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doi:10.15199/48.2024.11.13

Unlocking the Potential of Distributed Renewables: A Battery Energy Storage Approach to Voltage and Frequency Stability

Abstract. *Distributed generation (DG) using converters presents challenges for voltage and frequency control compared to synchronous generators. Converters lack inherent inertia, hindering response to power fluctuations. This paper proposes a DG system with a Battery Energy Storage System (BESS) for improved control. A MATLAB simulation evaluates the system's performance under various switching and power imbalance scenarios. This revision condenses the information while maintaining key points.*

Streszczenie. *Rozproszona generacja (DG) wykorzystująca konwertery stwarza wyzwania w zakresie kontroli napięcia i częstotliwości w porównaniu z generatorami synchronicznymi. Konwertery nie mają wrodzonej bezwładności, co utrudnia reakcję na wahania mocy. W niniejszym artykule zaproponowano system DG z systemem magazynowania energii akumulatorowej (BESS) w celu poprawy kontroli. Symulacja MATLAB ocenia wydajność systemu w różnych scenariuszach przełączania i nierównowagi mocy. Ta rewizja kondensuje informacje, zachowując jednocześnie kluczowe punkty. (****Odblokowanie potencjału rozproszonych odnawialnych źródeł energii: podejście do magazynowania energii w akumulatorach w celu zapewnienia stabilności napięcia i częs****totliwości)*

Keywords*:* Solar photovoltaic system, battery energy storage system and voltage source inverter*.*
Słowa kluczowe: System fotowoltaiczny, system magazynowania energii w akumulatorach i źródło napięcia

Introduction

Standalone Distributed Generation (DG) systems are increasingly playing a vital role in modern power systems. These self-contained units offer autonomous power generation, particularly beneficial in remote areas or regions with limited grid access [1, 2]. Additionally, standalone DGs can leverage locally available renewable resources like solar or wind, promoting energy independence and environmental sustainability [3]. Storage systems are crucial for effective management and control of standalone DGs [4, 5]. By integrating storage with renewable energy sources like photovoltaics (PV), wind turbines, or biomass, DGs can provide a reliable and consistent power supply [6, 7]. However, maintaining stable voltage and frequency in these isolated systems poses a significant challenge [8]. The intermittent nature of renewable sources, coupled with the reliance on inverters for feeding AC loads, creates a fundamental issue: a lack of inherent inertia [9, 10]. This absence of inertia makes standalone DGs susceptible to fluctuations and requires robust control strategies.

This paper proposes a standalone Distributed Generation (DG) system designed for autonomous operation using renewable energy. The primary source is a solar photovoltaic (PV) system. To address the intermittent nature of solar power and fluctuating load demands, "a Battery Energy Storage System (BESS) is integrated". A bidirectional converter (BDC) facilitates the controlled charging and discharging of the BESS, acting as a buffer for energy imbalances.

During periods of low PV generation or high load, the BESS discharges to compensate for the deficit. Conversely, excess PV generation allows the BESS to charge, ensuring system energy balance. This balanced operation contributes to maintaining voltage and frequency within acceptable limits, crucial for autonomous operation.

The system utilizes power electronic converters to optimize energy transfer and control. A boost converter maximizes power transfer efficiency from the PV unit to the DC bus. Meanwhile, a voltage source inverter (VSI) supplies power to the varying AC load (VL), maintaining consistent voltage and ensuring stable delivery. Each system component connects to the DC bus through a dedicated converter tailored to its specific needs.

The proposed DG system facilitates coordinated control of power flows between the PV system, BESS, and VL. The system's dynamic operation can lead to discrepancies between PV generation and VL demand, potentially causing deviations in frequency and DC voltage. Section II details the test system configuration and control strategy employed to address these variations. Section III presents the results and discussion of the system's performance under various operating conditions. Section IV highlights the paper's key contributions, followed by the concluding remarks in Section V.

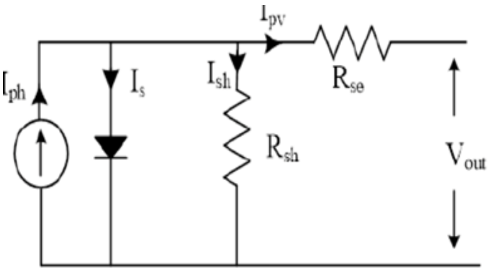

Fig 1. Single diode model of solar cell

Modelling and Control

Equation of single diode model is expressed as [11, 12]:

$$I_{pv} = I_{ph} - I_s[e^{\frac{q(V+IR_{se})}{(AKT)}} - 1] - \frac{V + I_{pv}R_{se}}{R_{sh}}$$

Photo diode current is :

$$I_{ph} = I_{sc} * \frac{I_{rr}}{1000} * [1 + (T_{cell} - T_{ref})^* K]$$

Equation of PV array is expressed as:

$$I_{pv} = I_{ph}N_{par} - I_0N_{par}[e^{(\frac{V + R_{se}(\frac{N_{ser}}{N_{par}})I_{pv}}{V_t a N_{ser}})} - 1] - \frac{V + R_{se}(\frac{N_{ser}}{N_{par}})I_{pv}}{R_{sh}(\frac{N_{ser}}{N_{par}})}$$

The Incremental Conductance (IC) technique is a widely used algorithm for Maximum Power Point Tracking (MPPT) in photovoltaic (PV) systems [13]. MPPT refers to the process of operating a PV system at its maximum power point (MPP) under varying environmental conditions like irradiance and temperature”. Here’s how the IC technique works:

Measure Voltage and Current: The system continuously measures the instantaneous voltage (V) and current (I) of the PV panel.
Calculate Conductance and Incremental Conductance: It calculates the current conductance (I/V) and the incremental conductance (dI/dV), which is the rate of change of current with respect to voltage.
Compare Conductance Values: The algorithm compares the current conductance (I/V) with the incremental conductance (dI/dV). This comparison determines the operating point of the PV panel relative to the MPP.
Operating at MPP: If I/V = dI/dV, the system is operating at the MPP. No adjustment is needed.
Operating Left of MPP: If I/V > dI/dV, the system is operating to the left of the MPP (higher voltage, lower current). The control algorithm needs to adjust the operating voltage slightly downwards to move towards the MPP.
Operating Right of MPP: If I/V < dI/dV, the system is operating to the right of the MPP (lower voltage, higher current). The control algorithm needs to adjust the operating voltage slightly upwards to move towards the MPP.
By continuously monitoring and adjusting the operating voltage based on the conductance values, the IC technique tracks the MPP and ensures the PV system operates at its maximum power output under varying conditions.

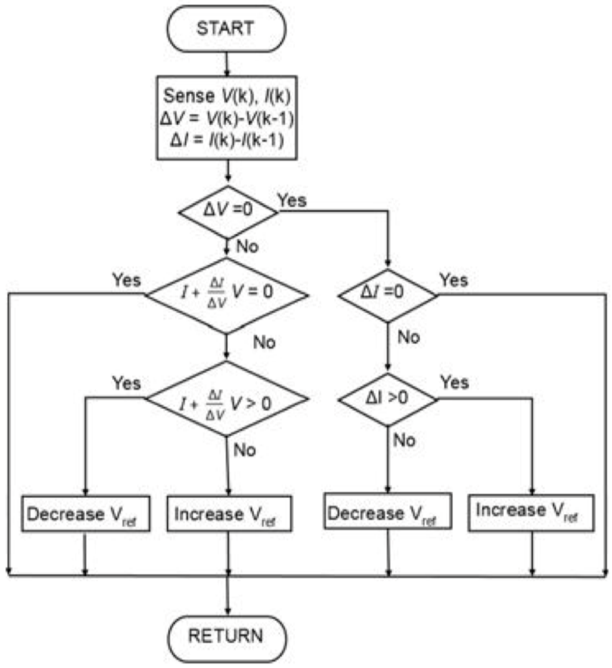

Fig 2 IC MPPT technique

Fig 4 shows the PV control diagram. The PV array generates DC voltage and current. The MPPT monitors the PV array's voltage and current and sends control signals to the inverter. Based on the MPPT signal, the inverter adjusts its operating voltage to extract maximum power from the PV array. The inverter converts the DC voltage to AC voltage. The AC power can be used to directly power AC loads or flow through the grid connection to the utility grid. If a battery bank is present, excess AC power can be used to charge the batteries via the inverter (acting as a charger) and the BMS.During times of low solar production, the inverter can convert battery DC power to AC power for powering loads, utilizing the BMS to manage discharge cycles. The control system monitors and manages the entire process, ensuring safe and efficient operation.

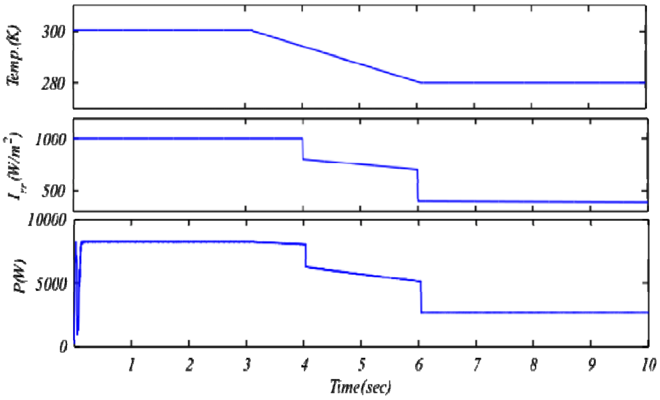

Fig 3 Result of IC MPPT algorithm

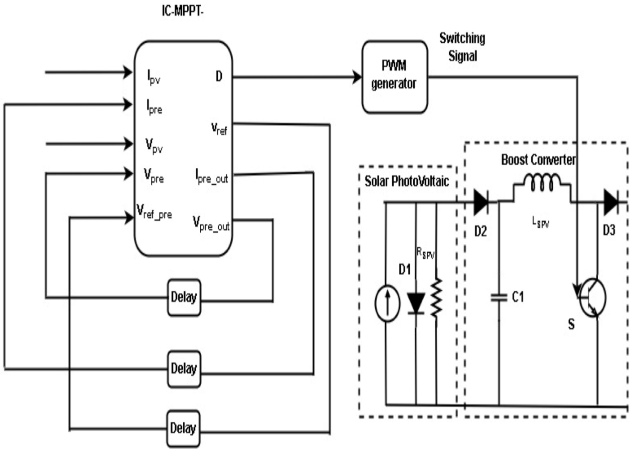

Fig 4. PV control

Test System Description and Control Strategy

This section describes the integration of a Battery Energy Storage System (BESS) with a 10kW solar photovoltaic (PV) system for a standalone distributed generation (DG) application (fig 5)(refer to [11] for details). The BESS plays a critical role in maintaining stable voltage and frequency at the DC bus, mitigating the inherent variability of solar power generation.

The system comprises of 10kW PV generation unit. A BESS with a bidirectional DC/DC converter (BDC) and a varying load connected through an inverter

The BDC (fig 6) acts as an intermediary between the BESS and the DC bus, ensuring optimal system operation through a control algorithm. This algorithm governs the BESS's charging and discharging behaviour:

- Charging: When excess solar power (beyond load requirements) is available, the BESS charges to store surplus energy.
- Discharging: During periods of insufficient solar generation or low irradiance, the BESS discharges to supply the load's power needs.
- Balancing: When the PV output perfectly matches the load demand, the BESS remains idle, optimizing energy utilization.

The BDC employs a buck-boost control methodology to regulate the BESS's operation and maintain DC bus stability. This control strategy typically involves two nested loops [15]:

- Outer Voltage Control Loop: This loop regulates the DC bus voltage by adjusting the BESS's charging/discharging current.
- Inner Current Control Loop: This loop ensures precise control of the current flowing between the BESS and the DC bus.

The buck-boost control methodology will be further elaborated upon in a subsequent section.

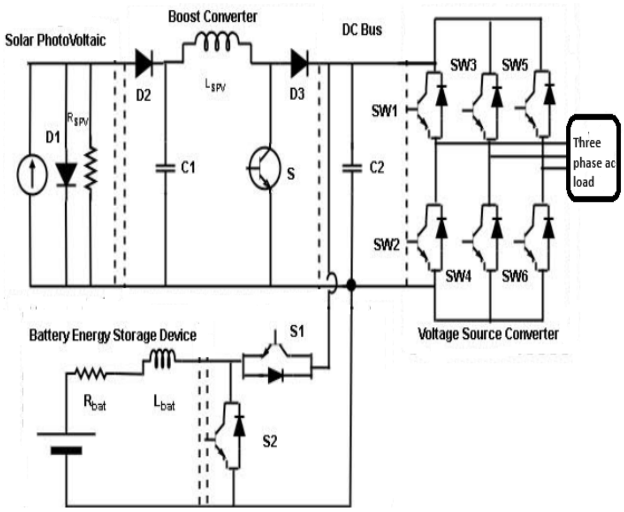

Fig. 5 Test system

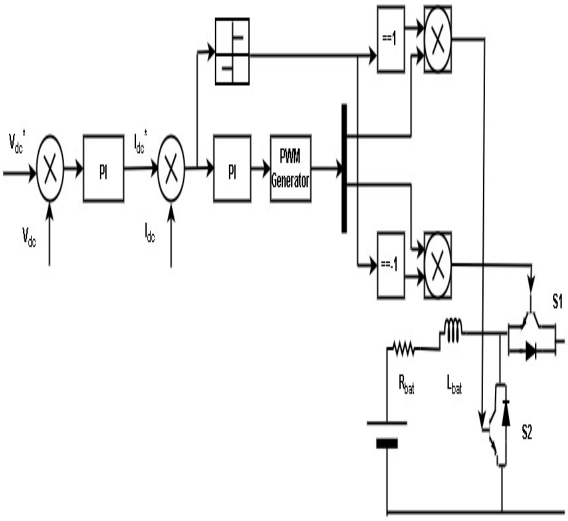

Fig. 6 Bidirectional Converter

Irradiance and PV Current (Fig. 7):

The experiment simulates fluctuating irradiance levels (sunlight intensity) by stepping it up and down in 0.5-second intervals. This creates various operating scenarios for the PV system, mimicking real-world conditions.

Load Variation and System Response (Fig. 8):

Figure 4 depicts the DC bus voltage, current, and power under different load scenarios. The load is deliberately varied to create situations of both power imbalance and balance.

This allows researchers to observe voltage and frequency behaviour under various switching conditions.

The BESS, aided by the bidirectional converter, maintains the DC bus voltage within a stable range (less than 5% variation), even with fluctuating power generation and load demands. The PV voltage remains constant at 350V during operation, while dropping to 0V when not generating power. Notably, the PV's power output directly correlates with the current flowing through it, as the voltage remains constant.

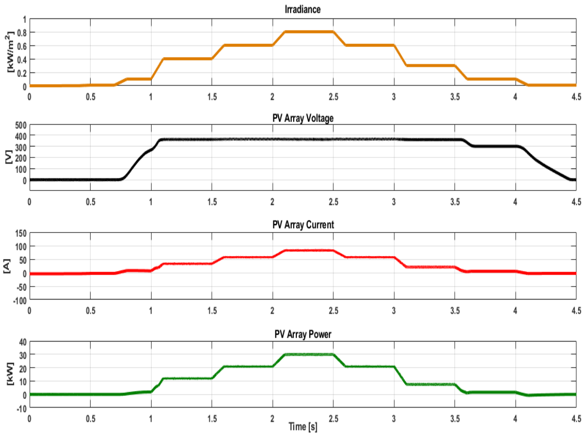

Fig. 7 operation of PV generation under various irradiance scenarios

Results and Discussion

Figure 7 explores the dynamic interaction between the”solar photovoltaic (PV) system, battery energy storage system (BESS)”,and varying load conditions.[11]

Dynamic Power Flow Analysis (Fig. 9):

Figure 9 showcases the temporal variations in power generated by the PV system, the BESS, and the load (VL).

It provides insights into the interplay between these components: When there's no PV generation, the BESS steps in to supply the load's power needs. As PV generation starts (around t = 1.1s) and meets the load demand, the BESS becomes idle. If excess solar power is available (t = 1.5s), it's used to charge the BESS, maximizing stored energy.

When PV output dips below load requirements (t = 2.6s), the BESS discharges to provide additional power, ensuring uninterrupted supply to the load.

These observations demonstrate the critical role of the BESS in a solar power system with variable generation. It acts as a buffer, storing excess energy and seamlessly filling in gaps when solar generation falls short, ensuring a stable and reliable power supply.[11]

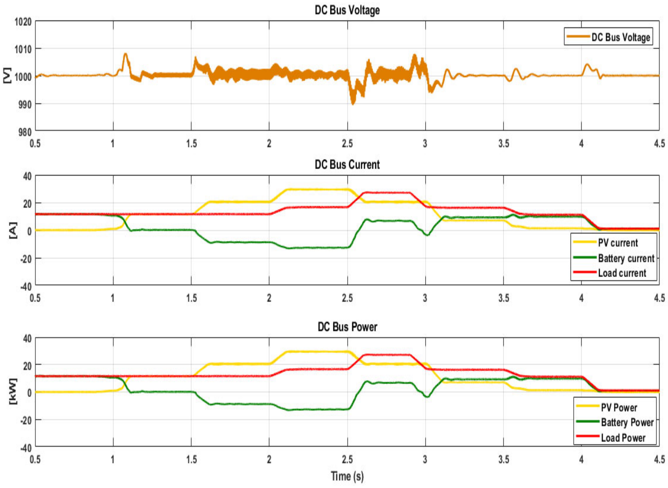

Fig.8 Various switching scenarios and power unbalance situations.

Figure 9 depicts the dynamic interplay between the solar photovoltaic (PV) system, battery energy storage system (BESS), and load power (VL) over time.

- **Prior to t = 1.1s:** In the absence of PV generation, the BESS assumes the primary role, supplying the load's entire energy demand.
- **t = 1.1s - 1.5s:** As the PV system initiates power generation, it seamlessly aligns with the load's requirements, prompting the BESS to enter an idle state.
- **t = 1.5s - 2.6s:** When PV generation exceeds load demand, surplus power is strategically directed towards charging the BESS, optimizing its energy storage capacity.
- **t > 2.6s:** As PV power output diminishes relative to load demand, the BESS transitions to boost mode, actively discharging stored energy to supplement the load's requirements.

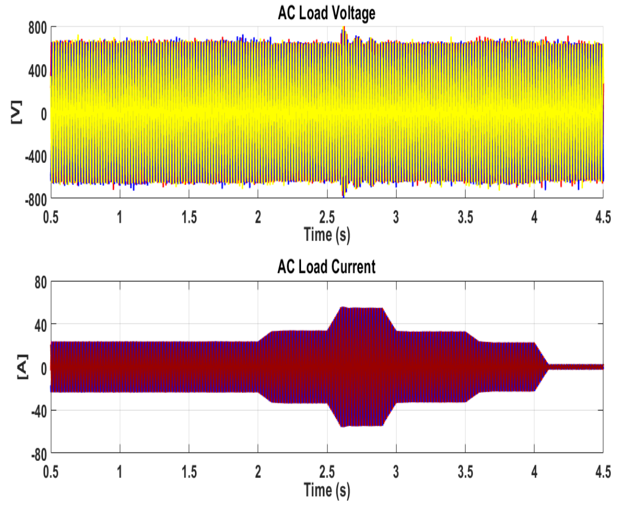

Fig. 9 AC load voltage and current.

This figure effectively demonstrates the complementary operation of the PV system and BESS, ensuring a continuous and reliable power supply.

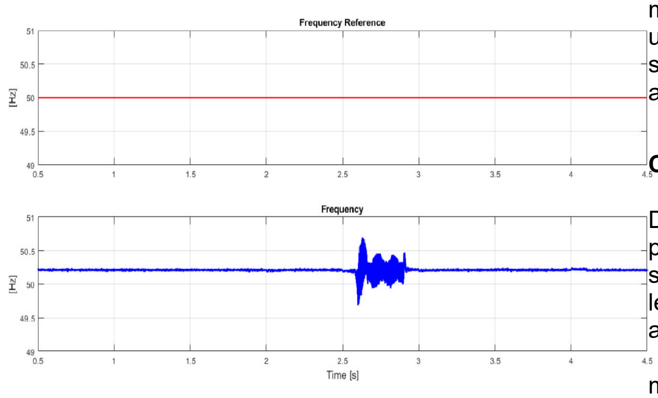

Fig.10 Variation of Frequency at load terminal

Figures 10 and 11 verify the system's ability to maintain stable voltage and frequency despite fluctuating load and irradiance.

Frequency Stays Steady: The BESS effectively regulates frequency at the load terminals (Fig. 10).**Active and Reactive Power:** Figure 11 shows the load's active and reactive power throughout the experiment. **Minimal voltage/frequency variations:** DC link voltage deviations remain well within acceptable limits. **Consistent performance:** The system effectively handles dynamic changes, demonstrating real-world applicability.

These results confirm the BESS's role in mitigating solar power variability and ensuring stable power delivery.

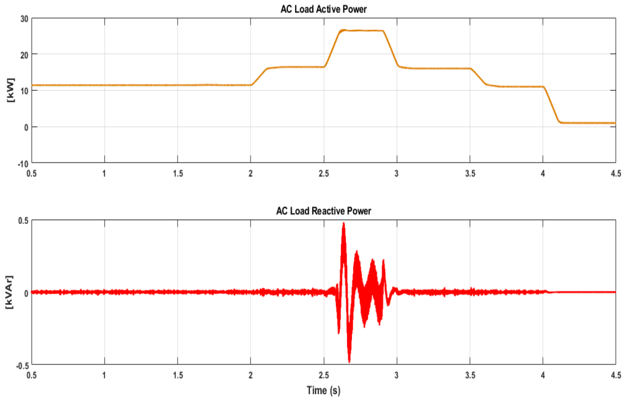

Fig. 11 AC load active and reactive power under various switching scenario.

Key Highlights of This Study

1) Frequency Autonomy with BESS: The microgrid generates the nominal system frequency autonomously using the BESS. This approach eliminates the need for a Synchronous Generator (SG), as the system's frequency control becomes independent of inertia-related considerations.

2) DC Link Voltage Regulation: The microgrid ensures the DC link voltage remains well within acceptable limits. During switching events and dynamic conditions, the voltage deviation is rigorously maintained, and it does not exceed 1%.

3) Seamless Mode Transitions: The proposed system demonstrates a seamless transition during switching events. This capability enhances the microgrid's adaptability and robustness in responding to varying load and generation conditions.

4) Remote Microgrid Application: The research findings suggest that such small-scale Solar Photovoltaic (SPV) systems can be effectively utilized in remote standalone microgrid deployments where grid electrification is unfeasible. These systems offer a viable solution to provide sustainable and reliable electricity to areas with limited access to centralized power infrastructure.

Conclusions

This paper investigates a small-scale, self-sufficient Distributed Generation (DG) system powered by solar panels and featuring battery storage. Unlike traditional DG systems that rely on synchronous generators, this design leverages a Battery Energy Storage System (BESS) for autonomous operation.

The implemented control strategy enables the system to manage power fluctuations inherent to solar energy. The results are promising, demonstrating that the BESS effectively maintains power balance within the system, even under various load and irradiance scenarios. Notably, the control strategy ensures voltage and frequency remain within acceptable limits throughout system operation.

This research paves the way for reliable and sustainable standalone power generation using solar panels and battery storage, particularly in remote areas or applications requiring grid independence.

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