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Renewable Energy Integration in Microgrids

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***Abstract*—The energy demand has kept on increasing over the years, with an increase in demand for clean and sustainable energy sources. To carry out efficient use of energy, renewable energy systems are being used with battery storage systems. In this paper, the performance of three-phase grid-connected PV BESS systems under different conditions is demonstrated. The incremental conductance MPPT algorithm is used for extracting the maximum power from the PV array. To ensure efficient use of energy a bi-directional converter was used for charging and discharging the battery. Achieving synchronization was possible because of dq0 transformation used by the grid and the 3phase voltage source inverter. To evaluate the system performance, it has been implemented in MATLAB Simulink. The results confirm that system's DC voltage is stable under power import and export. Also, a low THD value is recorded. The proposed system proves to be reliable for microgrid and renewable energy applications.**

***Index Terms*—Bi-directional DC-DC Converter, dq0 Transformation, Incremental Conductance MPPT, Power electronics, Three Phase Grid Connected Inverter.**

I. INTRODUCTION

The rapid growth in demand for energy and taking environmental concerns into consideration, we are actively moving towards renewable energy sources. Solar PV system is the fastest growing among the renewable energy sources because of their clean, abundant and sustainable nature. Although, the major challenge to overcome is intermittent behavior, as power generation relies on the environmental conditions like solar irradiance and temperature. This causes difficulties in maintaining continuous and reliable supply of power.

To overcome this discrepancy, the system has a Battery Energy Storage System (BESS). The battery acts as an energy buffer, by storing excess power during high generation period and supplying power during low generation or high demand period, improving system's reliability and supporting stable operation of the grid.

To achieve goals like grid synchronization, voltage stability and power quality, a converter plays an important role. A Bidirectional DC-DC Converter is employed to regulate PV output voltage and maintain DC bus voltage. Additionally, a voltage source inverter (VSI) is used to interface the system with the grid. Optimized control techniques are required to ensure efficient system operation. Incremental conductance a MPPT algorithm to fetch available maximum power from solar array is practiced. Moreover, the dq0 frame control method is widely adopted for inverter control, as it simplifies regulation of active and reactive power.

This paper focuses on developing a simulation Model for a three-phase grid connected Solar PV array integrated with an energy storage unit. System performance is analyzed with the help of MATLAB Simulink the study highlights effective power flow, a stable DC bus voltage regulation and improved power quality, making the proposed system suitable for microgrid and renewable energy applications.

II. LITERATURE SURVEY

The rising need for reliable energy solutions, deep research is being carried out on solar integration with energy storage and grid infrastructure. Various measures are being taken to improve the efficiency, power quality and control strategies in grid connected systems. The importance of the MPPT method for better efficiency is known from the studies conducted. Conventional method like Perturb & Observe is simple, but suffers from oscillations at maximum power point. To overcome this short come, Incremental Conductance method is proposed, this approach enhances accuracy under varying atmospheric conditions. This method determines the maximum power point; it compares incremental and instantaneous conductance to get improved tracking performance. Battery Energy Storage System (BESS) helps in balancing PV output. Batteries have proven to help in power fluctuations and grid reliability. Powering up and draining a battery is controlled by Bidirectional DC-DC Converter, allowing energy efficiency between PV system and grid.

The inverter plays a vital role in maintaining synchronization and power quality. The dq0 method is better than stationary reference method. This method converts three phase quantities into a rotating reference frame, which enables independent control of active and reactive power. It improves system stability and nearly operates at a unity power factor. Significant reduction of harmonic distortion is because of proper filtering technique and high frequency switching. For safe and efficient grid operation, maintaining Total Harmonic Distortion (THD) as per IEEE standards is mandatory. Improved load and energy management with stronger resilience of the system under dynamic conditions were observed.

The challenges like efficient power management, quick response to dynamic changes and maintaining power quality still requires attention. The present work aims to address these aspects by implementing an efficient MPPT technique, a bidirectional battery interface, and a dq0-based inverter control strategy for a three-phase grid-connected PV system.

III. PROPOSED SYSTEM ARCHITECTURE

The system has a three-phase grid connected to a solar PV system and also has a Battery energy storage system. This system is designed to fulfill purposes like continuous power supply; it ensures efficient energy usage and also it has stable grid connection. Overall, the system works smoothly. In simple words the system has a combination of solar panels, battery and grid so that power in this designed system is always available and stable too.

A. Solar PV Generation Unit:

The Solar PV generation unit converts the sunlight into electricity based on photovoltaic effect. The system architecture is structured so that it extracts maximum energy through sunlight. The unit consists of 15 panels in series which increases voltage while 2 strings in parallel which increases current. It has 7.5 kW total power while 250 W in panels. The power produced by a photovoltaic system depends on irradiance and temperature. Because of this the power is not constant as it depends on the weather. As solar output keeps changing, that is why we need MPPT. MPPT ensures that we always get maximum power which is possible from sunlight. MPPT has an electronic system that constantly adjusts the solar power operating voltage to extract the maximum obtainable power. Under standard test conditions (STC), the PV array has maximum voltage of 460.5 V and current of 8.15 A per spring, with peak output of 7.5 kW. The PV system acts as the main power source during daytime.

B. DC-DC Boost Converter and DC Bus:

Solar voltage is not stable and we need a regulated DC-link voltage. Maintaining regulated DC bus voltage is necessary for proper inverter operation and smooth grid synchronization. To obtain regulated DC-link voltage the DC-to-DC converter is used. Boost converter increases the variable PV output voltage and keeps it constant. The system's DC link acts as a common connection point between the PV system, Battery system and Inverter.

C. Battery Energy Storage System (BESS):

BESS enhances the reliability and flexibility of the overall system. We need BESS to store solar power as it is not always available. During the day too output of the solar power fluctuates. So we need BESS to store extra energy and to supply energy whenever it is needed. It consists of a lithium-ion battery which consists of 35 units in series and capacity is 48 Ah. It is managed by a Bidirectional DC-DC converter which has buck mode for charging and boost mode for discharging the battery.

D. Three Phase Voltage Source Inverter (VSI):

The Three-phase VSI converts the DC power from the DC bus into AC power and connects it to the utility grid. The inverter works using the advanced control techniques utilizing the dq0 transformation. This technique helps in decoupling real and imaginary power control. By this we get accurate control of power flow, and it ensures that the system functions at a unity power factor. The inverter and grid are connected through an LC filter; this reduces the switching harmonics and also enhances the quality of the output waveform. The inverter ensures synchronization with grid voltage and frequency, Controlled and proper power transfer between system and grid and Stable current output.

E. Grid and Load Interface:
The overall system is connected with a line-to-line voltage of 400 V and 50 Hz frequency. The system supplies DC load which is approximately 2500 W and AC load which is approximately 2000 W.
Depending on the solar power availability and the battery state of charge (SoC), the system can operate in different modes. In power export mode when PV generation is high and battery is charged sufficiently; in this case the excess power is supplied to the grid.
In power import mode when PV generation is low and battery charge is insufficient; power is taken from the grid to supply the loads and to charge the battery.
This intelligent power flow management ensures proper utilization of energy and reliable working of the system.

IV. CONTROL STRATEGY AND MODELING

A coordinated control strategy is applied to ensure efficient operation of the grid-integrated PV-BESS system. It includes MPPT control, DC-link voltage regulation, inverter control using dq0 transformation, and power flow management.
A. Incremental Conductance (Inc) MPPT:
The Incremental Conductance (InC) method is used to monitor the MPP of photovoltaic array.
The equation for the MPPT is: $dI/dV + I/V = 0$
The boost converter's duty cycle is adjusted based on this

B. DC-DC Converter and DC-Link Control:
It helps in balancing the PV output and maintaining a constant DC-link voltage.
The equation is $Vdc = Vpv/(1-D)$
The DC link voltage is maintained at desired reference value by the feedback loop control.

C. dq0-Based Inverter Control:
The inverter uses dq0 transformation to control power flow.

- Power Control

$$P = 3*\mathrm{Vd}*\mathrm{Id}/2,\ Q = 3*Vd*Iq/2$$

Id controls active power and Iq controls reactive power (zero for unity power factor)

- Current Control

A closed-loop controller generates PWM signals to ensure accurate current tracking and low harmonic

Distortion.

D. Grid Synchronization:
A Phase Locked Loop (PLL) is used to synchronize the inverter along with the grid by tracking the grid angle.

E. Battery Control:
A bi-directional DC-DC converter manages battery operation:

- Charging during excess PV generation
- Discharging during low PV output

F. Power Flow Control:

- Export Mode:
  Ipv>0.5A, SoC > 10%: Power supplied to grid
- Import Mode:
  Ipv<<0.5A, SoC < 10%: Power drawn from grid.

V. METHODOLOGY

The modelling and analyzing of the system are done with MATLAB Simulink for a 7.5kW three phase grid connected PV BESS system. This approach emphasizes on parameter-based design, control implementation, and validation under varying operating conditions.

A. System Parameters:
The PV array is 15 series × 2 parallel modules with:

$$Vmp = 460.5\text{V}$$
$$Imp = 8.15\text{ A}$$

The DC link is kept constant near 700V for proper inverter operation. The battery system consists of 35 series lithium-ion cells (48 Ah) connected through a bi-directional converter.

B. Converter Design:
The switching frequency of the DC-DC converter is 10 kHz.
The switching frequency of Inverter is 7.5 kHz
LC filter rating: 8 kW
Current ripple limit: 2%
Selection of these parameters are done on the criteria

of maintaining stability and reduction in harmonics.

C. Control Implementation:
The control system includes:
Inc MPPT method enables maximum power point tracking (1000–10 W/m²).
DC-link voltage control maintains 700 V.
dq0 based inverter control with Id for controlling active power and $Iq = 0$ To reach unity power factor.
PLL is for grid synchronization.

D. Power Flow Strategy:
The system operation depends on PV current and battery state of charge.

Export Mode: When PV current > 0.5A and State of Charge > 10%, the power is supplied into the grid with a reference current of −3A (at approximately 1460 W).

Import Mode: When PV current < $0.5A$ and state of charge < 10%, power is taken from the grid with a reference current of 10 A (at approximately 4830 W).

The battery operates in charging or discharging mode in order to maintain power balance.

VI. RESULT

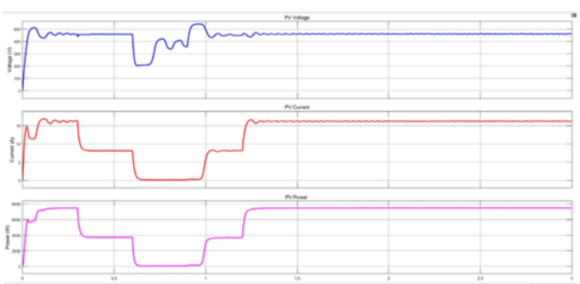

Fig 1: PV Measurement

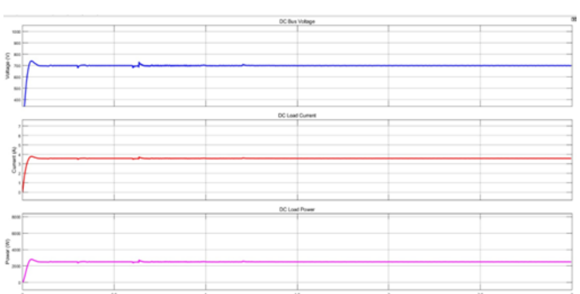

Fig 2: DC Load Measurement

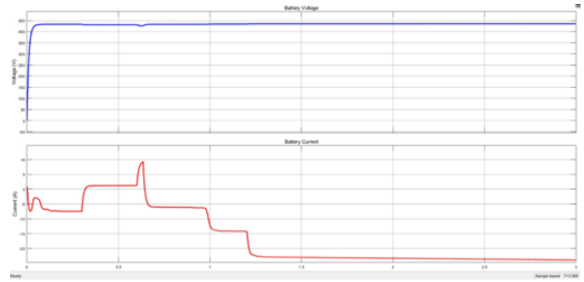

Fig 3: Battery Measurement

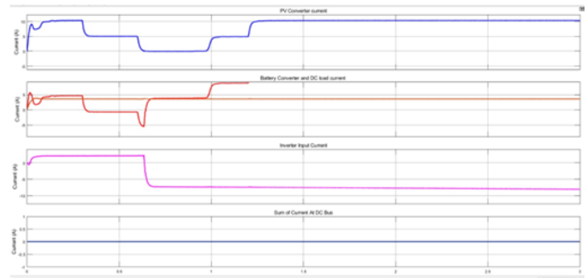

Fig 4: DC Bus Current

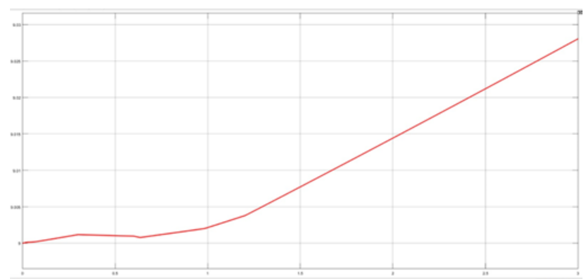

Fig 5: Battery SOC

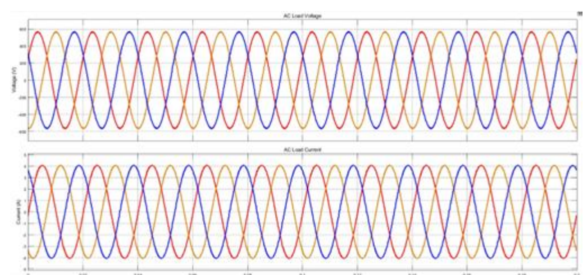

Fig 6: AC Load

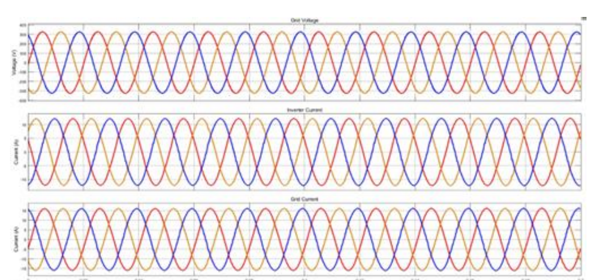

Fig 7: Grid Measurement

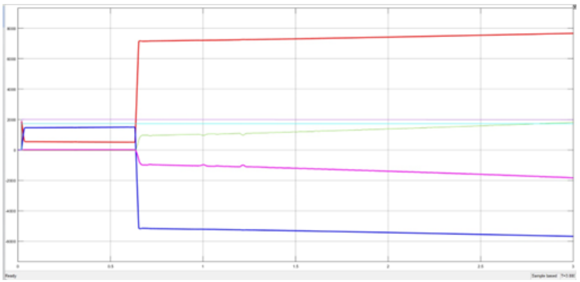

Fig 8: Power

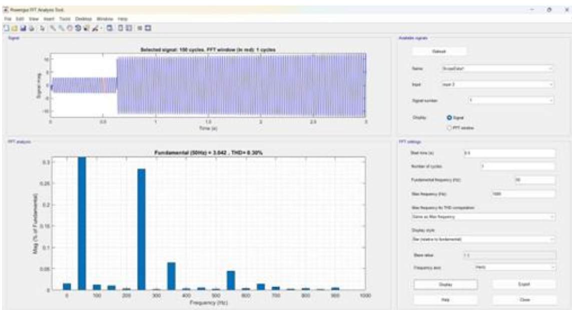

Fig 9: Total Harmonic Distortion

Fig 1: PV Measurement graph shows the variation of PV voltage, current and power under the various irradiance conditions. At high irradiance (1000 W/m²) the PV produces around 7.5 kW. As the irradiance decreases to 500 W/m² the PV also reduces and comes around 4 kW and further it drops to near to zero. When irradiance increases again, the PV output also increases. The MPPT ensures that the system works at maximum power point by effectively tracking maximum available power.

Fig 2: DC Load Measurement graph shows us DC Bus Voltage, DC Load Current and DC Load Power. Fig 2 shows that the DC voltage is maintained constant around 700 V throughout the simulation. Also, the current stays stable which results in a load power of approximately 2500 W. There are minor fluctuations due to system response to changing irradiance conditions. This ensures continuous and stable power supply to the DC load.

Fig 3: Battery Measurement graph shows that the battery voltage stays constant (430-440 V) showing stable battery operation. But the battery current can be seen fluctuating. Battery negative current indicates battery is charging while the positive current indicates battery discharging. During low PV generation the battery discharges to support the load, while during high PV generation, the battery charges. This change happens due to changes in irradiance. This shows the operation of a bidirectional DC-DC converter.

Fig 4: DC Bus Current has PV Converter Current which shows that converter current varies according to solar irradiance. PV current is high when there is good sunlight and drops at low irradiance. Battery Converter Current in the graph changes direction depending on charging or discharging mode. The inverter input current shows the power exchange with the AC side and the sum of currents at the DC bus stays zero showing and confirming that the power is balanced in the system.

Fig 5: It shows gradual increase in battery SoC over time, indicating it is operating in charging mode especially when excess power is available from PV or grid. The smooth variation in soc confirms stable battery operation. The charging and discharging of the SoC is based upon the PV power.

Fig 6: AC Load graph shows AC Load Voltage and AC Load Current are three-phase balanced sinusoidal waveforms having 120° phase difference between each phase. The clean sinusoidal waveform indicates to us that the system is maintaining a high-power quality and operates at unity power factor.

Fig 7: Here the grid voltage, inverter current and grid current are sinusoidal which shows proper synchronization. It indicates effective dq0 control, low harmonic distortion and good power quality.

Fig 8: It shows PV Power, grid Power and load Power. It represents power flow within the system. Initially when PV generates sufficient power the power is supplied to load and partially interacts with the grid (export mode). Around 0.6 due to sudden drop in irradiance change occurs. As there is now less power the system operates in import mode and power is taken from the grid. Load power remains the same while grid power changes accordingly showing power flow management.

Fig 9: After performing FFT analysis with taking start time as 0.5 sec the total harmonic distortion (THD) comes around 0.30%. So, the THD of the inverter current is less than 5% only according to IEEE standards.

VII. CONCLUSION

This paper presented a three-phase grid-connected solar PV system integrated with BESS to improve reliability and efficiency. The use of Incremental Conductance MPPT allows maximum power extraction, while the bidirectional converter enables effective battery management. The dq0-based inverter control provides proper grid synchronization and maintains good power quality. Simulation results show stable DC bus voltage, smooth power flow, and low harmonic distortion under varying conditions. Overall, the proposed system offers an efficient and reliable model for renewable energy integration and microgrid applications.

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