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Performance Improvement of PV-EV Integrated System Using Array Reconfiguration Approach Under Partial Shading Conditions

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This paper mainly focuses on the intelligent approach to reconfigure a Photovoltaic (PV) array to improve the performance of the PV-integrated Electric Vehicle (EV) systems under various partial shading conditions (PSCs). PSCs pose significant challenges in PV-EV integrated systems, leading to power mismatches, hotspot formation, and reduced overall efficiency. Unlike traditional mitigation techniques that rely on bypass diodes or fixed electrical configurations, the proposed Array Reconfiguration (AR)-based approach dynamically adjusts the interconnections of PV modules to minimise shading losses and enhance power generation. The AR-based approach analyses the shading patterns in real-time, determines the optimal reconfiguration strategy, and restructures the array accordingly to maximise PV power output. Simulation results validate the effectiveness of the proposed method, demonstrating a significant improvement in power yield and system reliability compared to conventional static and electrical reconfiguration techniques. The findings highlight the potential of AR-based strategies as a cost-effective and adaptive solution to mitigate partial shading effects, ultimately enhancing the efficiency and sustainability of PV-EV integrated systems.

Keywords: Array reconfiguration, Partial shading conditions, Photovoltaic system, Power optimisation, Reconfiguration algorithm, Mismatch loss reduction, Renewable energy, Solar power efficiency

1 Introduction

The integration of solar photovoltaic (PV) systems into the power grid is critical for the shift to sustainable and renewable energy solutions. Solar PV systems turn sunshine into electricity and can be installed in a variety of configurations, such as grid-tied, off-grid, and hybrid systems. When integrated into the power system, PV generation decreases dependency on fossil fuels, lowers greenhouse gas emissions, and improves energy security. However, difficulties such as intermittent power generation, voltage fluctuations, and grid stability must be handled using advanced technologies such as Maximum Power Point Tracking (MPPT), energy storage systems, smart inverters, and grid-supportive management mechanisms. Effective integration tactics, such as demand-side management, microgrids, and hybrid energy solutions, contribute to the power system's smooth operation, dependability, and efficiency.

As solar PV use grows internationally, successful integration will be critical to creating a cleaner, more robust, and sustainable energy system. Several defects can develop in a solar PV integrated power system, compromising its efficiency, dependability, and safety. These defects might be classified as DC-side faults, AC-side faults, or environmental difficulties[1-2].

DC-side failures include open-circuit faults, which occur when a module or connection fails, limiting power output, and short-circuit faults, which can cause overheating and dangerous fires. Partial shading and bypass diode failures result in mismatch losses and hotspots, limiting system longevity. Ground faults arise when current flows accidentally to the ground, causing safety issues. AC-side faults include inverter failures, grid synchronisation challenges, and harmonic distortions, which all have an impact on power quality and grid stability.

Several strategies have been proposed in past studies to improve the efficiency of PV array-integrated power systems, particularly under varied environmental conditions such as partial shade. These strategies include dynamically rearranging PV module connections (e.g., Total Cross-Tied (TCT), Bridge-Link (BL), Su Do Ku, and Honeycomb topologies) to reduce mismatch losses and increase power extraction[3-9]. Advanced MPPT approaches, including Particle Swarm Optimisation (PSO), Fuzzy Logic, Artificial Neural Networks (ANN), and Grey Wolf Optimiser (GWO), improve efficiency by constantly

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altering the operating point. Bypass and blocking diodes are used to reduce shading-induced power losses and prevent reverse current flow, which protects the modules from harm. Module-level power electronics (MLPE), such as microinverters and DC-DC power optimisers, boost performance by independently adjusting each panel's output. A solar tracking system increases the effectiveness of photovoltaic (PV) panels by altering their orientation to follow the sun's movement, allowing for maximum sunlight exposure throughout the day. Single-axis solar tracking systems spin along one axis either horizontal or vertical following the sun from east to west, improving energy generation by 25-35 % over fixed panels. These are simpler, cheaper, and often employed in large-scale solar farms. Dual-axis solar tracking systems, on the other hand, rotate along both horizontal and vertical axes, allowing panels to track the sun's movement in all directions and maximise sunlight capture year-round. This results in a 35-45 % increase in power output, but at a higher cost and with additional maintenance requirements. While single-axis trackers are more affordable and extensively used, dual-axis trackers offer higher efficiency, making them excellent for applications requiring maximum energy harvest, such as concentrated solar power (CSP) systems or high-efficiency PV installations[10]. Regular cleaning and anti-soiling coatings minimise dust buildup, which reduces PV performance over time. Adjusting the tilt and position of the PV panel according to seasonal and geographical variables improves sunlight capture.

The integration of EV charging stations and PV arrays into the IEEE 33-bus test system is an important area of research for improving grid resilience, voltage stability, and energy efficiency in distribution networks. As EV use grows, charging stations generate high dynamic loads, resulting in voltage fluctuations, power losses, and peak demand difficulties. PV arrays allow renewable energy to be generated locally, lowering reliance on the grid and mitigating the impact of EV charging on system stability. However, the intermittent nature of solar power demands advanced control strategies, such as optimal power flow (OPF), real-time demand response, and battery energy storage systems (BESS), to maintain a stable power supply.

Studies on the IEEE 33-bus system assess the best sites for EV charging infrastructure and PV integration, using approaches such as voltage sensitivity analysis, optimal DG layout, and load management algorithms. The combination of EVs, PV arrays, and smart grid technology improves electricity quality, reduces losses, and increases the sustainability of distribution networks. The integration of electric vehicles (EVs) and photovoltaic (PV) arrays into the IEEE 33-bus test system entails strategically locating EV charging stations and distributed PV generation to optimise power flow, improve voltage stability, and reduce system losses. EVs are incorporated by installing charging stations on certain buses based on load demand, traffic patterns, and grid capacity. The EV charging stations act as dynamic loads that vary during the day, necessitating demand-side management and optimal power flow (OPF) techniques to lower voltage drops and power congestion.

PV arrays are used as distributed generation (DG) units, strategically located on buses with high solar potential, to supply local loads, reduce active power losses, and enhance voltage profiles. Solar power's intermittent nature needs the use of battery energy storage systems (BESS) and smart grid technology to balance supply and demand. Advanced optimisation algorithms, power flow analysis, and real-time control mechanisms are used to establish the best placements and capacities for both EV chargers and PV systems[11]. Partial shade can cause voltage swings and have an influence on power quality in grid-connected systems, but it can also affect battery charging efficiency in independent systems.

Array reconfiguration (AR), dynamic MPPT algorithms, and shade-tolerant PV layouts are critical solutions for mitigating the negative impacts of partial shading and maintaining the steady and efficient functioning of solar-integrated power systems. Partial shadowing reduces the performance of a solar PV integrated power system by creating power mismatches, lowering energy generation, and increasing system inefficiencies[12]. When certain PV modules receive less sunlight due to barriers such as trees, buildings, or clouds, their output voltage and current drop, disturbing the uniform flow of power in the array. This causes mismatch losses, poorer MPPT efficiency, and hotspot formation, which can reduce module lifespan and pose safety issues. Furthermore, frequent bypass diode activation changes the array's effective voltage and current, lowering power extraction even more.

This study introduces an AR-based strategy to improve the performance of a PV-EV integrated system under PSCs. It introduces various innovative characteristics that improve efficiency, reliability, and cost-effectiveness. Unlike traditional static or electrical reconfiguration techniques, this technology allows for dynamic array reconfiguration by continuously modifying PV module interconnections in real time to reduce power losses. It includes an advanced shade detection and analysis system that recognises shading patterns, forecasts power losses, and offers the most efficient reconfiguration technique, ensuring adaptive and real-time optimisation even in quickly changing environmental conditions. This approach further improves MPPT efficiency by minimising mismatch losses and guaranteeing equal power distribution across modules, resulting in better overall power extraction. It contributes to system reliability and longevity by minimising hotspot formation and excessive stress on shaded modules, reducing potential degradation and failures.

2 Modelling of Photovoltaic Array

A PV array is mathematically modelled by describing the electrical behaviour of interconnected PV modules under various environmental conditions, such as irradiance and temperature. A PV array is made up of several PV cells coupled in series and parallel to provide the desired voltage and current levels. Figure 1 depicts the essential building block, the single-diode model, which consists of a current source representing photon-generated current, a diode accounting for recombination losses, and series and shunt resistances reflecting internal losses. The array's current-voltage (I-V) and power-voltage (P-V) characteristics are calculated using the Shockley equation, which considers parameters such as irradiance, temperature, and shading effects[13]. The MPP is determined using numerical or analytical techniques such as Newton-Raphson, Perturb and Observe (P&O), or Incremental Conductance (IC) algorithms to ensure optimal power extraction.

The governing equation for the output current of a PV cell is derived from the Shockley diode equation and is given as;

$$I = I_{ph} - I_d - I_{sh} \quad \text{... (1)}$$

The photocurrent is proportional to the incident solar radiation and is given by;

$$I_{ph} = [I_{sc} + K_i(T - T_{ref})] \times (G/G_{ref}) \quad \text{... (2)}$$

The diode current follows the Shockley diode equation and is given by;

$$I_d = I_0 \left[e^{((V + IR_s)/(nV_t))} - 1\right. \quad \text{... (3)}$$

The current loss due to the shunt resistance R_{sh} is;

$$I_{sh} = (V + IR_s) / R_{sh} \quad \text{... (4)}$$

Substituting all terms into the original equation, it is;

$$I = I_{ph} - I_0 \left[e^{((V + IR_s)/(nV_t))} - 1\right] - (V + IR_s)/R_{sh} \quad \text{... (5)}$$

PV modules are interconnected in series (S), parallel (P), and series-parallel (S-P) arrangements to create a high-power array. A PV array is an organised network of PV modules. Multiple modules are linked in series to form a series string, which is then merged in parallel to form the whole array. Figure 2 illustrates the equivalent circuit of a PV array. The model of a series-connected PV array at Standard Test Conditions (STC) depicts the electrical behaviour of many PV modules connected in series to provide a higher voltage output while keeping the same current. In this setup, the overall voltage of the array is the sum of the voltages of each module.

The PV array output current is expressed in Eq. (6).

$$I = N_p I_{ph} - N_p I_0 \left[\exp((V + (N_s/N_p) I_a R_s)/(N_s V_t a)) - 1\right] - (V + (N_s/N_p) I_a R_s)/((N_s/N_p) R_p) \quad \text{... (6)}$$

The overall power output is calculated as the product of the array voltage and current. The single-diode model governs the efficiency of a solar PV array under STC conditions, which include a standard irradiance level, cell temperature, and air mass. The given model considers photogenerated current, reverse saturation current, and internal resistances, all

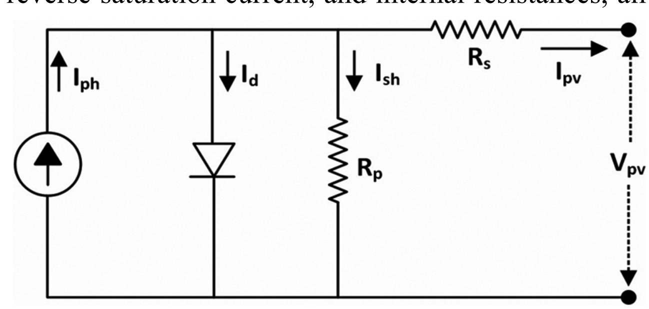

Fig. 1 — Single diode PV cell model

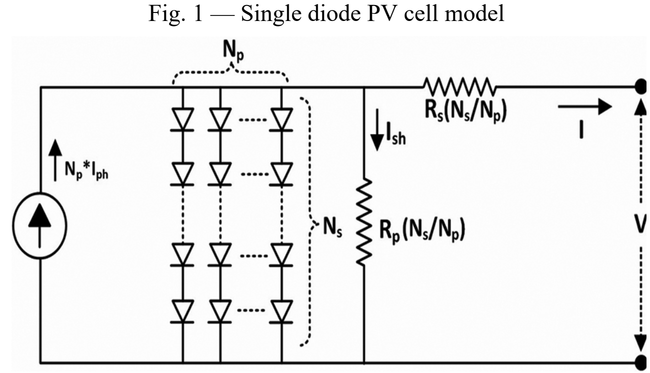

Fig. 2 — Equivalent circuit of a PV array

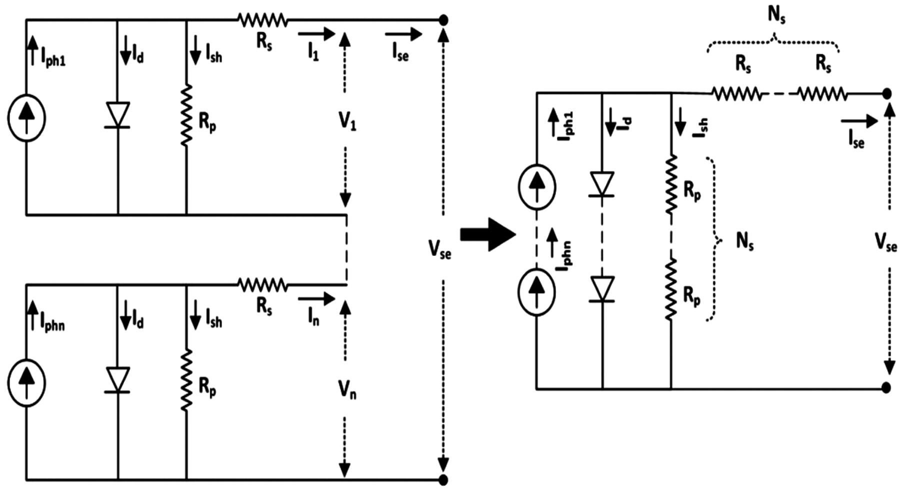

Fig. 3 — Equivalent circuit of a series-parallel connected PV array

of which have an impact on the array's electrical characteristics. The combination of these factors influences the current-voltage and power-voltage characteristics, affecting the efficiency of power generation and the system's capacity to monitor the maximum power point. Figure 3 depicts this model, which is critical for maximising the performance of solar photovoltaic systems in various environmental and operating scenarios.

The output current of the series-connected PV array at STC is as follows;

$$I_{se} = I_{ph0} - I_0 [\exp((V_{se} + N_s I_{se} R_s)/(N_s V_t a)) - 1] - (V_{se} + N_s I_{se} R_s)/(N_s R_p) \quad ... (7)$$

Figure 4 depicts a model of a series-connected PV array in partially shaded conditions, demonstrating how shading impacts the array's electrical performance. In a series design, all modules carry the same current, but partial shading on one or more modules limits their power generation, resulting in a mismatched array. This mismatch can result in a decline in overall power output, reverse voltage biasing in shaded modules, and hotspot formation, all of which can cause long-term harm. To address these concerns, bypass diodes are frequently included in modules, allowing current to skip shaded portions while preventing excessive power losses. However, bypass diode activation changes the current-voltage characteristics, resulting in many peaks in the power curve, making algorithms such as MPPT more difficult. The impact of shading is determined by elements such as the position, intensity, and distribution of the darkened areas. Modelling the behaviour of a series-connected PV array under partial shade aids in the development of reconfiguration strategies, the optimisation of MPPT techniques, and the enhancement of overall system efficiency.

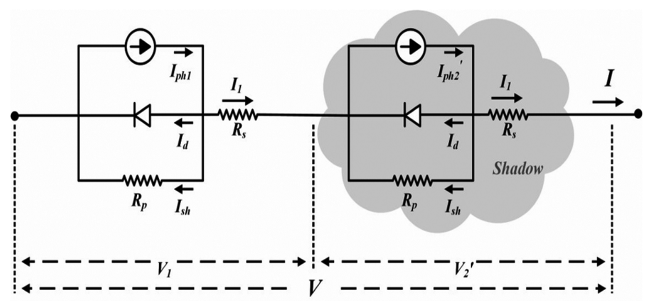

Fig. 4 — Series-connected PV array under partially shaded conditions

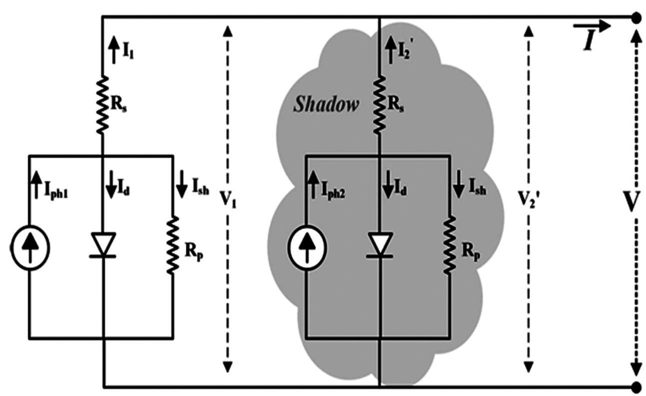

Fig. 5 — Parallel-connected PV array under partially shaded conditions

The output current of the two series-connected PV modules of the PV array is expressed as;

$$I = \alpha I_{ph0} - I_0 [\exp((V + 2IR_s)/(2V_t a)) - 1] - (V + 2IR_s)/(2R_p) \quad ... (8)$$

Figure 5 depicts a model of a parallel-connected PV array under partially shaded conditions. It investigates how shading affects the electrical performance of PV modules connected in parallel. In this design, each module has its own voltage, and the total array current is the sum of the currents created by the individual modules. Under partial shading, shaded modules generate less current than unshaded ones, resulting in an imbalance in power distribution. Unlike series-connected arrays, where shading on a single module can drastically limit overall output, a parallel arrangement reduces the impact of shading by allowing unshaded modules to operate to their full potential. However, voltage changes between modules can cause circulating currents, which increase power losses and reduce efficiency. To solve these challenges, MPPT controllers and power optimisers are employed to maximise power extraction from each module. Understanding the behaviour of a parallel-connected PV array under partial shade is critical for increasing energy yield, building efficient power management systems, and reducing losses in solar applications.

For two parallel-connected PV modules in the array, the output current under PSC is expressed as;

$$I = I_{ph1} + I'_{ph2} - 2I_0 \left[\exp((2V + IR_s)/(2V_t a)) - 1\right] - (2V + IR_s)/R_p \quad \text{... (9)}$$

$$I = I_{ph0} + \alpha I_{ph0} - 2I_0 \left[\exp((2V + IR_s)/(2V_t a)) - 1\right] - (2V + IR_s)/R_p \quad \text{... (10)}$$

$$I = (1 + \alpha)I_{ph0} - 2I_0 \left[\exp((2V + IR_s)/(2V_t a)) - 1\right] - (2V + IR_s)/R_p \quad \text{... (11)}$$

Figure 6 depicts a model of a series-parallel linked PV array under partially shaded conditions, which examines the effect of shading on an array with PV modules coupled in both series and parallel configurations. In this design, modules are initially joined in series to form strings, which are then connected in parallel to increase both voltage and current output. Under partial shadowing, certain modules receive less sunshine, resulting in a mismatch in power generation. This mismatch causes current changes between different strings, as well as voltage imbalances in the array, resulting in reduced overall efficiency. While bypass diodes reduce power loss by enabling current to bypass shaded modules, they cause several peaks in the power-voltage curve, making MPPT more complex. Furthermore, shadowing in one area of the array can result in unequal power distribution across strings, causing internal losses. Array reconfiguration algorithms, distributed MPPT controllers, and power electronics-based optimisers are commonly used to reduce shading effects and increase energy extraction. Understanding the behaviour of a series-parallel PV array under partial shadowing is critical for creating efficient solar power systems that are more reliable and perform well. A PV array's PV (Power-Voltage) and VI (Voltage-Current) characteristics explain its electrical performance when exposed to both normal and partial shade. Under normal conditions, where all modules receive uniform sunlight, the VI curve shows a smooth, nonlinear drop in current as voltage increases, but the PV curve has a single peak equal to the MPP.

The output current from the SP configuration, if any one of the modules is under PSC, is expressed as;

$$I = I_{ph1} - I_0[\exp((V_1 + I_1R_s)/(V_t a)) - 1] - (V_1 + I_1R_s)/R_p + I'_{ph2} - I_0[\exp((V_2 + I_2R_s)/(V_t a)) - 1] - (V_2 + I_2R_s)/R_p \quad \text{... (12)}$$

$$I = I_{ph1} + I'_{ph2} - 2I_0[\exp((V + IR_s)/(2V_t a)) - 1] - (V + IR_s)/R_p \quad \text{... (13)}$$

$$I = I_{ph0} + \alpha I_{ph0} - 2I_0[\exp((V + IR_s)/(2V_t a)) - 1] - (V + IR_s)/R_p \quad \text{... (14)}$$

$$I = (1 + \alpha)I_{ph0} - 2I_0[\exp((V + IR_s)/(2V_t a)) - 1] - (V + IR_s)/R_p \quad \text{... (15)}$$

However, under PSCs, certain modules produce less power due to lower irradiance, resulting in mismatch losses and modifying the array's electrical behaviour. Shaded modules run at lower currents, causing several steps or kinks in the VI curve. Similarly, the PV curve has several peaks, which

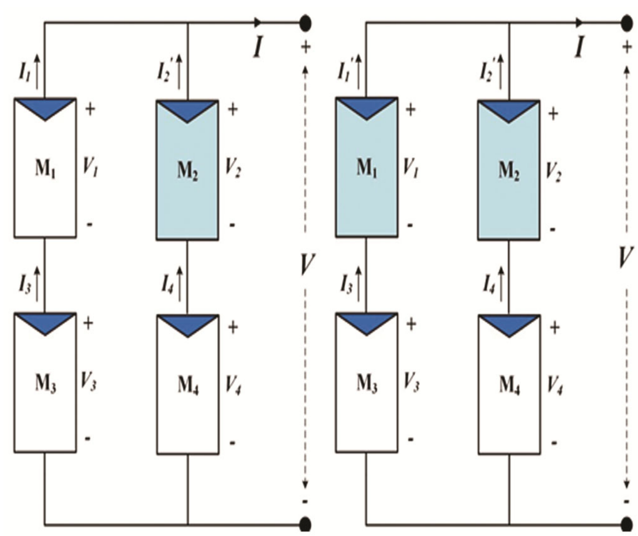

Fig. 6 — Series-parallel connected PV array under partially shaded conditions

complicates MPPT because the algorithm must discriminate between a local and a global maximum power point. Bypass diodes decrease shading effects by allowing current to flow around shaded modules, but they also affect the array's overall voltage responsiveness. Effective array reconfiguration, adaptive MPPT techniques, and power electronics solutions are critical for maximising PV array performance under varied shading conditions. Figure 7 depicts the I-V characteristics of a PV array under varying operating conditions.

3 Results and Discussion

The proposed method is tested using the standard IEEE 33-bus Test system. The IEEE 33-bus test system is a popular benchmark distribution network for evaluating power flow, voltage stability, and optimisation strategies in electrical power systems [14-16]. It is made up of 33 nodes (buses) and 32 branches, which comprise a radial distribution network with a base voltage of 12.66 kV, a total actual power demand of 3.72 MW, and a reactive power demand of 2.3 MVAR. The system is commonly used to evaluate distributed generation (DG) integration, network reconfiguration, loss minimisation, voltage profile enhancement, and fault investigation. Because of its radial design, it has a high resistance-to-reactance (R/X) ratio, rendering it susceptible to voltage drops and power losses.

Researchers often use this test system to assess advanced optimisation algorithms, load flow analysis methodologies, and the influence of renewable energy

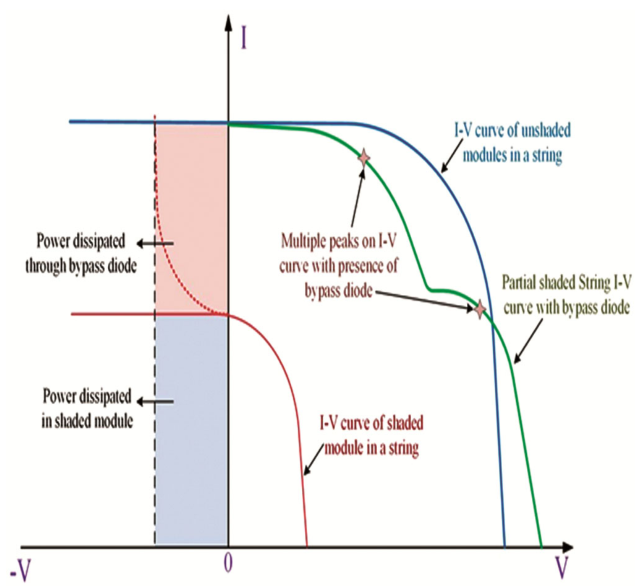

Fig. 7 — I-V characteristics of PV array

sources like solar PV and wind energy. It is used as a standard reference for creating and validating novel techniques in power distribution system planning and operation. This integration improves the grid's stability, efficiency, and sustainability while also facilitating the transition to a renewable-energy-powered transportation system. Figure 8 depicts a single-line schematic of an EV charging station and PV array combined with an IEEE 33-bus test system. The voltage and current charts of the IEEE 33-bus distribution system alter dramatically when EV charging stations and PV arrays are combined, demonstrating the dynamic nature of power generation and consumption[17].

Without PV integration, EV charging stations operate as additional loads, increasing current flow, increasing power losses, and lowering voltage on buses with high charging demand. The voltage profile often decreases at distant buses due to increased resistance in the radial network. When PV arrays are integrated, they add active power to the system, increasing voltage levels and reducing grid stress. The voltage charts demonstrate swings caused by PV intermittency, with peak voltages occurring during periods of high solar generation and dips during times of low solar availability. The current graphs vary according to EV charging schedules, with larger current magnitudes during peak charging hours and lower currents when PV generation offsets charging demand. Real-time voltage regulation, energy storage systems, and demand-side management are all examples of advanced control mechanisms that serve to stabilise these fluctuations, resulting in a more balanced and efficient distribution system. Figure 9 depicts the grid current as influenced by EVs and PV. The influence of various shading circumstances on a 6 × 6 PV array was researched to assess the performance of different array designs. All shading scenarios were conducted at the same temperature of 25 °C. The shading scenarios considered variations in the sun's irradiation levels, which were 400 W/m², 600 W/m², 700 W/m², 800 W/m², 900 W/m², and 1000 W/m². Figure 10 depicts the partial shading circumstances employed in the experiment. Figure 11 shows the modelled AR configuration.

The series-parallel connection with the necessary modified TIE connections is applied to form the new AR configuration.

To reduce partial shade and mismatch losses, a 6×6 PV array reconfiguration dynamically adjusts the

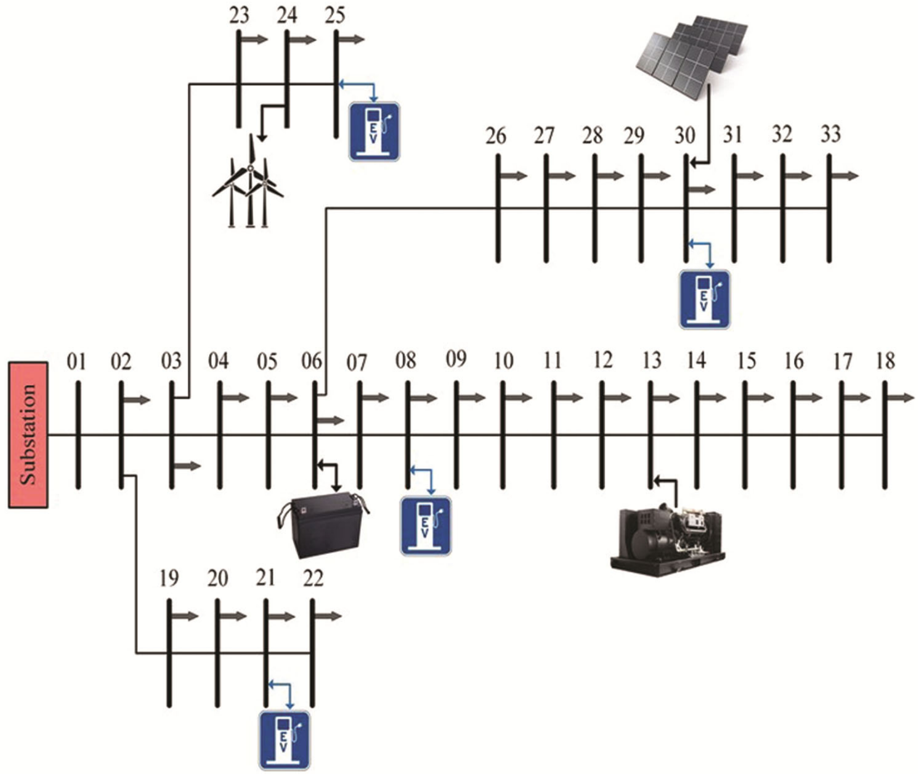

Fig. 8 — Single-line diagram of EV charging station and PV array integrated into IEEE 33-bus test system

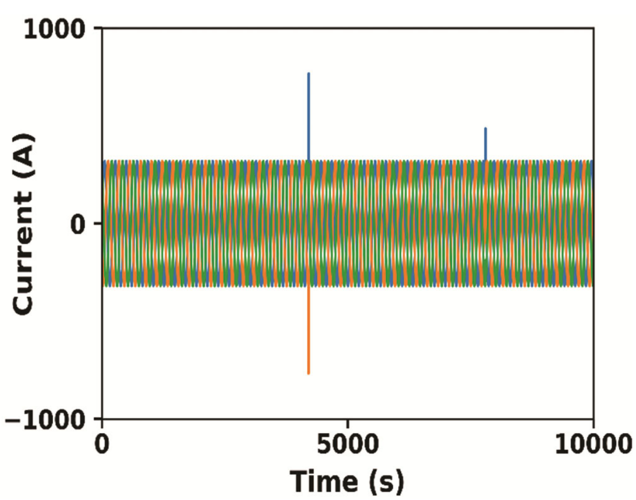

Fig. 9 — Grid current under EV charging station and PV array influence on the power system

electrical connections of a 6-row, 6-column module design. In a fixed design, shading on certain modules dramatically affects overall power output due to series-string current restrictions and bypass diode activation. Bridge-Link, Total Cross-Tied, and Series-Parallel reconfiguration approaches, as well as SuDoKu and Dynamic Reconfiguration (DR), alter module interconnections to redistribute shading effects more evenly across the array. This improves power extraction by minimising current mismatch, increasing voltage levels, and moving the MPP closer to an unshaded array. Intelligent control techniques, such as metaheuristic optimisation, artificial intelligence (AI), and IoT-based switching, improve the reconfiguration process in real time. Reconfiguring a 6×6 PV array improves energy yield and dependability and decreases hotspots, leading to better performance of PV-integrated power systems. The AR method's performance is compared to SP, TCT, and BL. Under uniform partial shade conditions, the PV curve of a PV array shown in Figure 12 has several peaks due to the activation of bypass diodes, which generate local and global MPPs. Traditional topologies such as SP, TCT, and BL struggle to extract maximum power under shading because they do not adequately redistribute the irradiance imbalance. The AR technique dynamically adjusts the connections between PV modules to provide a more uniform distribution of shading effects, resulting in increased power extraction. In comparison to SP, TCT, and BL, the AR technique improves the PV curve by lowering power fluctuations, minimising the number of local MPPs, and bringing the global MPP closer to that of an unshaded array. This leads to increased power production, better voltage stability, and more efficiency.

Various Partial Shading Conditions

Uniform	1000	1000	1000	1000	1000	1000
	1000	1000	1000	1000	1000	1000
	1000	1000	1000	1000	1000	1000
	1000	1000	1000	1000	1000	1000
	1000	1000	1000	1000	1000	1000
	1000	1000	1000	1000	1000	1000
Case-1	800	600	1000	1000	1000	1000
	800	600	1000	1000	1000	1000
	800	600	1000	1000	1000	1000
	800	600	1000	1000	1000	1000
	800	600	1000	1000	1000	1000
	800	600	1000	1000	1000	1000
Case-2	1000	1000	1000	1000	1000	1000
	1000	1000	1000	1000	1000	1000
	1000	1000	1000	1000	1000	1000
	1000	1000	1000	1000	1000	1000
	800	800	800	800	800	800
	600	600	600	600	600	600
Case-3	1000	1000	1000	1000	1000	1000
	1000	1000	1000	1000	1000	1000
	1000	900	800	600	400	1000
	1000	900	800	600	400	1000
	1000	1000	1000	1000	1000	1000
	1000	1000	1000	1000	1000	1000
Case-4	1000	1000	1000	1000	600	800
	1000	1000	1000	1000	600	600
	1000	1000	1000	1000	1000	600
	600	600	1000	1000	1000	1000
	600	600	1000	1000	1000	1000
	800	600	1000	1000	1000	1000

Colour legend: 1000 W/m² 900 W/m² 800 W/m² 700 W/m² 600 W/m² 400 W/m²

Various Partial Shading Conditions

Case-5	800	600	400	1000	1000	1000
	800	600	400	1000	1000	1000
	1000	1000	1000	1000	1000	1000
	1000	1000	1000	1000	1000	1000
	1000	1000	1000	1000	1000	1000
	1000	1000	1000	1000	1000	1000
Case-6	900	800	700	600	400	1000
	900	800	700	600	400	1000
	1000	1000	1000	1000	1000	1000
	1000	1000	1000	1000	1000	1000
	1000	1000	1000	1000	1000	1000
	1000	1000	1000	1000	1000	1000
Case-7	800	800	1000	1000	1000	1000
	600	600	1000	1000	1000	1000
	400	400	1000	1000	1000	1000
	1000	1000	1000	1000	1000	1000
	1000	1000	1000	1000	1000	1000
	1000	1000	1000	1000	1000	1000
Case-8	800	800	1000	1000	1000	1000
	800	800	1000	1000	1000	1000
	600	600	1000	1000	1000	1000
	600	600	1000	1000	1000	1000
	400	400	1000	1000	1000	1000
	1000	1000	1000	1000	1000	1000
Case-9	1000	1000	1000	1000	1000	400
	1000	1000	1000	1000	400	1000
	1000	1000	1000	600	1000	1000
	1000	1000	600	1000	1000	1000
	1000	800	1000	1000	1000	1000
	800	1000	1000	1000	1000	1000

Colour legend: 1000 W/m² 900 W/m² 800 W/m² 700 W/m² 600 W/m² 400 W/m²

Fig. 10 — Various partial shading conditions

i Under short-wide partial shade situations, where shading impacts numerous adjacent rows of a PV array, the PV curve depicted in Fig. 13 has multiple peaks due to the unequal distribution of irradiance across the modules. In conventional approaches such as Bridge-Link, Total Cross-Tied, and Series-Parallel, the mismatch in current between shaded and unshaded modules causes several local MPPs, making it difficult for MPPT algorithms to detect the genuine global MPP. The AR approach addresses this restriction by dynamically altering the electrical connections between modules, resulting in a more equal distribution of shading effects across the array. This produces a smoother PV curve with fewer local peaks and a more noticeable global MPP, which improves overall power extraction. In comparison to SP, TCT, and BL, the AR approach decreases power losses, mitigates mismatch effects, and improves voltage stability, resulting in a more efficient and dependable PV system. AR's capacity to adapt to

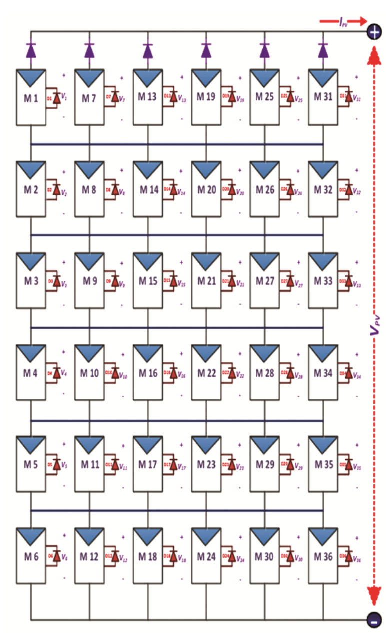

Fig. 11 — 6 × 6 AR-based PV array

changing shading conditions gives it a superior method for increasing energy yield in short-wide partial shading settings.

ii Under short-narrow PSCs, where shading impacts just a small portion of the PV array, the PV curve depicted in Fig. 14 has several peaks due to current mismatch and uneven power generation across modules. In traditional topologies such as SP, TCT, and BL, shading on a tiny fraction of the array can drastically lower overall power output by restricting current flow through the series-connected modules. This creates several local MPPs, making it impossible for typical MPPT algorithms to efficiently track the global MPP. The AR technique dynamically adjusts the interconnections between PV modules, dispersing shading effects more equally throughout the array. This produces a PV curve with fewer local peaks, a higher global MPP, and better power extraction. In comparison to SP, TCT, and BL, the AR technique decreases mismatch losses, reduces voltage instability, and increases energy production in short-narrow partial shade situations. AR's versatility makes it a better solution for ensuring consistent and efficient PV system operation in a variety of shading circumstances.

iii Under long-wide PSCs, where shading persists across multiple rows of the PV array, the PV curve in Fig. 15 becomes highly irregular, with multiple local MPPs caused by unequal irradiance distribution. Traditional topologies like SP, TCT, and BL struggle to maintain efficient power extraction because shaded rows undergo significant current reduction, which causes bypass diode activation and voltage dips. This produces a fragmented PV curve with several local peaks, making it difficult for MPPT algorithms to accurately pinpoint the global MPP. However, the AR technique dynamically adjusts the modules' electrical interconnections, resulting in a more equal distribution of shading effects across the array. This reconfiguration smoothed the PV curve, reduced the number of local peaks, and improved overall MPP. When compared to SP, TCT, and BL, the AR

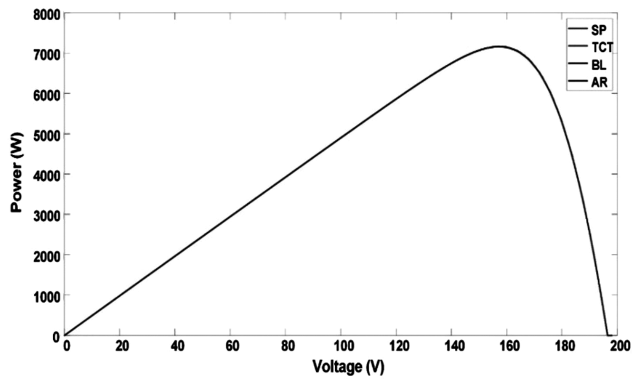

Fig. 12 — Performance comparison under uniform condition

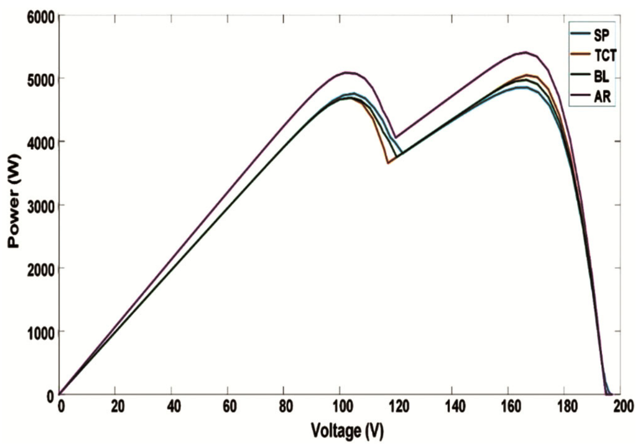

Fig. 13 — Performance comparison under short-wide condition

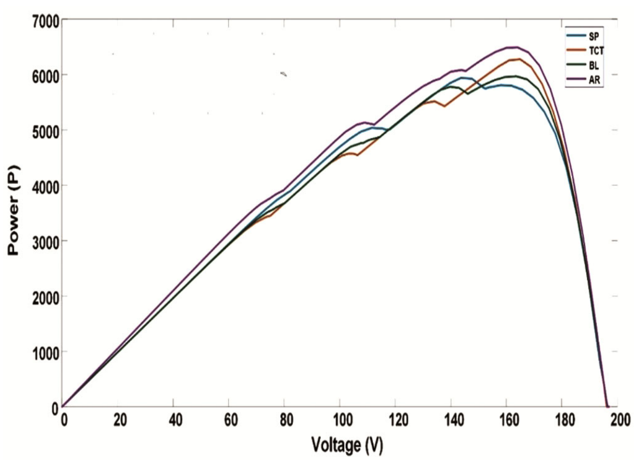

Fig. 14 — Performance comparison under short-narrow condition

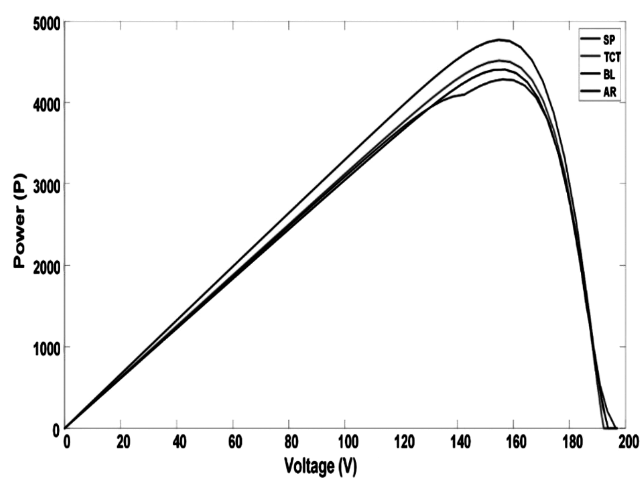

Fig. 15 — Performance comparison under long-wide condition

approach greatly reduces power losses, minimises mismatch effects, and increases energy production, making it the best alternative for maximising PV performance under long-wide partial shadowing conditions.

iv Under long-narrow PSCs, the PV curve is substantially deformed with many local MPPs because of the uneven current production across series-connected modules, where shadowing affects multiple modules in a single column or a narrow vertical area of the PV array. The shade of a whole vertical section in traditional topologies such as SP, TCT, and BL restricts the current flow in the impacted strings, resulting in large power losses, bypass diode activation, and voltage instability. This leads to a multi-peaked PV curve in Fig. 16, which makes it difficult for MPPT algorithms to precisely follow the global MPP. By dynamically changing the connections between modules to disseminate shading effects and guarantee a balanced current flow throughout the array, the AR technique solves this problem more evenly. This enables improved power extraction and voltage stability by producing a PV curve with a smoother profile, fewer local peaks, and a higher global MPP. The AR method is the best way to sustain PV system performance under long-narrow partial shadowing conditions because it efficiently lowers mismatch losses, boosts energy yield, and optimises MPPT monitoring when compared to SP, TCT, and BL.

v Under diagonal PSCs, the PV curve becomes extremely erratic, where shading happens across modules in a diagonal pattern, because of the intricate distribution of irradiance across both series and parallel connections. Shading on diagonally aligned modules in conventional topologies such as SP, TCT, and BL results in non-uniform current flow, producing many local MPPs and lowering the PV system's overall efficiency. When bypass diodes are activated, abrupt voltage drops and power fluctuations are introduced, significantly complicating the PV curve depicted in Fig. 17. This causes a multi-peaked, fragmented PV curve, which makes it challenging for MPPT algorithms to accurately identify the global MPP. The AR technique reduces existing mismatches by rearranging module connections to distribute shading effects more evenly throughout the array. This results in a smoother PV curve with fewer local peaks and a more noticeable global MPP, which improves MPPT tracking and increases power production. The AR approach is the best way to maximise PV array performance in situations with diagonal partial shadowing since it dramatically lowers power losses, increases energy yield, and improves system reliability when compared to SP, TCT, and BL.

Under different shading patterns—including uniform, short-wide, short-narrow, long-wide, long-narrow, and diagonal shading several designs, including SP, TCT, and BL, have been investigated to reduce shading effects; however, they frequently suffer from inadequate MPPT tracking, power losses, and voltage instability. A better approach is the AR technique, which dynamically adjusts module connections to redistribute shading effects more equally, increasing energy efficiency, power output, and voltage stability.

The performance comparison of solar array configurations like SP, TCT, BL, and AR is tabulated in Table 1. The SP configuration suffers from low Pmax, unstable Vmp, and low Imp due to severe mismatch losses, making it the least efficient. The TCT and BL configurations improve shading tolerance by redistributing mismatch effects, resulting

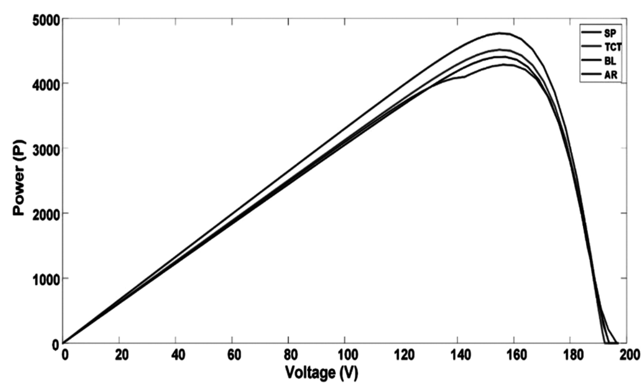

Fig. 16 — Performance comparison under long-narrow condition

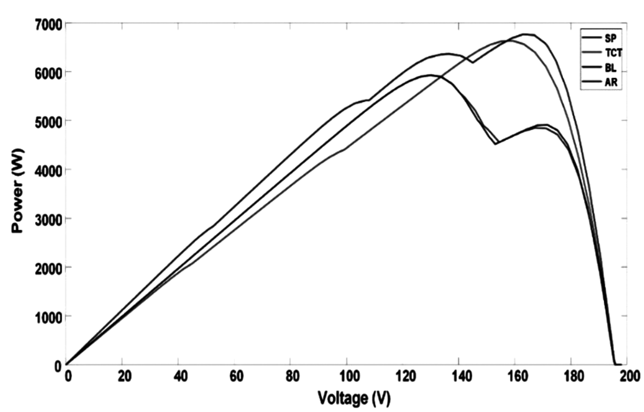

Fig. 17 — Performance comparison under diagonal condition

Table 1 — Performance comparison of PV array configurations

Shading condition	Array configuration	Vm	Im	Pm
Uniform	SP	156.83	45.69	7165.56
	TCT	157.23	45.56	7163.69
	BL	154.69	45.65	7163.12
	AR	157.67	45.43	7163.24
Short narrow	SP	144.85	40.38	5849.38
	TCT	160.59	39.15	6287.29
	BL	157.68	38.16	6017.18
	AR	164.14	39.17	6429.72
Short wide	SP	156.24	30.16	4712.24
	TCT	163.47	31.21	5102.01
	BL	158.68	30.83	4892.17
	AR	169.47	31.63	5360.42
long narrow	SP	161.72	35.87	5801.16
	TCT	166.08	36.80	6112.08
	BL	167.23	35.42	5923.46
	AR	162.92	38.56	6282.24
Long wide	SP	149.81	28.12	4212.85
	TCT	152.44	29.73	4532.27
	BL	146.68	29.98	4397.56
	AR	162.78	29.62	4821.63
Diagonal	SP	134.98	44.35	5986.68
	TCT	159.84	42.12	6732.54
	BL	134.82	44.64	6018.43
	AR	158.42	43.02	6815.54

in moderate Pmax, improved Vmp stability, and better Imp, though they still face challenges with multiple local MPPs. The AR method outperforms all other configurations, achieving higher Pmax, stable and optimised Vmp, and increased Imp by dynamically reconfiguring module connections to minimise shading effects. This makes AR the most efficient approach, providing superior power extraction, better voltage regulation, and enhanced shading tolerance compared to conventional configurations.

4 Conclusion

The present work evaluates the effect of array reconfiguration on the performance of a PV–EV integrated system operating under different partial shading patterns. The results show that the AR configuration provides better power extraction than the SP, TCT, and BL arrangements in most shading cases. The improvement is mainly due to the redistribution of irradiance mismatch across the PV array, which reduces the effect of shaded modules on the overall array output. As a result, the proposed approach improves maximum power, operating voltage, and current response under short-wide, short-narrow, long-wide, long-narrow, and diagonal shading conditions. Compared with conventional configurations, the AR method offers better shading tolerance and helps maintain a more stable operating point for the PV system. This is useful for PV–EV applications, where stable PV output is important for supporting EV charging loads and reducing stress on the distribution network. The findings indicate that array reconfiguration can be used as a simple and effective method to improve energy yield without major changes in the PV module structure. Future work may focus on validating the proposed configuration using hardware implementation and real-time control. Further improvement can also be achieved by combining AR with intelligent MPPT algorithms, battery energy storage, and smart grid-based monitoring for better operation under rapidly changing irradiance conditions.

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