A Unified P&O MPPT Strategy for a Single Buck Converter in Small-Scale VAWT–PV Hybrid Energy Systems

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Received: May 28, 2026; **Revised:** Jun 19, 2026; **Accepted:** Aug 24, 2026

Abstract

This paper presents a unified Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) strategy for a small-scale hybrid renewable energy system integrating a vertical-axis wind turbine (VAWT) and a photovoltaic (PV) source through a single buck converter. Unlike conventional approaches employing separate MPPT controllers for individual renewable energy sources, the proposed Unified P&O MPPT strategy uses the total harvested power of the PV–VAWT system as the optimization variable and generates a single duty-ratio command for the buck converter. The proposed control scheme is developed and evaluated using MATLAB/Simulink and experimentally validated using a dSPACE-based control and measurement platform. Simulation results demonstrate the generation of the individual PV and wind power responses, the combined total harvested power, and the corresponding duty-ratio control for 12V battery charging. Experimental results further verify the practical operation of the proposed controller, including the generation of the PWM control signal, buck-converter operation, and battery charging. In addition, source-combination tests demonstrate successful transitions from PV-only to hybrid PV–VAWT operation and from VAWT-only to hybrid VAWT–PV operation while maintaining continuous power-conversion operation. The results demonstrate that the proposed Unified P&O MPPT strategy provides a simple and practical control approach for coordinated power extraction from small-scale PV and VAWT sources using a single power-conversion stage.

Keywords: Hybrid PV-Wind System, Unified MPPT, Energy Management

1. Introduction

The increasing global demand for energy, environmental concerns, and the depletion of fossil-fuel resources have accelerated the development of renewable energy technologies. Photovoltaic (PV) and wind power have become widely adopted renewable energy sources because of their clean energy generation, sustainability, and decreasing technology costs [1]. In recent years, hybrid renewable energy systems have attracted considerable attention because the integration of complementary energy sources can improve energy availability and reduce the effects of the intermittent nature of individual renewable sources [2]. Such systems are particularly attractive for small-scale, decentralized, and off-grid applications.

Among wind energy technologies, vertical-axis wind turbines (VAWTs) offer several advantages over horizontal-axis wind turbines (HAWTs), including the capability to accept wind from different directions, relatively low acoustic emissions, and suitability for operation in turbulent and low-speed wind environments [3]. These characteristics make VAWTs attractive for small-scale and distributed renewable energy applications. Recent studies have also indicated the potential of compact VAWT configurations for rooftop and community-scale installations [4]. In parallel, PV systems provide a complementary daytime energy source and are widely adopted because of their modular structure, scalability, and relatively low maintenance requirements [5].

Despite these advantages, both PV and wind energy systems exhibit nonlinear power characteristics and are strongly affected by environmental conditions, particularly solar irradiance and wind speed. Consequently, the available power from each source can vary continuously, making appropriate power control essential for effective energy extraction [6]. Maximum Power Point Tracking (MPPT) techniques are therefore commonly employed to maintain the operating point of renewable energy sources near their maximum power regions. Several MPPT techniques have been reported, including Perturb and Observe (P&O), Incremental Conductance (INC), fuzzy-logic-based methods, and artificial-intelligence-based approaches [7]. Recent studies reported during 2024–2025 have investigated advanced MPPT techniques to improve transient response and reduce steady-state oscillations, while conventional methods remain attractive for applications requiring simple implementation and low computational requirements [8],[9].

Among the various MPPT techniques, the P&O method remains widely used because of its simple control structure, low computational requirements, and suitability for real-time embedded implementation [10]. However, conventional P&O control inherently produces oscillations around the maximum power point and may experience reduced tracking performance during rapid changes in operating conditions [11]. To address these limitations, modified and hybrid MPPT methods incorporating adaptive step

sizes, optimization techniques, or intelligent control strategies have been proposed [12]. Although such approaches can provide improved tracking characteristics, their implementation may require additional computational resources, sensing elements, or more sophisticated digital controllers.

In hybrid PV–wind systems, the simultaneous integration of multiple renewable energy sources introduces an additional control challenge. Independent MPPT controllers can be employed for each energy source; however, this approach requires multiple control loops and may increase the number of control variables, sensing requirements, and overall system complexity [13]. To simplify the control structure, unified MPPT approaches have been investigated, in which a common control strategy is employed to track the maximum power points of multiple renewable energy sources within a hybrid system [14]. Synergetic control methods have also been investigated to improve MPPT performance and maintain power balance in hybrid PV–wind systems under varying environmental and load conditions [15]. In addition, artificial-intelligence-based MPPT techniques have demonstrated potential for improving power extraction in photovoltaic systems, although they generally require greater computational resources and implementation costs than conventional MPPT methods [16].

Therefore, this paper proposes a Unified Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) strategy for a small-scale hybrid PV–VAWT system using a single buck converter. Unlike conventional configurations employing separate MPPT controllers for individual renewable energy sources, the proposed strategy uses the total harvested power of the PV–VAWT system as the optimization variable and generates a single duty-ratio command for the buck converter. The proposed approach provides a simplified single-loop control structure for coordinated power extraction from both renewable energy sources. The performance of the proposed strategy is investigated using MATLAB/Simulink and experimentally validated using a dSPACE-based control and measurement platform under different source operating conditions.

2. Proposed Unified P&O MPPT Strategy

The proposed Unified Perturb and Observe (P&O) maximum power point tracking (MPPT) strategy is developed for the hybrid photovoltaic (PV)–wind energy conversion system. The proposed strategy employs a single MPPT controller and a common buck converter to regulate the operating point of the hybrid energy sources. Unlike conventional hybrid renewable energy systems that employ independent MPPT controllers for individual energy sources, the proposed approach uses a single duty ratio as the control variable and the total harvested power of the hybrid system as the optimization objective. This configuration provides a simplified control structure while enabling the operating point of the hybrid system to be continuously adjusted according to variations in the available PV and wind power.

At each sampling instant k, the controller measures the voltage and current of the PV and wind energy sources, denoted by V_{PV}, I_{PV}, V_{wind} and I_{wind}, respectively. The instantaneous power generated by the PV source is calculated as Eq. (1).

$$P_{PV}(k) = V_{PV}(k)I_{PV}(k) \tag{1}$$

While the electrical power generated by the wind energy source is calculated as Eq. (2).

$$P_{wind}(k) = V_{wind}(k)I_{wind}(k) \tag{2}$$

The total harvested power from the hybrid PV–wind system is subsequently determined by Eq. (3).

$$P_{total}(k) = P_{PV}(k) + P_{wind}(k) \tag{3}$$

The total power P_{total} is used as the objective variable of the proposed Unified P&O MPPT controller. Therefore, the controller evaluates the combined contribution of both energy sources rather than independently optimizing the operating point of each source. This approach is consistent with the proposed single-converter architecture, in which the duty ratio of the common buck converter is used as the single control variable.

Unlike conventional P&O algorithms that directly perturb the operating voltage of a PV source, the proposed controller perturbs the duty ratio of the common buck converter. Therefore, the perturbation direction is determined from the change in duty ratio rather than directly from the change in source voltage. The change in the total harvested power between two consecutive sampling instants is defined as Eq. (4).

$$\Delta P = P_{total}(k) - P_{total}(k-1) \tag{4}$$

A positive value of ΔP indicates that the previous perturbation increased the total harvested power, whereas a negative value indicates that the previous perturbation reduced the total harvested power.

Since the duty ratio is used as the perturbation variable, the direction of the previous perturbation is determined from the change in duty ratio. In the implemented discrete-time controller, this change is expressed as Eq. (5).

$$\Delta D = D(k-1) - D(k-2) \tag{5}$$

where, $D(k-1)$ and $D(k-2)$ represent the duty ratios applied during the previous and preceding sampling intervals, respectively. Thus, $\Delta D > 0$ indicates that the previous perturbation increased the duty ratio, whereas $\Delta D < 0$ indicates that the previous perturbation decreased the duty ratio.

The proposed Unified P&O decision mechanism considers both ΔP and ΔD to determine the subsequent duty-ratio perturbation. When the previous perturbation results in an increase in the total harvested power, the controller continues the perturbation in the same direction. Conversely, when the total harvested power decreases, the perturbation direction is reversed. Accordingly, when $\Delta P > 0$ and $\Delta D > 0$, the duty ratio is increased because increasing the duty ratio has resulted in an increase in total power. When $\Delta P > 0$ and $\Delta D < 0$, the duty ratio is decreased because the previous decrease in duty ratio resulted in an increase in total power.

When $\Delta P < 0$, the perturbation direction is reversed. Therefore, if $\Delta P < 0$ and $\Delta D > 0$, the duty ratio is decreased. Conversely, if $\Delta P < 0$ and $\Delta D < 0$, the duty ratio is increased. The resulting duty-ratio update can be expressed as Eq. (6).

$$D(k) = \begin{cases} D(k-1) + \Delta D_{step}, \Delta P > 0, \Delta D > 0 \\ D(k-1) - \Delta D_{step}, \Delta P > 0, \Delta D < 0 \\ D(k-1) - \Delta D_{step}, \Delta P < 0, \Delta D > 0 \\ D(k-1) + \Delta D_{step}, \Delta P < 0, \Delta D < 0 \end{cases} \quad (6)$$

This decision mechanism ensures that the perturbation direction is not determined solely by the sign of ΔP. Instead, the controller considers the relationship between the change in total power and the direction of the previous duty-ratio perturbation. In other words, when the power variation and duty-ratio perturbation have the same sign, the perturbation is continued in the same direction. When their signs are different, the perturbation direction is reversed. In the proposed implementation, the duty-ratio perturbation step is set to $\Delta D_{step} = 0.002$. To prevent the converter from operating outside the predefined duty-ratio range, the duty ratio is constrained according to Eq. (7).

$$0.05 \leq D(k) \leq 0.95 \quad (7)$$

After the duty ratio is calculated and limited, it is applied to the PWM generator to control the IGBT switch of the common buck converter. The measured voltage and current values of the PV and wind sources are then stored as previous values for use in the subsequent sampling interval. Accordingly, the previous total power used by the controller is calculated from the stored measurements as Eq. (8).

$$P_{old} = V_{PV,old} I_{PV,old} + V_{wind,old} I_{wind,old} \quad (8)$$

The previous duty-ratio values are also stored to determine the direction of the subsequent perturbation according to Eq. (5).

The complete operating sequence of the proposed Unified P&O MPPT algorithm is illustrated in **Figure 1**. Initially, the controller measures V_{PV}, I_{PV}, V_{wind} and I_{wind}. The instantaneous PV and wind powers are then calculated using Eq. (1) and Eq. (2), respectively, and the total harvested power is obtained from Eq. (3). The current total power is compared with the previously stored power to determine ΔP. At the same time, the previous duty-ratio perturbation is determined from ΔD. The controller subsequently determines whether the duty ratio should be increased or decreased according to the decision rules given in Eq. (6). After the duty ratio has been updated, the duty-cycle limitation in Eq. (7) is applied. The resulting duty ratio is then used to generate the PWM signal for the IGBT of the buck converter. Finally, the present PV and wind voltage and current measurements and the duty ratio are stored as previous values for the next sampling interval. This process is continuously repeated to regulate the operating point of the hybrid PV–wind system. At initialization, the duty ratio is set to $D = 0.5$. Consequently, the initial value of ΔD is zero, and the first duty-ratio update follows the decreasing-duty direction in the implemented controller. After the first perturbation, the value of ΔD is determined from the actual duty-ratio changes, and the subsequent perturbation direction is governed by the proposed P&O decision mechanism.

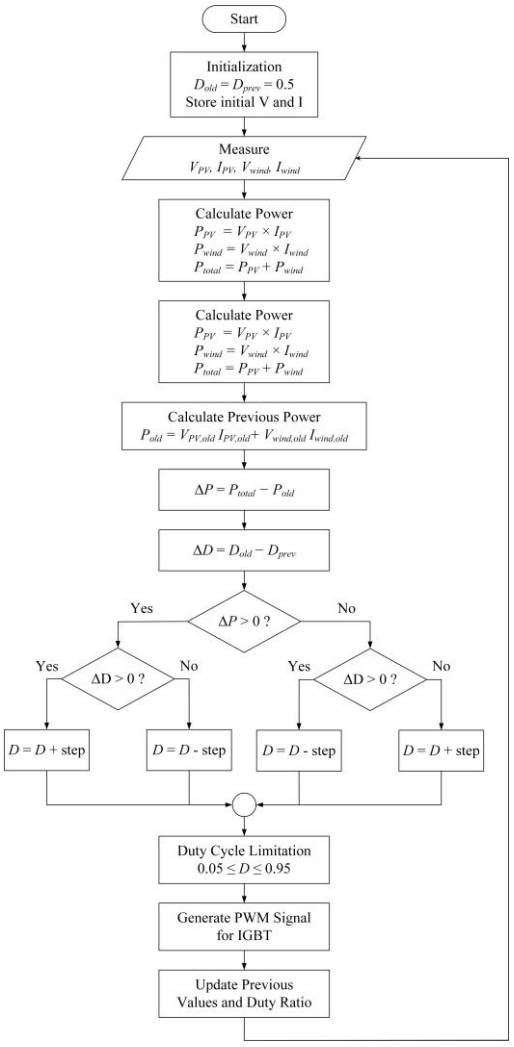


Figure 1 Flowchart of the proposed Unified P&O MPPT algorithm

The proposed Unified P&O MPPT strategy therefore provides a simple control structure based on a single duty-ratio control variable and the total harvested power of the hybrid PV–wind system. By combining the PV and wind power measurements into a single optimization variable, the proposed controller avoids the need for separate MPPT decision loops for each energy source. The effectiveness of the proposed strategy under different PV and wind operating conditions is evaluated through the simulation and experimental results presented in the following sections.

3. Buck Converter

The buck converter is a fundamental DC–DC power electronic converter used to reduce the input voltage to a lower output voltage while providing controlled power transfer. In renewable energy systems, the buck converter can serve as an interface between renewable energy sources and energy storage systems, particularly when the generated source voltage is higher than the required battery voltage. In the proposed hybrid PV–VAWT system, a single buck converter is employed as the common power-conversion stage for both renewable energy sources [11],[17].

3.1 Operating Principle

The buck converter functions through high-frequency operation of a semiconductor switching element, commonly a MOSFET, together with a diode (or synchronous switch), an inductor L, and a capacitor C.

The switching operation alternates between two states:

1. Switch ON state:
   The source voltage V_{in} is supplied to the inductor, resulting in a linear rise of inductor current while magnetic energy is accumulated within the inductor field.
2. Switch OFF state:
   The stored magnetic energy in the inductor is transferred to the load through the diode, thereby sustaining continuous current flow. Assuming ideal devices and continuous conduction mode (CCM), the relation between the input and output voltages can be expressed as Eq. (9).

$$V_{out} = D \cdot V_{in} \tag{9}$$

where, D represents the switching duty ratio. This expression indicates that the output voltage is regulated by varying the duty cycle, which makes the buck converter appropriate for MPPT applications [18].

3.2 Inductor and Capacitor Design

To ensure stable operation and low ripple, proper selection of the inductor and capacitor is essential. The inductance value is selected to guarantee operation in continuous conduction mode (CCM), as given by Eq. (10):

$$L = \frac{(V_{in} - V_{out})D}{\Delta I_L f_s} \tag{10}$$

where, ΔI_L denotes the ripple current of the inductor, while f_s represents the switching frequency. In addition, the output capacitor is chosen to reduce voltage ripple, as given by Eq. (11):

$$C = \frac{\Delta I_L}{8 f_s \Delta V_{out}} \tag{11}$$

where, ΔV_{out} is the allowable output voltage ripple. In this study, the switching frequency is selected at 25 kHz to balance efficiency and switching losses, while ensuring a compact passive component size suitable for small-scale applications.

4. Proposed Control Scheme

The proposed control scheme integrates the PV and wind energy sources using a single Unified P&O MPPT controller. The controller measures the PV voltage and current (V_{PV}, I_{PV}) and the wind-generator voltage and current (V_{wind}, I_{wind}), and calculates the corresponding individual powers and total harvested power. The total power is then used as the optimization variable of the proposed MPPT algorithm to determine the appropriate duty ratio for the common buck converter.

Unlike conventional hybrid renewable energy systems that employ separate MPPT controllers for individual energy sources, the proposed approach uses a single control loop based on one duty-ratio control variable and the total harvested power of the hybrid PV–wind system. The control process consists of the following steps:

1. Measurement of the PV and wind voltages and currents.
2. Calculation of the PV power, wind power, and total harvested power.
3. Evaluation of the power variation ΔP and duty-ratio variation ΔD for the Unified P&O decision process.
4. Adjustment of the duty ratio according to the P&O decision.
5. Generation of the PWM signal for controlling the IGBT of the buck converter.

As shown in **Figure 2**, the proposed configuration was developed to investigate a hybrid renewable energy generation system combining a small-scale vertical-axis wind turbine (VAWT) and a photovoltaic (PV) generation unit. The PV and wind sources are interfaced with the common DC bus through their respective rectification stages. The generated electrical power is subsequently supplied to the buck-type DC–DC converter [19–21], which regulates the DC voltage for charging the 12V battery storage system. The buck converter provides the power-conversion interface between the hybrid DC source and the battery while allowing the operating point of the hybrid sources to be controlled through the duty ratio.

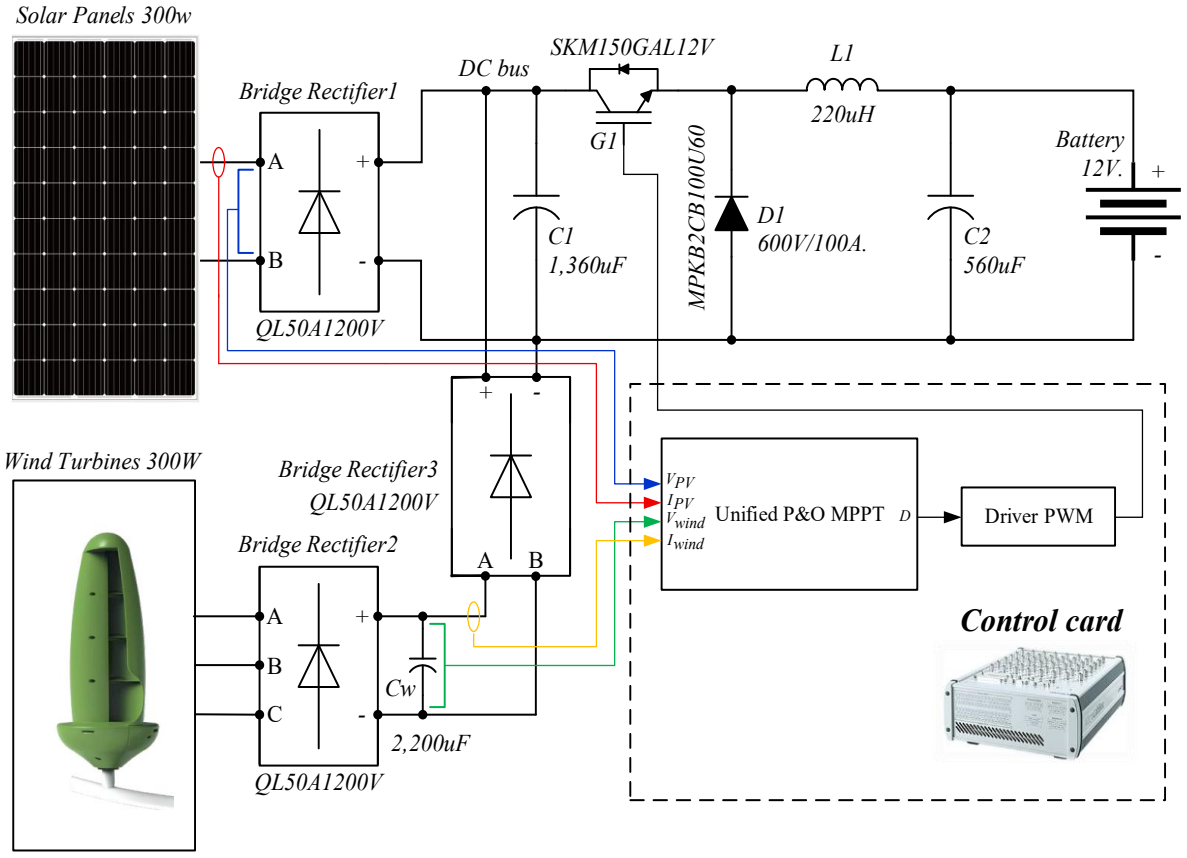


Figure 2 Proposed control and power-conversion structure of the hybrid PV–VAWT system

The proposed Unified P&O MPPT controller receives the measured voltage and current signals from both energy sources and calculates the total harvested power according to Eq. (12).

$$P_{total} = P_{PV} + P_{wind} \tag{12}$$

The resulting duty ratio D is provided to the PWM generator, which produces the switching signal for the IGBT. By continuously adjusting the duty ratio based on the variation in total harvested power, the proposed controller seeks to maintain the hybrid PV–wind system near its maximum power operating region under changing solar irradiance and wind-speed conditions.

The overall system consists of four main components:

1. Hybrid renewable energy sources: PV array and small-scale VAWT.
2. Power-conversion stage: rectification stages and a buck-type DC–DC converter.
3. Unified P&O MPPT control system: measurement, power calculation, MPPT decision logic, and PWM generation.
4. Energy storage system: 12V battery.

The complete performance of the proposed control scheme under different operating conditions is evaluated through simulation and experimental validation, as presented in Section 5.

5. Simulation and Experimental Validation

The proposed Unified P&O MPPT strategy was evaluated through MATLAB/Simulink simulations and experimental hardware testing. The simulation study was conducted to investigate the dynamic responses of the hybrid PV–VAWT system under variations in solar irradiance and wind operating conditions. The experimental investigation was subsequently performed to verify the practical operation of the proposed control scheme, including the MPPT controller, PWM generation, buck converter, and battery charging process. The obtained results are presented in terms of source voltage and current responses, duty-ratio behavior, DC-bus and converter responses, and battery charging characteristics.

5.1 Simulation Results

To evaluate the effectiveness and applicability of the proposed Unified P&O MPPT strategy for the hybrid small-scale vertical-axis wind turbine (VAWT) and photovoltaic (PV) system, system-level simulations were conducted using MATLAB/Simulink with the SimPowerSystems toolbox [22]. As shown in **Figure 3**, the simulation model consists of the PV generation unit, wind energy conversion unit,

rectification stages, DC-link capacitor, buck converter, battery storage unit, and the proposed Unified P&O MPPT controller, as described in the preceding sections. The detailed electrical specifications and component parameters of the proposed hybrid PV–VAWT system used for both simulation and experimental validation are summarized in **Table 1**, including the 300 W PV panel, 300 W VAWT, DC–DC buck converter passive components (L_1, C_1, C_2 and C_w), switching frequency of 25 kHz, and simulation sampling time of 0.4 μs. These subsystems were integrated into a complete hybrid PV–VAWT system to investigate its operating characteristics under varying renewable energy conditions.

The simulation study focused on the electrical responses of the PV and wind sources, the operation of the proposed Unified P&O MPPT controller, the duty-ratio response, and the voltage and current characteristics of the DC–DC buck converter and battery storage system. In particular, the proposed controller determines the duty ratio based on the variation in the total harvested power obtained from the PV and wind sources. The simulation scenarios were established by varying the available solar irradiance and wind operating conditions to examine the ability of the proposed controller to track the appropriate operating point under changing input conditions.

The simulation results are presented in terms of the source voltage and current responses, generated power, duty-ratio behavior, DC-bus voltage, buck-converter output characteristics, and battery charging response. These results are used to verify the functional operation of the proposed Unified P&O MPPT strategy and its integration with the buck converter and battery storage system. The simulation results also provide the basis for subsequent experimental validation of the proposed control scheme.

Figure 4 illustrates the simulated voltage waveforms of the vertical-axis wind turbine (VAWT), including the three-phase line-to-line AC voltages (V_{a-b}, V_{b-c} and V_{c-a}) and the rectified DC output voltage (V_{wind}). As seen in the waveform, the wind turbine begins generating electrical power at t = 1s. Following a brief initial transient, the rectified DC output voltage (V_{wind}) stabilizes at a steady-state value of approximately 38 V.

Figure 5 presents the simulated voltage and current responses of the photovoltaic (PV) system, denoted by V_{PV} and I_{PV}, respectively, under varying solar irradiance conditions. The solar irradiance is maintained at 800 W/m² during the initial 0–2 s interval and is reduced to 500 W/m² from 2 to 3 s. The reduction in solar irradiance results in a decrease in the PV current I_{PV} at approximately 2 s, accompanied by a small transient variation in the PV voltage V_{PV} during the transition. Since **Figures 5–6** represent the same simulation time interval, their dynamic responses can be considered together to characterize the operating conditions of the two renewable energy sources. **Figure 6** presents the simulated voltage and current responses of the vertical-axis wind turbine (VAWT), denoted by V_{wind} and I_{wind}, respectively. The results show that the VAWT begins generating electrical power at approximately 1 s when the rotor speed reaches 300 rpm. **Figures 7–8** present the simulated power responses of the individual renewable energy sources and their combined total power, respectively. **Figure 7** shows the PV power P_{PV} and wind power P_{wind} obtained from the corresponding voltage and current measurements. The PV power changes in response to the variation in solar irradiance, while the wind power becomes available after the VAWT reaches its operating condition. **Figure 8** presents the total harvested power P_{total} of the hybrid system, which is calculated from the PV and wind power contributions according to Eq. (12). The resulting P_{total} represents the combined power available from the two renewable energy sources and is used as the optimization variable of the proposed Unified P&O MPPT controller. Therefore, variations in P_{totol} provide the basis for determining the power change ΔP and subsequently updating the duty ratio according to the proposed MPPT algorithm. The voltage and current signals obtained from the PV and VAWT sources are subsequently supplied to the proposed Unified P&O MPPT controller, as shown in **Figure 9.** The controller uses these input signals to calculate the individual source powers and the total harvested power, which is then used to determine the appropriate duty ratio for the buck converter.

Following the operation of the proposed Unified P&O MPPT controller, the resulting duty-ratio command shown in **Figures 10–11** are used to generate the PWM switching signal for controlling the IGBT of the buck converter. The duty ratio is continuously adjusted according to the variation in the total harvested power from the PV and VAWT sources, thereby regulating the operating point of the hybrid system. **Figure 12** presents the simulated DC-bus voltage (V_{DCbus}) and the input current (I_{in}) of the buck converter, representing the combined electrical power supplied by the PV and VAWT sources. **Figure 13** illustrates the simulated output voltage (V_{out}) and inductor current (I_L) of the buck converter. The results show that the converter output voltage is regulated at a level suitable for charging the 12V battery, while the inductor current follows the corresponding power-conversion conditions**.** **Figure 14** presents the simulated battery voltage (V_{Batt}) and charging current (I_{Batt}) during buck-converter operation. **Figure 15** further shows the battery charging current when the buck converter is inactive, where the charging current decreases to approximately zero. These simulation results verify the functional operation of the proposed Unified P&O MPPT controller together with the buck converter and battery storage system under the investigated operating conditions.

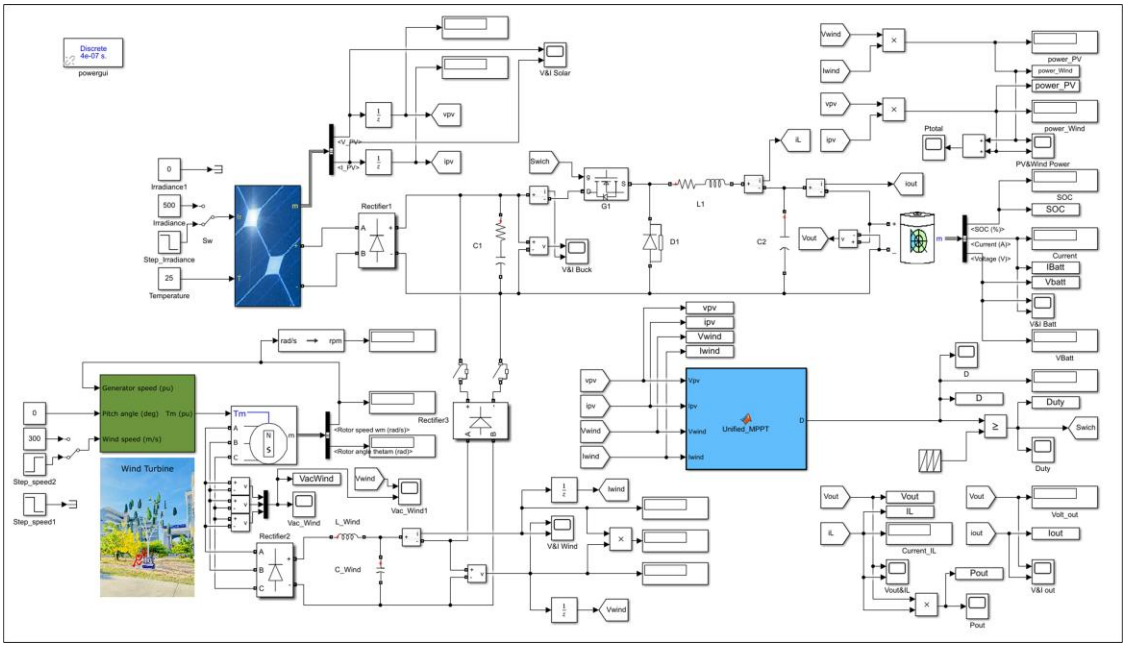


Figure 3 MATLAB/Simulink simulation block diagram

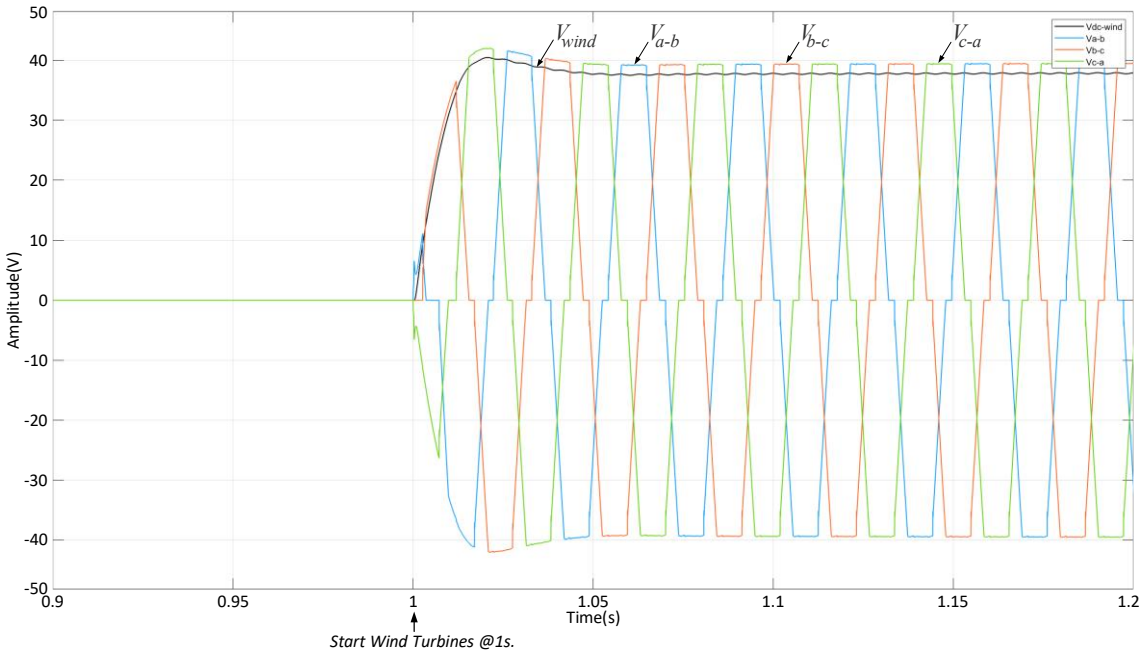


Figure 4 Simulation of the Voltage Waveform of a Vertical Axis Wind Turbine (VAWT)

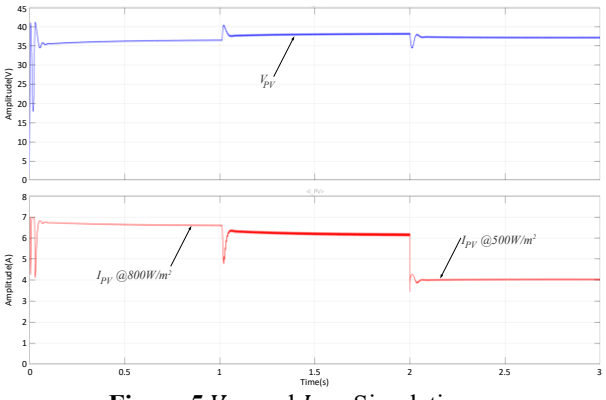


Figure 5 V_{PV} and I_{PV} : Simulation

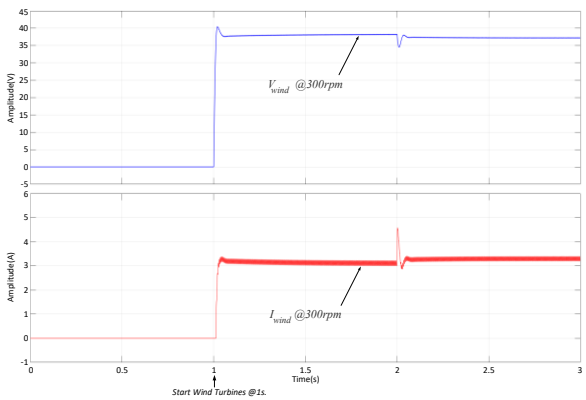


Figure 6 V_{wind} and I_{wind} : Simulation

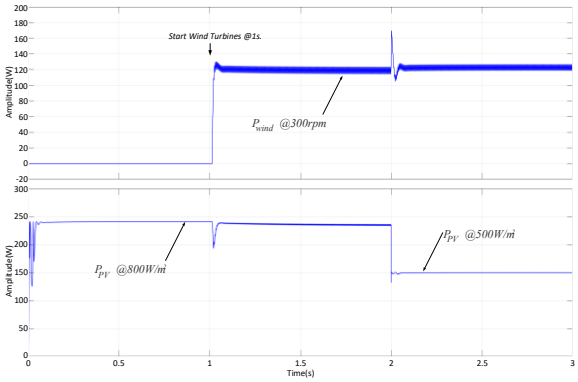


Figure 7 P_{PV} and P_{wind} : Simulation

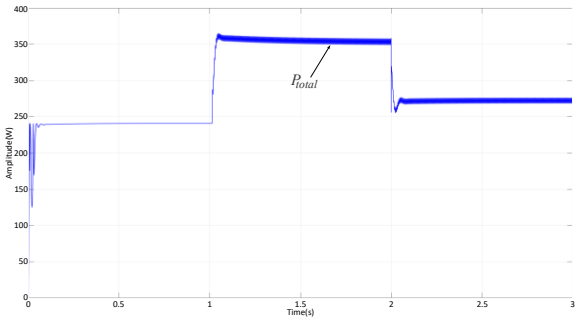


Figure 8 P_{total} : Simulation

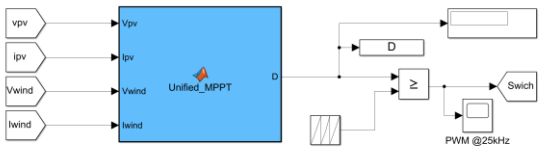


Figure 9 Block diagram of the proposed Unified P&O MPPT controller

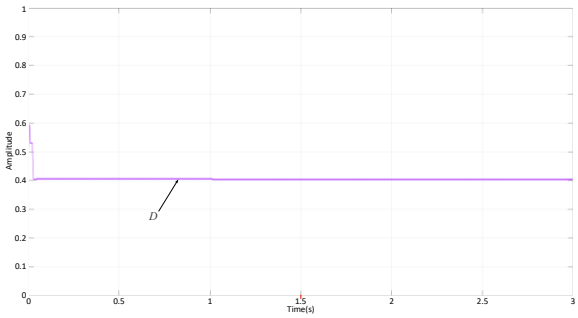


Figure 10 Duty-ratio response

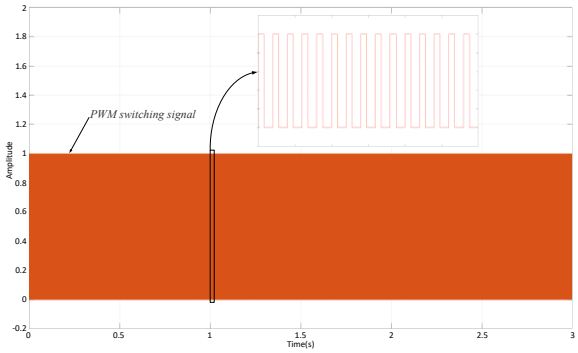


Figure 11 PWM switching signal at a switching frequency of 25 kHz

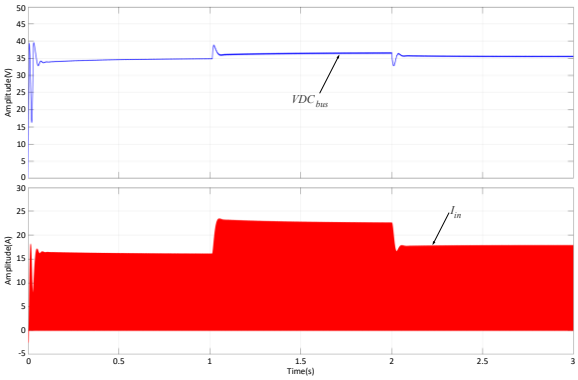


Figure 12 VDC_{bus} and I_{in}

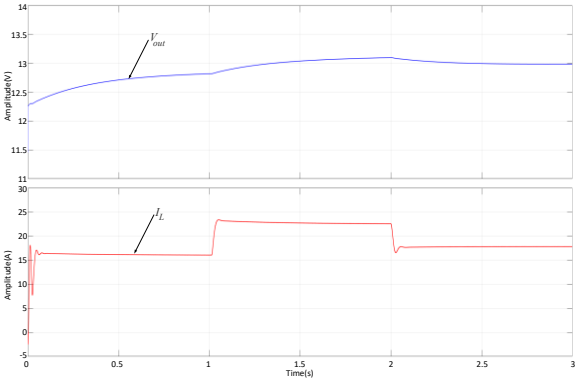


Figure 13 V_{out} and I_L

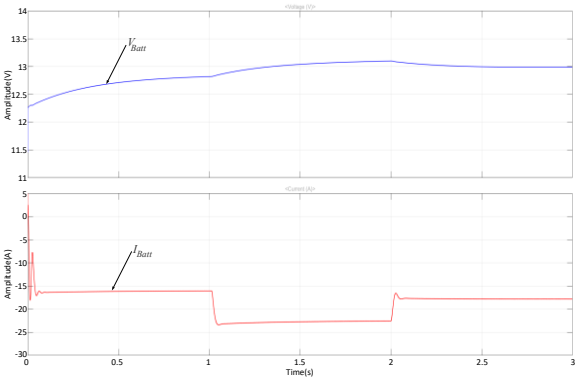


Figure 14 V_{batt} and I_{batt} :Operation

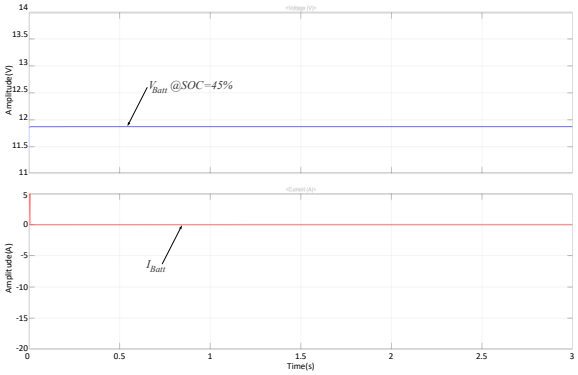


Figure 15 V_{batt} and I_{batt} : Non-operational

5.2 Experimental Results

The experimental investigation was conducted to validate the practical operation of the proposed Unified P&O MPPT controller and its integration with the hybrid small-scale vertical-axis wind turbine (VAWT) and photovoltaic (PV) system. The experimental setup consists of the VAWT and PV generation units, power conversion circuits, voltage and current measurement circuits, the proposed MPPT controller, a buck converter, and a 12V battery storage unit. The experimental tests were performed under practical operating conditions to verify the electrical characteristics of the renewable energy sources, the generation of the control signals, the operation of the buck converter, and the battery charging process. The experimental results are presented in terms of the source voltage and current responses, power-conversion operation, control-signal generation, and battery charging characteristics.

Figure 16 illustrates the experimental operation of the vertical-axis wind turbine (VAWT) at a rotational speed of 312 rpm. The VAWT drives a permanent magnet synchronous generator (PMSG), producing three-phase AC voltage waveforms, denoted by V_{a-b}, V_{b-c} and V_{c-a}. The generated three-phase AC voltage is subsequently converted into DC voltage through Bridge Rectifier 2. A filter capacitor C_w with a capacitance of 2,200 µF is connected at the rectifier output to reduce the DC-voltage ripple before the generated power is supplied to the DC bus. The experimental results confirm the electrical power generation of the VAWT–PMSG unit and provide the required DC-side input for integration with the proposed hybrid power conversion system.

Figure 17 presents the measured voltage and current waveforms of the vertical-axis wind turbine (VAWT) system, denoted by V_{wind} and I_{wind}, respectively, at a rotor speed of 312 rpm. **Figure 18** shows the measured voltage and current responses of the photovoltaic (PV) system, denoted by V_{PV} and I_{PV}, respectively, under a solar irradiance of approximately 700 W/m². The voltage and current signals from both renewable energy sources are acquired using dedicated voltage and current sensing circuits and are subsequently provided to the Analog-to-Digital Converter (ADC) channels of the dSPACE interface for real-time data acquisition and control processing. The acquired signals are used by the proposed Unified P&O MPPT controller to calculate the power generated by each source and determine the appropriate duty ratio for the buck converter.

Figures 19–20 present the experimentally obtained power responses of the PV and VAWT sources and their combined total power, respectively. **Figure 19** shows the PV power P_{PV} and wind power P_{wind} calculated from the measured voltage and current signals. The VAWT operates at a rotor speed of 312 rpm, while the PV system operates under a solar irradiance of approximately 700 W/m². The obtained power responses demonstrate the simultaneous contribution of the two renewable energy sources under the investigated experimental conditions. **Figure 20** presents the total harvested power P_{total} of the hybrid PV–VAWT system, calculated according to Eq. (12). The resulting P_{total} represents the combined electrical power available from the PV and VAWT sources and is used as the optimization variable of the proposed Unified P&O MPPT controller. The experimental power response therefore provides direct validation of the power calculation and unified power-based control principle used in the proposed MPPT strategy.

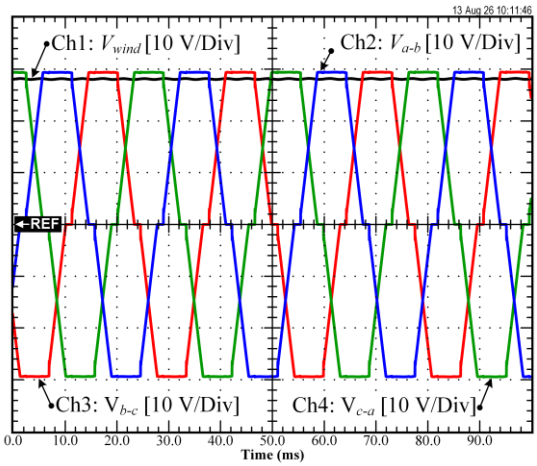


Figure 16 waveform of the VAWT operating at a rotational speed of 312 rpm

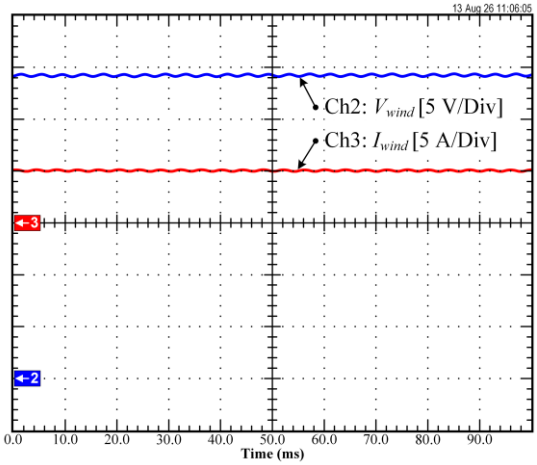


Figure 17 V_{wind} and I_{wind}

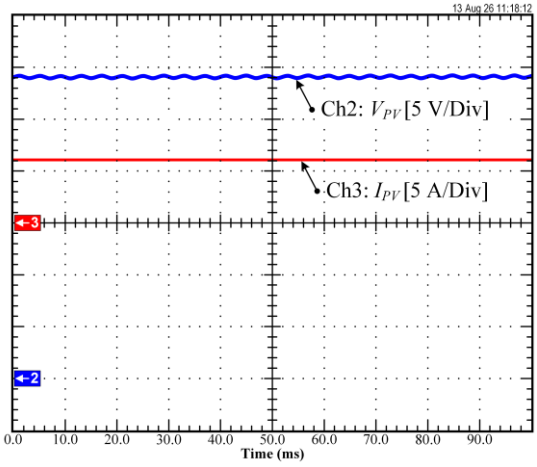


Figure 18 V_{PV} and I_{PV}

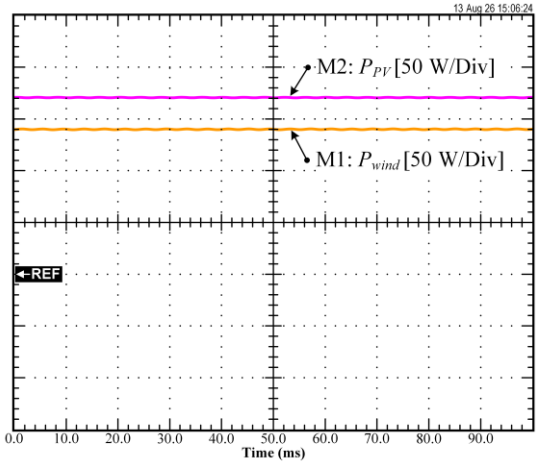


Figure 19 P_{PV} and P_{wind}

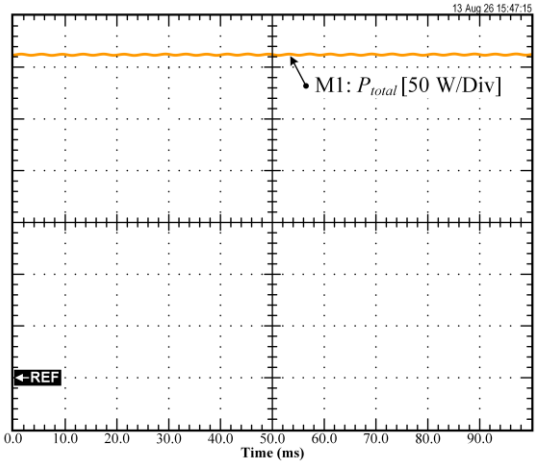


Figure 20 P_{total}

Figure 21 presents the experimentally observed control signals generated by the proposed Unified P&O MPPT controller. Channel 2 (Ch2) represents the duty-ratio command D generated by the controller and transmitted through the Digital-to-Analog Converter (DAC) channel of the dSPACE interface for monitoring. Channel 3 (Ch3) represents the corresponding PWM gate-drive signal applied to the IGBT of the buck converter. The experimental waveforms demonstrate the transfer of the controller output from the dSPACE platform to the power-switching stage. The generated PWM signal is therefore used to control the IGBT switching operation of the buck converter according to the duty ratio determined by the proposed Unified P&O MPPT algorithm.

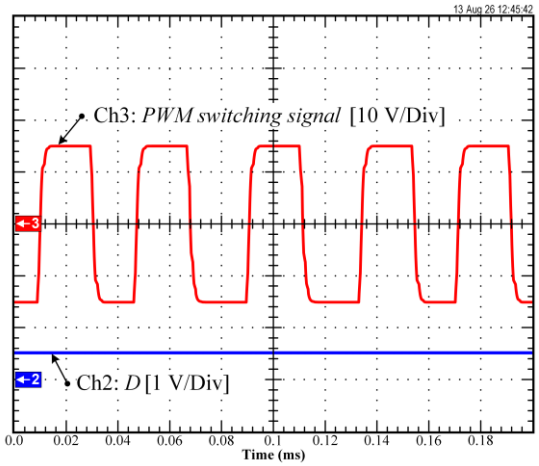


Figure 21 Duty cycle (D) waveform obtained from the hybrid MPPT algorithm block and the gate signal waveform of the IGBT

Figure 22 presents the experimental output voltage V_{out} and inductor current I_{L1} of the buck converter. The experimental results show that the converter output voltage is maintained at a suitable level for charging the 12V battery, while the inductor current responds according to the applied operating conditions. **Figure 23** presents the experimental battery terminal voltage V_{Batt} and charging current I_{Batt} during buck-converter operation.

The source-combination tests were subsequently performed to evaluate the capability of the proposed Unified P&O MPPT controller to accommodate changes in the available renewable energy sources. **Figures 24–25** present the experimental V_{out}, V_{Batt}, I_{L1} and I_{Batt} responses when the PV source operates alone before the specified switching instant t_{on}. At t_{on}, the VAWT source is connected to the system, resulting in the simultaneous operation of the PV and VAWT sources. The experimental waveforms show that the buck converter and battery charging process continue operating during the transition from single-source PV operation to hybrid PV–VAWT operation. After the VAWT is connected, the additional wind power contributes to the total harvested power of the system, while the proposed Unified P&O MPPT controller continues to regulate the operating point based on the combined power of the two sources.

Similarly, **Figures 26–27** present the experimental V_{out}, V_{Batt}, I_{L1} and I_{Batt} responses when the VAWT source operates alone before t_{on}. At the specified switching instant, the PV source is connected to the system, resulting in the transition from single-source VAWT operation to hybrid PV–VAWT operation. The experimental results demonstrate that the power-conversion and battery-charging processes are maintained during this transition. Following the connection of the PV source, the additional photovoltaic power contributes to the total harvested power, and the proposed Unified P&O MPPT controller continues to operate using the combined power contribution from both renewable energy sources. These experimental results verify that the proposed control scheme can accommodate changes in the available power sources and maintain continuous power-conversion operation during the transition between single-source and hybrid operating conditions. **Figure 28** shows the complete hardware implementation and experimental test bench of the proposed hybrid PV–VAWT system. The setup comprises the 300 W monocrystalline PV panel, the

300 W vertical-axis wind turbine, the bridge rectifier stages, the DC–DC buck converter prototype with voltage and current measurement sensors, and the 12V battery storage unit. In addition, the Unified P&O MPPT control algorithm is implemented on a dSPACE interfacing platform connected to a Control Desk and an oscilloscope for real-time control and waveform monitoring.

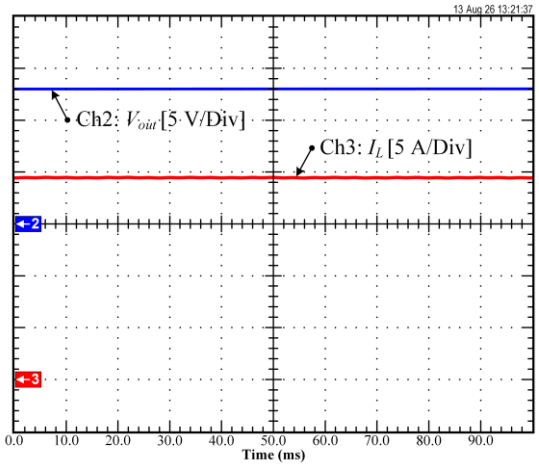


Figure 22 V_{out} and I_L

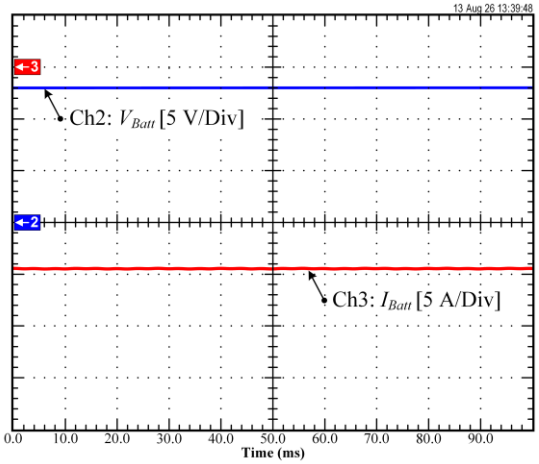


Figure 23 V_{Batt} and I_{Batt}

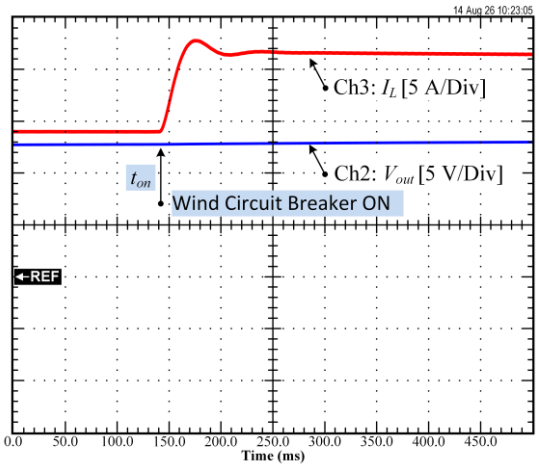


Figure 24 Experimental V_{out} and I_L Waveforms During Wind Turbine Startup

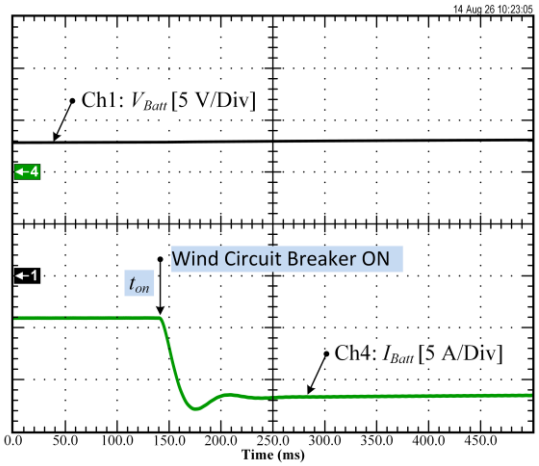


Figure 25 Experimental V_{Batt} and I_{Batt} Waveforms During Wind Turbine Startup

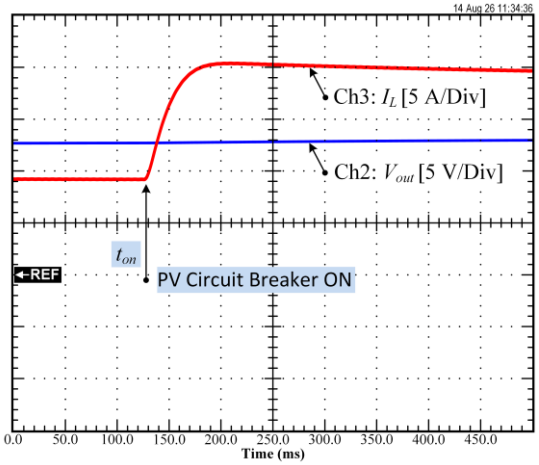


Figure 26 Experimental V_{out} and I_L Waveforms During PV Startup

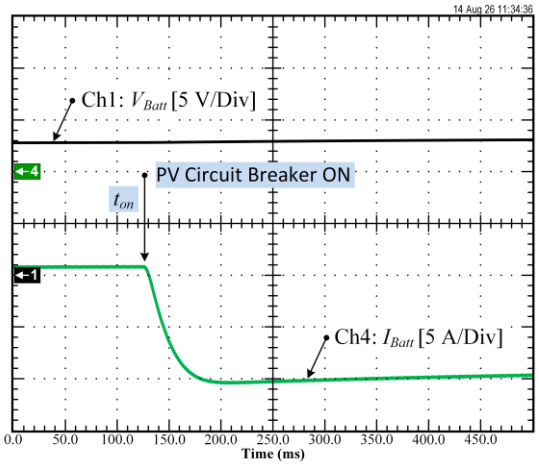


Figure 27 Experimental V_{Batt} and I_{Batt} Waveforms During PV Startup

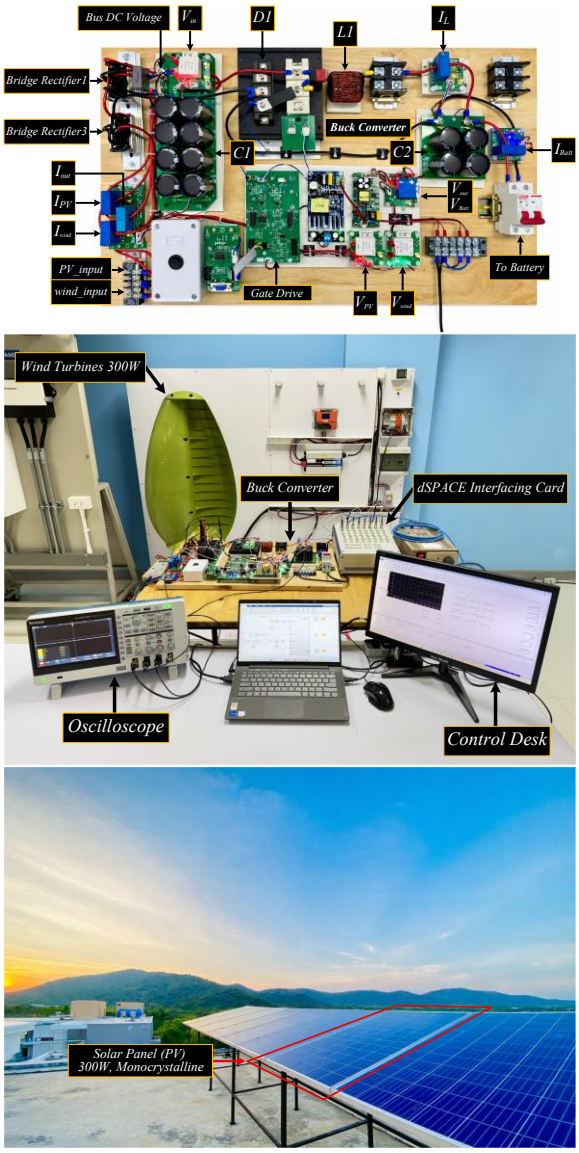


Figure 28 Hardware implementation of the proposed system

6. Conclusion

This study presented the development and experimental validation of a unified Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) strategy for a small-scale hybrid photovoltaic (PV) and vertical-axis wind turbine (VAWT) system using a single buck converter. Unlike conventional approaches that employ independent MPPT controllers for individual renewable energy sources, the proposed Unified P&O MPPT strategy uses the total harvested power of the PV–VAWT system as the optimization variable and a single duty ratio as the control variable. This configuration provides a simplified control structure while enabling coordinated power extraction from both renewable energy sources.

Simulation results demonstrated the operation of the proposed Unified P&O MPPT controller under varying PV and VAWT operating conditions. The simulated power responses confirmed the calculation of the individual source powers and the corresponding total harvested power used by the MPPT algorithm to determine the buck-converter duty ratio. The simulated buck-converter and battery responses further demonstrated that the proposed control scheme can regulate the converter output and support 12V battery charging under the investigated operating conditions.

Experimental results further validated the practical implementation of the proposed control scheme using a dSPACE-based control and measurement platform. The experimental results confirmed the electrical power generation of both the VAWT–PMSG and PV sources, the generation of the duty-ratio and PWM control signals, and the operation of the buck converter and battery charging system. In addition, the source-combination tests demonstrated that the system can transition from single-source operation to hybrid operation when the second renewable energy source is connected. Specifically, the system successfully transitioned from PV-only to PV–VAWT operation and from VAWT-only to VAWT–PV operation while maintaining continuous power-conversion and battery-charging operation.

Although the conventional P&O principle provides a simple and computationally efficient MPPT implementation, power fluctuations around the maximum power point may occur during transient changes in irradiance and wind conditions. Nevertheless, the experimental results demonstrate that the proposed Unified P&O MPPT strategy provides a practical and relatively simple approach for coordinating power extraction from small-scale PV and VAWT sources through a single buck converter. Future work will focus on improving the transient response and reducing steady-state power oscillations, as well as investigating the performance of the proposed strategy under a wider range of irradiance, wind-speed, and load conditions.

Table 1 Specification and Parameters of proposed system

Vin	15–60VDC
Vout	13.7VDC
Switching frequency (f_s)	25 *k*Hz
Inductor ($L1$)	220 μH
Capacitor ($C1$)	1,360 μF, 900 V
Capacitor ($C2$)	560 μF, 900 V
Capacitor (Cw)	2,200 μF, 450 V
IGBT ($G1$)	1,200 V, 150 A
Power Diode ($D1$)	600 V, 100 A
Solar Panel (PV)	300W, Monocrystalline
Wind Turbines	300W, PMSM motor
Sampling time of simulation	0.4 μs

7. Acknowledgements

The research team would like to express their sincere gratitude to Rajamangala University of Technology Rattanakosin (RMUTR) for the financial support provided through the Fiscal Year 2025 Annual Revenue Budget. We also extend our appreciation to the Faculty of Industry and Technology and the Institute of Research and Development at RMUTR for providing laboratory facilities and workspace. Furthermore, we would like to thank them for their continuous monitoring of the project's progress and for their excellent coordination in handling all research-related documentation.

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