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Dead time control signal for non-isolated synchronous buck DC-DC converter

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ABSTRACT

This study introduces a simple dead-time control signal for the non-isolated synchronous buck DC-DC converter, incorporated alongside maximum power point tracking (MPPT) for a stand-alone photovoltaic (PV) system. Dead-time control in non-isolated DC-DC converters is challenging due to difficulties in accurately sensing and predicting errors, especially during the transition between switching modes. The introduction of the dead-time control method resulted in optimal efficiency for the stand-alone PV system. The dead-time control was implemented in the hardware prototype using a bootstrap technique. Power generation from the PV module was optimized through the DC converter's implementation of an improved perturb and observe (P&O) MPPT approach. According to the results, the proposed design achieved an overall system efficiency of 80%. Moreover, the enhanced P&O MPPT algorithm prototype was observed to produce a maximum output power of 60 W.

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1. INTRODUCTION

Renewable energy sources are replenished naturally over time, thus providing sustainable energy. Photovoltaic (PV) technologies are among the most widely exploited renewable energy (RE) sources today [1]. Over the years, renewable energy sources have grown rapidly, with growth rates comparable to those of coal and lignite, although still lower than that of natural gas. In 2028, RE accounted for 42% of global energy production, with hydroelectric power making up 14% of that total, leaving solar PV energy at a small share of 12.6% [2]. Despite challenges like silicon shortages, the PV sector continues to expand at a rate of over 30% per year, and the cost of PV energy is predicted to reach competitive levels with traditional energy sources in many countries in the coming years [3]-[5]. Photovoltaic modules utilize semiconductor materials like silicon to convert the sun’s light into electrical energy [6], [7]. The amount of PV module output power depends on several factors, such as sunlight intensity, especially in terms of module direction, as well as the tilt angle, the temperature of the PV surface, and the cell surface cleanness [8]-[10]. Given the relatively low conversion efficiencies of PV modules, it is crucial to relocate the maximum power point (MPP) during its operation. Nevertheless, the PV module exhibits nonlinear I-V and P-V characteristics that vary with changes in irradiance as well as the PV surface temperature, which significantly affect its power output [11], [12]. On the I-V and P-V curves, the PV module operates at its maximum efficiency at MPP.

Therefore, numerous MPP searching strategies have been developed and are known as maximum power point tracking (MPPT) techniques, designed to pinpoint the optimal MPP. MPPT is a power regulation algorithm employed to dynamically locate and follow the MPP by adjusting the PV system's voltage and current, thereby ensuring continuous operation at peak efficiency [13]-[15]. These MPPT approaches are broadly categorized into traditional methods and those based on artificial intelligence [16], [17]. Notably, the perturb and observe (P&O) algorithm is a prevalent choice for MPPT controllers due to its straightforward implementation and minimal complexity [18], [19]. The P&O method identifies the MPP of PV modules by iteratively introducing small changes, observing the resulting power output, and comparing successive power values [20]. Consequently, the configuration of the PV modules dictates the output voltage of the PV array. For example, a BP 275 F PV module produces 75 W with a 21.4 V open-circuit voltage. To meet load specifications and enhance efficiency at lower voltage levels, the majority of PV systems require a DC regulator or DC converter. The operational behavior of a typical buck DC-DC converter is distinguished by two discrete modes, namely continuous conduction mode (CCM) and discontinuous conduction mode (DCM), and these modes are defined by the nature of the current flowing through its inductor. CCM is generally preferred for DC-DC power conversion as the inductor current remains consistently above zero, while DCM is more appropriate for low-power or standby applications [21], [22]. Given that the primary objective of this research is to transfer DC power from PV modules to a battery bank, which typically operates at a nominal DC voltage of 12 V, a step-down DC converter has been selected.

For light loads, reference [23] presents an adaptive dead-time approach in a synchronous buck converter, which reduces power losses through precise dead-time adjustment. Zishan *et al.* [24], a non-isolated synchronous buck (NSB) DC-DC converter operating with soft switching, which was introduced and evaluated under both discontinuous conduction mode (DCM) and continuous conduction mode (CCM) at a maximum power rating of 30 W. To optimize the efficiency of NSB DC-DC converters, research in [25] provides a comparative analysis of optimal control techniques and identifies key challenges in dead-time control for future research. This study utilizes a non-isolated synchronous buck (NSB) DC converter specifically designed for a standalone PV system. The NSB DC-DC converter effectively reduces the higher input voltage from the PV array to a lower DC output voltage by employing synchronous switching elements like power metal-oxide-semiconductor field-effect transistor (MOSFETs), without providing electrical isolation between the PV source and the load [26]. A key benefit of using two MOSFET switches is their ability to minimize conduction losses that can arise with diode usage [27]. Considering factors such as the reliance on PV modules, rate of convergence, dynamic response, and the complexity of the system's structure, the study concludes that the enhanced P&O MPPT method demonstrates greater effectiveness and superior performance compared to other MPPT techniques for standalone PV systems. Consequently, this study implements a direct control strategy that incorporates an improved P&O MPPT for applications involving PV-battery charging.

2. METHOD

The design of a dead-time control signal for the hardware prototype of the NSB DC-DC converter, integrated with the MPPT technique, can be separated into four main sections, as illustrated in Figure 1. The study methodologies begin with an investigation into the list of parameters that affect the generation of PV output power and the design strategy of PV systems. This is followed by an in-depth investigation of the design of a digital MPPT controller, culminating in the design of a selected step-down DC converter. Next, an improved P&O MPPT is implemented, followed by a computer simulation using MATLAB/Simulink software. The overall system performance is then evaluated and discussed at the end of the paper.

Located between the photovoltaic (PV) module and the battery, the NSB DC-DC converter's primary function is to adjust the PV module's output voltage, thereby ensuring the PV panel consistently operates at its MPP. The NSB DC-DC converter is implemented to overcome drawbacks such as the isolated grounding of the MOSFET driver typically found in a standard buck converter, making it more appropriate for real-world applications. Figure 2 illustrates the circuit block diagram of the proposed system. The Roman numerals I through VIII represent the following components, namely a current sensor, a 12 V voltage regulator, MOSFET switch drivers, a bootstrap circuit, the high-side switch (S1), the low-side switch (S2), LC filters, and the main controller, respectively. A high-side current sensing resistor (Rs) is connected in series with the INA138 current sensor to measure the input current from the PV module. This sensor converts the current (Is) into a proportional voltage (Vsense) that the main controller can interpret. Simultaneously, voltage dividers are employed to generate voltage signals proportional to the actual PV and battery voltages, which are then fed into the main controller.

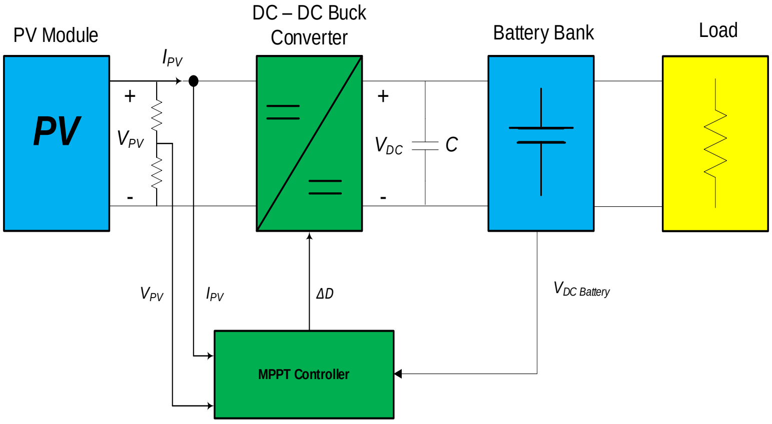


Figure 1. A block diagram illustrating the proposed stand-alone PV system

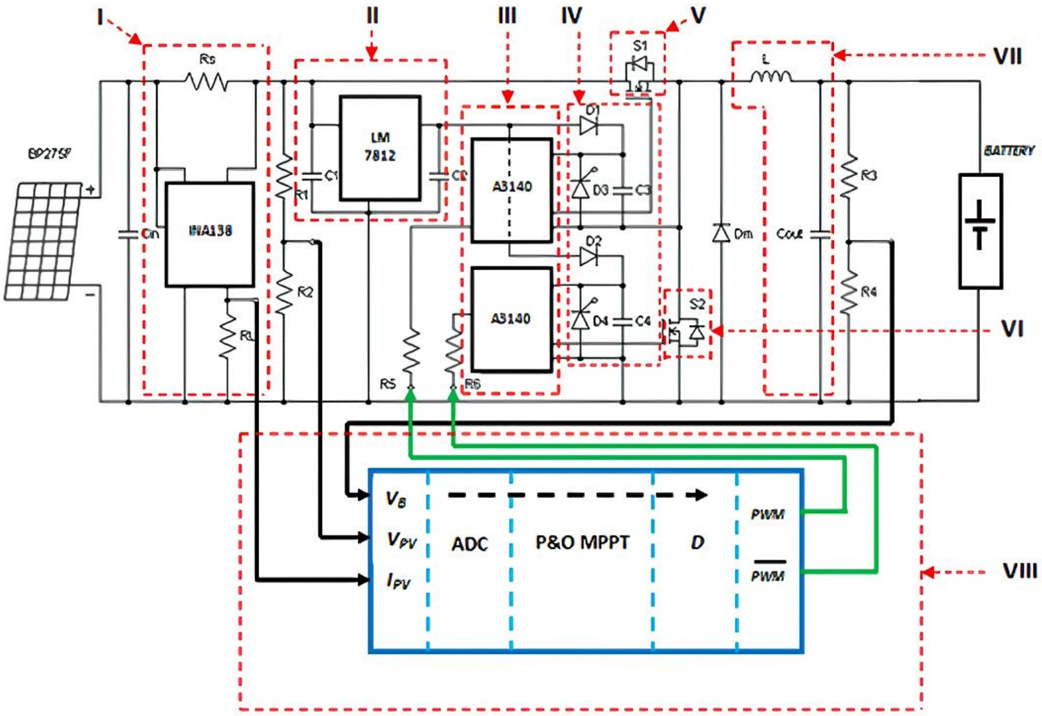


Figure 2. NSB DC-DC converter with MPPT technique

A corresponding value of the duty cycle is computed in real-time using the proposed MPPT to generate a pulse width modulation (PWM) signal, which is subsequently used to control both power MOSFET switching sequences and adjust the PV MPP set point based on the chosen MPPT strategy. Two N-channel power MOSFETs, designated as S1 and S2, are incorporated into the NSB DC-DC converter for hardware prototype purposes. Nevertheless, there are two significant considerations regarding this arrangement. As depicted in Figure 3, the NSB DC-DC converter exhibits specific waveform characteristics. The control of a floating high-gate-charge N-channel MOSFET switch (S2) is achieved using a low-side switch driver. The gate voltage needed for the high-side switch driver is generated by an external bootstrap circuit composed of a bootstrap diode (D1) and a capacitor (C3). These two components are connected and flanked by the power line of both power switch MOSFET drivers. The capacitor (C3) supplies the required power to the high-side MOSFET switch. Figure 4 illustrates a simulation model conducted using MATLAB/Simulink software. Meanwhile, a stand-alone PV system hardware prototype is constructed to validate the overall system's performance. This study uses the BP275F PV module as the simulation reference model, and the overall system's major experimental components are listed in Table 1.

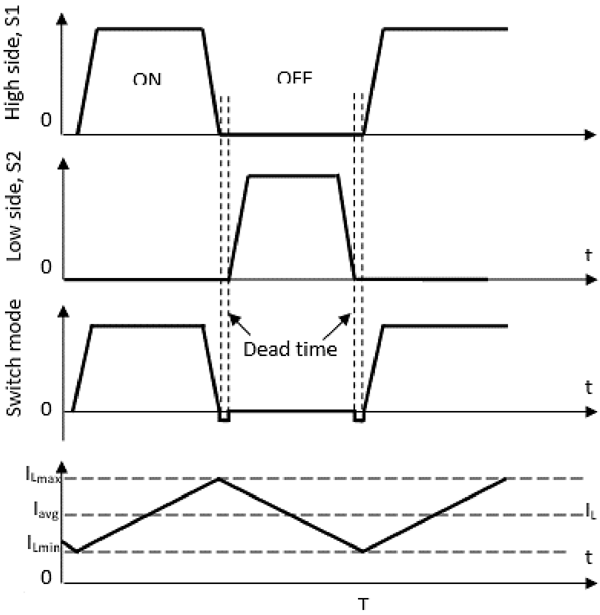


Figure 3. Typical operation waveforms of both switches, S1 and S2

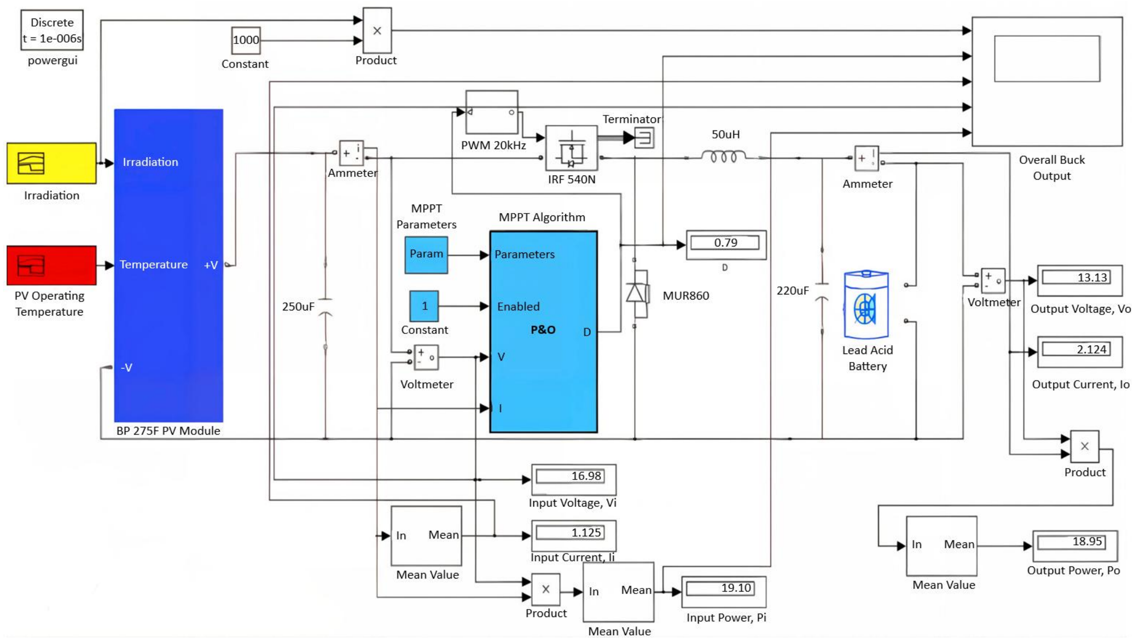


Figure 4. Simulation model of a PV system with the MPPT method

Table 1. List of major experimental components

No.	Item	Symbol	Part number	Specification
1	PV module	PV	BP275F	75 W
2	MOSFET switch	S	IRF540N	100 V, 33A, $R_{DS(ON)}$ = 44 mΩ
3	MOSFET driver	-	HCPL-3140	0.4 A_P, V_S =15 V
4	Microcontroller	-	PIC16F877A	10-bit, 8-channel A/D
5	Current sensor	-	INA138	$V_{S(min)}$ = 2.7 V, I_q = 25 µA
6	Battery	Bat	NP7-12	12 V, 7 Ah
7	Power inductor	L	Customed	50 uH
8	Fast recovery diode	D_m	MUR 860	600 V, 8 A
9	Output capacitor	C	-	220 uF
10	Resistive load	R	-	4 Ω

3. RESULTS AND DISCUSSION

This study has implemented an improved P&O MPPT technique, as illustrated in Figure 5. This algorithm is embedded in the main controller to generate a proportional duty cycle for the buck DC-DC converter. Once the corresponding value of the duty cycle is properly determined, two reciprocal PWM signals will be generated to turn on two power MOSFETs (low-side and high-side MOSFET switches) simultaneously without causing the main power circuit to be exposed to short circuits. To optimize the effectiveness of the proposed P&O MPPT technique, the sampling period, T_a is set to 10 ms, while the perturbation size (ΔD) is 0.01. Using a small sampling period helps minimize the number and amplitude of oscillations near the MPP, especially in a steady-state condition, thereby minimizing power losses.

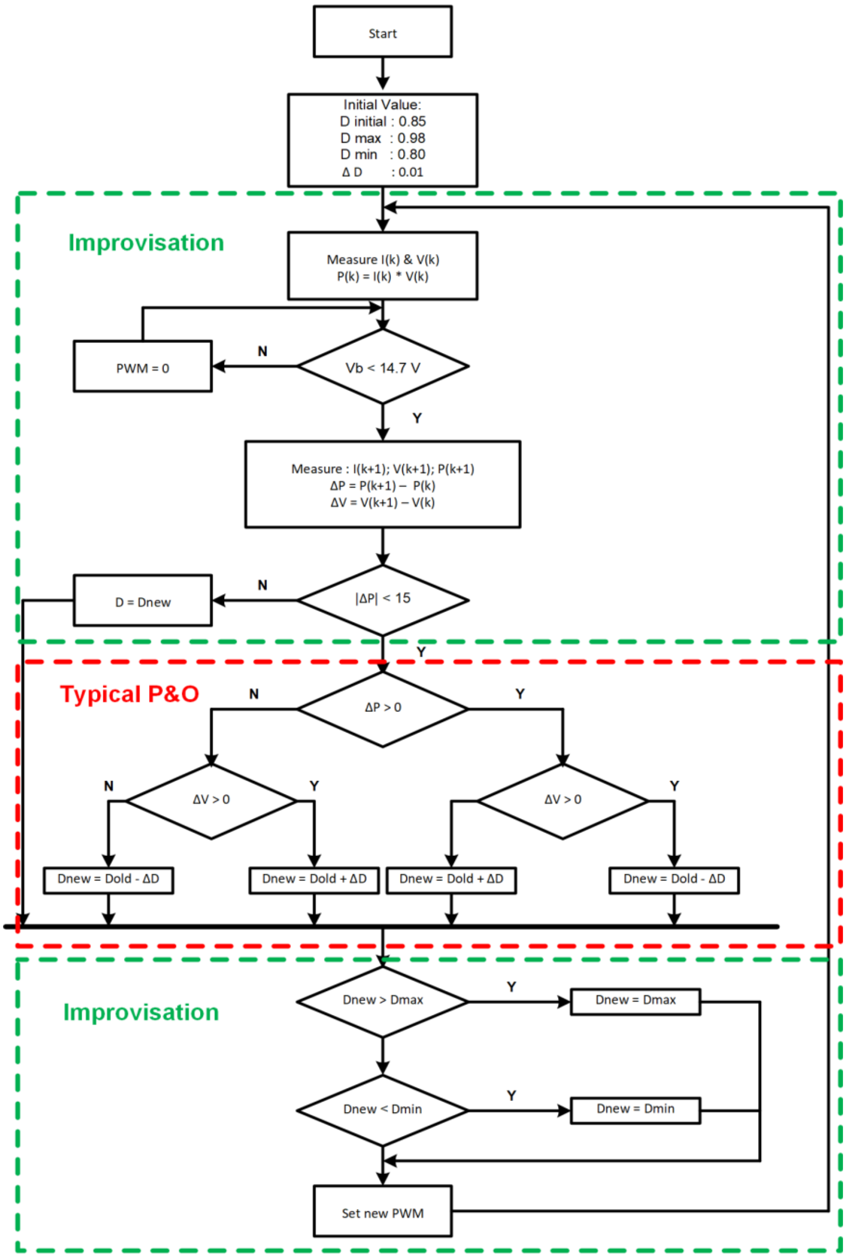


Figure 5. An improved P&O MPPT technique

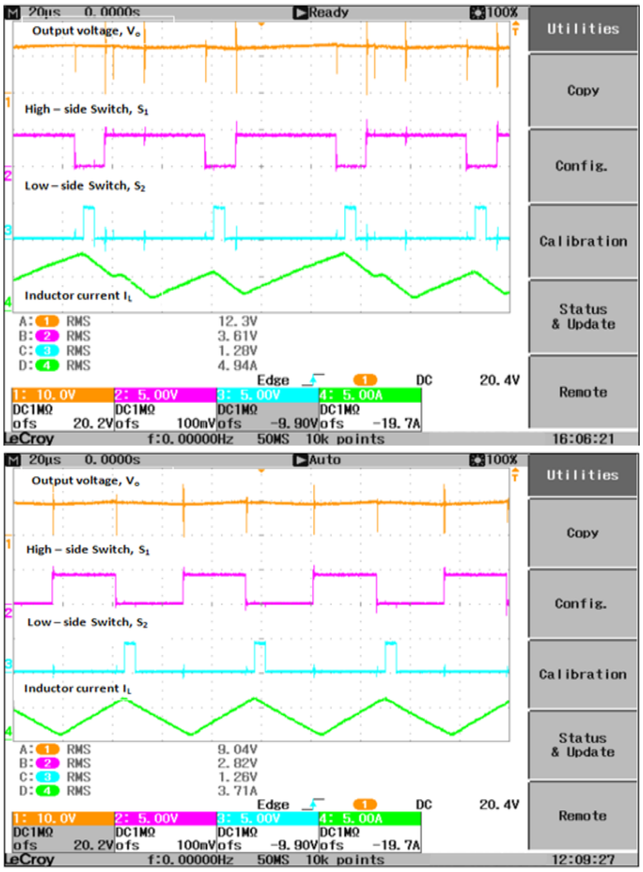
Figures 6(a) and 6(b) illustrate the experimental configuration of the PV system designed for charging batteries, including the complete circuit layout. The developed prototype of the NSB DC-DC converter was tested and its performance assessed by adjusting the duty cycle, D, across a range of 0.1 to 0.9. The primary analysis parameters for evaluating the overall performance of this proposed system were the average efficiency and the correlation between duty cycle values and the maximum power output of the

PV module. Furthermore, to validate the efficacy of the proposed dead-time control method, two comparable autonomous PV systems were constructed, one incorporating an MPPT control algorithm and the other without.

The generated output waveforms of the selected DC converter, with input voltages of V_i = 20 V, duty cycle D = 0.5, R = 4 Ω, and V_i = 20 V, D = 0.8, R = 4 Ω, are displayed in both Figure 7(a) and Figure 7(b) respectively. Referring to both mentioned figures, the first waveform (orange color) represents the output voltage, V_o, of the NSB DC-DC converter, the second waveform (purple color) displays the PWM signal for the high-side driver, and the third waveform represents the PWM signal for the low-side MOSFET driver. Finally, the fourth waveform corresponds to the inductor current, I_L.

(a) (b)

Figure 6. Experimental setup of the proposed stand-alone PV system: (a) laboratory and (b) hardware validation setup



(a)

(b)

Figure 7. Generated output waveforms of the NSB DC-DC converter: (a) D = 0.5 and (b) D = 0.8

A dead-time control interval is inserted into the MOSFET switching waveform to avoid a short-circuit situation. A 3 µs dead time is introduced after the high-side switching waveform of S1 turns off and on, as illustrated in Figure 8. This 3 µs dead time duration is longer than the critical delay time (t_d), the rise time (t_r), as well as the fall time (t_f) of the selected MOSFETs, ensuring that short-circuiting between the two power switches during simultaneous conduction is well avoided. Meanwhile, as illustrated in Figure 9, the efficiency of the NSB DC-DC converter is assessed in relation to the duty cycle values, showing the hardware prototype can achieve a peak efficiency of 80%, compared to the simulation model's efficiency of 96%.

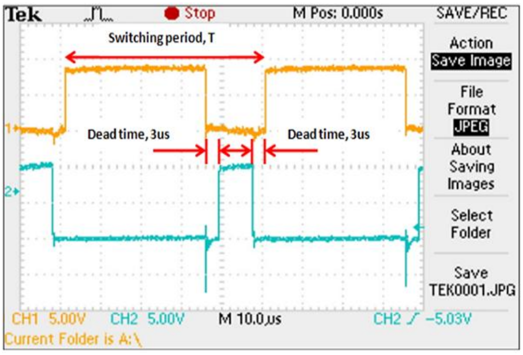


Figure 8. The period of dead time control applies to both the drivers of the high-side and low-side MOSFETs

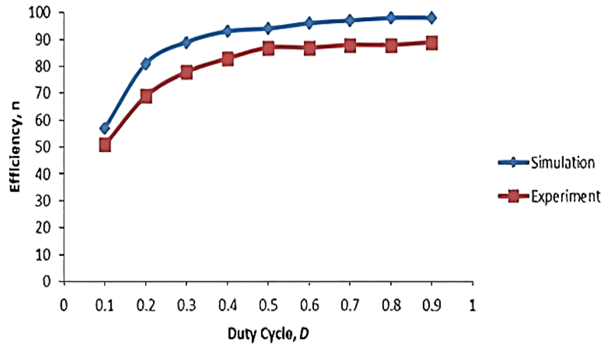


Figure 9. DC-DC buck converter efficiency versus the duty cycle values, D

As shown in Figure 10, the proposed system could achieve a maximum efficiency of 80% across different output power values (P_o). Several factors may affect the proposed hardware system's efficiency. One major cause of efficiency loss in this proposed NSB DC-DC converter is the power dissipation in both power switch MOSFETs. In addition, the forward voltage drops across each connected diode used in the hardware prototypes may also contribute to the overall degradation of system efficiency. Nevertheless, the implementation of the dead-time control method is effective with the proposed NSB DC-DC converter's architecture, preventing any short circuits during operation.

To further validate the proposed system's efficacy under actual operating conditions, an experimental setup of a standalone PV system was constructed both with and without an MPPT controller, as depicted in Figure 6(b). Both configurations utilized identical setup parameters, including the PV module model and battery capacity, and were operated for a minimum of 20 minutes. The PV cell temperature remained largely stable throughout the experimental run. As shown in Figure 11, the PV output power exhibits some deviation from ideal irradiation levels due to various influencing factors such as temperature variations, partial shading, MPPT response times, and sensor limitations. However, the standalone PV system incorporating the enhanced P&O MPPT technique operated seamlessly and demonstrated a 13% increase in maximum PV output power compared to the system without MPPT implementation, achieving an overall system efficiency of 80%.

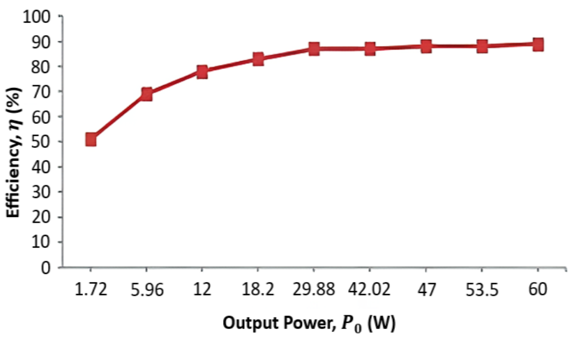


Figure 10. The relationship between system efficiency (η) and output power (P_o)

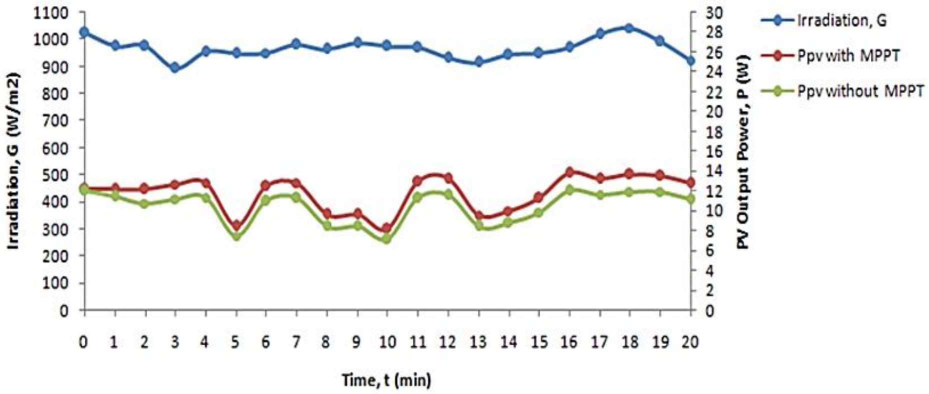


Figure 11. The variance in PV power output in relation to irradiation level

4. CONCLUSION

This study designs and develops an improved P&O MPPT technique for stand-alone PV systems. The NSB DC-DC converter is implemented to transfer the DC power from PV modules to battery storage, ensuring the system operates with simplicity, high efficiency, and stable dynamic behavior. The results demonstrate that by incorporating the appropriate value of dead-time control waveform in the hardware prototype using a bootstrap technique, the proposed system achieves a peak efficiency of 80% with the rated output power of 60 W. The findings can be extended to other DC-DC converter topologies, tailored to the specific needs of PV systems and their load demand. Furthermore, the proposed system architecture can be adapted for integrated smart-grid applications, where the main controller simultaneously manages the MPPT regulator and multiple renewable energy sources.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration. All authors have contributed to the study conception and design.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

DATA AVAILABILITY

Data availability does not apply to this paper.

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