Design Features of Nonisolated DC/DC Converters for Maximum Power Point Tracking in Photovoltaic Systems

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Abstract—**The maximum power point tracking (MPPT) algorithm is essential for the system to operate at the maximum power point (MPP) under different irradiance and temperature conditions to improve efficiency. This paper presents a comparative study of various non-isolated DC/DC converter topologies using several MPPT methods: the perturbation and observation (P&O) method, the constant voltage method, and the power increment method using simulation. It can be concluded that there is no universal optimal solution for photovoltaic systems with MPPT methods and DC/DC converters, and the choice of MPPT depends on factors such as location, cost, implementation complexity, tracking accuracy and speed, and provides practical recommendations for the application of stand-alone photovoltaic systems.**

Keywords— Photovoltaic system, shading, maximum power point tracking

This MPP shifts with changing weather conditions. For illustration, P–V curves of a PV module, including the effects of irradiance and temperature, are simulated and shown in Figure 1. When cells within a module are subjected to varying irradiance levels, partial shading conditions arise, causing the P–V curve to exhibit multiple peaks. Despite this, there exists a single Global MPP (GMPP). To ensure optimal efficiency, maximum power point tracking (MPPT) algorithms must accurately identify and track the GMPP amid other local peaks [1]. his work investigates three MPPT algorithms and three DC/DC converter topologies: the accurate and relatively fast perturb and observe (P&O), the fast but relatively inaccurate constant voltage, and the power increment method, which is capable of tracking the GMPP. These MPPT techniques are applied to control the duty cycle of three nonisolated DC/DC converters: the voltage step-down buck, the voltage step-up boost, and the bidirectional buck–boost converter [1].

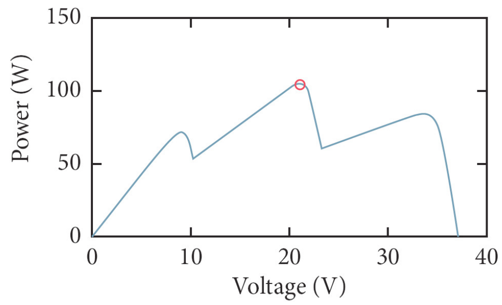

Figure 1. P–V curves under partial shading condition

Many MPPT algorithms were proposed and discussed in the literature [2]. Three algorithms are discussed in this work as follows: P&O, constant voltage, and power increment. One downside of the P&O is the inverse relationship between accuracy and speed, where achieving high accuracy and precisely locating the MPP rather than perturbing around it is on account of its convergence speed and vice versa. In addition, tracking the MPP under partial shading conditions is not guaranteed with the P&O, as it may get trapped in a local maximum of the multipeaked P–V curve under partial shading conditions and fail to reach the GMPP. Method Constant Voltage gained popularity due to its low implementation complexity and minimum hardware requirements. It tracks the MPP by simply neglecting the effects of temperature and irradiance on the voltage at MPP, relying on the fact that the voltage required to operate at MPP is almost constant with changing weather conditions, especially in the level of irradiance. This technique cannot locate the GMPP under partial shading conditions. Power increment is one of the few MPPT techniques that support tracking the GMPP of the multipeaked P–V curve in the event of partial shading without any added complexity. Unlike the intelligent techniques, which are relatively complex to implement and require prior knowledge or training for the utilized PV system. The power increment tracks the GMPP by scanning the entire PV power curve and saves the duty cycle value at which the ultimate MPP occurs. However, this scanning affects its speed.

A. DC/DC Converters Topologies

It is mandatory to introduce a DC/DC converter connecting the PV modules to the load to compensate for the mismatch between the fixed resistance of the load and the varying weather-dependent resistance of the PV source. The derivation of the duty cycle required to equate those resistances and thus track the MPP can be derived for the buck converter. Buck converter decreases the input voltage while increasing the current according to Equations (1) and (2) as follows $V_0 = D \cdot V_{in}$, (1), $I_0 = I_{in} / D$, (2), where Vo and Io are the output voltage and current, Vin and Iin are the input voltage and current, respectively (in this case, the PV voltage and current), and D is the converter's duty cycle [3].

Observing Figure 2, the buck–boost converter has the apparent advantage of no practical MPP tracking limitations due to the relation between its output and input voltages, which dictates a duty cycle lying in its practical range between 0 and 1. Hence, the buck–boost converter is better when implementing an MPPT system than the buck and the boost topologies.

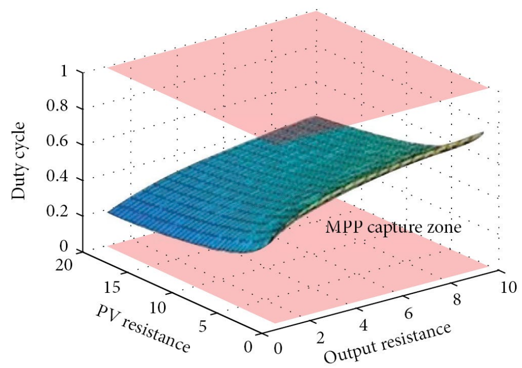

Figure 2. MPPT capture zone for buck–boost converters

II. Prepare Performance Evaluation Indices

Buck, boost, and buck–boost converters were chosen for their dominance in low-to-medium power PV systems and manageable control dynamics, in contrast to higher-order or isolated converters that, while more versatile, introduce unnecessary complexity for the intended scope. The MPPT techniques: P&O, constant voltage, and power increment, cover a representative range from low-complexity to high-accuracy strategies, ensuring practical insight into real-world performance trade-offs. An MPPT system with optimal performance does not exist. Hence, selecting the MPPT algorithm and the DC/DC topology becomes a function of various parameters that determine the desirable performance traits; these selection parameters are system application, location, and cost. 1. Convergence speed: The time the MPPT technique takes to drive the system's operating point to the MPP. The tracking speed of MPP algorithms is influenced by various factors, including some that are determined by the designer's expertise and preferences, often involving a trade-off between accuracy and oscillations.

2. Implementation complexity measured by main factors: the algorithm's complexity and factor is the universality of the MPPT algorithm; as such, AI-based algorithms require prior knowledge of the PV system, which limits its usage. Application and cost are the main deterministic selection parameters. This feature can be quantified by assessing the computational resources, the number and type of sensors required, and the complexity and cost of a compatible hardware control platform.

3. Tracking accuracy: the more accurate the MPPT technique is at locating the MPP, the higher the efficiency of the MPPT system. However, the desired high accuracy is usually attained on account of increased implementation complexity and convergence speed.

4. Tracking the GMPP under partial shading conditions: This MPPT's ability to track the GMPP of a multipeaked P–V curve improves the system's overall accuracy and efficiency. Generally speaking, algorithms with curve scanning features should be capable of tracking the GMPP

A. Quantitative Measures Description for MPPT Algorithms

1. Accuracy: Accuracy is a crucial metric for any algorithm's performance. This data point offers a meaningful insight into the benchmark performance of state-of-the-art algorithms.

2. Implementation complexity: This measure is essential for the practical applicability and implementation of the MPPT algorithms. Several factors contribute to algorithm complexity, such as hardware and PV panel specificity, sensor dependency, and generalizability of the algorithm.

3. Global MPPT tracking: An often-debated aspect of MPPT algorithms is their capability to trace the GMPP.

In summary, while certain aspects of MPPT algorithms can be viewed from a qualitative perspective, these quantitative measures provide a tangible framework for systematic evaluation and comparison across the board [4].

DC/DC converter

1. MPPT capture zone: This PI is set by the utilized DC/DC converter topology irrelative to the MPPT technique. This index represents the restriction the DC/DC converter imposed on the region where the MPP can be tracked. The selection of the DC/DC topology highly depends, in the first place, on the voltage gain. Thus, this PI is mainly determined by the application as a selection parameter.

2. Control complexity: This index measures the DC/DC converter-switching network control complexity. An easier-to-control switch is the grounded one instead of a floating high-side one, which increases system cost and necessitates a more complex gate drive controller. According to this PI, the boost converter is recommended as its switch is grounded.

3. DC/DC converter efficiency: Conversion efficiency is an important parameter determining the system's overall performance. The application governs the converter efficiency as a selection parameter PI.

4. Voltage and current ratings: Component ratings can be regarded as another index with an impact on the selection of the DC/DC topology, which in turn affects the efficiency and the cost of the implemented MPPT system [5].

B. Constant Voltage With the Three Nonisolated DC/DC Converters

The constant voltage algorithm investigated for the different DC/DC converters and loads as in Figure 3 250 W/m2 irradiance.

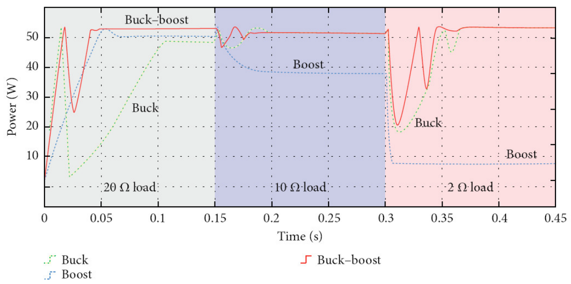

Figure 3. Constant voltage method under 250 W/m^2.

The constant voltage method is highly recognized by its convergence speed despite the DC/DC topology requiring around 0.05 s, as illustrated in Figure 3 However, this fast-tracking speed comes at the expense of accuracy, which impairs efficiency. This feature significantly increases energy harvested using constant voltage, especially in large-scale PV systems. It can be noted here that MPPT algorithms are irrelevant regarding the capture and noncapture zones of the DC/DC converter. In other words, similar to the P&O, the buck converter with the constant voltage method could only operate appropriately in its MPP capture zone under 2 Ω load at STC and 2 Ω and 10 Ω at 250 W/m2.

C. Power Increment With the Three Nonisolated DC/DC Converters

Where Figure 4 shows performance at and 250 W/m^2.

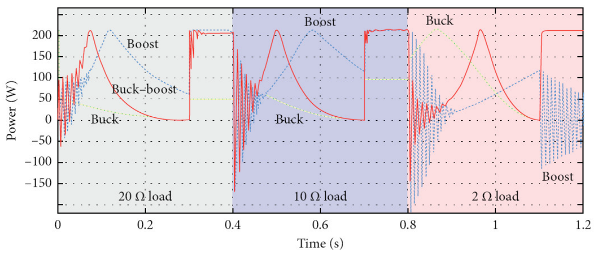

Figure 4. Power increment method under 250 W/m^2.

The power increment scans the whole P–V curve, enabling it to monitor all power points and accurately locate the GMPP. As was the boost with 2 Ω under STC and 10 Ω and 2 Ω under 250 W/m2. This confirms the system's failure regardless of the MPPT algorithm if the converter lies in its MPPT noncapture zone. Moreover, due to its linearity, the buck (in the dotted green trace) introduced an oscillation-free response under all operating conditions. In contrast, the boost and buck–boost suffered high oscillations at extreme duty cycles. This operational condition can lead to two distinct phenomena, especially when assuming ideal components: 1. Discontinuous conduction mode (DCM): This mode can result in varied transient responses, which may subsequently lead to voltage fluctuations or variations.

2. Nonlinear behavior of components: Essential components in DC–DC converters, such as diodes, exhibit nonlinear characteristics, particularly during swift switching events. The pronounced effects of this nonlinearity become more evident when the duty cycle is approaching zero, given the extremely short duration of switching events.

This nonlinearity can lead to output voltage instability at certain duty cycle values. Specifically, a duty cycle value that theoretically results in infinite output voltage will induce oscillations [6].

D. The Three MPPT Algorithms Under Varying Temperature

Figure 5 highlights the effect of temperature variation on the performance of the MPPT algorithms, which is irrelevant to the DC/DC topology; thus, the buck converter was used. A sudden extreme temperature drop was investigated, decreasing from 45 to 10°C at 0.4 s.

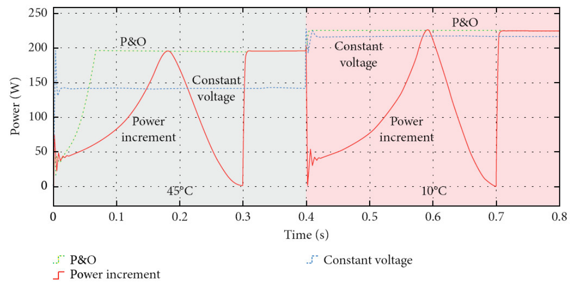

Figure 5. P&O, constant voltage, and power increment MPPT under varying temperature

Starting with the P&O (in dotted green), it clearly maintains its accurate MPP tracking under different temperatures. The P&O reached the new MPP very rapidly compared to a sudden change in irradiance. This can be explained concerning (3), as the temperature change slightly affects the voltage, which in turn insignificantly affects the MPP resistance, unlike the change in irradiance, which significantly affects the current, and hence the resistance is considerably changed. On the other hand, as seen in Figure 5, this change in MPP voltage caused by temperature fluctuation significantly impacted the constant voltage tracking accuracy (in dashed blue), which depends, in theory, on setting the voltage to a stable value.

The final MPPT comparison aspect is the ability of the MPPT algorithm to operate under partial shading conditions, which is irrelevant to the DC/DC converter. Therefore, due to its linearity, the buck converter was selected here. The power increment outperforms the P&O and the constant voltage because it scans the entire P–V curve, allowing for the recording of all power points and the ability to identify the maximum, which is crucial for detecting the GMPP in conditions of partial shading [7].

E. Design guidelines as follows

Headings, or heads, are organizational devices that guide the reader through your paper. There are two types: component heads and text heads.

1. The boost and buck–boost need higher inductance than the buck for the same current ripple.

2. The buck converter's required output capacitor is lower than that for the other converters.

3. An additional blocking diode is required for the buck and the buck–boost to avoid the reverse flow of the current, whereas, in the boost converter, the bypass diode does this job.

Enerally, the initial duty cycle selection significantly affects the speed at which the P&O algorithm locates the MPP.

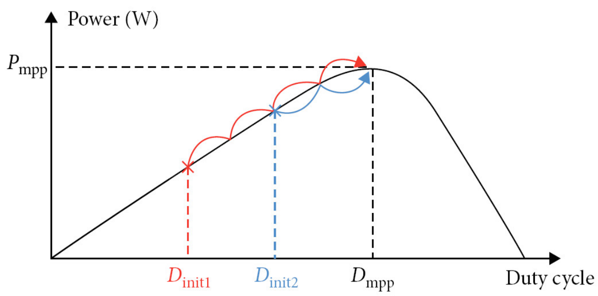

Figure 6. Visualization of initial duty cycle on speed of MPP Tracking.

Figure 6 demonstrates that the time savings are proportional to the absolute difference between the initial duty cycle Dinit and optimal Dmpp for a given step size. A P&O algorithm starting with initial duty cycle Dinit1 requires twice as much time as it would with an initial duty cycle Dinit2 at the same step size. However, an effective MPPT controller and converter design should limit the duty cycle search space to a narrow range, which helps improve the overall speed of locating the MPPT.

The buck–boost topology showed its superiority in MPP tracking under different weather and load conditions, as it has no limitations or restrictions, unlike the buck and boost topologies. However, the fact that it can step up or down the voltage undesirably, along with inverted output polarity, may lead the user to avoid its use. From a broad perspective, selecting the optimal DC/DC converter is application-specific, but some general guidelines can assist in this process. For instance, the linear Buck might be ideal for applications with high resistive loads to ensure an MPP capture zone. On the other hand, the simplest-to-control boost could be a better option for low-resistive loads. The buck–boost is the best choice in highly fluctuating loads due to its nonrestrictive capture zone, despite its inverting output and gain nonlinearity.

Regarding the MPPT techniques, the P&O showed a very accurate performance at a slower speed to reach the MPP compared to the constant voltage, which in turn lacks the level of accuracy achieved by the P&O. However, neither the P&O nor the constant voltage was able to track the GMPP relative to the power increment. Once again, the choice among MPPT algorithms depends on the specific application and location. The P&O is often a better choice for regions prone to dynamic weather changes. In contrast, locations with partial shading issues may require the power increment and the constant voltage, which are the easiest to implement and the fastest in MPP tracking.

Last but not least, neither the initial duty cycle choice nor the MPPT algorithm could overcome the inherent constraint of the DC/DC converter's MPP noncapture zones, primarily governed by irradiance compared to temperature change. Similarly, the inability to track the GMPP is due to the MPPT algorithms, which the DC/DC converter topology cannot enable.

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