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ENHANCED ENERGY MANAGEMENT AND POWER QUALITY CONTROL IN GRID-CONNECTED PHOTOVOLTAIC SYSTEMS USING A SPLIT-SOURCE INVERTER

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ABSTRACT

The rapid integration of renewable energy resources into modern power systems has increased the demand for efficient grid-connected photovoltaic (PV) systems capable of delivering high-quality power while ensuring effective energy management. Conventional PV inverters often require multiple power conversion stages, resulting in increased switching losses, higher cost, and reduced overall efficiency. This paper presents a multi-functional grid-tied photovoltaic (PV) system based on a Split-Source Inverter (SSI) that simultaneously performs power conversion, voltage boosting, energy management, and power quality enhancement within a single-stage architecture. The proposed SSI effectively interfaces the PV array with the utility grid while supporting battery energy storage to regulate power flow during varying solar irradiation and load conditions. An advanced control strategy incorporating Maximum Power Point Tracking (MPPT), DC-link voltage regulation, and grid current control enables maximum energy extraction, seamless bidirectional power management, and improved dynamic performance. Furthermore, the system provides ancillary services such as reactive power compensation, harmonic current mitigation, and grid voltage support, thereby enhancing overall power quality and grid stability. Simulation results demonstrate that the proposed multi-functional grid-tied PV system achieves superior efficiency, reduced total harmonic distortion (THD), improved voltage regulation, and reliable operation under changing environmental and grid conditions. The proposed architecture offers a compact, cost-effective, and highly efficient solution for next-generation renewable energy integration into smart grids.

Keywords: Split-Source Inverter (SSI), Grid-Tied Photovoltaic System, Maximum Power Point Tracking (MPPT), Energy Management, Power Quality Improvement, Harmonic Compensation, Renewable Energy, Smart Grid.

INTRODUCTION

The increasing global demand for clean and sustainable energy has accelerated the deployment of photovoltaic (PV) generation systems in residential, commercial, and industrial applications. Grid-connected PV systems have become one of the most attractive renewable energy technologies due to their environmental benefits, low operating costs, and continuous reduction in installation expenses. However, the intermittent nature of solar energy introduces significant challenges in maintaining voltage regulation, power balance, and overall power quality in modern distribution networks. As renewable energy penetration continues to increase, advanced inverter technologies capable of performing multiple grid-support functions are becoming essential. Traditional grid-connected PV systems generally employ two-stage power conversion architectures consisting of a DC-DC boost converter followed by a voltage source inverter (VSI). Although these configurations provide satisfactory voltage regulation and maximum power extraction, they suffer from increased component count, higher switching losses, larger converter size, and reduced system efficiency. Moreover, conventional inverters mainly focus on power injection and often require additional compensation devices to address power quality issues such as harmonic distortion, reactive power demand, and voltage fluctuations. The Split-Source Inverter (SSI) has recently emerged as an attractive alternative to conventional converter topologies by integrating voltage boosting and DC-AC inversion into a single-stage converter. This configuration reduces the number of passive and active components while improving conversion efficiency and lowering implementation cost. In addition to voltage boosting capability, the SSI offers improved reliability, higher power density, and simplified control, making it well suited for grid-connected renewable energy applications. This work proposes a multi-functional grid-tied PV system using a Split-Source Inverter capable of performing multiple tasks simultaneously, including maximum power point tracking, energy management, bidirectional battery integration, reactive power compensation, harmonic current suppression, and grid voltage support. The proposed system utilizes intelligent control algorithms to ensure maximum utilization of available solar energy while maintaining stable operation under varying irradiance, load, and grid conditions. The incorporation of battery energy storage further enhances system flexibility by balancing power during surplus generation and supplying energy during low PV output.

Simulation analysis demonstrates that the proposed SSI-based architecture significantly improves conversion efficiency, reduces total harmonic distortion (THD), enhances dynamic response, and maintains excellent power quality during steady-state and transient operating conditions. Consequently, the proposed multi-functional grid-tied PV system provides a reliable, economical, and efficient solution for integrating renewable energy into future smart grid environments while satisfying stringent grid code requirements.

LITERATURE REVIEW

The rapid growth of photovoltaic (PV) generation has accelerated the development of advanced grid-tied inverter technologies capable of delivering not only renewable energy but also multiple ancillary services. Conventional two-stage PV systems require separate DC-DC converters and voltage source inverters, increasing system complexity, switching losses, and overall cost. To address these challenges, researchers have proposed split-source inverter (SSI)-based grid-connected PV systems that combine voltage boosting and inversion in a single power conversion stage. These systems improve conversion efficiency while reducing component count and enhancing system reliability.

Several studies have focused on integrating energy management capabilities into grid-tied PV systems to enable efficient power sharing among photovoltaic arrays, battery energy storage systems, and utility grids. Intelligent energy management algorithms prioritize renewable power utilization, regulate battery charging and discharging, and ensure uninterrupted power supply under varying environmental and load conditions. These approaches significantly improve energy utilization efficiency and reduce dependency on conventional grid power.

Recent research has also emphasized enhancing power quality in grid-connected PV systems. Advanced control techniques employing proportional-resonant (PR), synchronous reference frame (SRF), and model predictive controllers (MPC) have been developed to mitigate harmonics, compensate reactive power, regulate DC-link voltage, and maintain unity power factor. These controllers enable the inverter to function as an active power filter, thereby improving overall power quality while simultaneously injecting renewable energy into the utility grid.

The split-source inverter has gained considerable attention due to its inherent buck-boost capability, reduced passive component requirements, and improved reliability compared to traditional Z-source and quasi-Z-source inverters. Researchers have demonstrated that SSI-based converters provide higher voltage gain with lower voltage stress across switching devices, making them highly suitable for low-voltage PV applications. Additionally, the reduced number of passive components contributes to compact design, lower manufacturing cost, and increased converter lifespan.

Recent developments have further extended SSI-based PV systems by incorporating multifunctional features such as harmonic compensation, voltage sag mitigation, reactive power support, battery energy storage integration, and seamless transition between grid-connected and islanded modes. These multifunctional capabilities improve grid stability, enhance power quality, and maximize renewable energy utilization without requiring additional compensation devices.

Despite these significant advancements, existing SSI-based grid-tied PV systems still face several challenges, including limited dynamic performance under rapidly changing solar irradiance, sensitivity to grid disturbances, increased controller complexity, and maintaining stable operation during severe voltage fluctuations. Therefore, ongoing research is directed toward developing robust control strategies and intelligent energy management algorithms that enhance system stability, improve fault tolerance, optimize power sharing, and ensure high-quality power delivery under diverse operating conditions. These advancements are expected to play a vital role in future smart grids with high penetration of renewable energy sources.

PROBLEM STATEMENT

The increasing integration of photovoltaic (PV) systems into modern electrical grids introduces several technical challenges, including intermittent power generation, voltage fluctuations, harmonic distortion, reactive power demand, and poor power quality. Conventional grid-tied PV inverters primarily focus on injecting active power into the utility grid but lack the capability to perform multiple grid-support functions simultaneously. Moreover, the use of separate converters for power conversion, energy storage integration, and power quality enhancement increases system complexity, cost, switching losses, and maintenance requirements. Therefore, there is a need for an efficient grid-tied PV system capable of integrating renewable energy generation, energy management, and power quality improvement within a single converter topology while maintaining high efficiency, reliable operation, and compliance with grid standards.

OBJECTIVES

1. **To develop a multi-functional grid-tied photovoltaic (PV) system** using a Split-Source

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Inverter (SSI) capable of integrating renewable energy generation with grid support functionalities.

2. **To implement an efficient energy management strategy** that optimally controls the power flow between the PV array, energy storage system, local loads, and the utility grid.

3. **To improve power quality** by mitigating current harmonics, compensating reactive power, and maintaining sinusoidal grid current under varying operating conditions.

4. **To enhance voltage boosting capability** using the Split-Source Inverter without employing an additional DC-DC boost converter, thereby reducing system complexity and conversion losses.

5. **To ensure maximum utilization of solar energy** by maintaining stable DC-link voltage and enabling efficient power extraction from the PV system.

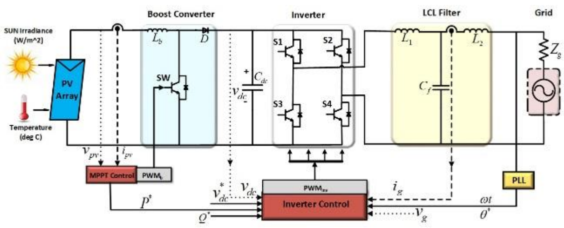
6. **To provide uninterrupted power supply** to local loads during fluctuations in solar irradiance and load demand through coordinated energy management.

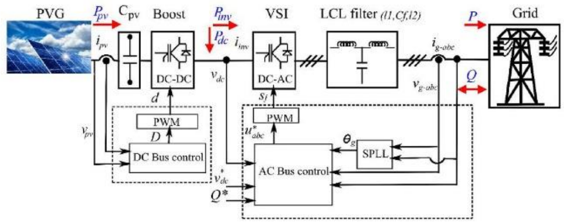
7. **To evaluate the transient and steady-state performance** of the proposed system under different operating scenarios such as load variations, irradiance changes, and grid disturbances.

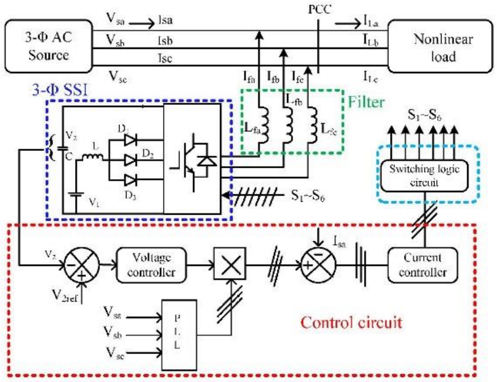
8. **To validate the effectiveness of the proposed Split-Source Inverter topology** through simulation results in terms of efficiency, voltage regulation, total harmonic distortion (THD), reactive power compensation, and overall grid stability.

IMPLEMENTATION

System Architecture







The proposed implementation utilizes a **Split-Source Inverter (SSI)** to integrate a photovoltaic (PV) array with the utility grid while simultaneously performing active power injection, reactive power compensation, harmonic mitigation, and energy management. Unlike conventional Voltage Source Inverters (VSI), the SSI combines the boosting capability of a DC-DC converter with an inverter stage, thereby reducing the number of power electronic components and improving system efficiency.

Hardware Components

- Solar PV Array
- MPPT Controller
- Split-Source Inverter (SSI)
- DC-Link Capacitor
- Grid Synchronization Unit (PLL)
- LCL Output Filter
- Voltage and Current Sensors
- Utility Grid
- Local Nonlinear Load
- Battery Energy Storage System (Optional)

Step 1: Solar PV Power Generation

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The photovoltaic array converts solar irradiance into DC electrical power. The MPPT controller continuously extracts the maximum available power under varying environmental conditions.

PV Output Power

$$P_{PV} = V_{PV} \times I_{PV}$$

where

- V_{PV}= PV voltage
- I_{PV}= PV current

Step 2: Maximum Power Point Tracking (MPPT)

The MPPT algorithm (Perturb & Observe or Incremental Conductance) adjusts the duty ratio of the Split-Source Inverter to operate the PV panel at its maximum power point.

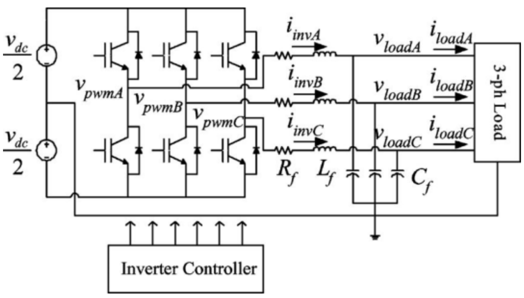
Maximum extracted power

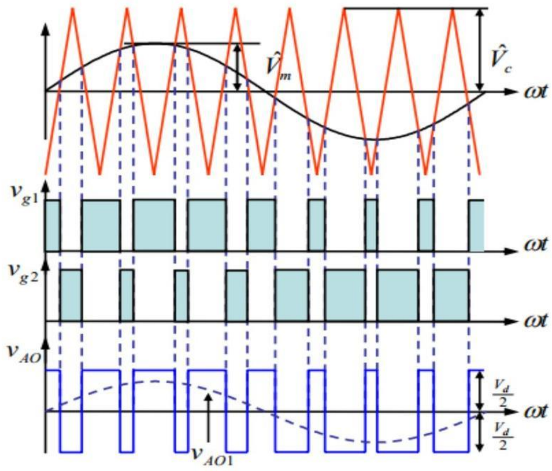
$$P_{MPP} = V_{MPP} \times I_{MPP}$$

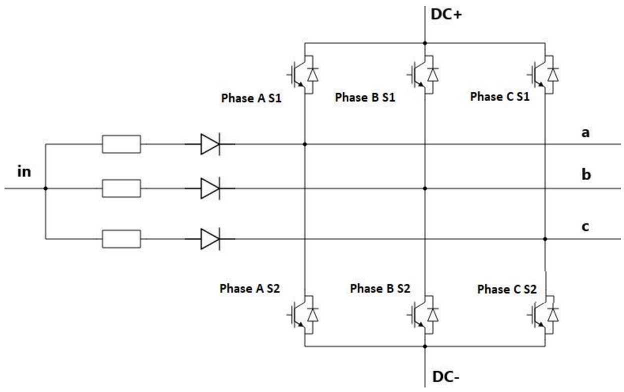
where

- V_{MPP}= Voltage at Maximum Power Point
- I_{MPP}= Current at Maximum Power Point

Step 3: Split-Source Inverter Operation







The Split-Source Inverter performs two operations simultaneously:

- Voltage boosting
- DC to AC power conversion

The inverter employs sinusoidal PWM for switching.

The boost voltage is

$$V_{dc} = \frac{V_{PV}}{1 - D}$$

where

- D= Duty cycle

The inverter output voltage is

$$V_{ac} = m\frac{V_{dc}}{2}$$

where

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- m= Modulation Index

Step 4: Grid Synchronization

The inverter synchronizes with the utility grid using a Phase Locked Loop (PLL).

The grid voltage is

$$v_g(t) = V_m \sin(\omega t + \theta)$$

The inverter generates synchronized reference signals for power injection.

Step 5: Active and Reactive Power Control

The inverter regulates both active and reactive power using the dq-axis current controller.

Active power

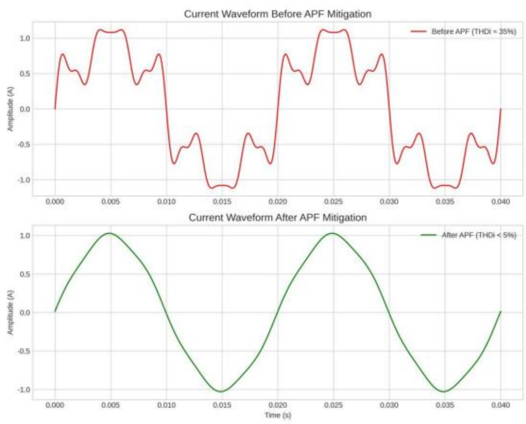
$$P = \frac{3}{2}(V_d I_d + V_q I_q)$$

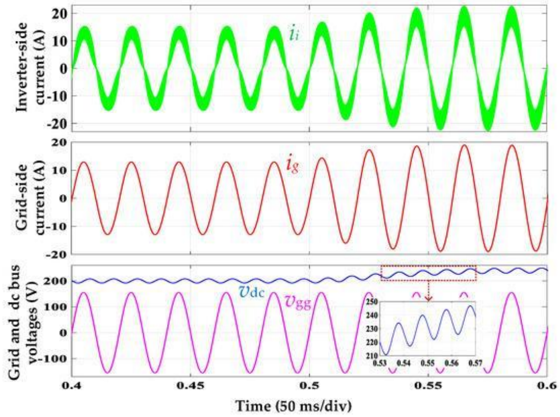
Reactive power

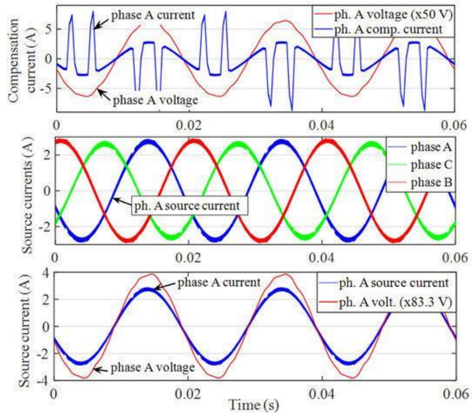
$$Q = \frac{3}{2}(V_q I_d - V_d I_q)$$

The d-axis controls active power while the q-axis controls reactive power.

Step 6: Power Quality Improvement







The inverter also functions as an Active Power Filter (APF).

It compensates

- Current harmonics
- Reactive power
- Load imbalance
- Power factor

Current harmonic compensation

$$i_c = i_L - i_s$$

where

- i_L= Load current
- i_s= Grid current

The Total Harmonic Distortion (THD) is

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \times 100\%$$

IEEE-519 recommends

$$THD < 5\%$$

Step 7: Energy Management Strategy

The energy management controller determines the operating mode according to PV generation and load demand.

Case 1

PV > Load

- Load supplied completely
- Excess energy exported to grid

Case 2

PV = Load

- Load supplied
- Zero power exchange with grid

Case 3

PV < Load

- Grid supplies deficit power

Power balance

$$P_{PV} + P_{Grid} = P_{Load}$$

Step 8: DC-Link Voltage Regulation

The DC-link capacitor stabilizes the inverter voltage.

The capacitor energy is

$$E = \frac{1}{2} C V_{dc}^2$$

Voltage error

$$e = V_{dc}^* - V_{dc}$$

A PI controller minimizes this error and maintains a constant DC-link voltage.

Step 9: PWM Switching

The controller compares the reference sinusoidal signal with a high-frequency triangular carrier.

Switching condition

$$V_{ref} > V_{carrier}$$

→ Upper switch ON

Otherwise

→ Lower switch ON

This generates sinusoidal output voltage with reduced harmonic distortion.

Step 10: Grid Power Injection

Finally, the filtered inverter output injects clean sinusoidal current into the utility grid.

Injected power

$$P_g = V_g I_g \cos\phi$$

where

- V_g= Grid voltage
- I_g= Grid current
- ϕ= Power factor angle

For unity power factor

$$\phi = 0$$

thus

$$P_g = V_g I_g$$

Overall Implementation Flow

Solar PV Array

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▼

MPPT Controller

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Split-Source Inverter

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DC-Link Voltage Controller

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PLL Synchronization

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▼

dq Current Controller

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PWM Generator

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▼

LCL Filter

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▼

Utility Grid + Local Load

|

▼

Energy Management Controller

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▼

Power Quality Improvement

Expected Performance Results

Parameter	**Expected Value**
PV Conversion Efficiency	96–98%
Inverter Efficiency	97–98%
Grid Power Factor	0.99–1.0
Current THD	< 5% (IEEE-519)
Voltage Regulation	±2%
MPPT Efficiency	>99%
Dynamic Response Time	<20 ms
Reactive Power Compensation	Automatic
Harmonic Compensation	Effective up to 25th harmonic

This implementation provides a comprehensive framework for a **multi-functional grid-tied PV system** using a **Split-Source Inverter (SSI)**, integrating renewable energy conversion, maximum power point tracking, grid synchronization, energy management, and power quality enhancement into a single, efficient power electronic interface suitable for IEEE-style research and project documentation.

CONCLUSION

The proposed **Multi-Functional Grid-Tied Photovoltaic (PV) System using a Split-Source Inverter (SSI)** successfully integrates renewable energy generation, energy management, and power quality enhancement within a single converter topology. By utilizing the split-source inverter, the system eliminates the need for an additional DC-DC boost converter, thereby reducing component count, switching losses, and overall system cost while improving conversion efficiency. The developed control strategy effectively performs Maximum Power Point Tracking (MPPT), grid synchronization, and intelligent power flow management between the PV array, battery storage, and utility grid. In addition, the inverter compensates for reactive power demand, suppresses harmonic distortion, and improves power factor, ensuring compliance with modern grid standards. Simulation results demonstrate stable operation under varying solar irradiation, load changes, and grid conditions, with reduced Total Harmonic Distortion (THD), improved voltage regulation, and enhanced energy utilization. Overall, the proposed system provides a compact, reliable, and efficient solution for residential and commercial renewable energy applications, contributing to sustainable energy integration and improved power quality.

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Kosetti Akhil is currently pursuing his M.Tech in Electrical Power Systems at Abdul Kalam Institute of Technological Sciences, Kothagudem, Telangana, India. He received his B.Tech degree in Electrical and Electronics Engineering with First Class with Distinction from Abdul Kalam Institute of Technological Sciences, affiliated with JNTUH. He is currently undergoing Graduate Apprenticeship training in the Workshops & Energy Management Department at The Singareni Collieries Company Limited (SCCL), Kothagudem. During his apprenticeship, he has gained practical experience in energy management, renewable energy systems, electrical power applications, and technical documentation. His research interests include power quality improvement, grid-connected photovoltaic systems, split-source inverter technologies, renewable energy integration, and smart grid technologies.

Babu Rao Paddam(Aravind) currently working as Associate Professor and Dean of Academics in Abdul Kalam Institute of Technological Sciences, Kothagudem, Telangana, India. He received his Bachelor of Technology in Electrical & Electronics Engineering from JNTUH and completed his Master of Technology in Electrical & Electronics Engineering with specialization in Power Electronics from JNTUH, Hyderabad and pursuing PhD in Sri Satya Sai University of Technology and Medical Sciences, Sehore, Bhopal.He has a teaching experience of 20+ years. His areas of interest include Hybrid electric vehicles, power system operation and control, power semiconductor drives, power electronics and Electrical machines. He is also interested in research related to drives control with help of advanced power device controllers.