Unit-Minimum Least Power Point Tracking for the Optimization of Photovoltaic Differential Power Processing Systems

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Abstract

Recently, the module integrated converter (MIC) and differential power processing (DPP) architecture were introduced to enable the PV power conditioning system (PCS) to maintain the optimal operating condition of PV cells, such as Maximum Power Point Tracking (MPPT), even under partial shading conditions. However, the DPP architecture was found to have more room to optimize the performance of the systems, by the application of an extra extremum-seeking control, the so-called Least Power Point Tracking (LPPT) method that was introduced last year. The main idea is that most of the power from the PV modules is processed through the main-string high-efficiency non-isolation converter, and only a minimal faction of the power that changes depending on the PV-string current is transferred through the low-efficiency bidirectional isolated DPP converters. This paper suggests a second version of the LPPT method, called Unit-Minimum (UM) power-distributing LPPT, which improves the first version of LPPT, called Total-Minimum (TM) centralized power-distributing LPPT. Instead of minimizing the total power of DPPs, the proposed LPPT minimizes the power of the DPP converter unit, which is the largest among them. Then, the system size and cost can be reduced by the proposed LPPT method, which enables the multiple DPP converters to have smaller power capacity and losses than those of the previous LPPT method. The real-time extremum-seeking algorithm employs a perturb-and-observe method, which comes from the conventional MPPT one, while the optimization process directs minimal extremity, not maximal. The peak system efficiency achieved with a 400-W prototype DPP system employing the LPPT algorithm is 96.7 %.

Index Terms

Unit-minimum LPPT, photovoltaic, differential power processing (DPP), perturb-and-observe, PV-bus architecture, Unit minimum, direct LPPT

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I. INTRODUCTION

Advances in photovoltaic (PV) technology have increased the capacity of solar-power systems, such as grid-scale solar plants, rooftop systems, and building integrated photovoltaic (BIPV) modules, atmosphere solar power-plants, so on. In this change, the cost, size, and efficiency of the PV power conditioning systems (PCS) have become decisive factors of PV-power-system commercialization. Therefore, in order to optimize these elements, a large number of circuit topology and system-architecture researches have been performed [1–2].

The first generation presented a centralized PV power conditioning architecture, which has a single power conversion circuit for a single PV string. The low energy-conversion efficiency due to the single MPPT controller and inability to operate individually-optimized MPPT required the architecture to make improvements during weather or climate changes, such as partial shading, and variations of temperature [3–5]. The next second generation is a multi-string architecture that achieves a significant improvement, especially for uneven external conditions, by dividing the previous single PV string into multi-strings. However, it significantly increases the cost, because it requires multiple power conditioning systems that correspond to the multiple PV string to obtain individual MPPT control. Also, the individual MPPT is not module-based, but string-based, it was not able to overcome the drawback of partial shading condition [6–7]. The third generation Module integrated converter (MIC) system can perform Distributed Maximum Power Point Tracking (DMPPT) control, due to the distributed DC-DC power conditioning pre-regulators that have a power-interface with each PV panel under individual MPPT control. The following DC-AC conversion stage interfacing with utility grid is a single centralized inverter, which contributes to the high cost-effectiveness. If the converters and the centralized inverter have high efficiency, this system maintains excellent overall efficiency compared with previous generations, even under partial shading conditions, by operating the DMPPT controller [8–15]. However, since the whole power from all the PV panels flows through the MICs to reach the centralized inverter, the design requirement of power capacity should be large, as much as the whole PV power generation. Therefore, despite the DMPPT control, the MIC topology is still somewhat distant from the optimal design of cost, size, and efficiency in terms of the system architecture. Recently, a differential power processing (DPP) system architecture was proposed to overcome the limitation of the MIC ones, which has a trade-off between the power capacity and the DMPPT control [16].
A. Differential Power Processing converter

The DPP PV power conditioning architecture has been proposed to achieve an independent control of each PV panel for DMPPT, while reducing the manufacturing cost and size of the converters compared to the MIC architecture [17–27]. The DPP architecture can be considered as a hybrid of the totally centralized one and the totally distributed MIC architecture. The PV panels are connected directly in series as for the centralized version, and the same number of DPP converters is connected in shunt to the PVs, in order to allow power differences between them to bypass the PVs through the converters, based on their mismatch level. Typically, the pre-subsystem of the main PV string with the DPP converters is then connected to a central inverter that delivers the PV power to the AC grid.

The general operating principle of DPP architecture is that the majority of PV power goes through the main string of the PVs in series, and only the differential power, caused by PV mismatch, is handled by the DPPs. Therefore, the power capacity and overall losses are lower than that of the MIC architecture, because only a fraction of the power, rather than the full PV power, is processed through the DPP converter, while DMPPT is achieved for each PV panel. In previous articles, the DPP converters have also been referred to as PV balancers [24], or PV equalizers [17]. In that case, a couple of main DPP converters are located between the PV and DC bus (PV-bus), or between two PV modules (PV-PV) [2, 23]. In addition, various topologies have been proposed in previous articles for DPP systems, including flyback converters [11], buck-boost converters [2, 26-27] switched capacitors [17, 19], and ladder converters [18, 28]. Figure 1 shows the PV-bus architecture that this work focuses on. The DPP PV-bus converters use bi-directional power flow to achieve the DMPPT operation for each PV module, and also a uni-directional DC-DC converter is employed to deliver the main string power to the DC-link (bus). The string converter topology is usually non-isolation type, because the converter input-output has a common ground, and under moderate voltage conversion ratios, the optimal efficiency is higher than that of the isolation type. Therefore, the DPP architecture maintains a high MPPT efficiency even under partial shading conditions, because each distributed PV module has its own MPPT controller. The DPP architecture is now considered a promising candidate for distributed power sources, such as rooftop and BIPV modules.
B. Bi-directional PV-bus system.
A bidirectional flyback converter and a unidirectional boost topology were chosen for the system realization in this paper. Figure 2 shows a testbed circuit structure of the PV-Bus DPP architecture that utilizes two flybacks as DPP converters. Between the PV string and the DC-link, a boost converter is employed as a central converter to control the main string current ($I_{\text{string}}$) [16, 29]. Figure 2 shows that each flyback converter is connected in shunt to the PV module to transfer some differential current of the module directly to the DC-link, in order to compensate the difference from $I_{\text{string}}$. In some previous DPP architectures, the DPP converters are connected between each PV module and the central boost input [18, 28]. However, the input voltage fluctuates consistently to achieve the MPPT operation, so to avoid the complex controller design and additional power conversion losses, the DPP converter output is connected directly to the link.

The majority of the PV current (power) commonly produced by each module flows through $I_{\text{string}}$, the input current of the non-isolation string boost converter in high efficiency. Then, the DPP flyback converters inject or withdraw the rest of the PV current necessary to achieve the distributed MPPT control for each PV module. Because all of the PV modules are independently controlled by the bidirectional DPP converter, individual MPPT can be achieved by the amount of differential current from the $I_{\text{string}}$ values. Thus, the power capacity required by the DPP converters and the device stress level on each converter depends on the $I_{\text{string}}$ value, which is controlled by the central string-level boost converter. Therefore, it is meaningful to adjust the string current in real time to minimize the power of the isolated flyback converter in poor efficiency, which is determined by the input and output currents.
In ideal condition with the assumption of perfectly identical PV modules, all of the PV current goes through the boost string, and also, all the DPP converters turn off, such that the system acts the same as a centralized PV inverter. In other conditions, assume that there is an insolation difference between two arbitrary cells; let the MPP current of PV1 be 3 A, and the MPPT of PV2 be 5 A. Then, the relationship between the string current $I_{\text{string}}$ and the PV currents, may have three cases; the string is lowest, in between, or greatest above these two $I_{pv}$ values. In any case, assuming that the DPP converters are designed with high enough power rating, they add or take some current from the PV string, in order to fix the bias of each PV at its MPP. Figure 3 shows an example. The string current between the two PV cell MPPs is 4 A, such that the DPP2 converter draws the excessive current (1 A) from the PV cell, while the DPP1 converter supplies a supplementary current (1 A) to the PV1 panel to compensate the current difference between the string and the PV1 MPP current by the bidirectional power flow operation. Whereas, if the String current changes to 5 A, then DPP2 is paused, and DPP1 achieves the MPP current tracking of PV1 by supplying 2 A to the PV2. These examples show that the total and each unit power of the DPP converters depend on the string current.
Another control issue then emerges, from the perspective of power conversion efficiency according to the DPP power-stress variation. In grid-tied applications, in order to meet the inverter requirements, the DC-link voltage ($V_{\text{dc\_link}}$ in Fig. 3) is usually far higher than each PV voltage. Thus, the voltage gain from the PV to the DC-link in the DPP converters is extremely high. DPP converters also require galvanic isolation, because the ground nodes of the PV voltages are different from each other. Therefore, the DPP converters need an isolation topology, which usually has a lower efficiency than the non-isolation type. Furthermore, isolation-type converters have the drawbacks of complicated design of the magnetic devices, low power capacity, and high manufacturing cost. Hence, in order to relieve the problems of the DPP system, an extra controller should operate to adjust the string current at an optimal point that minimizes the power stress processed in the DPP converters [23]. This general control concept, called Least Power Point Tracking (LPPT), which has been introduced in previous literature [2, 23], minimizes the summation of the power processed in all of the DPP converters, in order to reduce the total power losses [16]. However, the conventional scheme has a drawback of the power concentration of a single DPP converter unit, which increases the power-capacity requirement of the converter design. Hence, to optimize the manufacturing cost as well as the efficiency, DPP systems should be controlled by a new control algorithm, which pursues a unit-minimum power rating that as far as is possible, evenly distributes the power stresses to the respective unit. In this paper, the proposed LPPT control algorithm is validated with the PV-bus DPP converters through simulation in PSIM and experimental testing using a 290 W hardware prototype.

This paper is organized as follows. Section II introduces the operating principles of the proposed LPPT algorithm. Section III provides a detailed power stress analysis of the system for feasibility validation. Section IV explains the proposed unit-minimum LPPT control algorithms. Section V describes the simulation results,
while Section VI presents the experimental results of the waveforms in steady-state, and offers an efficiency comparison for the prototype hardware. Section VII concludes the paper.

II. OPERATION OF THE PROPOSED LPPT CONTROLLER

A. The previous LPPT control system

Most of the DPP architecture systems have the main purpose of minimizing power losses during energy conversion in PV PCS. The first and only conventional method introduced the LPPT control algorithm for optimizing the total power stress in all of the DPP converters, while the system simultaneously maintains the effective DMPPT of each PV module. According to the total power analysis of DPP converters in the two-PV example, the power stress on each bidirectional DPP can be calculated based on the string current and PV voltage [16]. Then, the LPPT controller perturbs the string current, and observes the summation of all the DPPs, and then perturbs again to the direction that minimizes the aggregation of the individual DPP converter power. For example, let the MPP of PV1 be $V_{pv1}=30\,\text{V}$, $I_{pv1}=3\,\text{A}$, and that of PV2 be $V_{pv2}=40\,\text{V}$, $I_{pv2}=5\,\text{A}$. The total power processed by the DPP converter is instantaneously observed according to the string current variation. Figure 3 shows that if the string current is 4 A, the total power processed by the DPP converter is 70 W, which is calculated by:

$$\sum |P_d| = |P_{dpp1}| + |P_{dpp2}|$$

$$= V_{pv1}|I_{pv1} - I_{\text{string}}| + V_{pv2}|I_{pv2} - I_{\text{string}}|$$

(1)

where, $P_{dpp1}$ is the power through DPP converter 1, and $P_{dpp2}$ is that of DPP converter 2. By the control of the conventional LPPT algorithm, the string current converges into 5 A as shown in Fig. 4, since the total power becomes 60 W, less than the case when the string is 4 A. However, the converter power distribution of $P_{dpp1} = 60\,\text{W}$ and $P_{dpp2} = 0\,\text{W}$, mean that the power units are quite unbalanced from each other. From the viewpoint of converter design, the power-capacity requirement of every DPP converter should be greater than 60 W, even though the other converter does not operate. This imbalance causes cost increase and size reduction, and also the reliability becomes poor, because of the thermal concentration.
Fig. 4. Example of the bidirectional DPP structure power flow in the conventional LPPT control (arrows show the direction of the power flows).

B. The proposed LPPT system

In the previous work, the LPPT has a problem of power concentration at a certain DPP unit. This paper suggests a new LPPT method distributing the DPP power well among the converters, called Unit-Minimum (UM) LPPT. In this scheme, instead of the total sum of the DPP power, the converter unit power is minimized by the instantaneous perturb-and-observe algorithm. For example, when the string current is perturbed to 5 A as shown in Fig. 4, the proposed LPPT observes the largest power stress among the DPPs, and holds the DPP1 power stress \( P_{dpp1} \) at 60 W. In the next perturbation, the string current becomes 4 A, then \( P_{dpp1} \) is 30 W, and \( P_{dpp2} \) is 40 W. Hence, the LPPT controller holds the value 40 W. Even though the total DPP power is 70 W greater than the conventional one of 60 W, the power is divided properly in each DPP converter, which significantly contributes to the design of the standard modularized DPPs for cost and size reduction. However, for application of a real-time extremum-seeking algorithm, the so-called perturb-and-observe (P&O) to the UM LPPT control, the unique existence of the parameter of peak (valley) power point in the DPP-unit according to the string current variation should be proven in the architecture. In order to examine the possibility of the proposed LPPT control, Section III examines the converter power stress based on the string current.

III. ANALYSIS OF THE PROPOSED LPPT CONTROL
A. UM LPPT Analysis – Two PV-module Case

In the two-PV module example, the power stress on each bidirectional DPP converter \(P_{dpp1}, P_{dpp2}\) can be calculated based on the string current \(I_{string}\), such as:

\[
P_{dpp1} = V_{pv1}|I_{pv1} - I_{string}|
\]

\[
P_{dpp2} = V_{pv2}|I_{pv2} - I_{string}|
\]

Since each power value is solely determined by the parameters in its own module, we can give the module number to the PV and DPP modules according to the amount of current, without consideration of the physical connections. In this analysis, \(I_{pv1} \leq I_{pv2}\), where \(I_{pv1}, I_{pv2}\) are the current for the first and second PV modules in negligible losses, respectively.

Now let us consider the unit power stress according to the string current. The analysis is performed by dividing the operating condition into three sections, according to the order between the string current and the PV current. The first section is 1). The largest unit power \(P_{worst}\) is found as Eq. (4):

1) \(I_{string} \leq I_{pv1} \leq I_{pv2} (\alpha < 1)\)

\[
P_{worst} = P_{dpp,k} = -V_{pv,k}I_{string} + V_{pv,k}I_{pv,k} \quad (k = 1 \text{ or } 2)
\]

where, \(I_{string} = \alpha I_{pv1}\).

In this case, the largest unit power \(P_{worst}\) decreases whichever DPP converter is the largest, according to the string current.

2) \(I_{pv1} \leq I_{string} \leq I_{pv2}\)

In this case, the function of the largest unit power is divided into two subsections (i) and (ii). The power is presented as Eqs. (5) and (6):

(i) \(1 \leq \alpha \leq \frac{k_1 l_2 + 1}{k_2 + 1}\)

\[
P_{worst} = P_{dpp2} = -V_{pv2}I_{string} + V_{pv2}I_{pv2}
\]

(ii) \(\alpha > \frac{k_1 l_2 + 1}{k_2 + 1}\)
where, \( I_{pv1} = l_2 I_{pv1}, V_{pv1} = k_2 V_{pv1} \) (\( l_2 \geq 1, k_2 > 0 \)).

In the first case, \( P_{worst} \) is the power of DPP converter 2. Then, in the case of (ii), it turns into DPP1.

3) \( I_{pv1} \leq I_{pv2} < I_{string} \)

\[
P_{worst} = P_{dpp,k} = V_{pv,k}I_{string} - V_{pv,k}I_{pv,k} \quad (k = 1 \text{ or } 2)
\]  

In this case, the largest unit power \( (P_{worst}) \) increases whichever DPP converter is the largest, according to the string current.

From the functions of all the cases, it can be seen that the unit power monotonically decreases as the string current increases, until the case of 2) and (i). Then, the slope changes from negative to positive from the case of 2) and (ii), and monotonically increases according to the increase of \( I_{string} \). Therefore, only a single minimum point of the tracking target \( P_{worst} \) exists. Figure 5 shows an example of the greatest unit-power graph according to the variation of \( I_{string} \) with the parameter values in Section II. There is a clear minimum-valley point of the unit-processed power at \( I_{pv2} = 4.0 \) A, which is the desired operating point of the proposed UM LPPT controller to distribute and attenuate the power stress of the DPP converters. Due to the unique characteristic of the power curve, similar to the PV voltage-power curve in reverse, the least power point (LPP) of the DPP system can be tracked instantaneously by applying a reverse P&O algorithm, which is used primarily in PV MPPT control. Section III.C compares this with the total power tracking of DPP converters.

![Fig. 5. DPP power stresses based on the string current variation. \( P_{worst} \) is the greatest unit-power graph in DPP converters according to the variation of the PV string current with the parameter values in Section II (black), and \( P_{total} \) is the total DPP power (gray).](image)
B. UM LPPT Analysis – Generalized N-module Case

The power stress is considered for an arbitrary number of n PV modules and DPP converters. As previously mentioned, assume that the PV module and the corresponding DPP converter are numbered in the order of the PV current; this order is independent of the physical connection order. Also, the voltage variation is relatively smaller than that of the current. Therefore, the current difference is supposed to be dominant to that of voltages among the PV cells, as usual. Then, it is assumed that $V_{pv1} \approx V_{pv2} \approx \ldots \approx V_{pv,n}$ and $I_{pv1} < I_{pv2} < \ldots < I_{pv,n}$ where $V_{pv1}, V_{pv2}, \ldots, V_{pv,n}$ and $I_{pv1}, I_{pv2}, I_{pv,n}$ are the voltage and current for the order of PV modules in negligible losses, respectively. The general form for the power processed by n DPP converters is:

$$P_{dpp1} = V_{pv1}|I_{pv1} - I_{string}|$$
$$\ldots$$
$$P_{dppn} = V_{pv,n}|I_{pv,n} - I_{string}|$$  \hspace{1cm} (8)

where, $V_{pv,n}$ and $I_{pv,n}$ are the voltage and current for the $n^{th}$ module, respectively. The analysis is done by dividing the operating condition into 3 sections, according to the order between the string current and the PV current. The first section is as follows. The largest unit power ($P_{\text{worst}}$) is found as Eq. (9):

1) $I_{\text{string}} < I_{pv1}$

$$P_{\text{worst}} = P_{dppn} = -V_{pv,n}I_{\text{string}} + V_{pv,n}I_{pv,n}$$  \hspace{1cm} (9)

This result occurs, because the current difference is greater between $I_{\text{string}}$ and $I_{pv,n}$, than between $I_{\text{string}}$ and $I_{pv1}$.

Before we consider the second case, it is helpful to check in what condition the current differences are balanced. In this case, the function of the largest (worst) unit power $P_{\text{worst}}$ is divided into two subsections 2) and 3). The power is given by Eqs. (10) and (11):
2) \( I_{pv1} \leq I_{string} < \frac{I_{pv1} + I_{pv,n}}{2} \)

\[
P_{worst} = P_{dpp,n} = -V_{pv,n}I_{string} + V_{pv,n}I_{pv,n}
\]

This result occurs because the current difference is greater between \( I_{string} \) and \( I_{pv,n} \), than between \( I_{string} \) and \( I_{pv1} \).

3) \( \frac{I_{pv1} + I_{pv,n}}{2} \leq I_{string} < I_{pv,n} \)

\[
P_{worst} = P_{dpp1} = V_{pv1}I_{string} - V_{pv1}I_{pv1}
\]

This result occurs because the current difference is greater between \( I_{string} \) and \( I_{pv1} \), than between \( I_{string} \) and \( I_{pv,n} \).

4) \( I_{pv,n} < I_{string} \)

\[
P_{worst} = P_{dpp1} = V_{pv1}I_{string} - V_{pv1}I_{pv1}
\]

This result occurs because the current difference is greater between \( I_{string} \) and \( I_{pv1} \), than between \( I_{string} \) and \( I_{pv,n} \).

From this analysis, the power curve versus the string current is a valley function, such that there is a single point that minimizes the power processed through the DPP converters to always be the middle value between \( I_{pv1} \) and \( I_{pv,n} \). Thus, for any number of PV modules connected with PV-bus DPP converters, there exists a unique point or unique set of points that minimizes the power processed through the DPP converters, called the least power point (LPP). Due to the uniqueness, it can be guaranteed that the instantaneous perturb-and-observe (P&O) algorithm can converge to the point. The LPP controller tries to find the target operating point to minimize the power losses in the PV system.

C. Comparison between the proposed UM and the conventional TM LPPT

Figure 5 shows an example of how, under the conventional and proposed LPPT control P&O algorithms, the observed power stress changes according to the string current. The X-axis is the string-current variation, while
the Y-axis shows the worst (largest) power stress among the DPP-converter units ($P_{\text{worst}}$) (power observance of the proposed LPPT), and the overall power summation ($P_{\text{total}}$) in all the DPP converters (that of the conventional LPPT case), respectively. The graphs are a series of theoretical estimations of the operating points under the LPPT controllers when $V_{pv1} = 30$ V, $I_{pv1} = 3$ A, and those of PV2 are $V_{pv2} = 40$ V, $I_{pv2} = 5$ A. At that case, the steady-state operating point of UM LPPT control is located at the 4-A string current, whereas the TM is at 5 A, which means the operating area can be different, according to the LPPT algorithm. Therefore, the proposed UM algorithm can have a penalty in total power stress, compared to the TM. However, the TM has a unit power (worst) that is the same as the total power, which moves the design parameter away from the optimal DPP-converter size and cost. For detailed analysis, Table I considers more examples.

Table I shows the power-stress comparison result between the proposed LPPT (unit minimum, UM) and the conventional centralized LPPT (total minimum, TM) methods under 5 partial-shading cases. Case 0 is the full-irradiance case, and cases 1 to 4 are various cases where the PV module 1 has shading. Case 4, where the power difference is 110 W (almost half of the full power), has 60 W of total DPP power stress in the conventional LPPT, and 70 W in the proposed LPPT, hence the proposed scheme seems slightly poor in system efficiency. However, from the perspective of individual DPP-converter design, the proposed scheme is far superior to the conventional one, since the unit power stress is just 40 W, smaller by 20 W than the conventional 60 W. The result means that when a multiple number of DPP converters are employed, the system size and cost can be significantly reduced. Figure 6 shows the graphs.
The X-axis is PV power difference, while the Y-axis is the total DPP power. The figure shows that the UM has a very similar pattern to the TM, and also the gap is a maximum 10 W, until the partial shading reaches 110 W in the PV-power difference. This implies that the total DPP power loss and the overall system efficiency would be insignificant. Whereas, according to Table I, the unit power stress of the UM maintains almost 30 % reduction through all of the operating conditions, compared to the TM. This large improvement signifies the contribution of the proposed LPPT algorithm for many PV-power system design perspectives, such as the power capacity and the manufacturing cost.

![Image](image.png)

**Fig. 6.** The theoretical total power stress at the steady-state of the LPPT algorithm according to the PV power difference. The LPP current is the optimal string current for each of the LPP operations.

### IV. UNIT MINIMUM LPPT ALGORITHM

The suggested LPPT control algorithm is designed to minimize the greatest power among DPP converters, while operating effective MPPT control of each PV module. Because the LPP is a single unique point at the bottom of a concave function, a P&O algorithm normally used for PV MPPT operation can be used. Figure 7 shows the process flowchart for the proposed UM LPPT control algorithm, where \( V_k(n) \) is the \( n \)-th sampling voltage of the \( k \)-th module among \( m \) number of modules, \( I_k(n) \) is the sampling current, \( P_k(n) \) is the power, \( P_{\text{worst}}(n) \) is the greatest power among the DPP converters called \( P_{\text{worst}} \), and \( I(n) \) is the string current reference updated as \( I_{\text{stringRef}} \). The process is as follows.

First, the current and voltage for each DPP converter is measured, and each power is also calculated. Then, all the unit powers are compared to each other, and the greatest power value is chosen as the worst unit-power.
Then the current value is compared to the previous one. If the value decreases, then the algorithm directs the string-current reference to move towards the same direction of the previous update. Otherwise, the reference is updated to the other direction. This updated reference becomes a new reference for the proportional-integral (PI) controller, which drives the main string converter to provide the exact string current as the reference. Then, the LPPT control loop iterates continually, such that the string current tracks the instantaneous variation of the LPP, while the individual MPP current and voltage of the PV modules move, or do not.

The LPPT and MPPT algorithms must work simultaneously; however, the controllers are highly coupled to each other in the power stage, such that the dynamic bandwidth of the two controllers must be separated from each other. If their dynamic responses have similar time scales, the perturb signal from the MPPT algorithm can cause an unintended response in the LPPT algorithm. Thus, the control bandwidth should be considered to avoid
their interaction. Actually, the optimal string current for LPPT changes according to the PV module’s operating point, which periodically moves during the MPPT operation. Whereas, each PV module’s MPP is not influenced by the string current variation. Thus in this work, the perturbation frequency of the LPPT controller is designed to be faster than that of the MPPT. During a single perturbation step of MPPT, multiple LPPT steps are performed, fast enough to reach a new optimal point in steady-state before the next step begins. The next section shows the ability of these two P&O algorithms (LPPT and MPPT) to work simultaneously, without interfering with one another.

V. PSIM SIMULATION

The proposed LPPT control algorithm was simulated with the previously mentioned example of two PV modules and DPP converters, shown in Figs. 3 and 4. A P&O MPPT algorithm was also implemented by PSIM software C-block within each DPP converter controller. The perturbation method was the so-called direct-duty-cycle perturbation, which directly adjusts the converter duty cycle in every MPPT period, based on the measured PV current and voltage values. In this work, the MPPT perturbation operates in every single second. Figure 8 shows the simulation results for the two-PV modules in MPPT steady state operation. Figure 8(a) shows that the PV 1 voltage continuously maintains the position above, at, and below its 30-V MPP, and also the PV 2 voltage steps around its 40-V MPP in the same pattern. This waveform shows that the P&O algorithm successfully tracks each PV module’s MPP independently.

The LPPT P&O algorithm was also implemented in the boost converter that directly controls the string (boost inductor) current using a PI feedback controller, in order to maintain the current to track the LPP current reference \(I_{\text{stringRef}}\) in Fig. 8(b)). This reference value is updated based on the LPPT algorithm, which optimizes the power of the DPP converters according to the string current variations. Figure 8(b), which shows that the LPPT perturbation occurs every 0.05 s, about 20 times faster than that of the MPPT, reveals that the LPPT waveform works properly with the MPPT algorithm in parallel. The \(I_{\text{stringRef}}\) changes 20 times within one MPPT step to quickly find the new optimal steady-state current value, because each MPP has its own LPP. To verify the P&O algorithm in LPPT control, Figs. 8(c) to (e) present the zoom-in waveforms of Fig. 8(b). Figure 8(c) shows that the boost converter power (\(P_{\text{boost}}\)) varies according to \(I_{\text{stringRef}}\) and also the DPP power stresses change to the difference between the string current and PV current under constant PV voltages, of (30 and 40) V. When
$I_{\text{stringRef}}$ is (4, 4.1, and 4.2) A, the worst power is ($P_{dpp2}$ 40, $P_{dpp2}$ 36, and $P_{dpp1}$ 36) W, respectively. The LPP string current reference ($I_{\text{stringRef}}$) moves around 4.1 A, the true LPP. Likewise, in Fig. 8(d) with constant PV voltages of (28.9 and 38.4) V, when $I_{\text{stringRef}}$ is (3.8, 3.9, and 4.0) A, the worst power is ($P_{dpp2}$ 38, $P_{dpp1}$ 35, and $P_{dpp1}$ 36) W, respectively. The LPP string current reference ($I_{\text{stringRef}}$) fluctuates around 3.9 A. Figure 8(e) shows that with PV voltages of (31.3 and 41.6) V, when $I_{\text{stringRef}}$ is (4.2, 4.3, and 4.4) A, the worst power is ($P_{dpp2}$ 36, $P_{dpp1}$ 35, and $P_{dpp1}$ 38) W, respectively. The LPP string current reference ($I_{\text{stringRef}}$) moves around 4.3 A. From these results, it can be concluded that the proposed P&O algorithm works well for the unit-minimum LPPT control. The experimental result section shows more detailed verification of the method.

(a) MPPT voltages and currents of the PV modules.

(b) LPPT string currents of the string boost converter.
(c) Power distribution among the DPP converters at $V_{p1} = 30$ V, $V_{p2} = 40$ V.

(d) Power distribution among the DPP converters at $V_{p1} = 28.9$ V, $V_{p2} = 38.4$ V.
Fig. 8. PSIM simulation waveforms showing (a) MPPT of the PV modules, (b) LPPT operating simultaneously with the MPPT, (c) Power distribution of DPP converters during the operation in the Fig. 8(c) area of Fig. 8(b), (d) Power distribution of DPP converters during the operation in the Fig. 8(d) area of Fig. 8(b), and (e) Power distribution of DPP converters during the operation in the Fig. 8(e) area of Fig. 8(b) (note: $P_{dpp1}$ has a negative polarity according to the power flow direction).

VI. EXPERIMENTAL RESULTS

A. MPPT-LPPT operation

A 400-W hardware prototype was made for a PV-bus DPP system, and tested at the worst case MPPT operation in the same condition as the previous simulation specification. Table II shows the key parameters, while Table III lists the hardware prototype parameters. The two PV panels were emulated using a dual-module PV simulator (TerraSAS ELGAR), to have MPP characteristics of PV 1 of $V_{pv1} = 30$ V, $I_{pv1} = 3$ A, (90 W), and of PV 2 of $V_{pv2} = 40$ V, $I_{pv2} = 5$ A (200 W).

<table>
<thead>
<tr>
<th>Components</th>
<th>Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPP switches of primary side</td>
<td>IRF4768</td>
</tr>
<tr>
<td>DPP switches of secondary side</td>
<td>IRFP450</td>
</tr>
<tr>
<td>Boost converter diode</td>
<td>LQA06T300</td>
</tr>
<tr>
<td>Boost converter switch</td>
<td>IRFP4768</td>
</tr>
<tr>
<td>DSP model</td>
<td>TMS320F28335</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
</table>

Table II. HARDWARE PROTOTYPE COMPONENTS.

Table III. PARAMETERS FOR DPP SYSTEM PROTOTYPE.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage for each DPP</td>
<td>25-45 V</td>
</tr>
<tr>
<td>Output/dc-link voltage</td>
<td>200 V</td>
</tr>
<tr>
<td>Output power rating</td>
<td>400 W</td>
</tr>
<tr>
<td>Boost converter switching frequency</td>
<td>20 kHz</td>
</tr>
<tr>
<td>Flyback converter switching frequency</td>
<td>20 kHz</td>
</tr>
<tr>
<td>Boost converter inductor</td>
<td>550 μH</td>
</tr>
<tr>
<td>Magnetizing inductance</td>
<td>100 μH</td>
</tr>
<tr>
<td>PV module capacitor</td>
<td>2200 μF</td>
</tr>
<tr>
<td>Flyback converter–transformer turn ratio</td>
<td>1:4</td>
</tr>
</tbody>
</table>

Figure 9. Experimental DPP-hardware waveforms with both an MPPT controller and an LPPT one. PV1, PV2 voltages (Ch1: $V_{pv1}$, Ch2: $V_{pv2}$) and the string current $I_{string}$ (Ch3). The solid black line is the corresponding LPP according to the PV-voltage perturbation of the MPPT controller. The LPPT controller tracks the LPP by perturbation and observation of $I_{string}$. Each PV voltage also tracks well the corresponding MPP, such as 40 V ($V_{pv2}$) and 30 V ($V_{pv1}$).

Figure 9 shows the experimental result waveforms. The results have the PV and the string-current waveforms that agree well with those of the PSIM simulation in Fig. 8. The figure shows $V_{pv1}$ in channel 1 (Ch1), $V_{pv2}$ in channel 2 (Ch2), and $I_{string}$ in channel 4 (Ch4). $V_{pv1}$ and $V_{pv2}$ have the steady-state MPPT operation with 0.1-Hz perturbations using a P&O algorithm with direct duty control method when the MPPT bias of the PV V-I curves are (30 and 40) V, respectively. The PV1 voltage steps fluctuate around its 30-V MPP in 3 steps, and the PV2 voltage steps around its 40-V MPP in the same 3 steps, which means the P&O algorithm successfully finds the MPPs. The string current controller operates with the P&O LPPT algorithm, and simultaneously with the MPPT controller. Figure 9 shows that each MPPT step has different LPP values, such as (3.9, 4.1, and 4.3) A. The unit duty-cycle step of the direct duty MPPT control is 0.01, and also, the unit step of the reference of the LPPT string current is 0.1 A. The figure shows that the LPPT controller tracks the LPP well by perturbation-and-observation of $I_{string}$, even under simultaneous PV voltage perturbations. The step...
period for MPPT is 10 s, and for LPPT is 0.8 s, such that the LPPT is 12 times faster during the MPPT period. The figure reveals that while the PV voltages are perturbed for real-time MPP control, the string current can successfully be tracked to the LPP within the MPP cycle.

Figure 10 shows the experimental zoom-in waveforms of $V_{pv1}$, $V_{pv2}$, and $I_{string}$ under current regulation for LPPT perturbations. The small figure inside is the zoom-out, and the box region is the area for the zoom-in. Figure 10(a) shows the perturbation waveforms of PV voltages ($V_{pv1}$, $V_{pv2}$) for the MPPT P&O algorithm, and of the string current ($I_{string}$) for LPPT P&O. The current has a switching ripple of 1.5 A, and the average moves in 0.1 A steps for the perturbation per second. For finding the LPP stably, the current dynamics are far faster than that of the voltages, and perform twelve current steps during a single PV step. Figure 10(b) shows more zoomed-in waveforms of Fig. 10(a). When the voltage step occurs, the transient response of the current takes 2 ms settling time, fast enough to perform the observation process in the LPPT P&O. Since the MPPT controller is based on the direct-duty cycle method, the PV voltage is in open-loop operation.

![Graph showing voltage and current waveforms](image-url)
Fig. 10. Experimental zoom-in waveforms of $V_{pv1}$, $V_{pv2}$, and $I_{string}$ under current regulation for LPPT perturbation (small figure inside is the zoom-out, while the box region is the area for the zoom-in).

B. Thermal measurement

This section validates the proposed unit-minimum LPPT method from the perspective of the thermal stress and power capacity, compared with the previous total-minimum LPPT (centralized) method. Figure 11 shows thermal images of the proposed and previous LPPT methods under an identical partial shading condition. Assume that PV 1 is $V_{pv1}=30$ V, $I_{pv1}=3$ A, (90 W), and PV2 is $V_{pv2}=40$ V, $I_{pv2}=5$ A (200 W), and of course, that the LPPT controller properly operates. Under the condition, the LPP of the previous LPPT control method is 5 A, while that of the proposed UM LPPT method is 4 A. According to the conventional TM, DPP converter 1 handles 60 W, whereas DPP converter 2 manages 0 W. As a result, $S1=43.0$ °C, which is the DPP converter 1 temperature, is higher than $S2=33.8$ °C, the DPP converter-2 temperature, due to the centralized power distribution among the DPP converters. Whereas, when the proposed LPPT control is applied, the LPP of the system becomes 4 A. Then, the total power managed by the DPP converters is slightly greater than the original TM, 70 W. Whereas, the worst unit power is only 40 W transferred by DPP converter 2, while the remaining power 30 W is transferred by DPP converter 1. Therefore, during the proposed LPPT operation, thermal stresses are well distributed as $S1 = 36.3$ °C and $S2 = 36.0$ °C, respectively. The evenly distributed power stress means that the proposed LPPT relieves the design limitation on the optimization of the power capacity and power concentration among the DPP converters. The conventional DPP system with TM LPPT has a design constraint of the DPP power rating of 60 W, whereas the proposed LPPT system has a smaller power capacity of 40 W.
This low power rating enhances the system reliability and cost-competitiveness. Actually, higher operating temperature negatively affects component lifetime, and by distributing the heat, we can make the failure rates for each DPP converter more similar, which increases the overall system reliability.

In the theoretical perspective of the reliability, the result is as follows. If the failure rates for like components are equal, then the system reliability is [2]:

$$R(t) = e^{-\lambda dt}[1 - (1 - e^{-\lambda_p t})(1 - e^{-\lambda_d t})]^n.$$  \hspace{1cm} (13)

This function shows that the DPP structure has a reliability that is dominantly affected by the factors on the PV module’s failure rate $\lambda_p$ and string converter one $\lambda_s$, compared to the DPP parameter $\lambda_d$, since the usual PV panels have far stronger robust characteristics than switching power converters, which means $\lambda_p$ is far smaller than $\lambda_d$. Therefore, it can be concluded that regardless of the LPPT method, the DPP architecture has similar reliability. From the hardware results, however, the temperature is more evenly distributed in UM, so the reliability should be better than that of the TM.

(a) Thermal image when conventional TM LPPT control is applied (S1 and S2 are the surface temperatures of the transformers of the DPP converters 1 and 2, respectively).
C. Efficiency Comparison

Figure 12 presents the hardware efficiency measurement for the DPP flyback converter and the boost string converter, and also the efficiency comparison between the previous and proposed LPPT systems. Figures 12(a) and (b) show that the string converter efficiency is higher than that of the DPP converters throughout the power variation. Figure 12(c) also shows the entire system power conversion efficiency under LPPT control. The operating conditions correspond to the five cases in Table I, when the largest power difference is 110 W, PV1 is $V_{pv1}=30$ V, $I_{pv1}=3$ A, (90 W), and PV2 is $V_{pv2}=40$ V, $I_{pv2}=5$ A (200 W). In the previous TM LPPT, one of the DPP converter deals 60 W, while the other DPP converter handles no power with the LPP string current of 5 A. Hence, one of the DPP converters operates at light-load condition in the TM LPPT system, whereas all of the DPP converters operate at medium-to-full load condition of (30 – 40) W in the proposed UM LPPT. Then, a series of the DPP system efficiencies, including the main-string boost converter, were measured according to the PV power differences of Table I. As the power difference increases, both of the previous and proposed LPPT efficiencies decrease. An interesting result is that since the DPP converters have continuous switching action even under no load condition for the constant perturbation of MPPT operation, the flyback DPP converter has very poor efficiency, which deteriorates the conventional TM LPPT system efficiency to show even worse than that of the proposed LPPT. Also, as the PV power difference increases, the efficiency gap becomes greater. Actually, in conventional DPP control system without LPPT as shown in Fig. 1, since the continuous PV voltage
(or current) perturbation for real-time MPPT control requires voltage (or current) regulation, even under the no-load condition, only one DPP converter among the DPPs can fully switch-off, due to the additional MPPT control of the boost string converter [30-31]. Whereas, neither the conventional LPPT nor the proposed control schemes allow any DPP converters to fully switch off during the no-load condition, because the boost cannot take over the MPPT from a DPP converter, but constantly performs the LPPT. Hence the difference between with and without LPPT is only one DPP converter on or off, and also the measured switching loss under no-load is less than 1 watt, which does not significantly affect the efficiency graph. From the results, it can be seen that the proposed UM LPPT has the advantage of reducing the power loss during the operation under partial shading conditions.

(a) Efficiency versus power of the DPP flyback converter with 30 V input.

(b) Efficiency versus power of the string boost converter with 60 V input.
D. Real PV array test with four modules

The comparison analysis between the proposed LPPT and conventional LPPT is extended to a larger number of elements, since the price of adjusting string current to reduce the power processed by multiple DPP converter will be much effective for more series PV units. A few outdoor hardware experiments with four real PV panels are conducted to verify the analysis. Figure 13 shows the hardware set-up.

Figure 14 shows an example of how the worst DPP-unit power changes according to the string current variations under sunny and PV4-only partial shading conditions. X-axis is the string-current variation, and the Y-axis shows the worst (largest) power ($P_{\text{worst}}$) among the DPP-converter units. Gray depicts partial shading, while black depicts full radiation. The graphs are a series of theoretical estimations of the operating points under the UM LPPT controllers when all of the panels have the same full-radiation MPP at $V_{\text{pv}} = 15 \, \text{V}$, $I_{\text{pv}} = 4 \, \text{A}$, or have one different MPP under shading (artificially made) in PV4, $V_{\text{pv}} = 15 \, \text{V}$, $I_{\text{pv}} = 2 \, \text{A}$. In the shading case, the...
steady-state operating point of UM LPPT control is located at the 3 A string current, whereas in the sunny case, the current is 4 A, which means the operating area can differ, according to the weather condition. For the verification, a hardware test is done.

![Graph showing worst DPP unit power curve based on the PV string current variation in the case of sunny and partial shading (PV 4 only).](image1)

**Fig. 14.** The worst DPP unit power curve based on the PV string current variation in the case of sunny and partial shading (PV 4 only) weather conditions.

![Experimental waveforms for MPPT and LPPT control with four solar panels in series in the case of sunny day (full irradiance) condition.](image2)

**Fig. 15.** Experimental waveforms for MPPT and LPPT control with four solar panels in series in the case of sunny day (full irradiance) condition. $V_{pv1}$, $V_{pv2}$, $V_{pv3}$ and $V_{pv4}$ represent the PV1, PV2, PV3 and PV4 voltages, respectively, as the input voltage of DPP1, DPP2, DPP3 and DPP4 converter, respectively. $I_{string}$ is the current of the string boost converter. The black solid line means the least power point that the string current should track. The steps at the envelop of the current show the P&O algorithm operation of the LPPT controller. Arrows depict the ground of each channel.

Figure 15 shows the full-radiation experimental waveforms captured by an 8-channel oscilloscope (picoscope4824, Picotechnology). All the operating parameters are the same as the sunny condition in Table IV, and then the results have the PV and the string-current waveforms, which agree well with those of the analysis in Fig. 14. The figure shows $V_{pv1}$ in channel 1 (Ch 1), $V_{pv2}$ in channel 2 (Ch 2), $V_{pv3}$ in channel 3 (Ch 3), $V_{pv4}$ in
channel 4 (Ch 4), and $I_{\text{string}}$ in channel 5 (Ch 5). All of the voltages have the steady-state MPPT operation with 0.1 Hz perturbations using a P&O algorithm with direct duty control method when all the MPPTs are the same as 15 V, respectively. The black solid line means the least power point, 4 A ($\pm$ 0.1 A according to the PV voltage perturbation), which the string current should track. The steps at the envelop of the current in switching ripples show the P&O algorithm operation of the LPPT controller. The string current controller operates well with the P&O LPPT algorithm, and simultaneously with the MPPT controller.

Figure 16 shows the PV4 shading experimental waveforms. All the operating parameters are the same as the sunny and PV4-shading conditions in Fig. 14, and the results have the PV and the string-current waveforms that agree well with those of the analysis in Fig. 14. At first, DPP operation under sunny condition is the same as Fig. 15; then, during the period marked with dotted lines, PV4 goes under a shading condition, which has an MPP change in the PV4 ($V_{\text{pv4}} = 15$ V, $I_{\text{pv4}} = 2$ A), and also causes the LPP current change from (4 to 3) A. In the DPP operation, when the irradiance changes, the string current instantly decreases to track the new LPP at 3 A. After the irradiance comes back to sunny condition, the string current increases to track the LPP at 4 A, and stays in steady-state at around 4 A. The black solid line means the least power point that the string current should track, and the oblique arrows represent the movement in the process of the LPP. The steps at the envelop

![Diagram](image_url)
of the current in switching ripples show the P&O algorithm operation of the LPPT controller. The string current controller operates well with the P&O LPPT algorithm, and simultaneously with the MPPT controller.

Fig.17. The worst DPP unit power curve based on the PV string current variation in the case of sunny, partial shading (PV 1, PV 2) and cloudy weather conditions.

Figure 17 shows an example of how the worst DPP-unit power changes according to the string current variations under sunny, PV1-and-PV2 partial shading, and cloudy conditions. X-axis is the string-current variation, while the Y-axis shows the worst (largest) power ($P_{\text{worst}}$) among the DPP-converter units. Rectangles in the graph depict partial shading, diamonds depict full radiation, and triangles depict cloudy. The graphs are a series of theoretical estimates of the operating points under the UM LPPT controllers under three cases when all of the panels have the same full-radiation MPP at $V_{p1} = 15 \text{ V}$, $I_{p1} = 4 \text{ A}$, or have two different MPPs under shading (artificially made) in PV1, $V_{p1} = 15 \text{ V}$, $I_{p1} = 0.5 \text{ A}$ and $V_{p2} = 15 \text{ V}$, $I_{p2} = 0.5 \text{ A}$, or all of the panels have the same cloudy-radiation MPP at $V_{p} = 15 \text{ V}$, $I_{p} = 3 \text{ A}$. In the shading case, the LPP of UM LPPT control is located at the 2.25 A string current. In cloudy condition, the LPP current is 3 A, whereas in sunny condition, the LPP is 4 A, which means the moving average of the string (boost inductor) current should track the different levels according to the weather condition. For verification, a hardware test is performed.
Figure 18 shows the (PV1, 2) shading-to-cloudy-condition experimental waveforms. All the operating parameters are the same as those of the sunny, shading PV1, 2, and cloudy conditions in Fig. 17, and then the hardware results have the PV and the string-current waveforms, which agree well with those of the analysis in Fig. 17. Firstly, sunny operation is the same as in Fig. 15, and then, during the period marked between first and second dotted lines, by shading PV1 and PV2, MPPs of the PV1 and PV2 ($V_{pv1} = 15\, \text{V}$, $I_{pv1} = 0.5\, \text{A}$, $V_{pv2} = 15\, \text{V}$, $I_{pv2} = 0.5\, \text{A}$) cause LPP change from (4 to 2.25) A. When the irradiance changes, the string current instantly decreases, to track the new LPP at 2.25 A. After the second dotted line, the irradiance comes back to sunny day condition, then the string current increases to track the LPP at 4 A. In 12 s, however, the weather changes again to cloudy conditions, and the perturbation moves the operating point into a new LPP of around 3 A. The black solid line means the least power point that the string current should track. The string current controller operates well with the P&O LPPT algorithm, and simultaneously with the MPPT controller, even under weather variation in a partial shading and a cloudy condition.

Table IV compares the DPP power-stress and LPP according to various weather conditions, between the proposed LPPT (unit minimum, UM), and the conventional centralized LPPT (total minimum, TM) methods.
Sunny day is the full-irradiance case. In this, the LPP string current is 4 A, and the DPP converters have no power delivery. In cloudy condition, the DPPs operate in a similar way, and the difference is that the LPP is 3 A, due to the new PV MPP current. In the partial shading case, all of the PV panels have the same MPPs except for PV4, which has a new MPP under shading (artificially made), \( V_{pv4} = 15 \text{V}, \quad I_{pv4} = 2 \text{A} \). Compared with the conventional TM LPPT, the proposed UM has a different LPP string current from the TM in 4 A (TM LPP is always the medium value among the PV MPP currents), the worst unit power is 15 W, just half of the TM, which has 30 W. In another shading case, which shades PV 1 and PV 2, the fully-radiated PV 3 and PV 4 have the same MPP at \( V_{pv3} = 15 \text{V}, \quad I_{pv3} = 4 \text{A} \), \( V_{pv4} = 15 \text{V}, \quad I_{pv4} = 4 \text{A} \). Whereas, PV 1 and PV 2 have new MPP \( V_{pv1} = 15 \text{V}, \quad I_{pv1} = 0.5 \text{A} \), \( V_{pv2} = 15 \text{V}, \quad I_{pv2} = 0.5 \text{A} \). Compared with the conventional TM LPPT, the proposed UM has a different LPP string current from the TM in 4 A, the worst unit power is 26.25 W, just half of the TM, which has 52.5 W. From the theoretical analysis and the hardware results, the proposed UM LPPT is superior to the conventional TM LPPT from the perspective of DPP-converter design, since the unit power stress is just half that of the conventional design, even under the greater number of PV module system realizations.

**Table IV. Comparison of DPP operating parameters according to the weather conditions.**

<table>
<thead>
<tr>
<th>Case</th>
<th>Sunny</th>
<th>Cloudy</th>
<th>Shading at PV4</th>
<th>Shading at PV1, PV2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{pv1}, I_{pv1} ) (MPP)</td>
<td>15V, 4A</td>
<td>15V, 3A</td>
<td>15V, 4A</td>
<td>15V, 0.5A</td>
</tr>
<tr>
<td>( V_{pv2}, I_{pv2} ) (MPP)</td>
<td>15V, 4A</td>
<td>15V, 3A</td>
<td>15V, 4A</td>
<td>15V, 0.5A</td>
</tr>
<tr>
<td>( V_{pv3}, I_{pv3} ) (MPP)</td>
<td>15V, 4A</td>
<td>15V, 3A</td>
<td>15V, 4A</td>
<td>15V, 4A</td>
</tr>
<tr>
<td>( V_{pv4}, I_{pv4} ) (MPP)</td>
<td>15V, 4A</td>
<td>15V, 3A</td>
<td>15V, 2A</td>
<td>15V, 4A</td>
</tr>
<tr>
<td>( I_{string} ) at UM (TM)</td>
<td>4A (4A)</td>
<td>3A (3A)</td>
<td>3A (4A)</td>
<td>2.25A (0.5A - 4A)</td>
</tr>
<tr>
<td>Unit power with UM (with TM)</td>
<td>0W (0W)</td>
<td>0W (0W)</td>
<td>15W (30W)</td>
<td>26.25W (52.5W)</td>
</tr>
<tr>
<td>Power DPP1</td>
<td>0W</td>
<td>0W</td>
<td>15W</td>
<td>26.25W</td>
</tr>
<tr>
<td>Power DPP2</td>
<td>0W</td>
<td>0W</td>
<td>15W</td>
<td>26.25W</td>
</tr>
<tr>
<td>Power DPP3</td>
<td>0W</td>
<td>0W</td>
<td>15W</td>
<td>26.25W</td>
</tr>
<tr>
<td>Power DPP4</td>
<td>0W</td>
<td>0W</td>
<td>15W</td>
<td>26.25W</td>
</tr>
</tbody>
</table>

E. Direct LPPT without perturbation

Table V shows a comparison between the P&O LPPT and direct one without P&O that tracks the unperturbed constant reference directly derived by calculating the center of the minimum and maximum PV currents (see section III.B). PV voltage, the current and the power as well as those of the DPP converters are shown. The design (worst) unit power is 36 W for the P&O, whereas 40 W for the direct. Whereas, total DPP power stresses are similar. Figure 19 shows the direct-LPPT simulation verification. The LPPT string current
has no perturbation except the MPPT one. From the result, it can be seen that since the direct LPPT has an approximate sub-optimal unit power compared to P&O, the direct LPPT without perturbation can be an effective alternative for the P&O LPPT. If the PV voltages have no difference each other, then the direct LPPT has exactly the same as the P&O. This direct has a strong advantage that it works even under a condition of multiple extremum points (valleys) in the DPP power curves according to the string current.

Table V. Comparison between P&O LPPT and Direct one

<table>
<thead>
<tr>
<th>Case</th>
<th>LPPT by P&amp;O</th>
<th>LPPT by directly</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{pv1}, I_{pv1}(MPP) )</td>
<td>30V, 3A</td>
<td></td>
</tr>
<tr>
<td>( V_{pv2}, I_{pv2}(MPP) )</td>
<td>40V, 5A</td>
<td></td>
</tr>
<tr>
<td>( I_{string}(LPP) )</td>
<td>4.1A</td>
<td>4A</td>
</tr>
<tr>
<td>Power DPP1</td>
<td>33W</td>
<td>30W</td>
</tr>
<tr>
<td>Power DPP2</td>
<td>36W</td>
<td>40W</td>
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<tr>
<td>Total power</td>
<td>69W</td>
<td>70W</td>
</tr>
<tr>
<td>Power PV</td>
<td>290W</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 19. PSIM simulation waveforms showing the direct LPPT control w/o perturbation, operating simultaneously with the MPPT

VII. CONCLUSION

This paper proposes a unit-minimum power-distributing LPPT control method for PV-bus DPP architectures that aims to minimize the power processed through the bi-directional DPP converters. As a result of the analysis of the DPP system power, it has been verified that a modified perturb-and observe algorithm that has been used for MPPT control can be applied to the LPPT control, since only one minimum power point for the DPP converter unit exists. The PSIM simulation result shows that the MPPT and LPPT controllers can operate successfully in parallel. Also, a 400 W hardware prototype was built for the validation of the proposed scheme with a couple of PV module simulators and flyback DPP converters. The experimental results show that the waveforms agree well with the simulation results, tracking successfully the least power point of the DPP converter unit, even under the constant variation of the PV voltages for MPPT control. Also, from the comparison of the system power-conversion efficiency, it can be seen that the proposed LPPT has greater
efficiencies than the previous TM LPPT system, due to the elimination of the no-load condition of the flyback.

Finally, the thermal distribution measurement verifies that the proposed power-distributing method has better thermal stresses of the main elements than those of the conventional one, which may contribute to enhancement of the reliability, cooling cost, and life span.

REFERENCES


Biography

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