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Integration Of Solar Pv With Battery Storage Via A Novel Three-Level Npc Inverter Configuration With Advanced Control Method

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ABSTRACT

This paper unique three-level Neutral Point Clamped (NPC) inverter design that integrates solar photovoltaic (PV) with battery storage systems in a grid-connected configuration. The proposed architecture leverages an innovative extended unbalanced three-level vector modulation technique, enabling it to maintain proper AC voltage output even under unbalanced DC voltage conditions, which is a common issue in multilevel inverter operations. The study elaborates on the theoretical underpinnings and design philosophy of this modulation strategy, highlighting its ability to decress Total Harmonic Distortion (THD), enhance voltage balancing, and improve system efficiency. novel control algorithm is introduced to regulate power distribution dynamically among the solar PV array, battery storage, and the utility grid. This algorithm simultaneously Maximum Power Point Tracking (MPPT) for the solar PV to maximize energy generation during changing solar irradiance while managing the battery's State of Charge (SOC) to maintain optimal charge-discharge cycles. The control strategy facilitates seamless integration with the grid, supports bidirectional power flow, and enhances the reliability and Balance of the entire system. Simulation results validate the impact of the proposed configuration and control method, demonstrating increase's power quality, reduced switching losses, and reliable operation under dynamic load and environmental conditions. This integrated system is ideal for modern distributed generation applications, promoting clean energy utilization and supporting grid stability with advanced inverter-based technologies.

1.INTRODUCTION

1.1 Background:

The growing energy demand and depletion of fossil fuels have increased the focus on renewable energy technologies. Solar photovoltaic (PV) systems are clean, sustainable, and modular nature. However, the intermittent nature of solar irradiance results in unreliable power supply from standalone PV systems. Integrating battery storage with PV systems addresses this limitation by Saving surplus energy for future use use, ensuring stable and continuous power. Efficient power conversion using advanced inverter topologies, such as the three-level Neutral Point Clamped (NPC) inverter, further enhances system performance by reducing switching losses and improving output voltage quality in renewable energy applications.

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OBJECTIVES

1. **Design and implement a three-level Neutral Point Clamped (NPC) inverter architecture** that integrates solar photovoltaic (PV) and battery storage systems for grid-connected applications.

2. **Develop an innovative extended unbalanced three-level vector modulation technique** to maintain stable AC voltage output under unbalanced DC voltage conditions, improving voltage balancing and reducing Total Harmonic Distortion (THD).
3. **Propose and validate an advanced MPPT control algorithm** capable of dynamically tracking the maximum power point of the solar PV array under rapidly changing environmental conditions.
4. **Integrate a battery management strategy** within the control framework to regulate the battery's State of Charge (SOC), ensuring optimal charge-discharge cycles and prolonging battery lifespan.

2.LITERATURE REVIEW

Toledo et al. (2010) emphasize the significance of integrating distributed photovoltaic (PV) systems with energy storage to address the variability of solar power. Their review underscores that energy storage is essential for grid reliability, peak load support, and power quality, laying a foundational argument for incorporating intelligent power conditioning systems like multilevel inverters in modern grids.

Bragard et al. (2010) further this concept by focusing on modular battery energy storage systems (BESS) and their synergy with advanced power electronics. They highlight that using power electronic converters allows dynamic control and rapid compensation of power imbalances, which aligns with the objective of deploying multilevel inverter topologies to maintain voltage and frequency stability in renewable-rich grids.

Yazdani and Dash (2009) address the critical control aspect of PV grid integration by proposing a voltage-oriented control strategy for PV inverters. Their work illustrates how accurate dynamic modeling and control enable stable power exchange and voltage regulation, a concept directly applicable to the fuzzy logic-based control methodology adopted in the proposed 31-level inverter system.

3.INVERTERS

3.1 Introduction:

An inverter is an essential power electronic device used to convert direct current (DC) into alternating current (AC) at required voltage and frequency levels. It enables the integration of DC power sources like solar PV panels and battery storage systems with AC loads or the electrical grid. Inverters are used across various applications, including household electronics, industrial motor drives, and large-scale grid-connected renewable energy systems.

Three-Level Neutral Point Clamped (NPC) Inverter

The Three-Level Neutral Point Clamped (NPC) inverter is a popular multilevel inverter topology used to convert DC power into AC power with multiple voltage levels. It is especially advantageous in medium- and high-power applications such as renewable energy integration and grid-connected systems.

Key Features:

Multilevel Output Voltage: Unlike traditional two-level inverters that switch between two voltage levels, the three-level NPC inverter produces three voltage levels at the output: positive DC bus voltage, zero voltage

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(neutral point), and negative DC bus voltage. This results in a staircase waveform that approximates a sine wave more closely.

Neutral Point Clamping: The neutral point (midpoint of the DC bus) is connected to the output via clamping diodes, which help reduce voltage stress on power switches and improve voltage balance across the DC link capacitors.

Reduced Harmonics and Switching Losses: By generating multiple voltage levels, the inverter significantly reduces Total Harmonic Distortion (THD) in the output waveform, leading to better power quality and lower electromagnetic interference. The switching frequency of each device is also reduced, minimizing switching losses.

Voltage Balancing: The NPC topology naturally facilitates balancing of the neutral point voltage, which is crucial for stable operation and preventing damage to components.

Table 1: The state of switches over 2π interval

Mode	Q_{1A}, Q_{1B}	Q_{2A}, Q_{2B}	Q_{3A}, Q_{3B}	Q_{4A}, Q_{4B}	Q_{5A}, Q_{5B}	Q_{6A}, Q_{6B}
1	ON	OFF	OFF	ON	ON	OFF
2	ON	OFF	OFF	ON	OFF	ON
3	ON	OFF	ON	OFF	OFF	ON
4	OFF	ON	ON	OFF	OFF	ON
5	OFF	ON	ON	OFF	ON	OFF
6	OFF	ON	OFF	ON	ON	OFF

4.SOLAR SYSTEM

4.1 Introduction:

A solar power system captures sunlight to produce electricity through photovoltaic (PV) technology. It comprises solar panels that transform solar energy into direct current (DC) electricity via the photovoltaic effect. These systems are extensively used because they provide clean, renewable, and sustainable energy, thereby playing a crucial role in lowering greenhouse gas emissions and reducing reliance on fossil fuels. Their modular and scalable design allows them to be implemented in residential rooftops, commercial buildings, and large-scale utility power plants. A standard solar PV setup includes PV modules, inverters to convert DC power into AC power, mounting frameworks, and various balance of system components, ensuring efficient and dependable electricity production across diverse applications.

A **solar system** in the context of energy generation refers to a setup designed to capture sunlight and convert it into usable electricity through photovoltaic (PV) technology. The system primarily includes:

Solar Panels (PV Modules): Devices made of semiconductor materials that convert sunlight into direct current (DC) electricity via the photovoltaic effect.

Inverter: Converts the DC electricity generated by the solar panels into alternating current (AC), which is compatible with household appliances and the utility grid.

Mounting Structures: Frameworks that securely hold the solar panels in place, optimized for maximum sun exposure.

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Balance of System (BOS) Components: Includes wiring, switches, batteries (if energy storage is used), charge controllers, and monitoring equipment.

Key Benefits:

Provides clean, renewable, and sustainable energy.

Reduces greenhouse gas emissions and dependence on fossil fuels.

Scalable and adaptable to residential, commercial, and utility-scale applications.

Solar systems have become a cornerstone of modern renewable energy solutions, supporting environmental sustainability and energy independence worldwide.

1. Voltage Vector Levels for Three-Level NPC Inverter

The NPC inverter output voltage levels V_{out} can be expressed as:

$$V_{out} = \{-V_{dc}/2,\ 0,\ +V_{dc}/2\}$$

where V_{dc} is the total DC link voltage.

For a three-phase system, the line-to-neutral voltage vector for phase a is:

$$V_a = V_{dc} \times \frac{n_a}{2}$$

where $n_a \in \{-1, 0, 1\}$ is the switching state for phase a.

5. Battery State of Charge (SOC)

SOC estimation can be done via coulomb counting:

$$SOC(t) = SOC(t_0) - \frac{1}{C_{bat}} \int_{t_0}^{t} I_{bat}\, dt$$

where:

- C_{bat} = battery capacity (Ah)
- I_{bat} = battery current (positive when discharging, negative when charging)

6. Power Balance Equation in Grid-Connected Mode

$$P_{PV} + P_{bat} = P_{load} + P_{grid} + P_{loss}$$

where:

- P_{PV} = power from solar PV
- P_{bat} = battery power (positive when discharging)
- P_{load} = load power
- P_{grid} = power exchanged with the grid
- P_{loss} = system losses (in inverter, cables, etc.)

4.2 Block Diagram:

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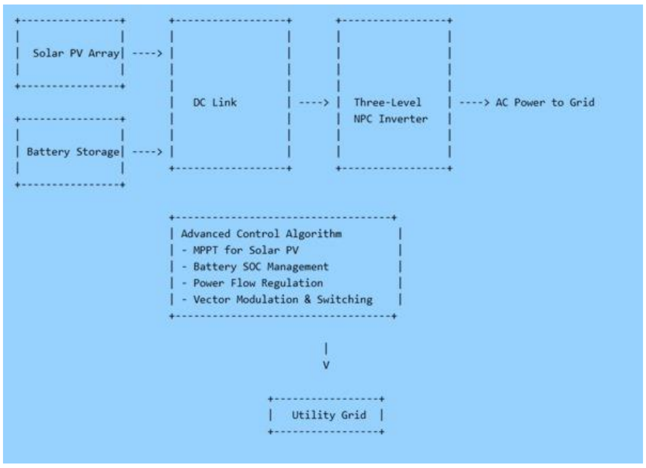

Fig: 3.1 Block diagram

5.ADVANCED CONTROL METHOD MPPT

Maximum Power Point Tracking (MPPT) is essential for maximizing the energy harvested from a solar photovoltaic (PV) system under varying environmental conditions such as changing solar irradiance and temperature. Traditional MPPT algorithms like Perturb and Observe (P&O) and Incremental Conductance (IncCond) have limitations in terms of tracking speed, steady-state oscillations, and efficiency in rapidly changing conditions. To overcome these limitations, an **advanced control method for MPPT** is proposed in this work, which includes the following features:

Adaptive Perturbation Step Size:

Unlike fixed-step MPPT algorithms, the perturbation step size dynamically adjusts based on the rate of change of the power signal. When the system detects rapid changes in irradiance or temperature, the step size increases to track the maximum power point faster. During stable conditions, the step size decreases to reduce steady-state oscillations and improve tracking accuracy.

Fuzzy Logic / Neural Network-Based MPPT:

Intelligent control techniques such as fuzzy logic or neural networks are integrated to enhance MPPT performance. These approaches can learn and adapt to nonlinear PV characteristics, providing faster convergence to the MPP without being trapped in local maxima. They also offer robustness against noise and measurement inaccuracies.

Model Predictive Control (MPC):

By predicting future PV output behavior based on environmental inputs and system dynamics, MPC optimizes the duty cycle of the DC-DC converter to maintain operation at the MPP. This proactive control strategy improves response time and reduces power losses.

Integration with Battery Management System (BMS):

The advanced MPPT algorithm works in synergy with the battery control unit to optimize power flow. It balances maximum energy extraction with the battery's State of Charge (SOC) constraints, ensuring long battery life and preventing overcharge/discharge conditions.

Real-Time Environmental Sensing and Data Fusion:

The controller incorporates real-time measurements of irradiance, temperature, and load demand to fine-tune the MPPT process. Data fusion techniques combine multiple sensor inputs to improve accuracy and responsiveness.

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6.BATTERY

6.1 Energy Storage:

Energy storage is essential for modern power systems, particularly in renewable energy integration. It involves storing electrical energy in various forms for use when generation is low or demand is high. In solar PV systems, energy storage addresses the intermittent nature of solar power, ensuring a stable and continuous electricity supply. Batteries are the most widely adopted storage technology with lithium-ion batteries gaining popularity due to their high energy density, efficiency, and long cycle life. Other storage technologies include lead-acid batteries, flow batteries, super capacitors, and emerging solutions such as hydrogen storage and compressed air systems. Effective energy storage integration enhances system reliability, facilitates peak load management, supports grid stability, and enables energy arbitrage. It also plays a significant role in microgrids and standalone systems by ensuring autonomy and backup during outages. As renewable energy penetration increases globally, advanced energy storage solutions become essential for achieving energy security, sustainability, and efficient grid operation.

6.2 Battery:

Batteries store energy in chemical bonds and convert it into electrical energy upon discharge when needed. It consists of one or more cells, each containing positive and negative electrodes and an electrolyte that facilitates ion movement during charge and discharge processes. Batteries are widely used in renewable energy systems to store excess power generated from sources such as solar PV and release it when generation is insufficient, ensuring uninterrupted power supply. Among various types, lithium-ion batteries are most preferred due to their high energy density, long cycle life, fast charging capability, and lightweight design. Lead-acid batteries, although cost-effective, have lower energy density and shorter lifespan compared to lithium-ion batteries. Battery systems require effective management strategies,

including State of Charge (SOC) monitoring, overcharge and deep discharge protection, and thermal management to ensure safety, reliability, and longevity. With advancements in battery technology, their role in grid support, electric vehicles, and large-scale renewable integration continues to expand, making them an essential component of modern power systems.

6.3 Modulator for Pulse Width:

Now, you might be asking, “How do we create a PWM wave?” It’s actually pretty simple! There are circuits available that can help you make one. The first step is to create a triangular wave, which looks like a series of peaks and valleys.

6.4 MATLAB & SIMULINK

MATLAB is like a super-smart toolbox for computers! It’s a programming language that helps you solve problems, look at data, and do math in a really cool way. If you’ve ever tried to solve a tricky math problem, you know it can take a long time. But with MATLAB, you can do it much faster than with older languages like C or FORTRAN. People use MATLAB for all sorts of things! It can help with things like processing sounds and images, designing controls, testing stuff, and even analyzing money matters.

7.SIMULATION RESULTS

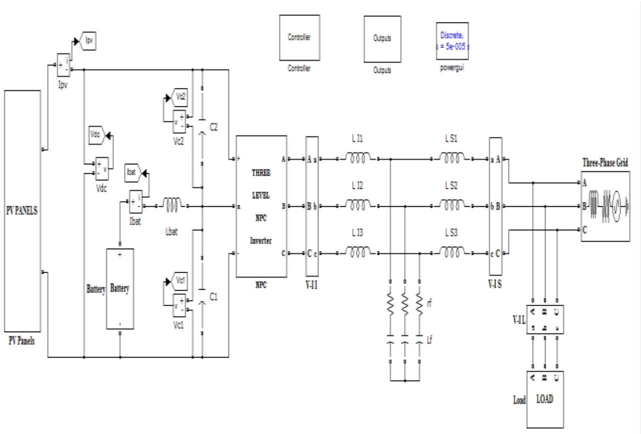


Fig: 8.1 simulation diagram of a grid connected three-wire three-level inverter

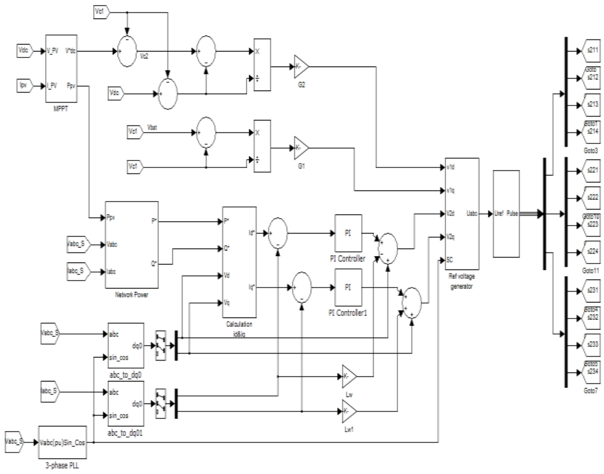
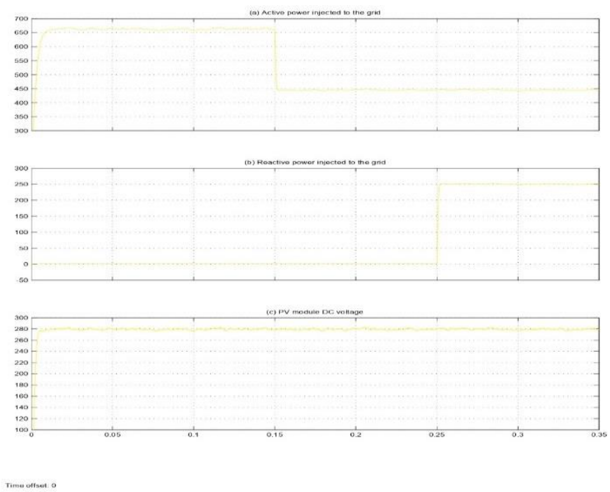
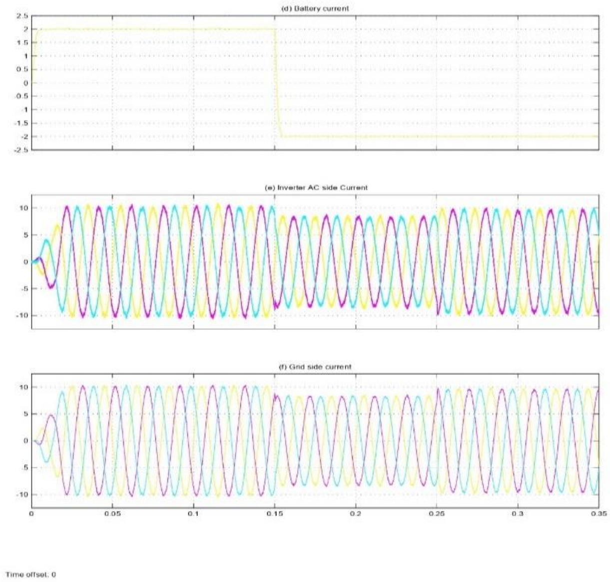
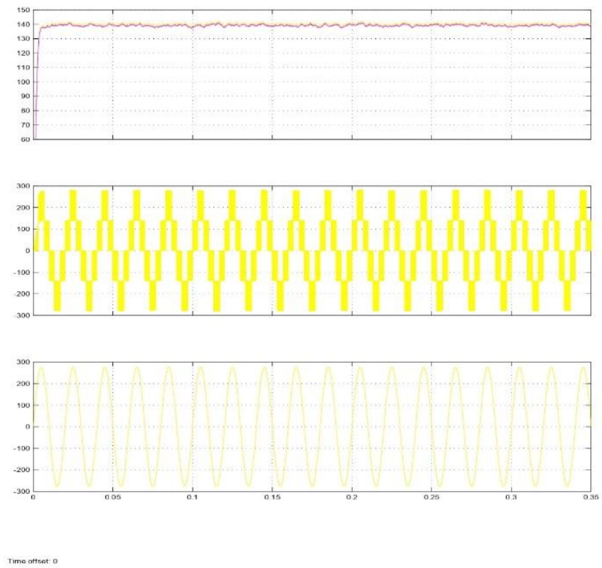


Fig 8.2 Control system diagram to integrate PV and battery storage







CONCLUSION

A new sketch for a three-level impartial factor clamped voltage supply inverter has been shown. This inverter can use each renewable strength and battery storage on the DC side. A new prolonged imbalance three-level vector a modulation technique has been devised as a theoretical foundation. This approach can make the proper AC voltage even when the DC voltage is unbalanced. A novel manage algorithm has been additionally suggested for the device to control the go with the flow of energy between the photo voltaic PV, battery, and grid gadget when the photo voltaic PV is additionally working in MPPT mode. We examined the proposed topology and manipulate approach with simulations and exhibit the results. The outcomes exhibit that the cautioned device can control the AC aspect present day and the currents for charging and discharging the battery at diverse stages of photo voltaic radiation.

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