

RESEARCH ARTICLE

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DESIGN AND IMPLEMENTATION OF A USB POWER DELIVERY SYSTEM WITH BIDIRECTIONAL POWER FLOW

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ARTICLE INFO

Article History

Received on: January 23, 2026
Reviewed on: February 22, 2026
Accepted on: April 10, 2026
Published on: June 30, 2026

Keywords:

USB Power Delivery,
Bidirectional Power Flow,
DC-DC Converter,
Maximum Power Point Tracking,
USB Type-C.

ABSTRACT

The need for effective and sustainable power management systems has increased recently. This has given rise to advanced forms of USB Power Delivery (USB-PD) having bidirectional power flow. This paper proposes a USB-PD system that uses solar panels (PV) to collect energy, stores that energy in a battery and smart power conversion to maximize energy delivery. This system has PV panel, Maximum Power Point Tracking (MPPT) controller, DC-DC converter, rechargeable battery, bidirectional DC-DC converter, and USB controller. The MPPT controller makes it possible to extract maximum energy of solar, and the DC-DC controller controls battery charging. A bi-directional regulator allows controlled charging and discharging of both battery and USB output to be used to charge the device and also allow reverse power flow. The USB controller supports USB-PD standards to negotiate dynamic power and fast charging of USB Type-C products. The suggested system improves the level of energy efficiency and renewable integration and less dependency on conventional power generation. It is shown through experimental validation that it is suited to portable electronics, systems operating renewable power sources and off-the-grid applications.



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I. INTRODUCTION

As the trend for portable electronics continues to increase along with the increasingly consumers looking for easy-to-use, efficient, and flexible charging solutions, the need for innovative power management systems has increased. USB Power Delivery (USB PD) has been established as the standardized, flexible protocol that can support higher power levels, and can support reversible, or directionally bi-directional power allowing devices to not only charge but supply power to devices when needed as well. The ability for bi-directional power is increasingly relevant to modern energy management scenarios, particularly where energy harvesting and renewable energy exist. Recent research has presented a number of different power management architectures that have facilitated energy harvesting, energy storage, and future intelligent power flow. For example, energy management systems (EMS) have developed a hybrid storage approach in order to utilize both batteries and supercapacitors, optimized the flow of power through a DC, DC bi-directional converter, and energy management controllers such as Sliding Mode Control (SMC) and PI in order to manage efficient charge and discharge measurements [1]. Additionally, hybrid energy management approaches have been recommended for the three-phase PV and energy Storage systems to manage the flow and harvesting of energy while dynamically allowing for maximum power point tracking (MPPT) performance with no inherent trade-off between stability and energy harvesting [2]. Bidirectional multi-input energy harvesting converters (MIECs) are capable of incorporating numerous energy sources in a portable device that can use ambient sources such as solar, vibration, and USB and provides power monitoring through MATLAB/Simulink simulations [3].

Bidirectional DC-DC converters are key to such processes with existing research into both two-phase and three-phase interleaved topologies to maintain constant DC bus voltage in different charging and discharging scenarios [4]. The control of interleaved converters is especially critical when integrating supercapacitors because switching and controlling duty cycles can minimize filter size and improve performance [5]. Additionally, soft-switching techniques such as Perturb and Observe (P&O) have been implemented in the designs of bidirectional converters to lower switching losses and improve MPPT efficiency in solar powered systems [6]. MPPT algorithms such as P&O and Incremental Conductance are still critical to optimizing PV output and reduce solar array size and cost from being forced into operation at the peak power points [7], [8]. Photovoltaic (PV) systems are some of the most promising renewable energy technologies due to their sustainability, modularity, and decreasing costs. However, power output from PV systems is inherently nonlinear and very sensitive to changing environmental conditions such as irradiance, temperature, and partial shading, resulting in inefficiencies of conversion and unstable output. To counteract this issue, Maximum Power Point Tracking (MPPT) algorithms are employed to periodically track the operating point of the system and extract maximum power from the PV arrays when it is available. Moreover, different DC-DC converter topologies, including Boost and SEPIC converters, have been widely implemented for photovoltaic applications due to their capability to handle wide range of varying input voltage.

Numerous studies have revealed that using MATLAB/Simulink – controlled Boost and SEPIC converters can greatly enhance the performance of PV Systems [9]. Likewise, SEPIC converter based MPPT control strategies have been implemented to improve voltage regulation and power extraction efficiency under changing environmental conditions [10]. Perturb and Observe (P&O) has been a common method used due to its ease of use and relatively low computational cost, however P&O is known to cause oscillations around the Maximum Power Point (MPP) and also fails to detect the global maximum power point (GMPP) in the situation of partial shading. Nature inspired optimization algorithms, such as GWO have been devised to overcome these limitations. The GWO algorithm is analogous to the hunting behaviour of grey wolves. GWO helped achieve faster and more precise convergence to the GMPP while tracking time is dramatically reduced, and stability is greatly improved than traditional methods [11]. A separate study further elaborates this discussion by comparing P&O with GWO, PSO, and The Firefly Algorithm (FA) under conditions of partial shading, when conventional MPPT algorithms are considerably less capable. The study suggests that while P&O struggles to reasonably access the GMPP, while GWO, PSO and FA demonstrate a greater capacity for convergence speed and efficiency [12]. These developments in MPPT control strategies are significant for improving the performance of renewable-integrated power systems, like the power delivery system implemented in this work, as they allow for improved power extraction from solar PV modules allowing the bidirectional USB Power delivery to manage and deliver energy more reliably and sustainably.

II. METHODOLOGY

II.1 BLOCK DIAGRAM

The block diagram shows a USB Power Delivery System with Bidirectional Power Flow which will manage energy from a solar photovoltaic (PV) panel, and delivery of that energy through USB Type-C to one or more devices while also providing power for reverse charging. This system dynamically integrates energy harvesting, battery storage, and bidirectional power into one system for effective and flexible power management. The process starts with the Solar PV Panel, which harvests sunlight and converts it to DC electricity. The amount of electricity provided successively from the PV panel, denoted by current (I_{PV}) and voltage (V_{PV}), depending on environmental conditions. To operate the PV panel at maximum power, the system employs the MPPT (Maximum Power Point Tracking) control unit. The MPPT controller can track, or dynamically adjust, the operating point of the PV panel using, for example, one of several algorithms like Perturb and Observe or Grey wolf optimization (GWO). Ultimately this component will allow the maximum amount of power to be extracted at the point of maximum power output from the PV panel, given changing light conditions provided by the environment.

The power harvested from the PV panel is regulated through a DC-DC converter. The converter changes the PV output voltage to a level suitable for charging the battery, ensuring that the harvest of energy is effective. The converter also acts in parallel with the MPPT controller to capture the optimal amount of energy from the panel. Once the power is regulated, it can be stored in a Battery, keeping excess energy stored for use during low sunlight times or for charging external devices via USB as the battery discharges. The use of a Bidirectional DC to DC Converter allows for bi-directional energy flow. The battery can be instructed to discharge through the USB interface to external devices, while also allowing charging of the battery with an external power source connected to the same USB port. Both Buck (step down) and Boost (step up) operation is possible in the Bi-directional DC to DC Converter meaning it is essential for ensuring voltage regulation in both directions. This system is a compact, energy efficient solar power delivery system that can deliver power from a solar source, store that power in a battery and deliver it to a USB Type-C device. The system's bidirectional power flow capacity allows flexible use with modern portable electronics, whether charge supporting via device charging, or can be charged from an external power source.

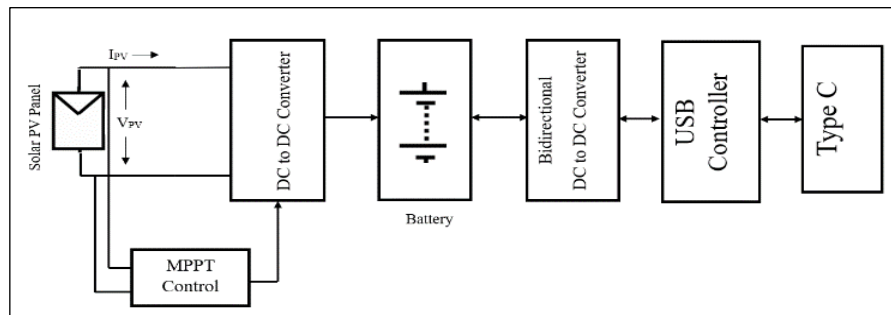


Figure 1: Block Diagram of the System.

Source: Authors, (2026).

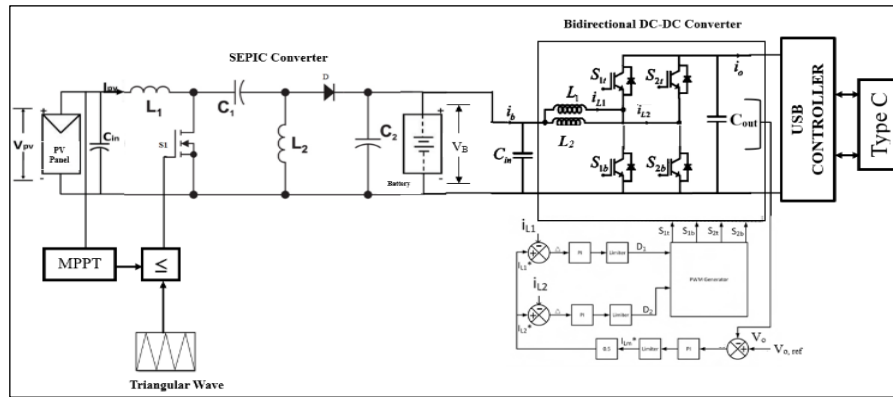


Figure 2: Circuit Diagram of the System.

Source: Authors, (2026).

II.1.1 PV Source & MPPT

The PV array produces DC power and absorbs solar energy to produce electrical energy. The PV panel output power varies with changes in irradiance and temperature. A Maximum Power Point Tracking controller is used for obtaining the maximum available power from the PV arrays. The MPPT controller ensures the PV system operates at peak efficiency by adjusting the duty cycle of the SEPIC converter. A PWM signal for controlling the switch (S1) of the SEPIC converter relies on comparing the MPPT output voltage with a triangular wave. The result is that the SEPIC converter efficiently converts solar energy into power regulated for battery charging.

II.1.2 Single-Ended Primary Inductor Converter (SEPIC)

The SEPIC converter will regulate the voltage received from the PV array, or solar energy source, before providing power to the battery storage system. Given that the PV voltage can vary, the SEPIC converter will provide a constant voltage to the storage battery by stepping the input voltage up or down to provide a constant output voltage required for charging the battery.

Parts of a SEPIC Converter:

- Inductors (L_1 , L_2): Efficiently store and transfer energy.
- Capacitors (C_1 , C_2): For voltage filtering. They smooth the output.
- Diode (D): Allows for correct current flow and unidirectional flow.
- Switch (S1): Controlled by the PWM signal produced by the MPPT algorithm.

The moment the switch S1 is turned ON, L_1 will then store energy while C_1 gets charged. When the switch S1 is turned OFF, the energy stored in the inductors L_1 and C_1 eventually transfers to L_2 and C_2 , which will then regulate the output voltage to make a suitable input for charging a battery.

II.1.3 Bidirectional DC-DC Converter

The bidirectional DC-DC converter allows for the transfer of energy from the battery and USB output. It runs in two different modes:

1. Boost Mode (Battery $\rightarrow$ Load): The battery is supplying power to the USB output, while the converter boosts the battery voltage to the level of USB output.
2. Buck Mode (Load $\rightarrow$ Battery): External power is supplied (USB input) and the converter is now bucking down to a safe voltage to charge the battery.

Components of Bidirectional DC-DC Converter:

- Inductors (L_1 , L_2): In the bidirectional converter, inductors store and transfer energy.
- Switches (S1t, S1b, S2t, S2b): direct the flow of power.
- Input Capacitor (C_{in}): Keeps the input voltage steady.
- Output Capacitor (C_{out}): filters the regulated output voltage.

The switching action of these components will either direct power to the USB output, or reroute the energy back into charging the battery. Therefore, allowing power to pass through the converter in both directions.

II.1.4 Control Circuit for Bidirectional DC-DC Converter

The bidirectional converter controls its operation through multiple loops, which enhances stability.

- Current Control Loops: uses integrated PI controllers to regulate inductor currents (i_{L1} , i_{L2}), maintaining energy flow without interruption.
- Voltage Control Loop: feedback loop that keeps the output voltage (V_o) in a range that allows controlled power delivery.
- PWM Generator: the switching signals (S_{1t} , S_{1b} , S_{2t} , S_{2b}) applied to control power conversion dependent on the input from the control loops.

II.1.5 USB Controller and Type-C Output

The USB controller has a major task in controlling power delivery to the USB Type-C port. It ensures that the attached devices will receive suitable voltage and current as defined by USB Power Delivery specifications.

II.2 MAXIMUM POWER POINT TRACKING (MPPT)

The MPPT algorithm is necessary in photovoltaic applications as the maximum power point of a solar panel changes with irradiation.

II.2.1 Perturb and Observe method (P&O)

The flowchart illustrates the operation of the Perturb and Observe algorithm, used for Maximum Power Point Tracking in photovoltaic systems. The P&O algorithm is to be used with the goal of extracting maximum power from the solar panel for charging the battery.

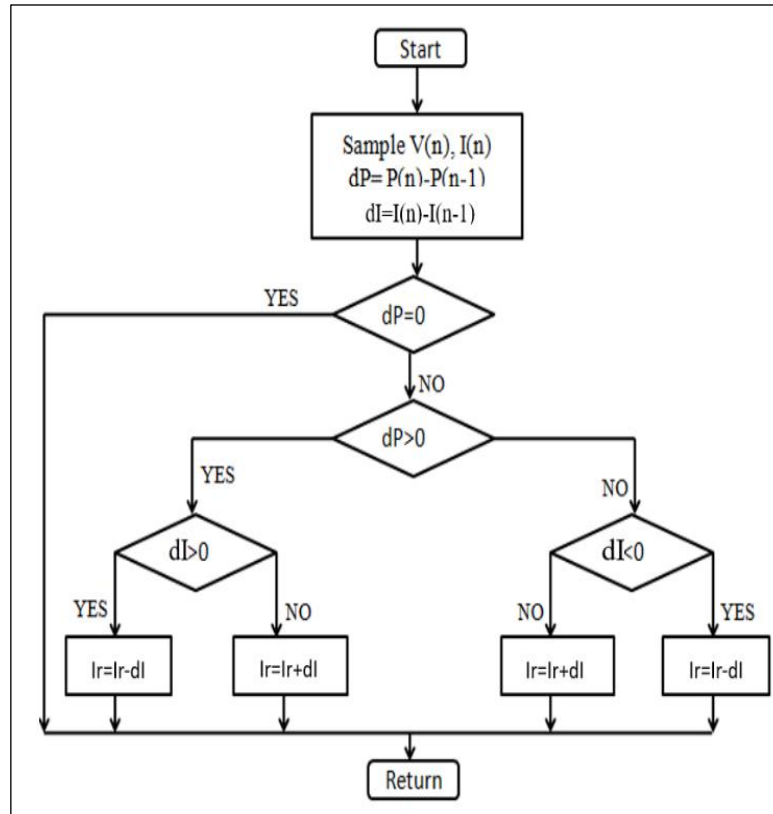


Figure 3: P&O-MPPT flowchart.

Source: Authors, (2026).

The Perturb and Observe algorithm functions by periodically sampling the voltage and current of the photovoltaic cells to determine the instantaneous power. The algorithm then looks at the changes in power (ΔP) and current (ΔI) at the next time step. If ΔP is equal to zero, the algorithm concludes that it is operating at the maximum power point and leaves the reference current (I_r) unchanged. If ΔP is nonzero, the algorithm will look for the signs of ΔP and ΔI to define the direction of the perturbation in the new time step. If ΔP and ΔI have the same sign, the reference current will shift in that same direction, indicating that the algorithm is moving towards the MPP. If ΔP and ΔI have different sign, the algorithm will shift in the opposite perturbation direction, hence moving back towards MPP. The iterative nature of the algorithm allows the system to excitably oscillate around MPP, following through all the contemporary changes in immediate environmental conditions.

II.2.2 Grey Wolf Optimization (GWO)

The control pyramid and typical chasing process of grey wolves serve as the basis for the optimization method, which is based on their natural pursuing behaviour in the wild. The GWO algorithm. The hunting mechanism and management structure of grey wolves in the wild are identical to those found in nature. Grey wolves prefer to live in packs and are regarded as the top predators. The leadership hierarchy is simulated using four different subspecies of grey wolves: alpha (α), beta (β), delta (δ), and omega (ω). In order to quantitatively depict the social structure of wolves during the development of GWO, the best option is utilized as alpha (α). Thus, the letters delta (δ) and beta (β) stand for the second and third best answers, respectively. Presumably, omega (ω) is the last viable solution.

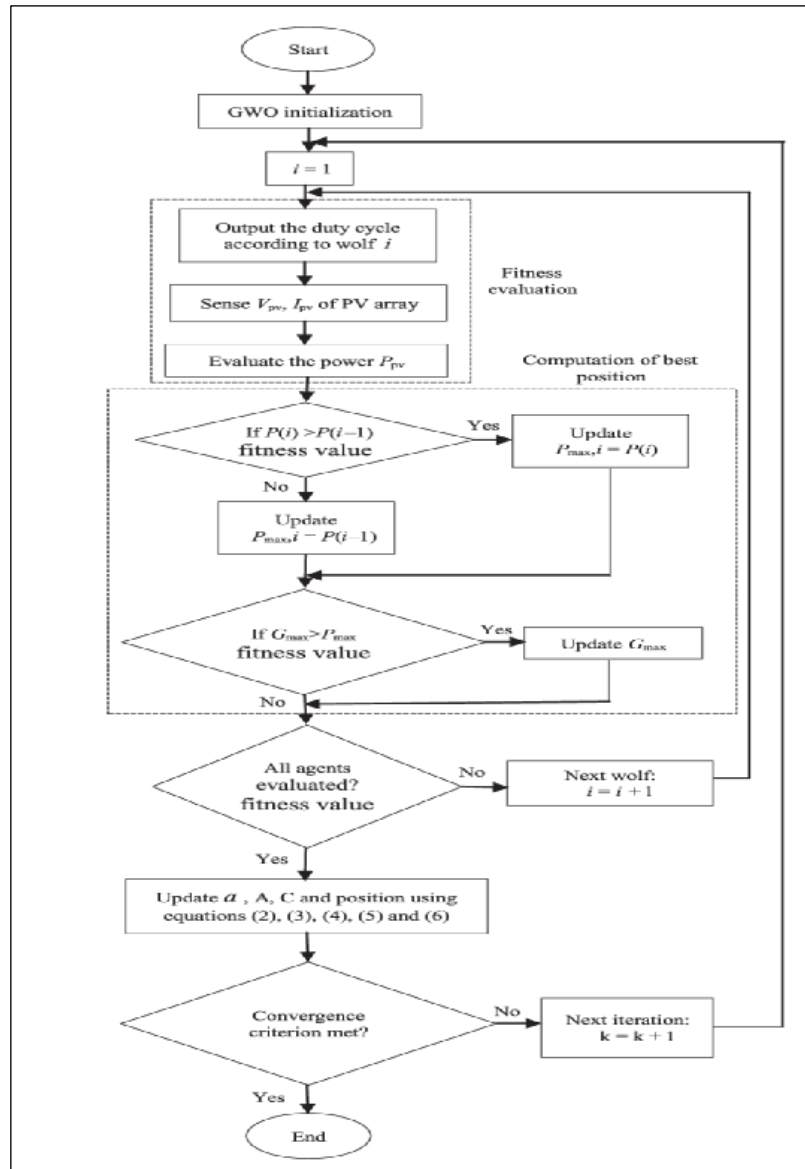


Figure 4: GWO-MPPT flowchart.

Source: Authors, (2026).

The control pyramid and typical chasing process of grey wolves serve as the basis for the optimization method, which is based on their natural pursuing behaviour in the wild. The GWO algorithm. The hunting mechanism and management structure of grey wolves in the wild are identical to those found in nature. Grey wolves prefer to live in packs and are regarded as the top predators. The leadership hierarchy is simulated using four different subspecies of grey wolves: alpha (α), beta (β), delta (δ), and omega (ω). In order to quantitatively depict the social structure of wolves during the development of GWO, the best option is utilized as alpha (α). Thus, the letters delta (δ) and beta (β) stand for the second and third best answers, respectively. Presumably, omega (ω) is the last viable solution. Three major stages of the GWO algorithm are applied to construct GWO for optimization purposes: hunting, following and tracking prey, surrounding prey, and attacking prey are shown in figure. Grey wolves surround their victim through the hunt, and this performance may be described using the following equations:

$$D = |C \cdot X_p(t) - X_p(t)| \quad (1)$$

$$X(t+1) = X_p(t) - A \cdot D$$

Where t represents the current iteration, D , A , and C signify coefficient vectors, X_p means the prey's position vector, and X is the grey wolf's position vector.

$$A = 2a \cdot r_1 - a \quad (2)$$

$$\vec{C} = 2.\vec{r}_2 \quad (3)$$

Where r_1, r_2 are random vectors in the range $[0, 1]$. The hunt is often directed by alphas known as leaders, followed by betas and deltas that may hunt on occasion. Delta and omega tend to the pack's injured wolves. As a result, we refer to alpha as the candidate solution that has a superior understanding of the location of prey. When the prey comes to a halt, the grey wolves complete the hunt by attacking it. Fig.4 depicts the suggested GWO-based MPPT algorithm's flowchart.

II.3 SPECIFICATIONS

II.3.1 PV Module Specification

Table 1: PV Module Specification.

Parameter	Specifications
Open circuit voltage, V_{OC}	15V
Short circuit current, I_{SC}	10.7A
MPP Voltage, V_{mp}	12V
MPP current, I_{mp}	10A

Source: Authors, (2026).

II.3.2 SEPIC Converter Specification

Table 2: SEPIC Converter Specification.

Parameters	Specifications
Input Voltage	12V
Input Capacitor	100 μ F
Output Voltage	24V
Voltage Ripple	2%
Switching frequency	100kHz

Source: Authors, (2026).

II.3.3 Design Values of SEPIC Converter

Table 3: Design Values of SEPIC Converter.

Parameters	Ratings
Inductor	20.01 μ H
Capacitor	138.96 μ F
Resistor	2.4 Ω

Source: Authors, (2026).

II.3.4 Bidirectional DC-DC Interleaved Converter Specification

Table 4: Bidirectional DC-DC Interleaved Converter Specification.

Parameters	Specifications
Input Inductance	0.5mH
Input Voltage	24V
Output Voltage	48V
Output capacitance	1.2mF
Switching frequency	20kHz
Battery Voltage	24/48V, 15Ah

Source: Authors, (2026).

III. RESULTS AND DISCUSSIONS

The system was simulated in the MATLAB/SIMULINK environment. The main parts of the model include the PV model, the converter model that connects the PV output to a resistive load, and the MPPT controller that keeps track of the maximum power from the PV array. Both the P&O and GWO tracking methods were used to find and follow the maximum power.

III.1 IV AND PV CHARACTERISTICS OF SOLAR PV MODULE

Figure 5 displays the I-V and P-V characteristics of the solar PV module under different irradiance levels (0.25–1.0 kW/m²). As anticipated, the short-circuit current and maximum power output increased with increased irradiance, supporting the responsiveness of the module to solar input. When exposed to 1000 W/m² the module had peak performance with maximum power output of 120 Watts.

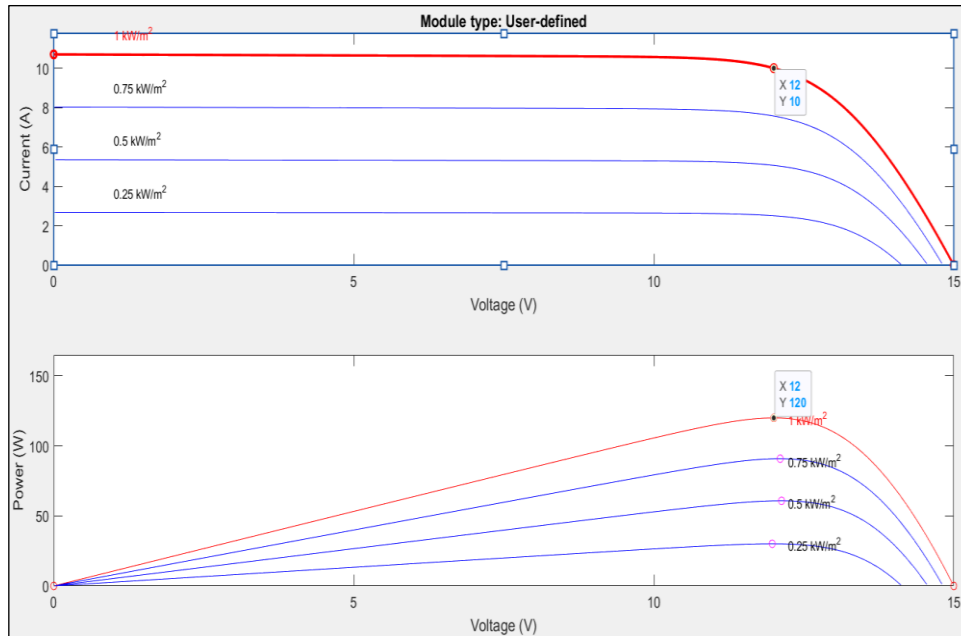


Figure 5: IV and PV Characteristics of Solar PV Module.

Source: Authors, (2026).

III.2 IRRADIANCE = 1000W/M2 AND TEMPERATURE, T=25° VPV AND IPV

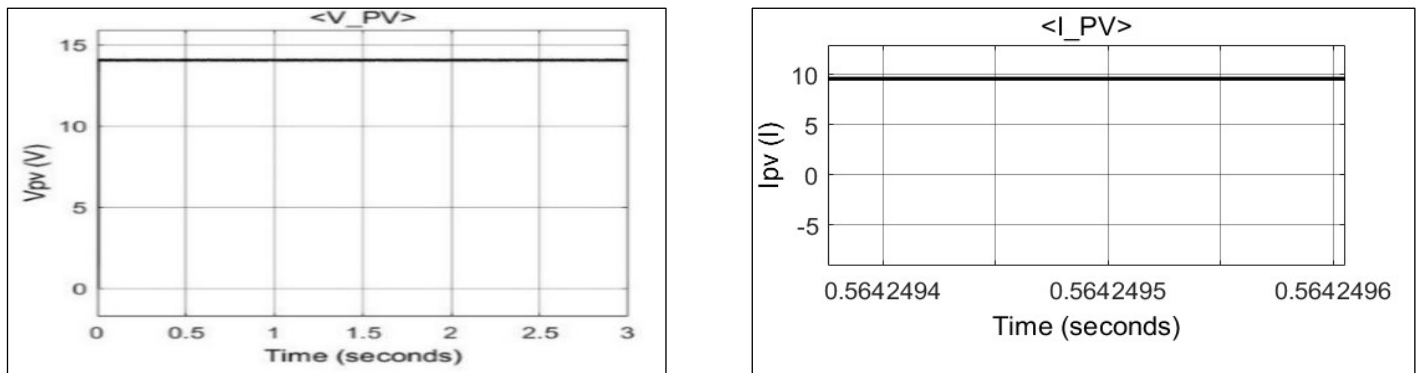


Figure 6: Irradiance=1000W/m² and Temperature, T=25° V_{PV} and I_{PV} of Solar PV Module.

Source: Authors, (2026).

The waveforms presented here represent the voltage and current output of the solar PV module under standard conditions (Irradiance = 1000 W/m², Temperature = 25 °C). We see that the PV voltage (V_{PV}) is steady near 12 V. The current (I_{PV}) has an approximate value of 10 A with little ripple- representing stable and efficient energy extraction of the PV module.

III.3 IRRADIANCE = 1000W/M2 AND TEMPERATURE, T=25° VOUT AND IOUT

The output voltage indexes goes to about 24 V and is steady, indicating adequate regulation by the power converter while under normal test situations (1000 W/m², 25 °C). The output current also is steady at about 10 A with minimal variance, indicating proper use and regulation of loading.

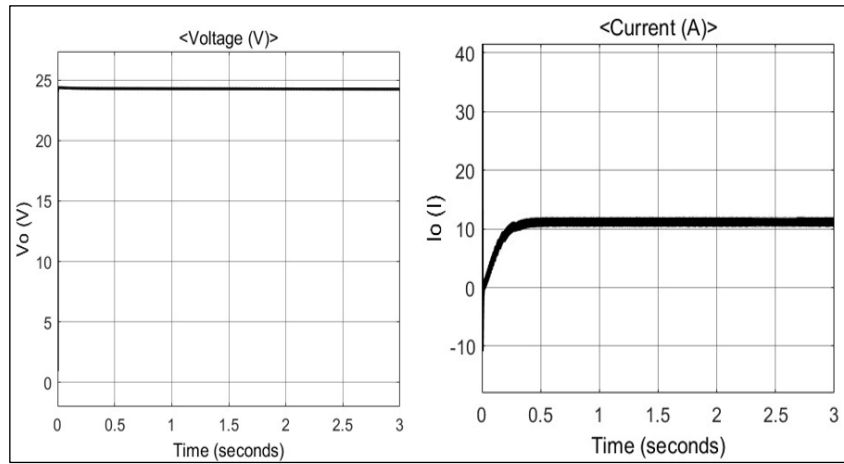


Figure 7: Irradiance=1000W/m² and Temperature, T=25° V_{out} and I_{out}.
Source: Authors, (2026).

III.4 DUTY RATIO

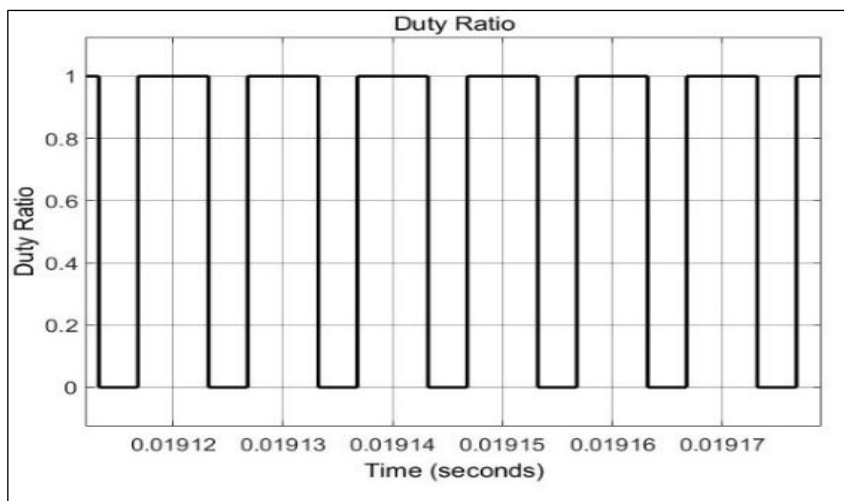


Figure 8: Duty Ratio.
Source: Authors, (2026).

In the SEPIC converter, the duty ratio waveform switches regularly from 0 to 1 quite quickly. The higher frequency of modulation enables dynamic energy transfer and voltage regulation by varying the switch ON and OFF times. The SEPIC converter duty ratio waveform in Figure 8 consistently shows a switching wave shape with a 66.67% duty cycle.

III.5 COMPARISON RESULTS BETWEEN P&O ALGORITHM AND GWO: A) VOLTAGE, B) CURRENT, C) POWER

The waveforms demonstrate the comparative performance of the Perturb and Observe (P&O) algorithm with that of the Grey Wolf Optimization (GWO) algorithm in relation to voltage, current, and power characteristics. Both methods show consistent input and output voltages, but GWO has faster settling response and less fluctuation. The input and output currents for the GWO case exhibited a smoother ramp up and faster settling compared to the P&O results which took longer time to get steady. Similarly, GWO obtains a significant boost in power output and a more stable amount of power with less ripple which indicates it shows better MPPT tracking performance. Overall, GWO has a faster dynamic response, more predictable transients, and overall higher efficiency than the P&O approach.

III.6 SIMULATION RESULTS OF BIDIRECTIONAL DC-DC INTERLEAVED CONVERTER DURING BOOST MODE

The battery current (I_B) and interleaved inductor currents (I_{L1} and I_{L2}) have entered boost mode operation of the bidirectional interleaved DC-DC converter, and they settle down to their steady state values indicating the currents are sharing effectively, and that because of the interleaving, they are sharing relatively same voltage ripple. The output voltage (V_o) shows that it responds almost instantaneously to the reference voltage (V_{ref}), remaining in close proximity to it, which indicates the output has extremely effective voltage regulation. The small decrease in state of charge (SOC) is also indicative of controlled battery discharge on support of the load to be able to supply the required load demand.

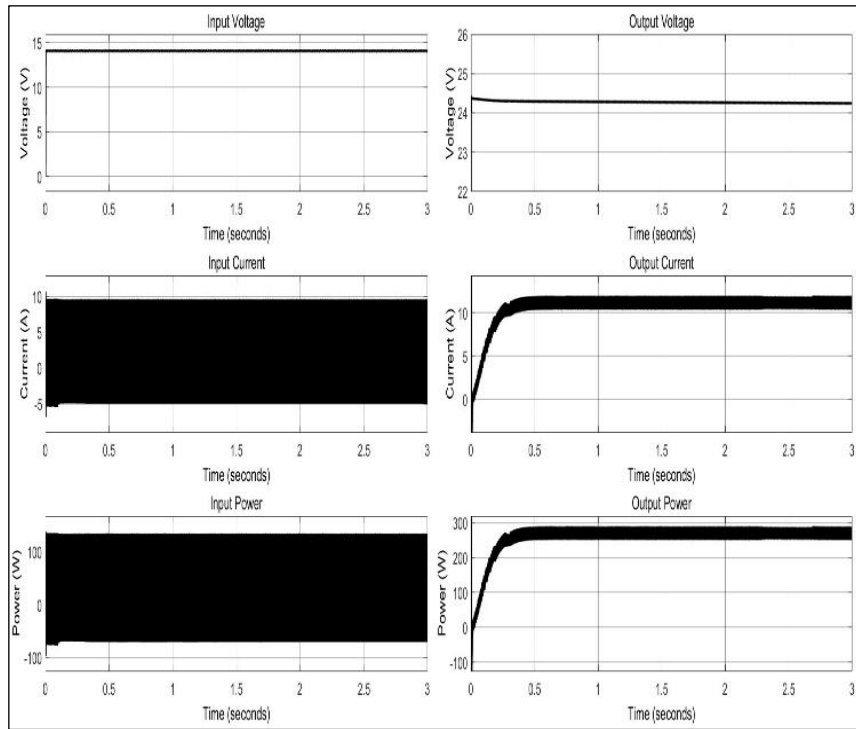


Figure 9: P&O Result.
Source: Authors, (2026).

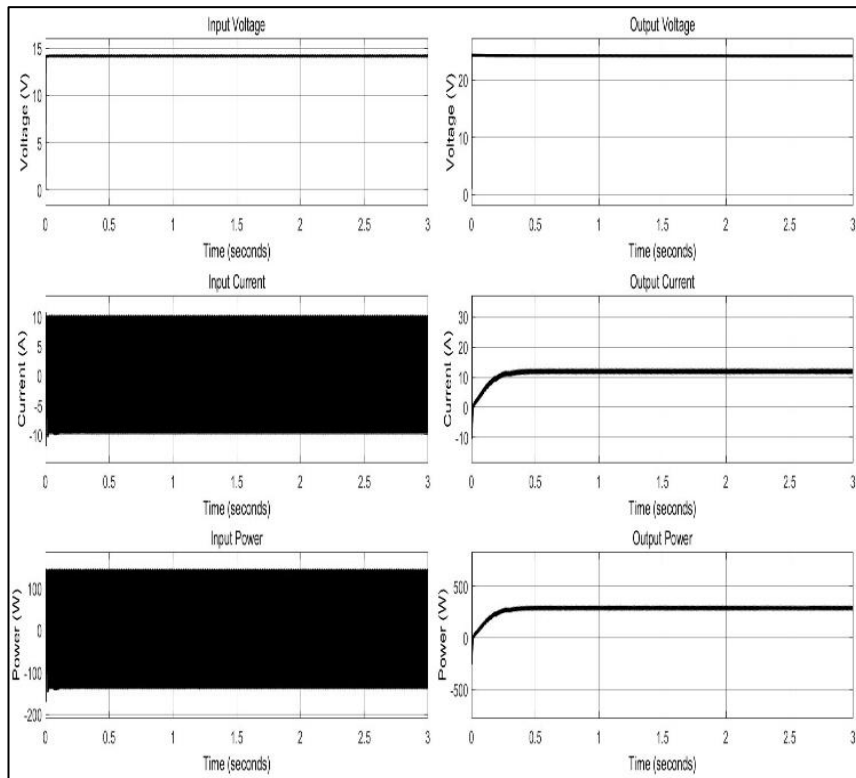


Figure 10: GWO Result.
Source: Authors, (2026).

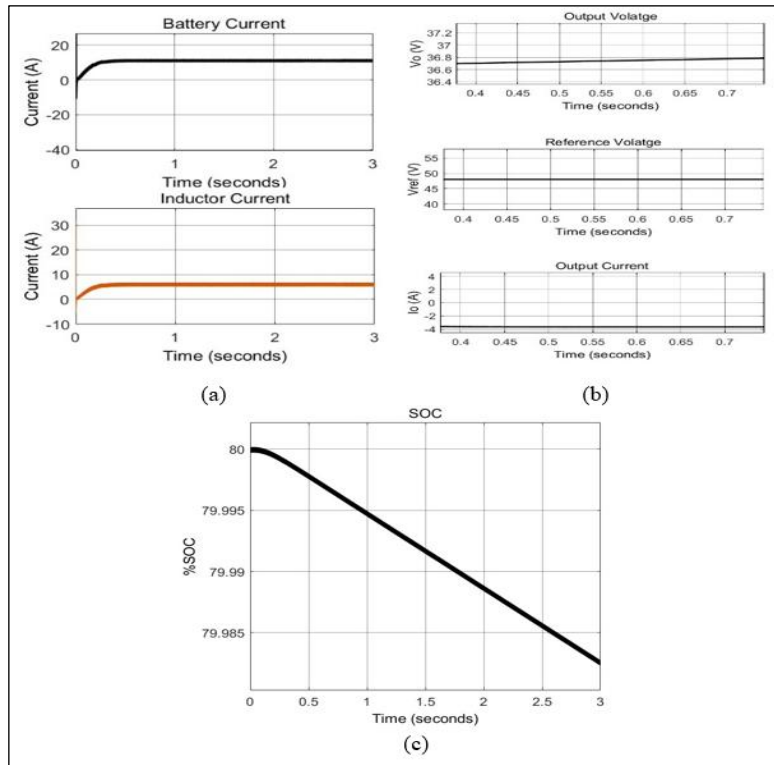


Figure 11: Simulation results of bidirectional DC-DC interleaved converter during boost mode (a) I_B , I_{L1} , I_{L2} (b) V_o , V_{ref} , I_o (c) %SOC.

Source: Authors, (2026).

III.7 SIMULATION RESULTS OF BIDIRECTIONAL DC-DC INTERLEAVED CONVERTER DURING BUCK MODE

During buck mode operation, the battery current (I_B) and interleaved inductor currents (I_{L1} and I_{L2}) show some initial transients and then settle nicely, which shows that the current control was effective, and effectively reduced ripple, due to the interleaving. The output voltage (V_o) cleanly tracks the reference voltage (V_{ref}), to confirm proper voltage regulation, while the steady increase in SOC indicates that the battery is effectively charging during this mode of operation.

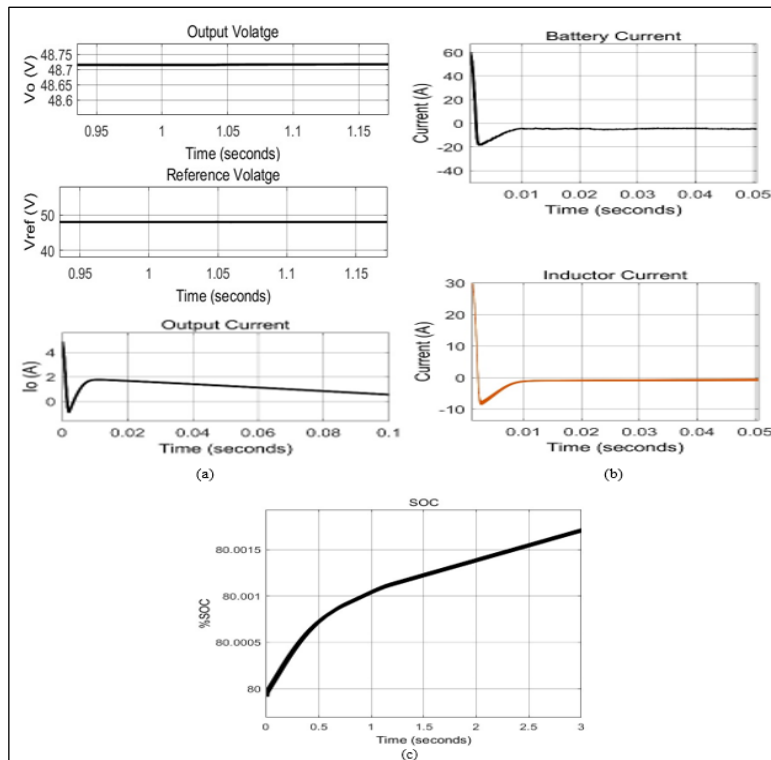


Figure 12: Simulation results of bidirectional DC-DC interleaved converter during buck mode (a) I_B , I_{L1} , I_{L2} (b) V_o , V_{ref} , I_o (c) %SOC.

Source: Authors, (2026).

IV. CONCLUSIONS

The use of a USB Power Delivery system with bidirectional power flow, as represented in the block diagram, is a proven system for managing power demands in contemporary energy systems. The bidirectional power flow system utilizes a solar PV panel with an MPPT controller, a DC-DC converter, a bidirectional converter, and a USB controller that will ensure optimal usage of the power generated by the solar panel, flexibility regarding energy storage and extraction, and device compatibility. The MPPT controller for the solar panel, DC-DC converter with battery feed, and the bidirectional converter both contacting the battery and being fed from the battery means that independent operation, i.e. charging the battery and dynamically powering local devices becomes seamless. The system also provides sustainable charging solutions for portable devices while allowing for unique energy independence through the ability to push power in both directions, from the battery to devices and devices to the battery. The adoption of advanced USB with USB-PD standards improve the User Experience by means of dynamic power negotiation, and fast charging. Overall, the implementation of the proposed solution presents improved energy efficiency, reliance on conventional power options were reduced, and a push towards renewable energy technologies is introduced. There are theoretical advances in power electronics, energy storage, and intelligent control that can help improve the performance, flexibility, and scale of such systems towards green and smart technologies.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Sampreethi B C and Nethravathi S.

Methodology: Sampreethi B C and Soniya Agrawal.

Investigation: Sampreethi B C, Nethravathi S, Prema V and Soniya Agrawal.

Discussion of results: Sampreethi B C, Nethravathi S, Prema V and Soniya Agrawal.

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Supervision: Nethravathi S and Prema V.

Approval of the final text: Sampreethi B C, Nethravathi S, Prema V, Soniya Agrawal, Venkatesh Boddapati and Nindra Sekhar.

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