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Affirmative Approach of BESS Integrated Solar Photovoltaic Systems for Both Grid and Standalone DC *M*grid

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Abstract:
The increasing penetration of solar photovoltaic (PV) systems has necessitated robust energy management strategies to address the challenges of intermittency and reliability in both grid-connected and standalone DC microgrid (μGrid) environments. This paper presents an affirmative approach to integrating Battery Energy Storage Systems (BESS) with solar PV to enhance power quality, energy availability, and system stability. The proposed framework emphasizes intelligent power flow control and adaptive energy dispatch strategies that ensure optimized performance under varying load and generation conditions. Attracting upon recent advancements in control algorithms and power electronics, the system architecture supports seamless transition between grid-connected and islanded modes, while maintaining voltage and frequency stability. The inclusion of BESS not only mitigates the volatility of solar power but also supports peak shaving, load leveling, and resilience during grid outages. Simulation results and case studies demonstrate significant improvements in energy utilization, reduced grid dependency, and enhanced reliability of the microgrid operation. Furthermore, this research aligns with current trends in decentralized energy systems and provides a scalable pathway for the deployment of smart, sustainable energy infrastructures. The findings reinforce the viability of BESS-integrated solar PV as a cornerstone of next-generation distributed energy systems, applicable across both utility and off-grid scenarios.

keywords: Renewable energy sources, Battery Energy Storage System (BESS), DC Microgrid, Solar Photovoltaic (PV) Integration, Grid-Connected & Islanded Operation and High Gain Double Inductor Boost Converter (DIBC).

I. INTRODUCTION

Global warming and carbon dioxide emissions, attributed to traditionally used energy sources, have become severe issues in the world for the last few years. Hence, the improvement of renewable energy sources (RES) has gained great research interest to mitigate and reduce such risks. Some RES, such as photovoltaic cells or wind turbines, are well-developed since they are clean and cost-effective [1]. However, other sources such as fuel cells and biomass are still in their growth stage [2]. Microgrid systems, which are classified as AC or DC microgrids, could merge RES with household and industrial loads [3]. The differences between both types of microgrids as well as their advantages are deeply discussed in the literature. In fact, power electronic devices (PED) have recently become a must in grid integration, since photovoltaic systems output DC power while wind systems' output is in the form of variable frequency/voltage AC power. Additionally, some modern electronic loads, such as computers and plug-in hybrid electric vehicles, and even traditional AC loads such as induction motors, require DC power when driven by a variable-speed drive. Consequently, DC microgrids have been proven as one of the most efficient and cost-effective systems in the integration of RES with loads, as they decrease the AC-DC and DC-AC power conversion stages compared to AC microgrids [4]. Machine learning and artificial intelligence have shown promising performance in different electrical engineering applications as well as power system components, e.g., power transformers and high voltage transmission lines [5]. Figure 1 illustrates the power flow in AC grid and DC microgrid components in which the load and the PV generator are connected to the AC side. In turn, PV units and battery energy storage systems (BESS) are tied to the DC side which is connected to the AC side by DC/AC inverter.

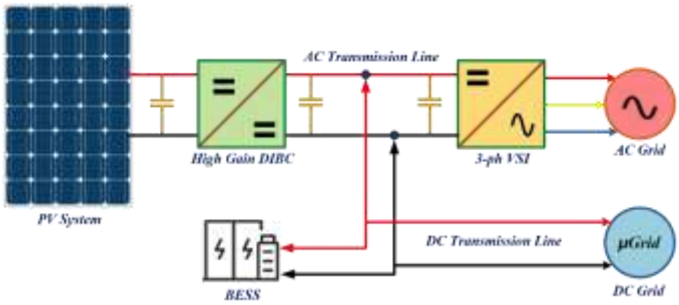

Fig. 1 Schematic block diagram of power flow of proposed System

The rest of the paper is organized as follows: The proposed PV-based DC microgrid structure in Section 2 and controller modeling are analyzed in Section 4. Detailed system configuration and modelling is illustrated in Section 3. Simulation results are presented in Section 5. Finally, the conclusions drawn from the results are presented in Section 6.

II. DESIGNING THE ARCHITECTURE OF PROPOSED APPROACH

In this paper, the integration of a PV system, a battery storage system, and DC load in a DC microgrid is simulated using the Simscape power systems toolbox, MATLAB/Simulink (2021a, MathWorks Inc., Natick, MA, USA) platform. The effects of various controllers on the voltage stability of the system is observed during different solar irradiation cases, load demands, batteries, and grid power transfers. In particular, DC–DC and DC–AC converters are managed to achieve DC voltage stability in the microgrid while the system is operated in two practical modes: (1) stand-alone and (2) grid-connected. The novelty of this work is that different operating techniques of the microgrid are simulated using the traditional Direct-Quadrature (DQ) control strategy in cooperation with the voltage current controllers, where the updated voltage-oriented current control regulates DC voltage and ensures power balance between sources and load. Additionally, maximum power generation from the photovoltaic system can be attained by the novel control strategy across different techniques for operating the microgrid. The proposed battery converter control can introduce stable operation and regulate DC voltage. The advantage of the integrated DC microgrid with batteries is that it accomplishes better flexibility and reliability while balancing power demand and generation. Accordingly, the microgrid can perform properly in both normal and sudden variation cases, thanks to the proposed control strategy that improves the voltage stability of the DC bus interconnected with energy storage systems and photovoltaics.

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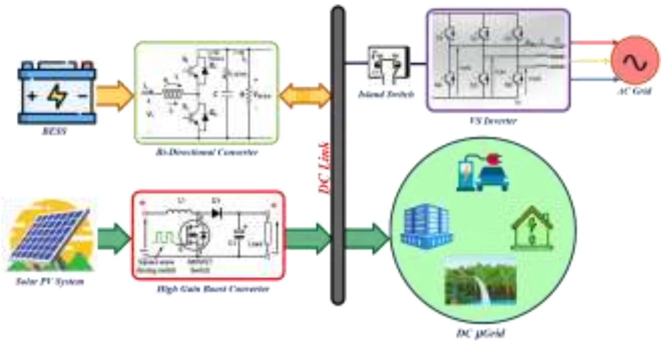

Fig. 2 Schematic block diagram of PV – BESS integrated Grid and DC μGrid

III. SYSTEM CONFIGURATION AND MODELING

The configuration of the proposed PV microgrid includes (1) PV arrays with the DC–DC boost converter and maximum power point tracking (MPPT), (2) a battery energy storage system (BESS) with DC–DC bidirectional buck–boost converters, (3) a voltage source converter (VSC) in the case of the grid-tied system. The utility grid is represented as the three-phase ideal voltage source. The BESS is used to maintain the power balance between PV power generation and the load demand in the islanded mode. A typical radial AC Grid and DC microgrid configuration is shown in Figure 2.

i. Photovoltaic System:

The single-diode circuit as it is characterized by its simplicity and accuracy. It is known also as the five-parameter model. The PV circuit is a shown in Figure 3 combination of a photo-generated controlled current source parallel to a single diode, series resistance, and parallel resistance representing power losses. The photovoltaic cell is constructed based on P–N junctions, which are made from semiconductor materials. Silicon is dominantly used due to its abundance, non-toxicity, high and stable cell efficiencies [6]. The I–V characteristic of the solar cell is given by simplicity, the below table shows the specifications implemented in proposed approach.

Table I: PV array specifications

Parameters	Value
Solar Irradiance; G_{ref}	1000 W/m^2
Cell temperature; T_{ref}	25^{o}C
Cell per each module	36
No. of modules connected in Parallel	10
No. of modules connected in Series	10
Open circuit voltage; V_{oc}	36.8 volts
Short circuit current; I_{sc}	5.96 Amps
Maximum voltage; V_m	34.7 volts
Maximum current; I_m	5.58 mps
Temperature co-efficient	6.175%

ii. Battery Energy Storage System

Solar power generation may exceed or fall behind load demand. In addition, intermittency of PV power leads to the need for BESS to store the surplus power, supply power when there are deficits, and maintain grid stability during fluctuations resulting from changes in weather conditions like cloud shadows on the PV array. The storage module consists of a Lithium-ion battery bank and a bidirectional DC–DC buck–boost converter. Lithium-ion batteries have high energy capacity, low maintenance needs, and a robust life cycle. The control of the bidirectional buck–boost converter regulates charging and discharging of the BESS based on DC bus voltage, so the control is designed in bus monitoring (BM) mode. The battery model can be modeled through a general dynamic model that can be described by the equations [7]:

$$V_{Bat} = E_g - i_{Bat}.R_{Bat} \quad (1)$$

$$E_g = E_{g_0} - K\frac{Q_R}{Q_R - \int i_{Bat}.dt} + Ae^{B\int i_{Bat}.dt} \quad (2)$$

where,

E_g = no-load voltage (V)

E_{go} = battery constant voltage (V)

K = polarization voltage (V)

Q_R = maximum battery capacity (Ah)

$i_{Bat}.dt$ = actual battery charge (Ah)

A = exponential zone amplitude (V)

B = exponential zone time constant inverse (Ah)

V_{Bat} = battery output voltage (V)

R_{Bat} = internal resistance (resistance that the battery opposes to the flow of energy) (W)

i_{Bat} = battery current (A)

iii. High Gain DIBC

In photovoltaic systems, the boost converter is often used in conjunction with Maximum Power Point Tracking algorithms to maximize the power extracted from the solar panels. The MPPT algorithm adjusts the duty cycle of the boost converter to match the impedance of the PV array to the load, ensuring that the panels operate at their maximum power point. This is essential for optimizing the overall efficiency of the photovoltaic system [8]. While the high gain double inductor DC boost converter offers advantages such as simplicity and low cost, it also faces limitations at high voltage gains due to increased component stress and losses. The schematic diagram of proposed converter and waveform of operation modes is depicted below in figure.

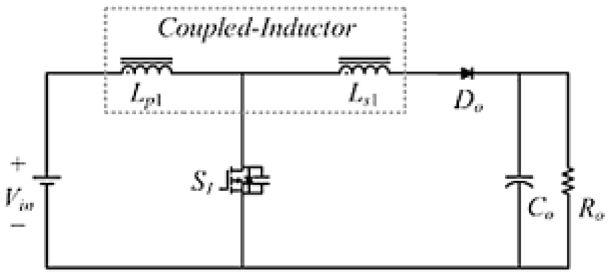

Fig. 3 Schematic diagram of High Gain DIBC

iv. Bi-Directional DC-DC Converter

The Bi-directional DC Converter focuses on the converter responsible for managing power flow between the battery energy storage system and the DC link. This converter enables both charging and discharging of the battery, allowing it to store excess energy from the PV array and supply power to the

DC microgrid when needed [9]. The bi-directional DC-DC converter is a crucial component for efficient energy management and ensuring the stability of the DC microgrid, especially during fluctuating PV generation or varying load demands.

(a) Buck mode (Discharge →Battery to DC bus):

When $V_{Bat} > V_{DC}$, and the converter steps down battery voltage:

$$V_L = V_{Bat} - V_{DC}.D \quad (3)$$

$$\frac{dI_L}{dt} = \frac{V_L}{L} = \frac{V_{Bat} - V_{DC}.D}{L} \quad (4)$$

(b) Boost mode (Charge → DC bus to Battery):

When $V_{Bat} < V_{DC}$, and the converter steps up to charge battery voltage:

$$V_L = V_{DC}.D - V_{Bat} \quad (5)$$

$$\frac{dI_L}{dt} = \frac{V_L}{L} = \frac{V_{DC}.D - V_{Bat}}{L} \quad (6)$$

v. Grid and Voltage Source Inverter

The grid circuit is composed of a three-phase AC voltage source, an inductive-capacitive-inductive (LCL) filter which is responsible for reducing voltage and current switching harmonics, and a converter. Although the capacitive–inductive–capacitive (CLC) filter has the merits of reduced cost and size, it is commonly used with low current equipment [10]. The used filter in the architecture is LCL, which has better capability in reducing total harmonic distortion compared to other filters, limits higher frequency current inflow, keeps the current harmonics in and around the operating frequency within the restricted limits, and could be designed to have a high dynamic response to meet the fast dynamics in power grids existing in Egypt. VSC is controlled to maintain the stability of the system and DC bus. A grid-connected VSC Control loop is used to adjust the DC voltage and generate pulse width modulation signals as shown in figure 5.

IV. CONTROL STRATEGY

For a Bi-Directional DC-DC Converter in a BESS-integrated solar photovoltaic system, a PI control strategy is commonly employed to regulate the voltage of the DC link and manage the power flow between the PV array, battery, and potentially a DC microgrid [13]. The PI controller adjusts the duty cycle of the converter switches to maintain the desired DC link voltage, ensuring stable operation and efficient power transfer. The error signal, derived from the difference between the reference voltage and the actual DC link voltage, is fed into the PI controller, which then generates a control signal to drive the converter [14].

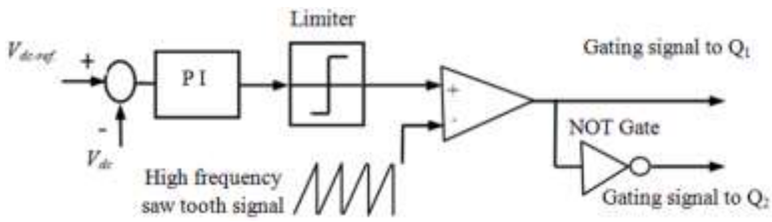

Fig. 4 Control approach of Bi-Directional DC Converter

The PI controller's performance significantly influences the system's dynamic response and stability. Pro per tuning of the proportional and integral gains is essential to achieve optimal performance, balancing factors such as settling time, overshoot, and steady-state error. Advanced optimization techniques, such as fuzzy logic, genetic algorithms, or particle swarm optimization, can be employed to determine the optimal PI controller parameters, as discussed in the previous turn [11]. Furthermore, the control strategy may incorporate additional features such as current limiting, state-of-charge management, and protection mechanisms to enhance the system's reliability and longevity [12].

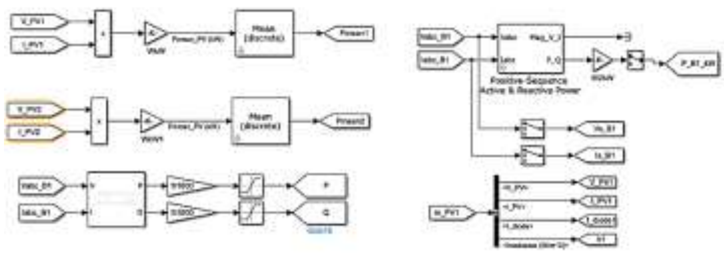

Fig. 5 Control signal of VSI for Grid connection

In a BESS-integrated solar photovoltaic system for grid and standalone DC microgrid applications, the grid-connected voltage source inverter plays a crucial role in converting the DC power from the PV array and battery storage into AC power suitable for grid. The VSI employs sophisticated control techniques, such as pulse width modulation, to generate a high-quality sinusoidal waveform with minimal harmonic distortion, ensuring compliance with grid codes and standards. Furthermore, advanced VSI control algorithms can be seen in the Simulink figure mitigate to enhance the overall efficiency and reliability of the grid-connected system.

V. RESULT AND DISCUSSIONS

The integration of PV microgrids with battery storage is simulated using the MATLAB/Simulink platform. The simulation sampling time is 10s, which is suitable to the switching frequency of the control components, so as to increase the accuracy of the controlling devices. Note that sampling time and hence sampling frequency is suitable for the switching frequency of the control components.

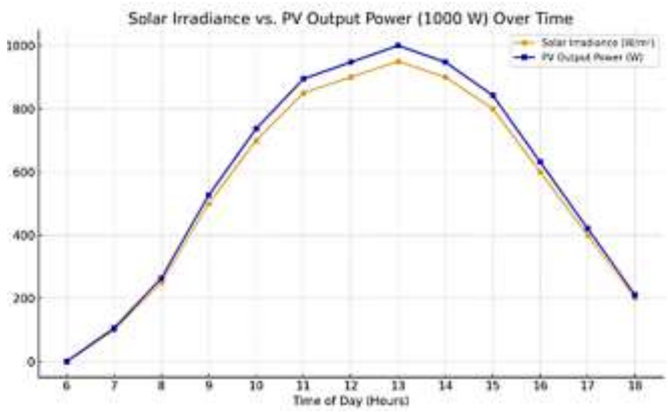

Fig. 6 Solar irradiance vs. PV output power over time.

The above figure demonstrate a clear correlation between the level of solar irradiance and the resulting power output from the photovoltaic system. The result illustrates the dynamic response of the PV system to changing environmental conditions, highlighting the importance of considering solar irradiance patterns when predicting system performance and optimizing energy management strategies.

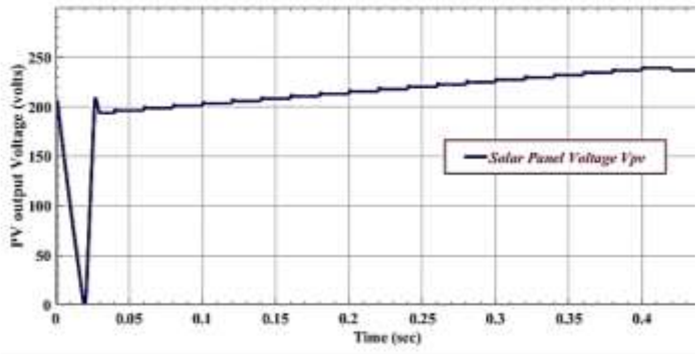

Fig. 7 DC output voltage from PV array

The results in figure 7 will showcase the stability and regulation of the DC voltage under varying solar irradiance conditions and load demands in evaluating the performance of the BESS-integrated solar photovoltaic system. Deviations from the nominal voltage may indicate issues with MPPT control, system imbalances, or the need for adjustments in the BESS operation.

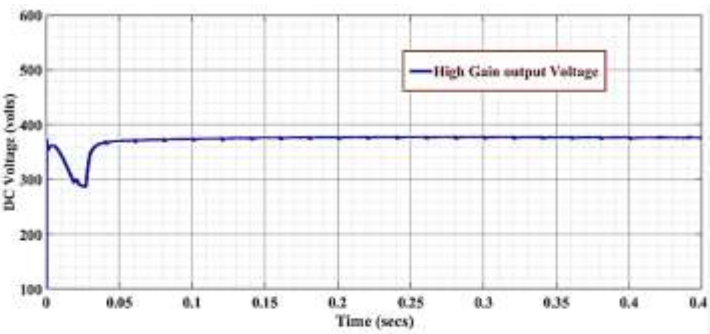

Fig. 8 DC output power from high Gain DIBC

The DC output power from the high gain double inductor boost converter, achieving 400V output, showcases the effectiveness of the converter in stepping up the voltage from the PV array to a level suitable for the DC microgrid or grid-tied inverter. The results should demonstrate the converter's ability to maintain a stable output power despite variations in input voltage (due to solar irradiance fluctuations).

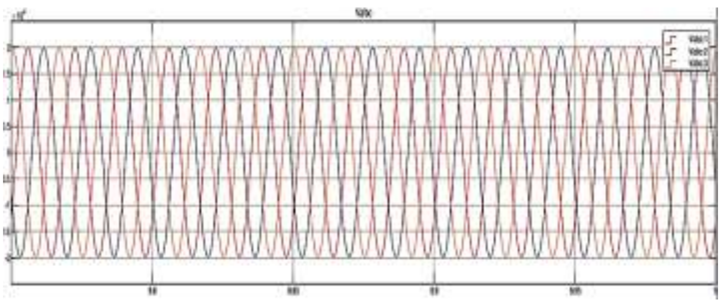

Fig. 9 VSI output voltages in a proposed PV-BESS system under varying insolation

The results in figure 9 illustrate the VSI's ability to maintain stable and sinusoidal AC output voltages delivered to the grid, even with fluctuations in solar irradiance. The analysis shows how the control system of the VSI modulates its switching patterns in response to the changing DC input from the PV array and battery, ensuring that the grid voltage remains within acceptable limit. The zoomed view of the 3-phase VSI converter output voltages in figure 10 provides a detailed look at the waveform quality and synchronization with the grid. This close-up view allows for precise measurement of parameters such as voltage magnitude, phase angle, and harmonic distortion. Ideally, the zoomed view should reveal clean, sinusoidal waveforms with minimal distortion, indicating proper operation of the VSI and effective control strategies.

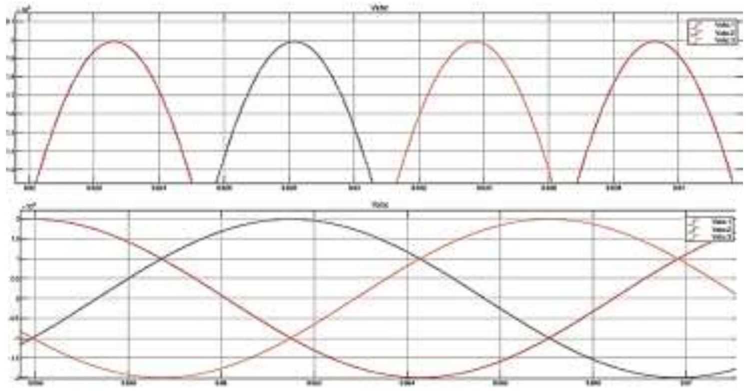

Fig. 10 Zoomed view of output of 3-ϕ VSI converter

VI. CONCLUSION

In conclusion, the affirmative integration of Battery Energy Storage Systems with solar photovoltaic infrastructures offers a transformative solution to the persistent challenges of intermittency and operational instability in both grid-tied and standalone DC microgrid systems. By leveraging advanced control strategies and intelligent energy management, the proposed approach significantly enhances system efficiency, reliability, and resilience. This work not only contributes to the optimization of distributed energy systems but also lays a foundation for future innovations in sustainable energy management, reinforcing the pivotal role of BESS-integrated PV systems in achieving a resilient and decarbonized power ecosystem.

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