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A comparative analysis of centralized and distributed MPPT-based inverter systems for grid-connected PV applications

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Abstract—**In this paper, using precise MATLAB/Simulink models, a thorough comparison of centralized and distributed inverter topologies for photovoltaic (PV) grid integration is presented. A single Voltage Source Converter (VSC) run using the traditional Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm is used in the centralized system design.**

In contrast, the distributed architecture consists of numerous module-level converters, each with an individual MPPT controller based on the Incremental Conductance (IC) approach and specialized three-level Neutral Point Clamped (NPC) inverters. Key performance metrics such as MPPT tracking efficiency, total harmonic distortion (THD), system scalability, fault tolerance, and power quality are thoroughly tested in both uniform and partial shade environments.

According to the study, the distributed inverter topology outperforms the centralized version, particularly in mismatch and partial shade circumstances, by providing higher energy yield, increased fault isolation, and superior modularity. Furthermore, the distributed system exhibits improved harmonic performance and more seamless connectivity with the electric grid. These findings emphasize the potential of distributed PV inverter systems as a more reliable and efficient solution for modern renewable energy needs.

Index Terms—**Photovoltaic (PV), Grid-Tied Inverter, Voltage Source Converter (VSC), Neutral Point Clamped (NPC) Inverter, Maximum Power Point Tracking (MPPT), Boost Converter, Simulink, Harmonic Distortion, Partial Shading, Modular Redundancy;**

1. INTRODUCTION

Photovoltaic (PV) systems have emerged as the primary source of renewable energy generation, owing to its environmental benefits, scalability, and the low cost of solar technology [1] [5]. Inverter technologies are critical in grid-connected PV systems because they convert DC power to grid-compatible AC while also maintaining operational dependability, power quality, and maximum energy collection. In medium and large-scale PV systems, the two most popular inverter topologies are centralized inverters and string inverters [4] [6].

Centralized inverter systems often use a single power conditioning device for many PV arrays, which simplifies design and lowers costs. However, they are prone to performance loss when partially shaded and lack redundancy. String inverter systems, on the other hand, use numerous separate inverters, which provide improved fault tolerance, superior MPPT tracking, and higher overall efficiency, but at a higher installation cost.

The paper examines both topologies with thorough MATLAB/Simulink models. Section 2 outlines the system designs; Section 3 elaborates on MPPT and DC-DC conversion techniques; Section 4 addresses inverter topologies; and Section 5 concentrates on grid integration. Section 6 describes the simulation setup, whereas Section 7 shows comparative results. Sections 8 and 9 contain

This study analyzes two popular topologies:

1. String-connected inverter systems offer decentralized MPPT and modular expansion capabilities.

2. Centralized VSC-based systems with a single conversion point for aggregated PV array outputs.

This study compares different systems under identical PV and grid circumstances to determine the most efficient arrangement.

2. SYSTEM CONFIGURATIONS

2.1. String-Connected Inverter System

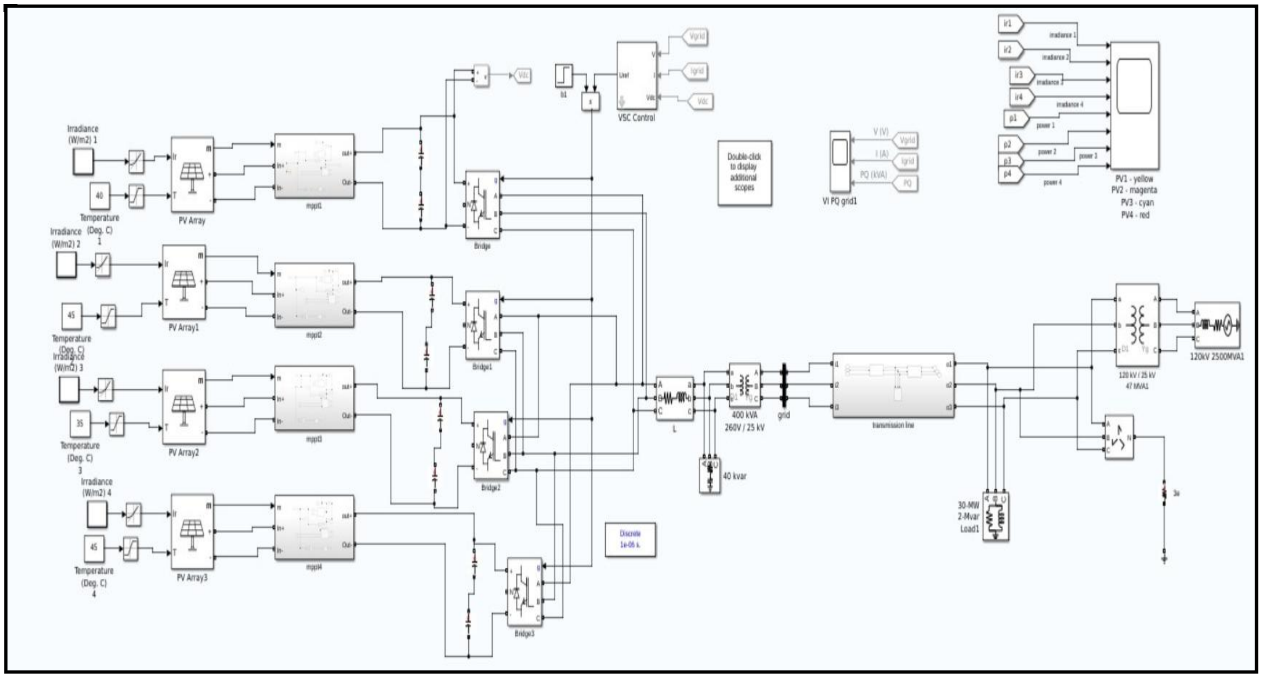


Fig.1 String connected PV grid tied system

The string connected inverter architecture, as illustrated in Figure 1, shown in fig (A).It consists photovoltaic (PV) power system consists of four PV arrays, each operating under distinct environmental conditions with irradiance levels between 40 to 45 W/m² and temperatures ranging from 33°C to 45°C. This configuration emulates the variability of solar resources encountered in real-world scenarios. To extract maximum power from each array under these non-uniform conditions, a dedicated DC-DC boost converter is employed for each PV array, utilizing the Incremental Conductance (IC) method for Maximum Power Point Tracking (MPPT). The IC algorithm enhances tracking precision during rapid environmental fluctuations by comparing incremental and instantaneous conductance. Each boost converter regulates the output voltage and optimizes power transfer efficiency before feeding into a common DC bus that acts as the central DC-link.

The centralized DC-link supports a three-level Neutral Point Clamped (NPC) inverter topology, known for its ability to reduce total harmonic distortion (THD), minimize voltage stress on semiconductor devices, and improve overall efficiency, especially at high power levels. Four NPC inverters, operating in synchrony, collectively deliver an output of 400 kW. These inverters interface with the grid through step-up transformers rated at 250 V/25 kV, and the resulting high-voltage AC power is transmitted over a 24 km line for remote grid integration. A Voltage Source Converter (VSC) controller manages the inverters, maintaining stable voltage and current while ensuring synchronization with grid voltage and frequency. The VSC strategy enables near-unity power factor operation, ensuring efficient, reliable, and grid-compliant performance of the PV system under dynamically changing environmental conditions.

2.2. Centralized VSC-Based System

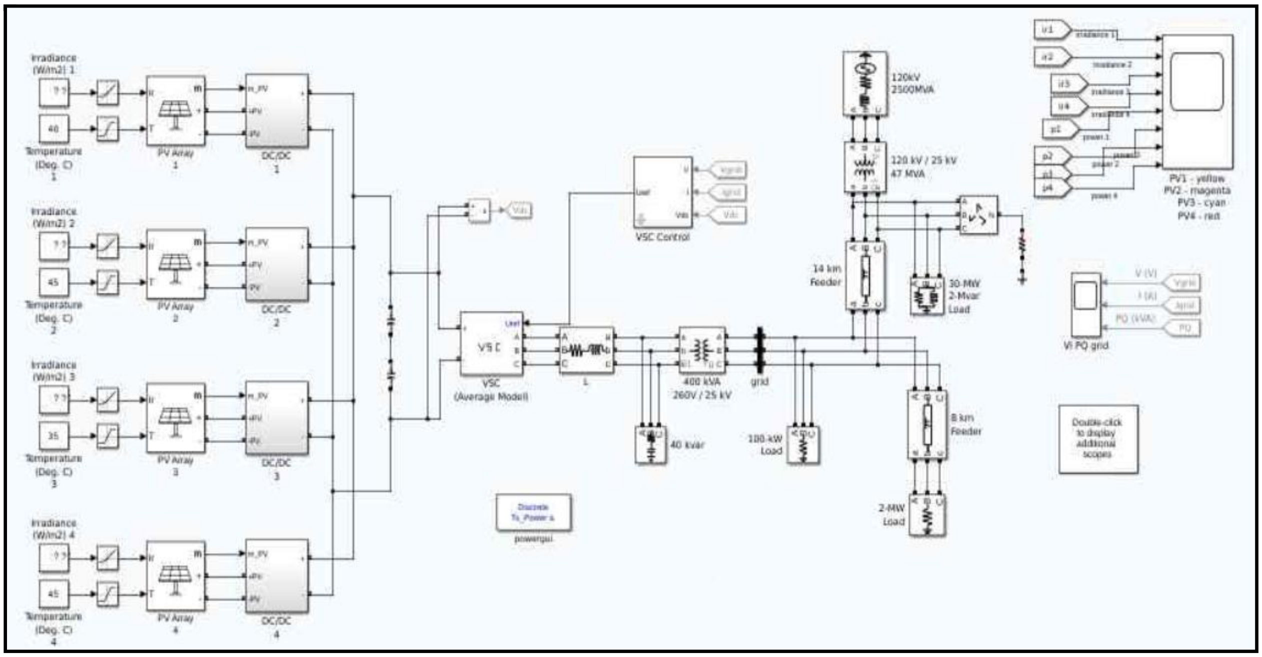


Fig (B) Centralized grid tied PV system

The centralized inverter architecture, as illustrated in Figure 2, integrates multiple PV arrays into a unified grid-connected system. Each array consists of identical PV modules and is subjected to the same irradiance and temperature conditions as in the string-based configuration, allowing for consistent performance comparison. To ensure optimal power extraction, each PV array is equipped with a DC-DC boost converter utilizing the Perturb and Observe (P&O) algorithm for Maximum Power Point Tracking (MPPT) [4]. The P&O method periodically perturbs the operating point and monitors the resulting change in power output, adjusting the duty cycle of the converter to maintain operation near the maximum power point [3]. These MPPT-controlled converters regulate and boost the array voltage, feeding a centralized DC bus maintained at 500 V.

This common DC bus serves as the input to a three-phase averaged Voltage Source Converter (VSC), which converts the 500 V DC into a 260 V AC output. The VSC operates at unity power factor, promoting efficient power delivery to the grid while minimizing reactive power and supporting grid stability. The inverter output is then stepped up to 25 kV using a 400 kVA transformer, allowing for transmission over a 25 kV distribution line to a 120 kV main grid. This high-voltage transmission minimizes losses and ensures effective integration with utility-scale infrastructure. The centralized inverter configuration offers a streamlined, cost-effective solution for medium- to large-scale PV systems, simplifying control and maintenance while ensuring compliance with grid interconnection standards.

3. MPPT AND DC-DC CONVERSION

Both systems utilize the Incremental Conductance MPPT algorithm. However, the string inverter offers finer control by implementing MPPT at the individual string level, enhancing energy harvesting under partial shading. The Incremental Conductance MPPT algorithm is adopted in string connected PV systems due to its high accuracy under varying irradiance. In the centralized system, all arrays share a common MPPT controller, potentially reducing the response to individual panel mismatches. Conversely, in the string inverter system, each array operates its MPPT controller independently, significantly enhancing performance during partial shading. The boost converter equations are governed by:

Vout =Vin/1-D;

Iout= I in/ (1-D);

Where, D is the duty cycle controlled via the MPPT algorithm.

4. INVERTER TOPOLOGIES

4.1 Centralized VSC Inverter

The centralized system uses a single VSC to interface the combined PV output with the grid. Key characteristics include:

- Reduced complexity in control and protection.
- Lower initial and operational cost.
- Susceptibility to single-point failures.
- Moderate THD due to two-level switching.

4.2 String NPC Inverters

Each string inverter uses a three-level NPC topology. Benefits include:

- High-quality output with reduced THD.
- Better fault isolation and maintenance.
- Modular operation allows scalability.
- Enhanced efficiency through localized MPPT.

5. GRID INTEGRATION AND CONTROL

- Both systems interface with a grid modelled at 25 kV, supplying a 120-kW load with a 2.5 MVA rating. The centralized system synchronizes using a VSC controller tuned with PI loops for voltage and current. The string inverter system employs multiple NPC controllers operating in parallel, ensuring load balancing and reactive power compensation.
- The power injected into the grid is monitored using grid PQ measurement blocks, ensuring compliance with grid.

6. SIMULATION PARAMETERS AND SETUP

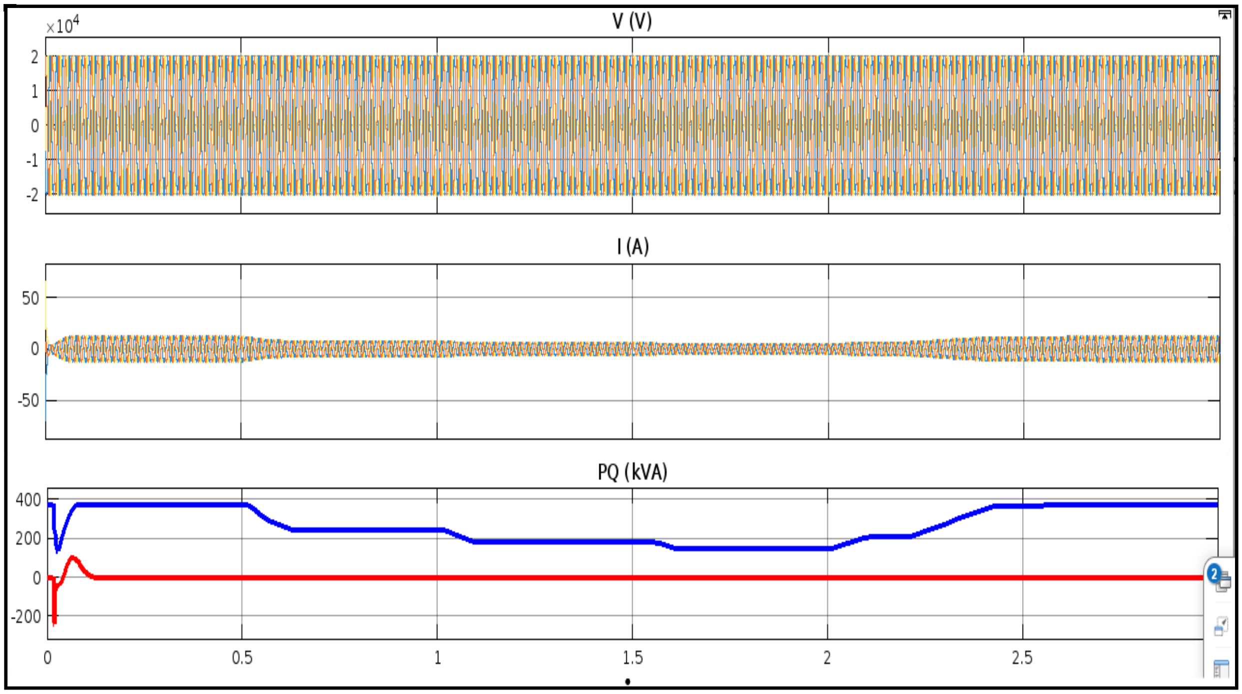
- Software: MATLAB/Simulink with Sim-Power Systems toolbox
- Simulation Time: 3 seconds
- Step Size: 1e-6 s (discrete)
- Irradiance Levels: 40–45 W/m² (variable)
- Temperature Range: 33–45°C
- Inverter Ratings: 400 kW for both systems
- Transmission Line Length: 14 km (centralized), 24 km (string)
- Load: 2 kW to 30 MW (variable loads)

7. COMPARATIVE ANALYSIS

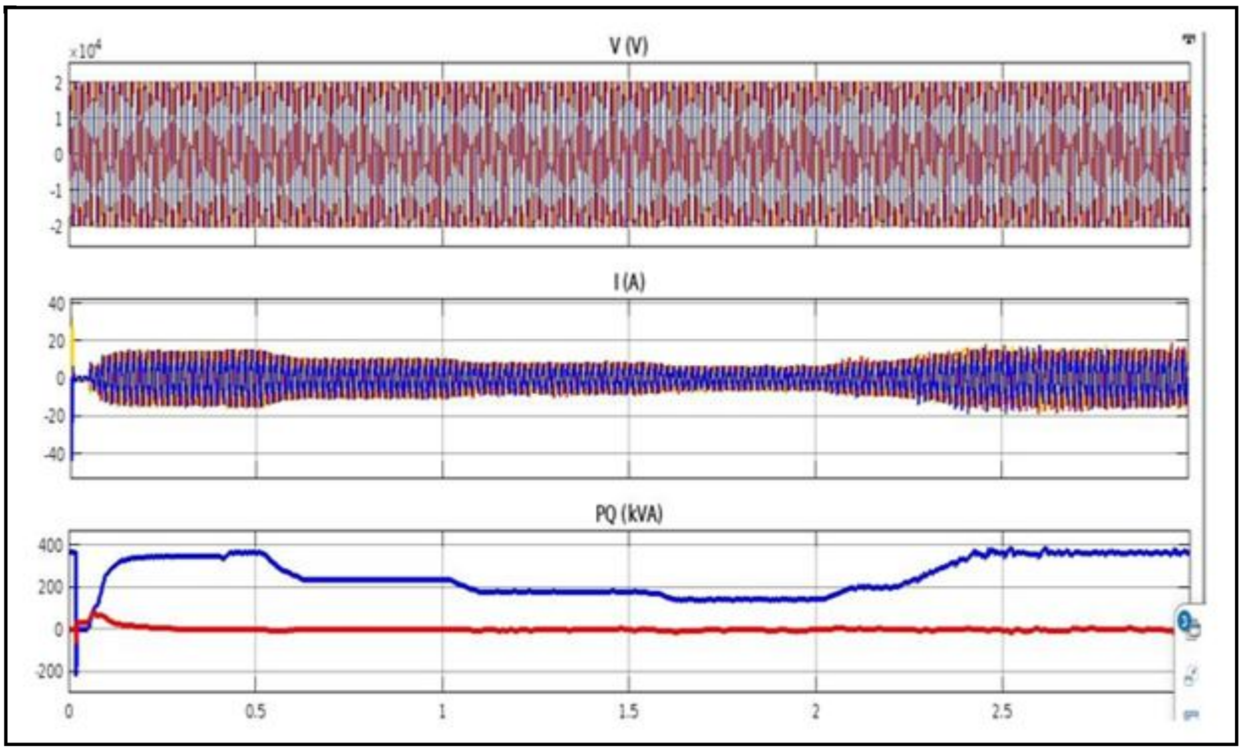
Criterion	Centralized System	Distributed System
MPPT Efficiency	Medium (shared MPPT)	High (per module)
Fault Tolerance	Low (single point failure)	High (modular isolation)
Synchronization	Centralized via PLL	Inherent via series connection
Scalability	Moderate	High
Control Complexity	High (global feedback + PLL)	Medium (local feedback + coordination)
Energy Harvest	Sensitive to mismatch	Resilient to mismatch

8. SIMULATION AND RESULTS

Simulations were performed using MATLAB Simulink with identical solar irradiance and variable temperature across modules. Grid voltage: 400V, 50Hz. Results showed:



- Centralized system: ~95% MPPT efficiency, ~94.2% conversion efficiency.



- Distributed system: ~98% MPPT efficiency, ~95% conversion efficiency.
- Distributed system demonstrated better performance under partial shading and temperature variations.

9. RESULTS AND DISCUSSION

- Power Extraction String inverters extracted up to 5–7% more power under partial shading due to per-panel MPPT.

- Total Harmonic Distortion (THD) NPC inverters maintained a THD below 3%, compared to 5.2% for the centralized VSC.
- Response Time and Dynamics Both systems stabilized voltage and current within 1.5 seconds, but the string inverter achieved smoother transitions due to modular control.
- Fault Tolerance String inverter topology offered superior reliability—failure in one inverter does not compromise the rest.
- Efficiency Average system efficiency was higher for the string inverter setup (98%) versus centralized (95 %) due to distributed MPPT.
- Cost-Benefit Analysis Though centralized systems offer lower upfront cost, long-term benefits from maintenance ease and energy yield make string inverters more viable for complex terrains.

10. CONCLUSION

This study provides a comprehensive comparison of centralized and string inverter-based PV systems. The centralized topology benefits from simplicity and lower cost, but its susceptibility to partial shading and reduced fault tolerance pose limitations. In contrast, the string inverter system demonstrates improved performance in modularity that is 98 % efficiency, power quality, and energy harvesting. For utility-scale PV installations especially under variable environmental conditions, string inverter systems are a technically superior choice.

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