International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 4, 2025
https://theaspd.com/index.php

DC Link-Based Integration Of PV Systems And Battery Energy Storage

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Abstract- *The demand for electrical power is increasing daily, which is supplied by fossil fuels, resulting in huge carbon emissions in the atmosphere. This leads electrical engineers to generate power using renewable energy sources. This paper is aimed at the simulation and development of a Solar PV system which is able to fulfil the power demand in isolated locations or a standalone condition. The system consists of various components like PV solar panel, DC-DC converter (Step up converter), and Battery storage System connected to the load. The control of the input loop of the solar PV system is shown with the help of a PI controller for maintaining the DC link constant irrespective of changes in the input side and output side parameters, resulting in a constant output. The Battery storage System is intended to make up for the deficiencies in the solar and provide uninterrupted power to the end user. The simulations are performed in the MATLAB/SIMULINK software.*
Keywords- *BESS, DC-LINK, Renewable Energy Sources, and PVECS.*

I.INTRODUCTION

The term grid is used for an electricity system that may support all or some of the following four operations: electricity generation, electricity transmission, electricity distribution, and electricity control [1]. The conventional grid distributes massive amounts of electricity generated by large power generation stations, mostly from fossil fuels, to remotely located load centres. Presently, the grid is facing security issues, a finite supply of fossil fuels, the increasing difficulty of extracting fuels, and unstable fuel prices have caused international concerns threatening the world economy [2],[3]. Using alternative energy sources to decentralise the production of electricity can help with some of these issues [4]. Consequently, there is a growing emphasis on exploring alternative energy sources that can supply communities with sustainable and reliable electricity [5]. Renewable energy sources proliferate on and off the grid as electrical power sources. Unpredictability in the power supply is a significant issue for off-grid standalone renewable energy systems (RES). This issue is addressed by solar/wind energy systems, which offer improved power reliability, better system efficiency, and less energy storage needed for standalone applications.

Renewable energy technology has become the most demanded energy resource due to its sustainability and environmentally friendly energy [6],[7]. In addition, renewable technologies are being developed, which are a cost-effective and attractive supply for electricity generation [8],[9]. Among the many renewable energy resources is solar energy application technology has come to the forefront, which has a vast deployment and installation worldwide [10]. Therefore, it is essential to depend more on the systems of solar energy technology, which is abundant, sustainable and renewable, due to the significant energy needs of the world [1,11]. Since progress has increased significantly in the past few decades, solar photovoltaic technology has become possible in meeting all of the world's energy needs [12], [13], [14].

Energy storage captures energy produced in a given period for usage at another time; hence, it reduces fluctuations between energy production and energy demand [15]. Energy shortages mostly occur due to fluctuations in weather conditions, which greatly influence the amount of energy produced. Although they result in financial losses, excess and shortage cases are interpreted as losses [16]. Energy storage systems are frequently presented as a practical economic solution to reduce losses and prevent the limitation of the generated electricity if it is not required. It can simultaneously increase the building's resilience while reducing energy losses [16],[17].

Batteries are key for photovoltaic systems that provide a steady and dependable power source and are used as an energy supply during night or cloudy days [18], [19], [20]. Battery lifespan, attainable power,

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maintenance requirements and efficiency are essential battery characteristics that influence the operation and performance of a solar system [15,21]. An optimum battery has affordable prices, great effectiveness, a high density of energy, and the capacity to be discharged and charged indefinitely under arbitrary charging and discharge cycles [21]. Many papers have attempted to study various perspectives of solar PV with battery systems and explained the most effective solar photovoltaic (PV) system designs for energy storage systems incorporating batteries.

The performance of a photovoltaic system is often influenced by incident irradiance in the plane of the solar panels, incident light spectrum and solar cell temperature. Consequently, system performance alters according to the time of day, solar insolation, direction and tilt of the modules, cloud cover, soiling, shading, temperature, state of charge, day of the year and location.

The following describes the format of this document. The overview of PVECS (Photo Voltaic Energy Conversion System) is covered in Section II. Section III provides a detailed description of the battery storage system. Section IV describes the hybrid integration of PVECS and battery energy storage systems. The simulation studies that were steered to scrutinise the performance of solar PV systems in Section V. A thorough examination of the findings is provided in Section VI, highlighting their importance. A summary of the key points is provided at the end of Section VII.

II. PVEC Systems

Solar energy is directly converted into electrical power by photovoltaic cells. As seen in Figure 1 [19], a current source (I_L) connected in parallel with a diode, series resistance, and shunt leakage resistance can be used to replicate a single PV cell.

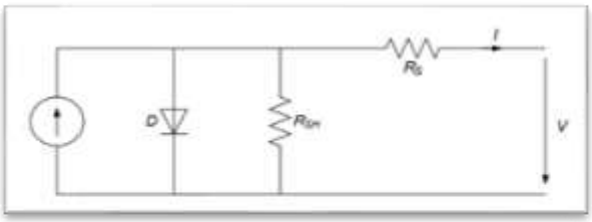

Figure 1. Single diode prototypical of a PV cell

Equation (1) represents the current-voltage characteristic,

$$I = I_L - I_O\left(e^{\frac{q(V-IR_S)}{AkT}} - 1\right) - \frac{V - IR_S}{R_{SH}} \quad (1)$$

Where I and V stand for the solar cell's output current and voltage, respectively. It is composed of the following: absolute temperature (T), diode quality (ideality) factor (A), electron charge (q), saturation current, Boltzmann constant (k), and solar cell series (R_S) and shunt resistances (R_{SH}).

The use of Solar PV technology is widespread today. The performance of all solar panels depends on two key atmospheric parameters: Temperature and solar irradiation. The I-V and P-V characteristics of the solar array are shown in Figure 2, which assumes a constant temperature of 25°C and different solar irradiances of 1000 W/m^2, 750 W/m^2, 500 W/m^2 and 250 W/m^2. As irradiance increases, the current across the panel rises significantly, with minimal change in voltage, leading to an increase in power output. Therefore, higher solar irradiation results in greater power generation.

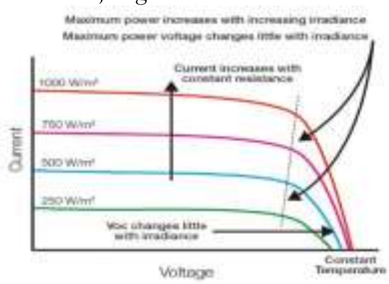

Figure 2. I-V curves at various levels of irradiance.

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III. Battery Energy Storage Systems

Battery energy storage systems (BESS) are vital components in modern power systems, enabling efficient energy management, reliability, and grid stability. They store electrical energy chemically and release it when required, allowing better integration of renewable energy sources, peak load shaving, and backup power supply. The integration of BSS with power electronic converters, especially bidirectional DC-DC converters, allows seamless energy flow control between the source and load in both charging and discharging modes**.** Bidirectional DC-DC converters provide the flexibility to handle such energy exchange with high efficiency and control. Their applications are widespread in electric vehicles (EVs), solar photovoltaic (PV) systems, uninterruptible power supplies (UPS), and smart microgrids.

Converter Topology And Operation

The converter topology usually involves a non-isolated half-bridge structure with two MOSFETs/IGBTs, an inductor, and passive filtering elements. The two modes of operation are buck mode and boost mode.

A. **Buck Mode (Battery Charging)**

When the input voltage exceeds the battery voltage, the converter operates in buck mode. The high-side switch is modulated using PWM, and the inductor current charges the battery.

$$v_{out} = D * v_{in}$$

$$\Delta I_L = \frac{(v_{in} - v_{bat}) * D * T}{L}$$

B. **Boost Mode (Battery Discharging)**

When supplying power to a higher-voltage DC bus, the converter steps up the battery voltage through controlled switching of the low-side MOSFET, thereby pushing energy to the load.

$$v_{out} = \frac{v_{bat}}{1 - D}$$

$$\Delta I_L = \frac{v_{bat} * D * T}{L}$$

IV. Integration Of PVECS And BESS

The model illustrates a hybrid DC microgrid that combines a photovoltaic (PV) system and a battery with bidirectional power flow, shown in Figure 3. It includes a PV array, an MPPT-controlled DC–DC boost converter, a DC-link, a load, and a bidirectional DC–DC converter linking the battery. The control strategy ensures efficient use of solar energy, stabilizes the DC bus voltage, and guarantees safe battery operation.

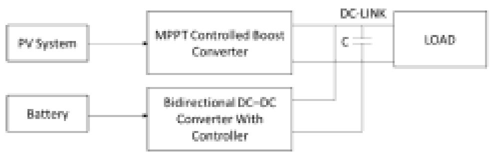

Figure 3. Integration Of PVECS And BESS**.**

a) PV Source and MPPT Control

The PV array model receives irradiance (W/m²) and temperature (°C) as inputs, producing corresponding PV voltage and current. An MPPT controller processes these outputs to determine the optimal operating point of the PV system. The MPPT generates a duty cycle command for the DC–DC boost converter to extract maximum power from the PV source under varying environmental conditions.

b) DC–DC Boost Converter

The boost converter raises the PV voltage to the DC bus voltage level. The MPPT output controls the PWM duty cycle to ensure efficient power transfer. A DC link capacitor is used to stabilise voltage and reduce ripple at the common bus.

c) Bidirectional DC–DC Converter and Battery

The bidirectional converter interfaces the battery with the DC bus, operating in two modes: (i) buck mode to charge the battery when PV generation exceeds load demand, and (ii) boost mode to discharge the battery when PV generation is insufficient. The battery control subsystem regulates the DC bus voltage via an outer voltage loop and controls battery current via an inner current loop. This ensures fast response and safe charging/discharging within specified limits.

The control system regulates the DC-link voltage of a microgrid using a two-loop PI controller structure for a bidirectional DC–DC converter connected to a battery. The architecture ensures fast dynamic response while maintaining safe battery operation during charging and discharging.

1. Outer Voltage Control Loop

The outer loop maintains the DC-link voltage (V_{DC}) at its reference (V_{DC_ref}). The measured voltage V_{DC} is subtracted from V_{DC_ref} to obtain the voltage error. A proportional–integral (PI) controller processes this error to produce a reference current (I_{ref}), which represents the desired net current to or from the battery to restore the DC-link voltage.

2. Inner Current Control Loop

The inner loop regulates the battery current to follow I_{bref}. The measured battery current (I_{Bat}) is subtracted from I_{bref} to obtain the current error. A PI controller processes this error to determine the duty ratio (D) command for the converter.

3. PWM Generation and Switching

The duty ratio command is converted into gate signals for the high-side and low-side switches of the converter. The high-side gate signal is output as Q1_Bat, and its logical inverse is used for the low-side switch (Q2_Bat).

d) DC link and Load

The DC link acts as the central connection point between the PV source, the battery, and the load. It is monitored for voltage and current to maintain stability. The load, modelled as a resistive element, draws power directly from the DC link, supplied by either PV, battery, or both.

e) System Operation

Under high irradiance, PV meets the load demand and charges the battery. During low irradiance or high load conditions, the battery discharges to maintain the DC link voltage. This coordinated control ensures a continuous power supply, optimal PV utilisation, and battery health preservation.

V. Simulation Circuits And Waveforms

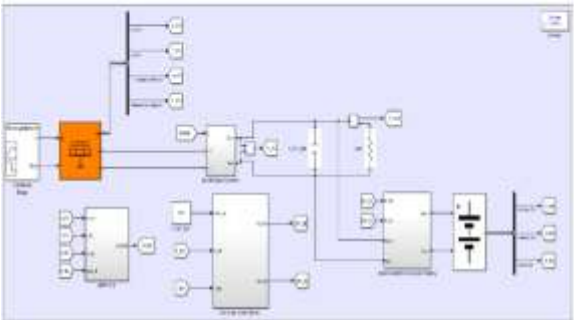

Figure 4. MATLAB/Simulink model Integration of PVECS and BESS.

A hybrid DC microgrid with bidirectional power flow that integrates a photovoltaic (PV) system and battery is shown in Figure 4. The usual assessment situations of irradiance 1000 W/m2 and temperature 25 °C are used to simulate the solar panel input of the recommended specifications. Tables 2 display the implemented circuit's specifics.

The Simulink model represents a solar PV system integrated with an MPPT-controlled DC-DC boost converter and a bidirectional battery interface for efficient energy management. The MPPT algorithm ensures maximum power extraction from the PV array, while the boost converter regulates the DC link voltage. A bidirectional DC-DC converter manages charging and discharging of the battery, thereby maintaining power balance and ensuring an uninterrupted supply to the load. This configuration demonstrates effective integration of renewable generation with storage, making the system reliable and suitable for standalone and microgrid applications.

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Table 1 Specifications of the PV System**.**

Component	Specification
PV Array	
Maximum Power (W)	248.97
Cells per module (N)	60
Open circuit voltage Voc (V)	38.4
Short-circuit current Isc (A)	8.85
voltage at maximum power point Vmp (V)	30.7
Current at maximum power point Imp (A)	8.11
Parallel strings	3
Series-connected modules per string	2
Boost Converter	
Inductor (μH)	L1 = 225
Capacitor (μF)	CL = 20
Switching frequency	30khz
DC LINK voltage	120v

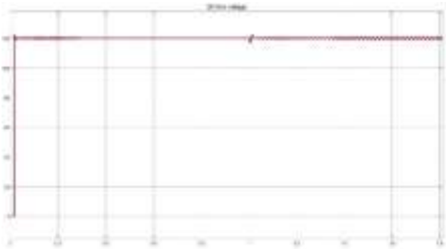

Figure 5: DC link voltage

VI. Significance And Discussion

Analysis of integration of PVECS and BESS involves evaluating various aspects of energy generation, storage and utilisation. The integration is carried out in MATLAB/SIMULINK. The PVECS and bidirectional converters with a battery are connected through a DC link shown in Figure 5. The DC link voltage is maintained constant as shown in Figure 5. The DC link connects the PVECS and BESS to the load. The designed system is off 4.5 kW PV and 2kw BESS supplying a load of 4 kW.

The integration system shown in Figure 4 is made to run for 1.8 seconds while continuously observing the system parameters. From Figure 6, it is shown that from 0-1 second, the PVECS provides power to the load, and the battery is charging as shown in the figure. From 1-1.8 seconds, it is seen that the irradiance is reduced, resulting in a reduction in power generation. The DC link draws the power from the battery, and thus, the load gets power continuously without any interruption. Table 2 shows a summary of various sources that provide power to the load.

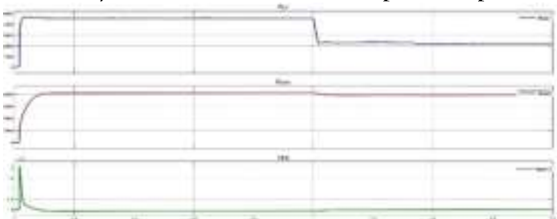

Figure 6: Waveforms of Total load power supplied from PVECS and BESS.

Table 2. Summary of different sources

Source Type	Source Capacity	0-1S	1-1.8S	Load Type
PVECS	4KW	4KW	2KW	R
BESS	2KW	0	2KW	R

VII. CONCLUSION

The developed Simulink model successfully demonstrates the integration of a photovoltaic (PV) system with a bidirectional DC-DC converter and a battery storage unit for efficient energy management. The Maximum Power Point Tracking (MPPT) algorithm ensures that the PV array consistently operates at its optimum power point, thereby maximising the energy harvested from solar irradiance. The bidirectional converter efficiently manages the charging and discharging of the battery, enabling stable operation under varying load and generation conditions. Simulation results validate that the system can regulate the DC bus voltage, supply uninterrupted power to the load, and store excess energy in the battery during surplus generation. During low or no solar input, the battery discharges to support the load, ensuring reliability and continuity of supply. This confirms the effectiveness of the proposed system for renewable energy integration, highlighting its capability for microgrid and standalone applications.

The proposed PV–battery system with MPPT and bidirectional DC-DC converters can be further enhanced through advanced control strategies such as fuzzy logic or AI-based algorithms to improve efficiency and dynamic response. Future work may include extending the system for grid-connected operation to enable bidirectional power exchange. Integration with additional renewable sources can develop a hybrid energy system, while hardware implementation and real-time validation will ensure practical feasibility. Optimising converter design for higher efficiency and reliability will make the system more suitable for smart grid and standalone applications.

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