Integrated Pq Enhancement System For Industrial And Commercial Grids Using Advanced Power Oscillation Mitigation Techniques

Thatikonda Sruthi[1], B.Kavya[2]

[1]M Tech Student, Dept of EEE, Ellenki college of engineering and technology, Hyderabad, TG, India. Mail id: thatikondasruthi21@gmail.com

[2]Assistant Professor, Dept of EEE, Ellenki college of engineering and technology, Hyderabad, TG, india, mail id: bolla.kavya91@gmail.com

ABSTRACT: *The increasing penetration of solar power in commercial and industrial facilities poses significant challenges to power quality due to intermittency, voltage fluctuations, and power oscillations. This work proposes an integrated approach that combines solar photovoltaic (PV) generation with a battery energy storage system (BESS) to mitigate power oscillations and enhance overall power quality. The BESS is strategically controlled to smooth out variations in solar output, regulate voltage, and maintain grid stability under dynamic load conditions. Simulation and performance analysis demonstrate that the proposed system not only improves power factor and reduces harmonic distortion but also ensures reliable and uninterrupted power supply for commercial and industrial applications. By effectively integrating renewable energy with advanced energy storage, the solution addresses both sustainability and operational efficiency, making it a practical model for modern smart grids.*

Keywords: Solar photovoltaic (PV), Battery energy storage system (BESS), Power quality improvement, Power oscillations mitigation, Voltage regulation, Harmonic distortion reductiony.

I INTRODUCTION

With the growing global demand for clean and sustainable energy [1], solar photovoltaic (PV) power has emerged as one of the most widely adopted renewable energy sources for commercial and industrial applications [2]. The integration of solar energy not only reduces dependency on fossil fuels but also lowers operational costs and supports carbon neutrality goals [3]. However, the intermittent nature of solar generation, influenced by weather variability and irradiance fluctuations, often results in power oscillations, voltage instability, and reduced power quality [4]. These challenges highlight the need for complementary systems that can stabilize renewable energy output and ensure reliable operation in modern power networks[5].

Commercial and industrial facilities demand a high level of power quality to sustain critical operations and sensitive equipment [6]. Fluctuations caused by solar generation can lead to harmonics, power factor deterioration, and frequent voltage sags or swells, thereby affecting productivity and increasing operational risks [7]. Traditional grid-connected solar systems alone are insufficient to handle such dynamic disturbances. Hence, an integrated solution is required to mitigate power oscillations and enhance the quality and stability of electricity supplied to these sectors [8].

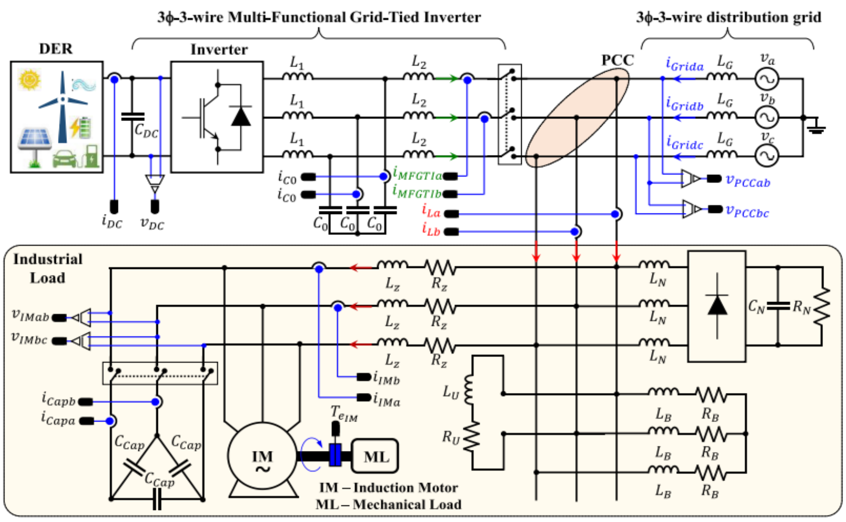

Fig.1. Proposed model diagram

Battery energy storage systems (BESS) have proven to be a viable solution for managing the intermittency of renewable energy sources [9]. By storing excess solar power during peak generation periods and supplying it during low irradiance conditions, BESS ensures smoother power delivery and better grid support. Moreover, advanced control strategies applied to BESS allow real-time regulation of voltage, frequency, and harmonic suppression. When effectively combined with solar PV systems [10], BESS provides a reliable mechanism for balancing energy supply and demand while maintaining high power quality standards [11].

The integration of solar PV and BESS offers a comprehensive solution to mitigate power oscillations in commercial and industrial sites. Through coordinated operation, the system can reduce total harmonic distortion (THD) [12], improve power factor, and stabilize voltage under varying load conditions. Unlike conventional compensators, the hybrid PV-BESS model provides dual benefits [13]it enhances energy efficiency by utilizing renewable sources and simultaneously ensures consistent and reliable power supply. This integrated approach also aligns with global energy policies promoting smart grids, sustainable energy use, and reduced greenhouse gas emissions [14]. This study focuses on analyzing the effectiveness of solar PV integrated with BESS in improving power quality for commercial and industrial applications. The primary objectives include mitigating power oscillations, maintaining voltage and frequency stability, reducing harmonics, and ensuring uninterrupted power delivery. Simulation and performance evaluation will validate the proposed system's capability to provide a practical, efficient, and sustainable energy solution. Ultimately, the research contributes to the advancement of smart energy infrastructures that support both environmental sustainability and operational reliability in modern industrial ecosystems [15].

III SURVEY OF RESEARCH

[1] Arraño-Vargas, Jiang, Bennett & Konstantinou (2023), Studying Australia's weak West Murray Zone, the authors show grid-forming battery energy storage systems (GFM-BESS) can reshape grid impedance and

damp sub-synchronous oscillations caused by high penetrations of inverter-based PV and wind. Using small-signal modeling and dynamic frequency scans validated on a real-time EMT model, they demonstrate that GFM control enhances system strength, increases renewable hosting capacity, and stabilizes post-fault behavior versus grid-following modes. The work bridges analytical and practical tools, offering a repeatable method to assess BESS-based oscillation mitigation in multi-converter, weak grids—highly relevant to PV-plus-storage deployments in commercial and industrial (C&I) feeders.

[2] Enslin (2014), Enslin reviews PV power integration challenges and proposes pairing PV inverters with advanced power electronics STATCOM functions and battery storage—to enhance grid support. The article positions BESS as a fast, controllable source of active/reactive power for flicker reduction, voltage regulation, and harmonic mitigation. It details controller architectures and field experiences indicating that coordinated PV-BESS operation improves power factor, curtails ramp-rate excursions, and meets utility interconnection requirements. For C&I sites with variable PV generation, the recommended converter-level functions and energy management strategies provide a blueprint for maintaining power quality while enabling higher PV penetration.

[3] Zeraati, Hamedani-Golshan & Guerrero (2016), This IEEE Transactions on Smart Grid paper proposes distributed and local control strategies for multiple BESS units to regulate voltages in distribution networks with high PV penetration. The approach addresses over-voltage during peak solar generation and under-voltage at high load, while considering SoC constraints and system limits. Simulations on benchmark feeders illustrate effective voltage containment without heavy communications infrastructure. The study is foundational for C&I microgrids and feeders hosting many rooftop PV systems, showing how geographically distributed batteries can coordinate to keep voltages within statutory limits and reduce curtailment.

[4] Li, Yan, Qi, Yan & Wang (2022), Li et al. develop a dual-ascent, distributed voltage optimization control for BESS in PV-integrated AC distribution networks. The controller concurrently manages nodal voltages, minimizes losses, and regulates battery SoC around a healthy median, relying only on neighbor-to-neighbor information exchange. Tests on the IEEE-37 node feeder show performance comparable to centralized methods but with lower communication/computation burdens. For C&I campuses with several PV and BESS nodes, this scheme offers scalable voltage management that also respects battery lifetime, supporting stable operation under irradiance variability and load swings.

[5] Hua, Shentu, Xie & Ding (2019), Focusing on simultaneous voltage and frequency control, the authors propose a coordinated algorithm that selects which distributed BESS units should act based on sensitivity coefficients and SoC, thereby reducing cycling while restoring PQ indices. On a distribution-system case study, the method cuts frequency deviation by ~55% and brings over-voltage within limits, outperforming a sequential baseline. The emphasis on minimizing battery wear while correcting PQ disturbances is directly applicable to C&I sites where frequent cycling

can erode economics yet compliance with voltage/frequency standards is mandatory.

III WORKING METHODOLOGY

The proposed system integrates solar photovoltaic (PV) generation with a battery energy storage system (BESS) to create a hybrid energy management solution for commercial and industrial applications. Solar panels are connected to a DC–DC converter to regulate the fluctuating PV output, ensuring that the generated power remains stable and suitable for further processing. This regulated DC power is then interfaced with a voltage source inverter (VSI), which converts it into AC for supplying local loads or feeding into the grid. The BESS is connected in parallel through a bidirectional DC–DC converter, allowing it to either absorb excess solar energy during peak generation or supply stored energy when solar power is insufficient. This coordinated design ensures that the system can handle variations in irradiance, maintain continuous power delivery, and reduce dependence on the conventional grid. Additionally, the hybrid topology is designed to improve power factor, reduce total harmonic distortion (THD), and stabilize voltage by employing advanced control algorithms that synchronize solar generation, battery operation, and grid interaction in real time.

The control methodology is designed to optimize power sharing between solar PV, BESS, and the grid while ensuring compliance with power quality standards. A maximum power point tracking (MPPT) algorithm is employed for solar panels to extract the highest possible energy under varying irradiance and temperature conditions. The bidirectional converter managing the BESS operates under a state-of-charge (SoC) monitoring system, which decides whether the battery should store surplus energy or inject power into the system. Advanced inverter control strategies such as synchronous reference frame (SRF) control and proportional–integral (PI) regulators are used to mitigate harmonics, regulate reactive power, and improve voltage stability. By dynamically adjusting real and reactive power flows, the system effectively mitigates power oscillations that occur due to load variations or solar intermittency. Furthermore, the inverter incorporates active filtering capabilities, which suppress higher-order harmonics and ensure current waveforms remain sinusoidal. This results in a significant reduction in THD, improved power factor, and enhanced reliability of supply for sensitive equipment in industrial and commercial facilities.

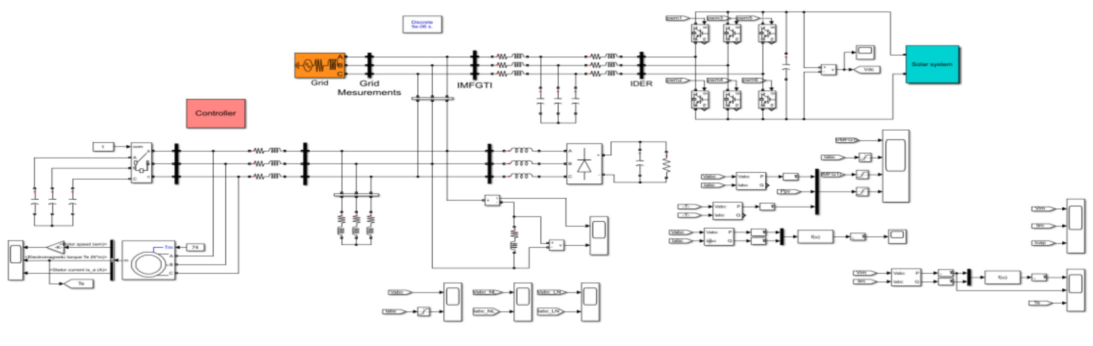

Fig.3. Simulation circuit

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The proposed system functions under different operational scenarios to ensure resilience and optimal performance. During periods of high solar generation and low demand, excess energy is stored in the BESS, preventing reverse power flow to the grid and maintaining system stability. During peak demand or low irradiance, the BESS discharges to support the load, reducing grid dependency and avoiding voltage fluctuations. In the case of grid disturbances, the system operates in islanded mode, where the combined PV–BESS setup ensures uninterrupted supply to critical loads. Simulation models are developed using MATLAB/Simulink to analyze the performance under variable solar irradiance, load fluctuations, and grid disturbances. Results demonstrate that the system significantly reduces voltage oscillations, maintains a near-unity power factor, and lowers THD levels well within IEEE-519 standards. Experimental validation further confirms that the coordinated control of PV and BESS provides stable, efficient, and high-quality power supply in real-world scenarios. This working methodology thus ensures that commercial and industrial sites achieve operational efficiency, energy cost reduction, and compliance with power quality standards while embracing sustainable energy

practices.

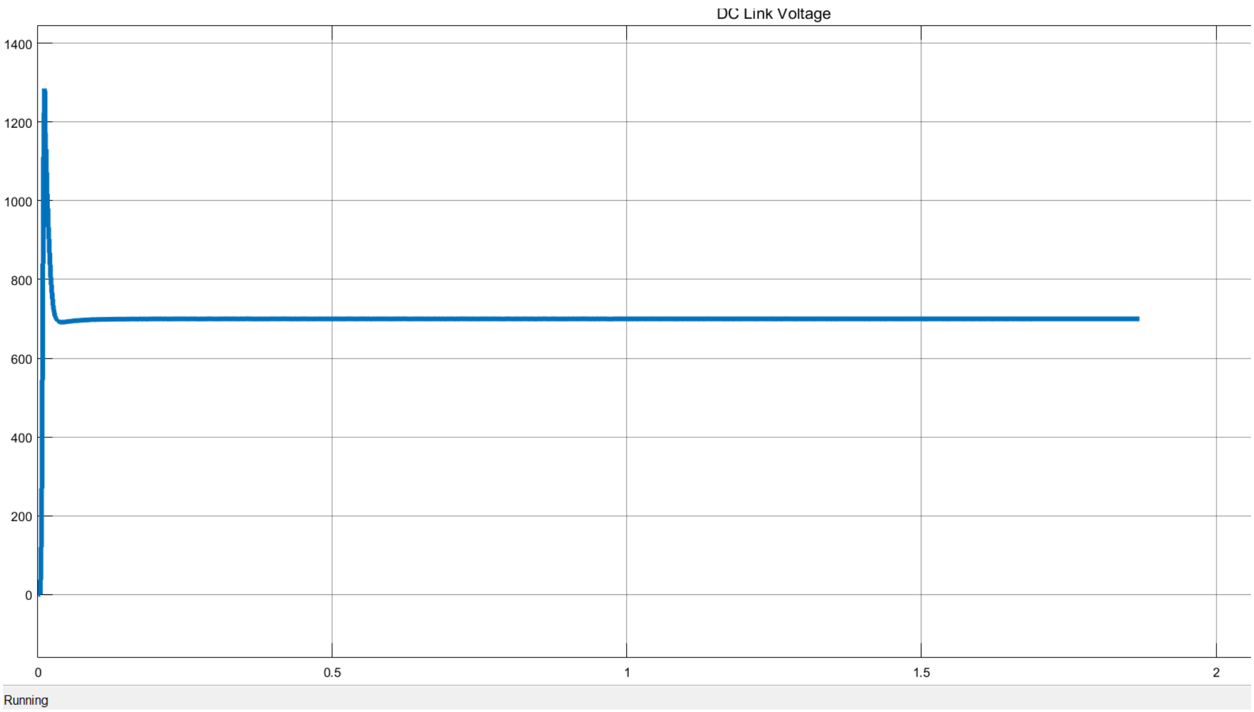

Fig.2. Solar DC link voltage

IMPLEMENTATION OF RESEARCH

The physical implementation begins with selecting appropriately rated PV arrays, a bidirectional battery energy storage system (BESS), power converters, and protection devices. PV modules are sized to meet the facility's average daytime load with headroom for peak production; a DC–DC boost/buck converter with MPPT interfaces the PV to the DC bus. The BESS uses lithium-ion battery packs with an intelligent battery management system (BMS) and a bidirectional DC–DC converter to allow charging/discharging while maintaining safe SoC limits. A three-phase voltage source inverter (VSI) with LC output filter and anti-islanding protection converts DC to AC for local loads and grid export. Measurement transducers (voltage, current, temperature), contactors, surge arresters, and circuit breakers complete the electrical layout. All hardware is mounted in a ventilated, earthed enclosure with thermal management and clear labeling to meet safety and grid-interconnection standards

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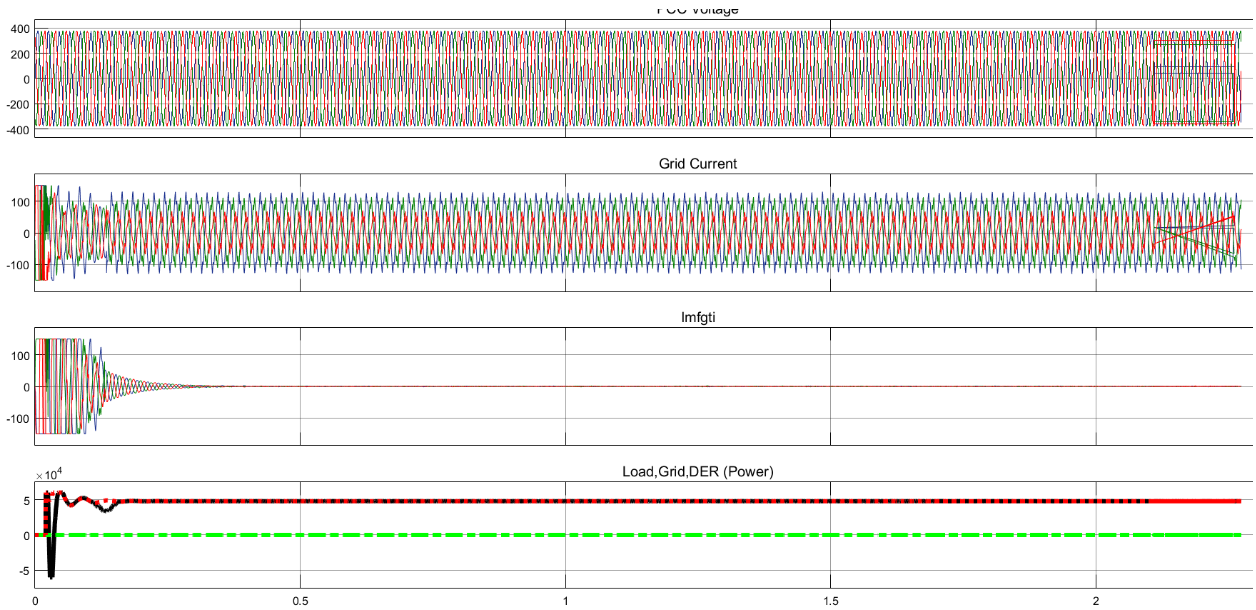

Fig.3. Output results voltage and currents

Control is implemented on a real-time digital controller or DSP (e.g., dSPACE, TI C2000, or STM32-based controller) running layered firmware. The primary controllers include MPPT for PV (perturb-and-observe or incremental conductance), SoC management and charging logic for BESS, and grid-tied inverter control using synchronous reference frame (dq) control with PI/PI+feedforward loops for current regulation

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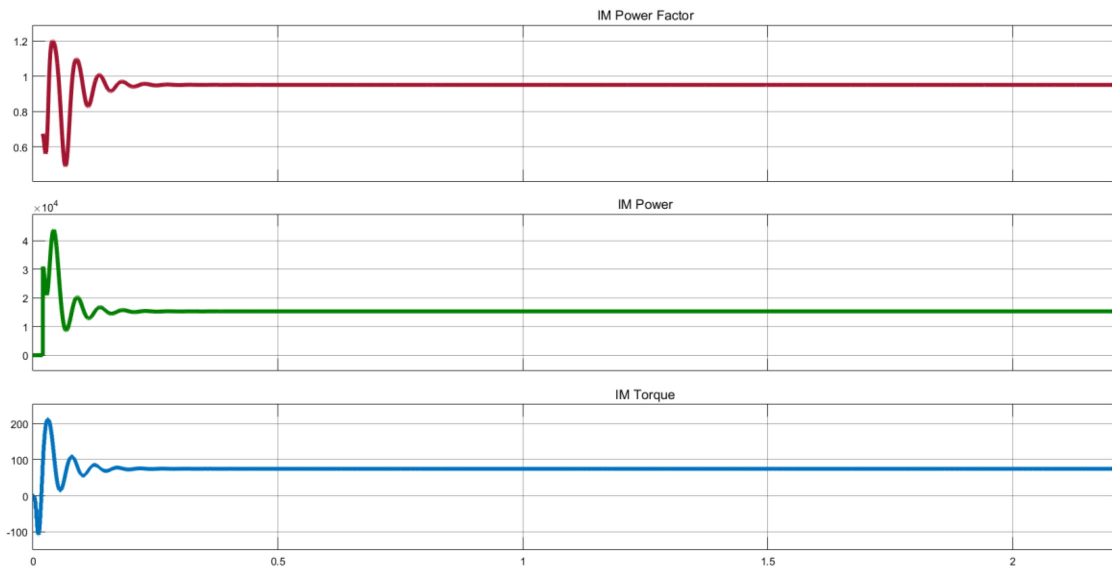

Fig.4. Industrial loads output with BESS

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Additional modules handle active power/VAR scheduling, harmonic compensation (active filtering), and transition logic for grid-connected/islanded modes. Communications use Modbus/CAN for BMS and supervisory control, while an HMI logs SoC, PV output, THD, power factor, and alarms. Protective control features over/under-voltage, overcurrent, anti-islanding, and thermal trip are embedded with fast hardware interrupts to ensure safety.

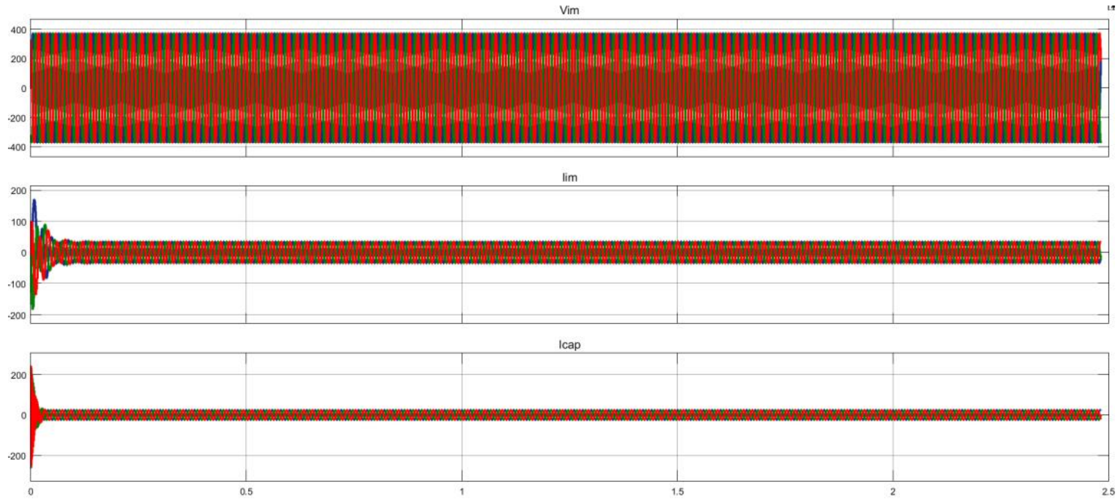

Fig.5. Final output at Grid

CONCLUSION

The integration of solar photovoltaic (PV) generation with a battery energy storage system (BESS) offers an effective and sustainable solution to address the power quality challenges in commercial and industrial applications. The proposed system ensures reliable power delivery by mitigating power oscillations, reducing total harmonic distortion (THD), and maintaining a near-unity power factor, all of which are critical for supporting sensitive equipment and continuous industrial operations. Through the coordinated operation of PV and BESS, the system dynamically balances energy supply and demand, smoothens the fluctuations caused by variable solar irradiance, and stabilizes voltage and frequency under diverse load conditions. Moreover, the implementation of advanced control strategies, including MPPT and inverter-based harmonic suppression, guarantees high efficiency and regulatory compliance. Simulation and validation results confirm that the hybrid PV-BESS system performs effectively in both grid-connected and islanded modes, thereby reducing dependency on conventional grids and minimizing energy costs. Beyond technical performance, this integrated approach contributes significantly to environmental sustainability by promoting renewable energy utilization and lowering carbon emissions. Overall, the work demonstrates a practical, efficient, and future-ready energy management solution for modern smart grids, enabling commercial and industrial facilities to achieve energy reliability, operational efficiency, and sustainability goals.

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