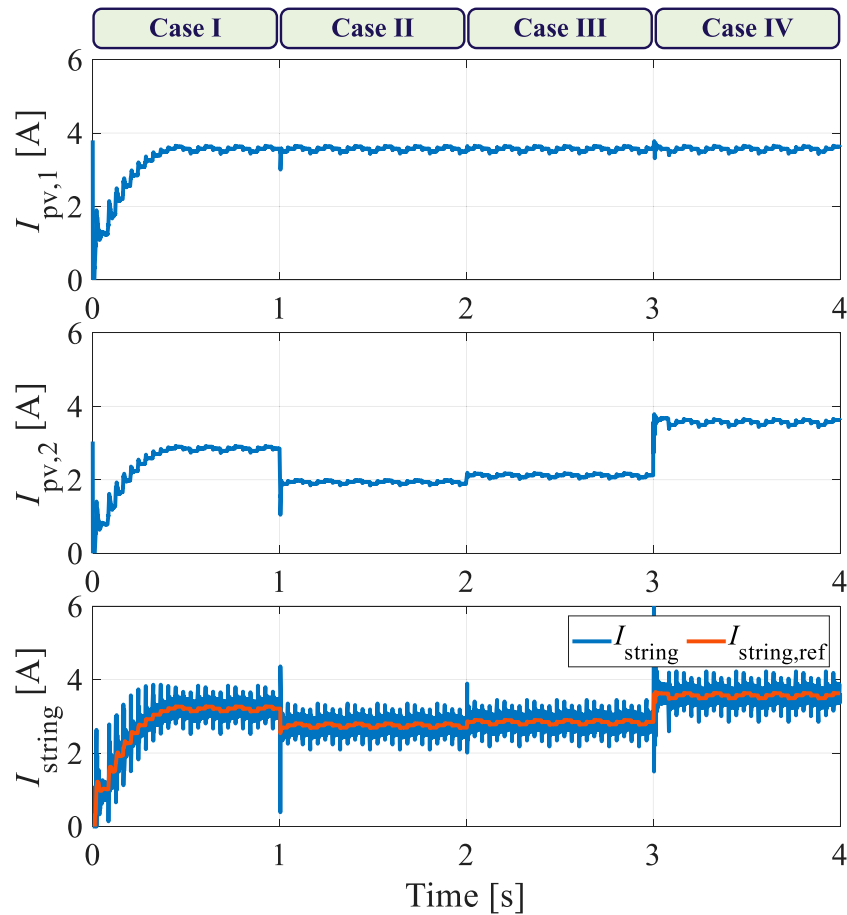


FIGURE 10
Simulation results of the PV element currents and string current under various shading scenarios.

uneven distribution by regulating the string current to the optimal UBP point. Thus, a UPRB control scheme is proposed herein, whose block diagram is illustrated in Figure 8. The proposed scheme requires periodic measurement of the currents and voltages of each of the PV elements.

3.1 MPPT block

To maximize the energy harvested from the PV modules, a P&O-based MPPT controller is integrated into each DPP converter. Based on periodic measurement of the PV voltage of each element, the change in voltage at the most recent sampling interval of the i^{th} element ($\Delta V_{pv,i}(t)$) is given by Equation 13:

$$\Delta V_{pv,i}(t) = V_{pv,i}(t) - V_{pv,i}(t-1) \quad (13)$$

where $V_{pv,i}(t)$ is the measured voltage of the i^{th} PV element in the present sampling period, and $V_{pv,i}(t-1)$ is the measured voltage of the i^{th} PV element in the previous sampling period.

Similarly, the current change in the i^{th} PV element between any two adjacent sampling intervals can be expressed by Equation 14:

$$\Delta I_{pv,i}(t) = I_{pv,i}(t) - I_{pv,i}(t-1) \quad (14)$$

where $I_{pv,i}(t)$ is the measured current of the i^{th} PV element in the present sampling period, and $I_{pv,i}(t-1)$ is the measured current of the i^{th} PV element in the previous sampling period.

Hence, the power change in the i^{th} PV element ($\Delta P_{pv,i}$) can be expressed by Equation 15:

$$\Delta P_{pv,i}(t) = P_{pv,i}(t) - P_{pv,i}(t-1) = \Delta V_{pv,i}(t) \cdot \Delta I_{pv,i}(t). \quad (15)$$

Accordingly, the voltage reference regulation for the i^{th} PV element to ensure maximum power extraction during the subsequent perturbation interval ($V_{pv_ref,i}(t)$) is determined by Equations 16a–d:

$$V_{pv_ref,i}(t) = V_{pv_ref,i}(t) + \Delta V_{\text{step}}, \text{ when } \Delta P_{pv,i}(t) \geq 0 \text{ and } \Delta V_{pv,i}(t) \geq 0 \quad (16a)$$

$$V_{pv_ref,i}(t) = V_{pv_ref,i}(t) - \Delta V_{\text{step}}, \text{ when } \Delta P_{pv,i}(t) \geq 0 \text{ and } \Delta V_{pv,i}(t) < 0 \quad (16b)$$

$$V_{pv_ref,i}(t) = V_{pv_ref,i}(t) + \Delta V_{\text{step}}, \text{ when } \Delta P_{pv,i}(t) < 0 \text{ and } \Delta V_{pv,i}(t) < 0 \quad (16c)$$

$$V_{pv_ref,i}(t) = V_{pv_ref,i}(t) - \Delta V_{\text{step}}, \text{ when } \Delta P_{pv,i}(t) < 0 \text{ and } \Delta V_{pv,i}(t) \geq 0 \quad (16d)$$

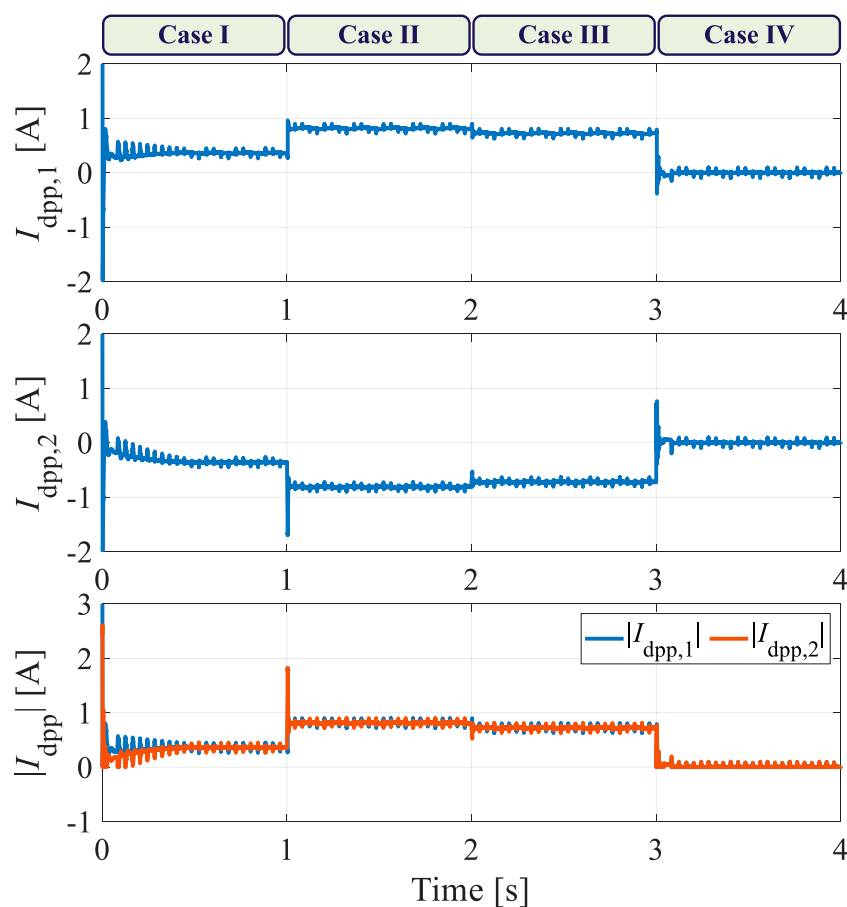


FIGURE 11
Simulation results of the differential currents flowing through the DPP converter units under various shading scenarios.

where ΔV_{step} is the optimal voltage step size for ensuring balanced tradeoff between the steady-state and dynamic performances of the MPPT control (Lv et al., 2024). Then, a proportional integral (PI) controller can be employed to determine the appropriate duty cycle of the bidirectional DPP converter unit.

3.2 UBPT block

To mitigate the unbalanced differential power distribution among the DPP converter units, a differential UBPT unit is employed to determine the optimal string current reference adaptively. Based on the power rating analysis above, power balance is achieved at the midpoint of the PV string. To mitigate the oscillations induced by the P&O mechanism for string current reference optimization, the string current reference $I_{\text{string,ref}}(t)$ is directly determined by Equation 17:

$$I_{\text{string,ref}}(t) = \frac{\max[I_{pv,1}(t) \quad I_{pv,2}(t) \quad \dots \quad I_{pv,n}(t)] + \min[I_{pv,1}(t) \quad I_{pv,2}(t) \quad \dots \quad I_{pv,n}(t)]}{2} \quad (17)$$

To regulate the string current with fast response and high accuracy, a PI controller is employed to control the string current based on the reference calculated in Equation 17. If the optimization

objective of the string current reference is with respect to the TMP, $I_{\text{string,ref}}(t)$ can be expressed by Equation 18:

$$I_{\text{string,ref}}(t) = \arg \min_{I_{\text{string,ref}}(t) \in [I_{pv,1}(t), \dots, I_{pv,n}(t)]} \left[\sum_{i=1}^n V_{pv,i}(t) I_{pv,i}(t) \right] \quad (18)$$

Hence, in a PV-NIP DPP system with even number of PV elements, the TMP is obtained by tracking the UBP, as shown in Figure 5 for the example with two PV elements.

4 Simulations

The proposed control strategy was simulated in PSIM using the example system setup shown in Figure 4. The MSX-60 PV module with an MPP voltage of 17 V and MPP current of 3.5 A was used as the PV source under standard test conditions. Bidirectional flyback converters with a switching frequency of 50 kHz were employed as the DPP converter units. The perturbation interval for the unit-level P&O-based MPPT control was set to 0.04 s.

The irradiation was changed every 1 s to simulate unpredictable environmental conditions for evaluating the proposed control scheme. During the first second (Case I), the irradiation on PV elements 1 and 2 were 1,000 and 800 W/m², respectively. During

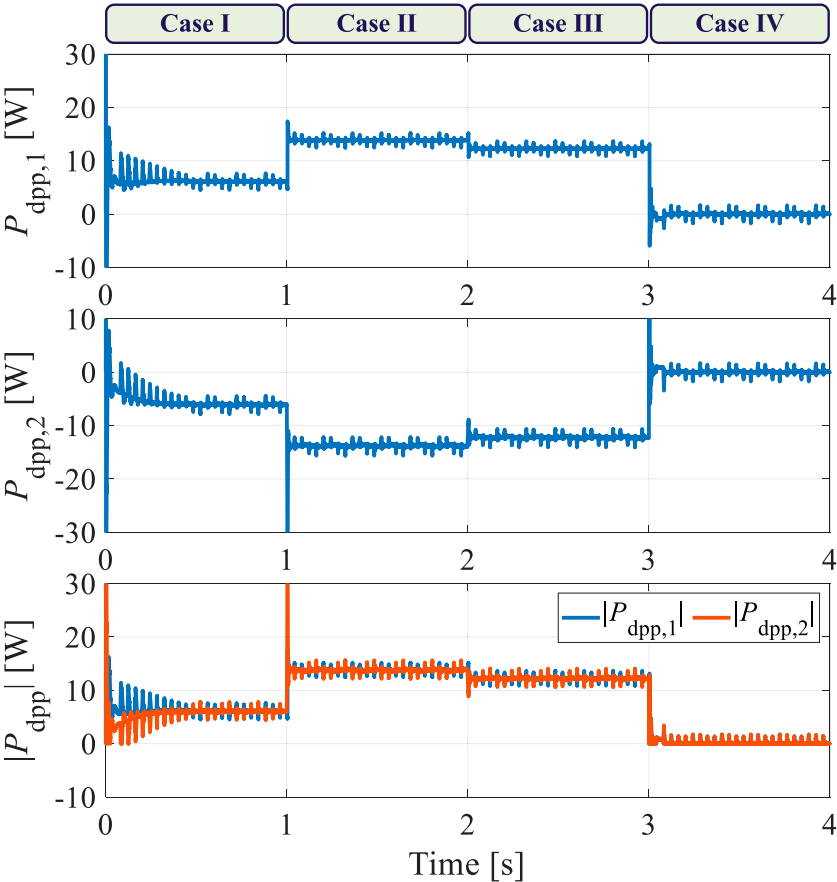


FIGURE 12 Simulation results of the differential power values processed by the DPP converter units under various shading scenarios.

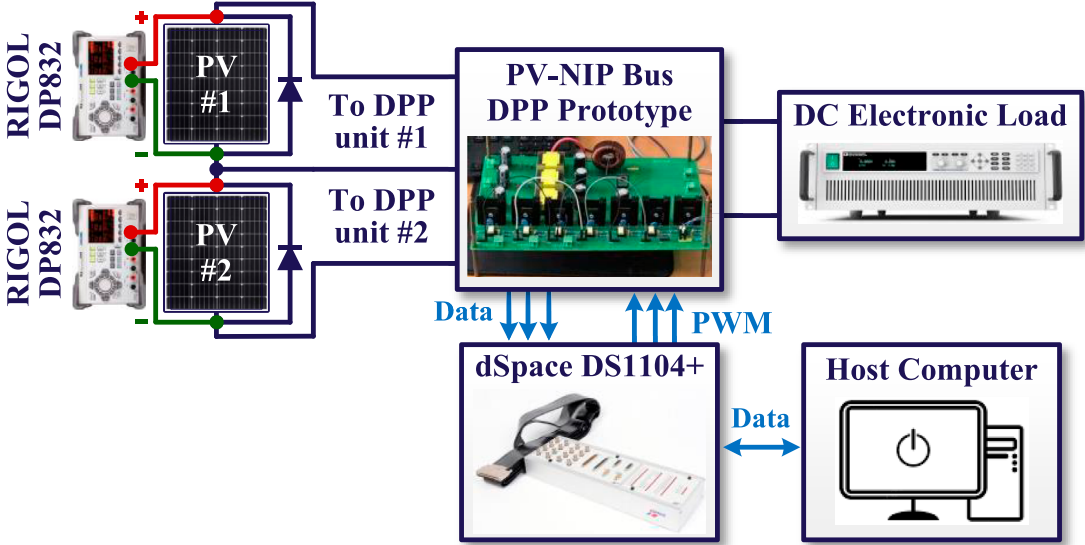
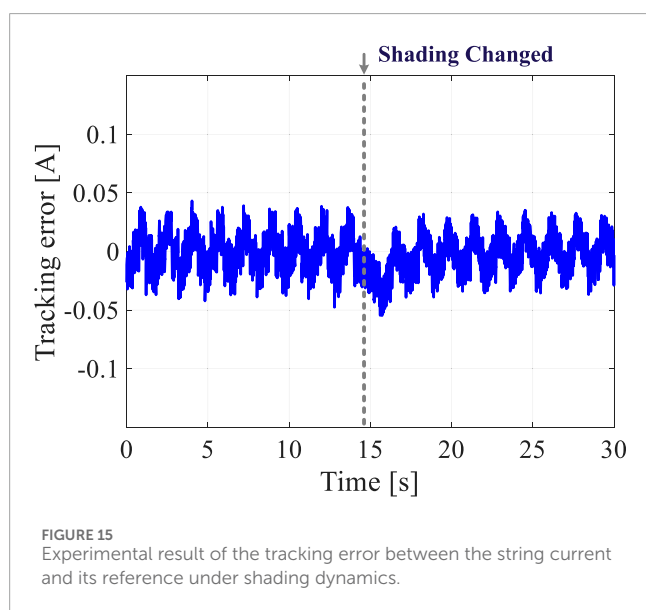
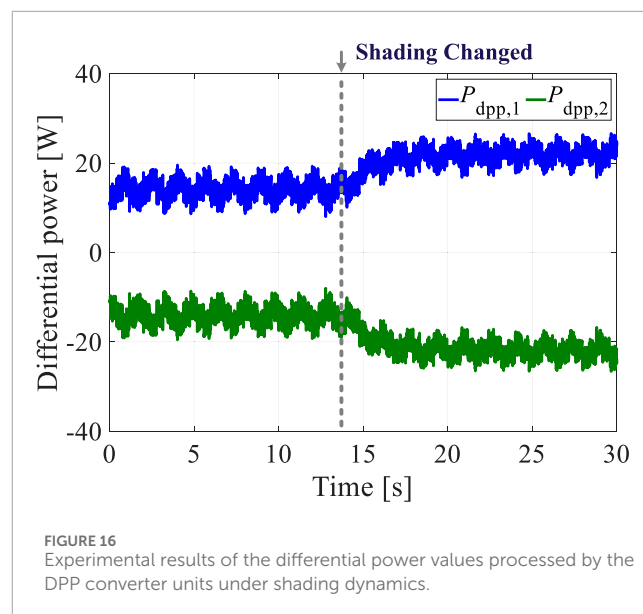
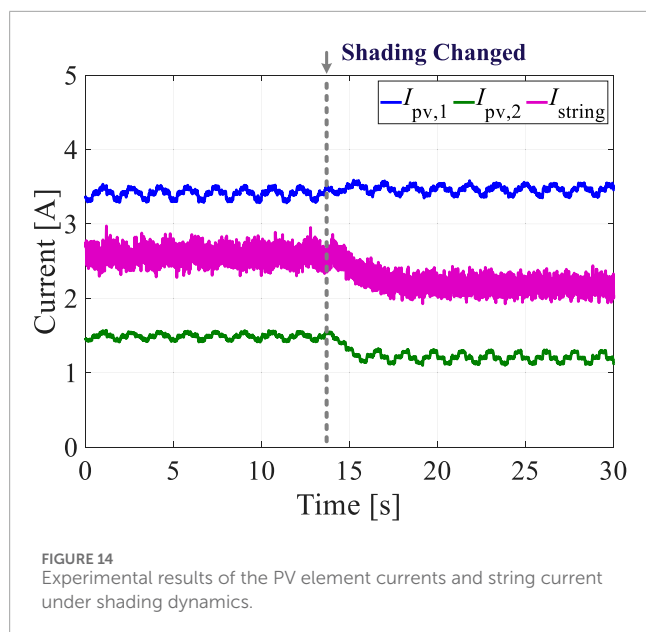


FIGURE 13 Diagram of the PV-NIP DPP experimental system.



the next second (Case II), the irradiation on PV elements 1 and 2 were 1,000 and 550 W/m^2 , respectively. During the third second (Case III), the irradiation on PV elements 1 and 2 were 1,000 and 600 W/m^2 , respectively. During the last second (Case IV), the irradiation on PV elements 1 and 2 were 1,000 and 1,000 W/m^2 , respectively. Figure 9 shows the output voltages satisfying the tracking for the MPPs of the two PV elements. Figure 10 shows the changing output currents of the two PV elements that match the corresponding MPPs during the stepped irradiation changes. The string current and its reference value are also shown in Figure 10. The current reference changes with irradiance and is equal to the average of the maximum and minimum measured PV currents. Furthermore, the reference changes immediately balance the unbalanced DPP currents upon changes in irradiation, as shown in Figure 11; the sign of the signal is repositioned in the direction of the differential current, which is

positive when flowing from the PV element to the DPP converter and negative when flowing from the DPP converter to the relative PV element. Figure 12 shows the differential power distributions and net differential power values of the two DPP converter units. The proposed control scheme aims to achieve relative balance of the DPP power in each converter, especially in units connected to PV elements receiving the maximum and minimum irradiation, which is used to balance the extreme values between the converter units; here, the effectiveness of the proposed UPRB scheme is validated through simulations under shading dynamics.

5 Experimental validations

To verify the effectiveness of the proposed scheme, experiments were carried out with prototypes based on the PV-NIP DPP architecture shown in Figure 4. Considering the characteristics of the proposed control scheme, the power rating of the flyback-based DPP converter unit was designed to be 40 W with a switching frequency of 20 kHz to cover the worst possible range of shading mismatches. The transformer inductance in the flyback DPP unit is 300 μH . The centralized boost converter is rated at 200 W and has a switching frequency of 20 kHz. Here, the programmable DC supply (RIGOL DP832) serves as a controllable current source and is connected in parallel with the MSX-60 PV elements to mimic irradiance changes in the laboratory. The proposed scheme was implemented on the dSPACE DS1104 R&D Controller Board, and the experimental platform is illustrated in Figure 13.

The experimental setup comprises a simplified DPP architecture with two PV elements and two bidirectional flyback DPP converters. The sample time for the algorithm is 0.4 s, and the data are measured using voltage and current probes before being stored in a host computer. To evaluate the proposed control scheme, a step change in irradiation was initiated for PV element 2 at 14 s, while the irradiation on PV element 1 remained unchanged. The current through each PV element during the entire recording time is shown

in Figure 14. When the irradiation on PV element 2 changed, the three-level oscillation observed at steady state was broken, and the current was regulated to the next steady state. During changes in irradiation, the string current changes in response to the changes in the PV elements, and the measured string current is the average of the unit currents. The tracking error between the string current and its reference is shown in Figure 15; here, the string current follows the changes in its reference under shading dynamics, and the tracking error is successfully restricted to the range of -0.05 A to 0.05 A. As shown in Figure 16, the differential power of each DPP converter unit can be balanced using the proposed method. Thus, the effectiveness of the proposed control scheme is validated through experiments under shading dynamics.

6 Conclusion

Unpredictable mismatch conditions, such as partial shading, manufacturing tolerances, thermal gradients, dissimilar aging, or dirt, can result in mismatched output characteristics of series-connected PV elements. DPP architectures are promising candidates for future PV generation systems as they help achieve higher efficiencies by processing only a portion of the full power generated while achieving the individual MPPs. In this work, we analyzed the differential power distributions in a bidirectional flyback-based PV-NIP bus DPP architecture. Then, we propose a UPRB scheme to reconfigure the differential power distributions among the unit converters with the aim of ensuring submodule-level optimization and enhancing the performance of the entire PV system. To achieve the individual MPPs of the PV elements, a P&O-based MPPT control is implemented in each DPP converter unit. To balance the power distribution among all DPP converter units in the system, UBPT control was implemented to optimize the string current. The proposed control scheme was verified using both simulations and experiments under shading dynamics and shown to reliably balance the differential power distribution.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors without undue reservation.

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Author contributions

JN: data curation, formal analysis, funding acquisition, methodology, validation, writing – original draft, and writing – review and editing. ZZ: formal analysis, methodology, software, and writing – review and editing. YZ: formal analysis, funding acquisition, methodology, validation, writing – original draft, and writing – review and editing.

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