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Operation of Dual MPPT Enabled Hybrid Microgrid under Variable Irradiation Conditions and its Positive Impact on Stability of AC Conventional Grid

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The growing population, technological advancements, and heightened economic activities drive a greater demand for energy within the AC conventional grid. However, this energy demand can be met by utilizing renewable energy sources such as solar, wind, and biomass. These alternative energy sources generate electricity influenced by varying input factors, such as solar irradiation and temperature for photovoltaic systems, as well as wind speed and pitch angle for wind turbines. Among these factors, solar irradiance is the most unpredictable, affected by numerous environmental influences such as air pollution, cloud cover, and changing weather patterns. As a result, photovoltaic arrays have a significant impact on energy production, thereby affecting the stability of the traditional AC grid as it seeks to meet the increasing power demand. This paper proposes a solution to enhance the stability of the AC conventional grid through a novel hybrid microgrid that integrates dual MPPT-enabled photovoltaic and wind turbine generators, particularly during peak load conditions.

Keywords: Dual MPPT, Resilient, Hybrid microgrid, Variable load, State of charge

1 Introduction

There was a significant surge in electricity demand from the beginning of the 21st century, particularly during the first decade (2000-2010). This increase in electricity demand can be attributed to several economic factors, including notable economic growth and industrialization initiatives[1]. In addition to these economic pursuits, a significant increase in the global population has been observed, accompanied by substantial advancements in urbanization efforts. These factors have also played a crucial role in driving the increasing energy demand[2-3]. The shift toward higher living standards and a notable rise in consumerism has led to greater demand for electricity, particularly evident in the increased per capita consumption rates in developed countries[4-5].

The outlined expectations indicate a significant increase in global energy demand over the coming decades, with developing countries like China and India set to play a vital role in this escalation[6]. Experts predict that global energy demand will increase by 1.25% to 1.5% annually, potentially doubling over the next 40 to 50 years[7]. In 2008, thermal power plants accounted for approximately 41.00% of global electricity generation, underscoring the crucial role of fossil fuels, including fuel oil, natural gas, and coal, in worldwide energy production[8]. Fossil fuels, including crude oil, natural gas, and coal, are pivotal in shaping the global economy and significantly impacting international geopolitics[9-10]. Many factors, including fuel type, fuel quality, supply chains, and the interaction between demand and supply, significantly impact the economic feasibility of fossil fuel use[11].

The rising energy demands have led to increased environmental pollution, primarily due to the burning of fossil fuels for electricity generation[12]. The increasing energy consumption will significantly impact the global environment and future generations, elevating atmospheric carbon dioxide levels and resulting in adverse changes in local climate patterns globally[13-14]. The increased energy consumption has led to higher carbon dioxide (CO2) levels in the environment, resulting in various environmental challenges such as acid rain, thermal pollution, lead contamination, and nuclear waste[15]. Effective public policies and international collaboration can tackle severe ecological threats, although a global consensus on reducing carbon dioxide levels has yet to be achieved[16]. To protect the environment, we must regulate energy consumption by improving energy-efficient power systems and incorporating alternative

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energy sources[17], which is essential. Relying on renewable energy sources, including solar, wind, geothermal, and biomass, is vital for enhancing energy and environmental security while ensuring stability and diversification in energy utilization[18-19]. Moreover, renewable energy sources are crucial in addressing societal challenges, including reducing unemployment, alleviating poverty, and providing electricity to remote rural areas[20]. Given the benefits of renewable energy sources in producing low-carbon electricity, countries worldwide need to shift towards their adoption, as they are environmentally sustainable and vital for improving energy efficiency[21-23].

2 Literature Survey

The sun, Earth's closest star, provides energy through solar power, which can be optimized using various technologies, such as concentrated solar power, solar water heating, and photovoltaic systems, to harness solar energy irradiation[24]. In aerospace, solar power satellites can efficiently capture solar energy from the sun and send it to Earth[25].Solar radiation has vast energy potential, offering endless clean and sustainable energy[26-27]. Solar energy provides a sustainable power source that can generate clean heat and electricity, positively impacting climate patterns[28-30]. The substantial demand for global energy can be effectively met by harnessing wind power, which has the potential to significantly reduce emissions and achieve climate change targets as a rapidly expanding and competitive renewable energy source source[31]. Wind energy capacity has the potential to be a substantial source of global electricity, providing more than 40 times the current global electrical power usage and more than five times the total global energy consumption across all sector categories[32-33]. Effectively harnessing wind energy faces many challenges due to changing atmospheric conditions; therefore, smart controllers for power management have been proposed to improve generation efficiency and manage excess output in small, autonomous wind energy systems systems[34].Wind power has the potential to meet global energy demands significantly; however, thorough research and innovation are crucial to overcoming technical challenges and market barriers[35-36]. Hybrid microgrids are essential for integrating various energy sources, including solar, wind, conventional generators, and energy storage systems, thus enhancing overall system performance efficiency[37]. Additionally, hybrid microgrid systems offer several advantages, including improved reliability, significant energy independence, and reduced environmental impact [38-39]. The strategic management and optimization of power usage and energy storage systems, particularly renewable energy sources, can be achieved by implementing hybrid microgrid operations[40]. These microgrids enhance energy system compatibility and minimize waste, fostering sustainable energy solutions for future generations[41]. Moreover, hybrid microgrids deliver reliable electrical power in various environments, including remote rural areas, critical infrastructure, commercial businesses, educational institutions, and many residential home areas[42]. Deploying hybrid microgrids in remote and rural areas significantly enhances the resilience and reliability of electrical power distribution, ensuring a stable power supply for consumers[43-44]. Integrating renewable energy sources into the power grid improves system sustainability and reduces carbon emissions emissions[45].Besides the benefits mentioned earlier, hybrid microgrids significantly enhance power grid resilience by providing backup energy during natural disasters and other critical situations[46].Ultimately, hybrid microgrids are crucial for optimizing resource planning and allocation, thereby minimizing the negative impacts on residential areas during significant power outages. Integrating load flexibility and efficient resource management significantly enhances the reliability and resilience of power distribution networks in remote and rural areas.

3 Impact of Partial Shading on Irradiation

The relationship between variable irradiation and partial shading in photovoltaic (PV) systems is complex and significantly impacts their performance. Partial shading, often caused by clouds or nearby obstructions, leads to heterogeneous irradiance across the PV array, complicating the power output characteristics and reducing overall efficiency[47-48]. The shading patterns, such as row-wise or column-wise, along with the number of shaded modules, further influence the power output, with column-wise shading typically resulting in a higher power output than row-wise shading shading[49]. Identifying the actual maximum power point (MPP) under partial shading conditions is challenging due to the presence of multiple MPPs, which necessitates advanced techniques like Maximum Power Point Tracking (MPPT) for optimal performance[49-51]. Various algorithms, including Fuzzy Logic Controllers (FLC), have been developed to optimize PV module efficiency by predicting current-voltage dynamics and ensuring output stability. The arrangement of PV arrays and shading patterns significantly affects the quantity of Maximum Power Points (MPPs) and total power output, with increased shading intensities correlating to greater MPPs, independent of shading localization[50-51]. Dynamic reconfiguration frameworks and heuristic-based algorithms have been proposed to optimize photovoltaic (PV) array configurations under partial shading, thereby minimizing local maxima and enhancing power output[47]. These studies collectively emphasize the critical need for adaptive strategies to mitigate the adverse effects of variable irradiation caused by partial shading on PV systems.

4 Proposed Method

The effective operation of hybrid microgrids depends on critical parameters, such as irradiance—measuring solar power per unit area—temperature of photovoltaic arrays, which influences efficiency, and the wind speed and pitch angle of wind generators, all of which significantly impact the system's energy production capabilities.

Under the proposed methodology, each input source in the hybrid microgrid is equipped with a maximum power point tracking system, thereby enhancing power availability for the load. The operational modes of the hybrid microgrid, which can be analyzed through various methods, are categorized into two distinct types, with load variations occurring at different levels over time.

The irradiance will operate under varying circumstances and changing load and grid conditions. Meanwhile, the other three parameters—temperature, wind speed, and pitch angle—are consistently kept at their optimal values.

The operational modes of a hybrid microgrid are classified into two categories as follows.

1.Grid-connected mode of operation.

2.Islanded mode of operation.

4.1 Grid-Connected Mode of Operation

The operation of a hybrid microgrid in grid-connected mode involves a setup where the traditional power grid mainly supplies the electrical load. In this operational state, it is essential to note that the battery storage system receives its energy from solar photovoltaic panels and wind turbine generators, which operate optimally under Maximum Power Point Tracking (MPPT) conditions to ensure efficiency. As a result, the state of charge within the battery and the charging current rate may increase or decrease, inherently depending on fluctuations in load demand and consumption levels.

Thus, the interaction between the load characteristics and the energy generation sources is crucial for determining the overall performance and reliability of the hybrid microgrid system. Furthermore, this dynamic relationship underscores the importance of advanced energy management strategies in optimizing resource utilization and maintaining system stability under varying operational conditions.

4.2 Islanded Mode of Operation

The islanded operational mode of the hybrid microgrid involves a configuration where the power supply to the load primarily comes from a combination of a photovoltaic (PV) array and a wind turbine. According to the load requirements, the battery meets the energy demands of the load. In this operational mode, the battery's state of charge and discharge current will vary based on load conditions. In specific scenarios, the state of charge is maintained as the discharge current increases, resulting in a decrease in the state of charge. Conversely, in other cases, the discharge current is decreased while the state of charge is improved enhancement.

In reference to Fig. 1, it illustrates the schematic representation of a hybrid microgrid operating in a grid-connected configuration. This indicates a unidirectional flow originating from both the photovoltaic array and the wind turbine generator. Through a bidirectional DC-DC converter, the battery bank is charged using the accumulated energy from renewable sources.

The schematic representation in Fig. 2 illustrates a hybrid microgrid functioning in an islanded configuration, wherein the integrated renewable energy sources and a charged battery bank collectively supply both AC and DC loads under fluctuating irradiation conditions.

5 Simulation Results and Discussion

The performance of the Hybrid Microgrid is significantly influenced by four critical input

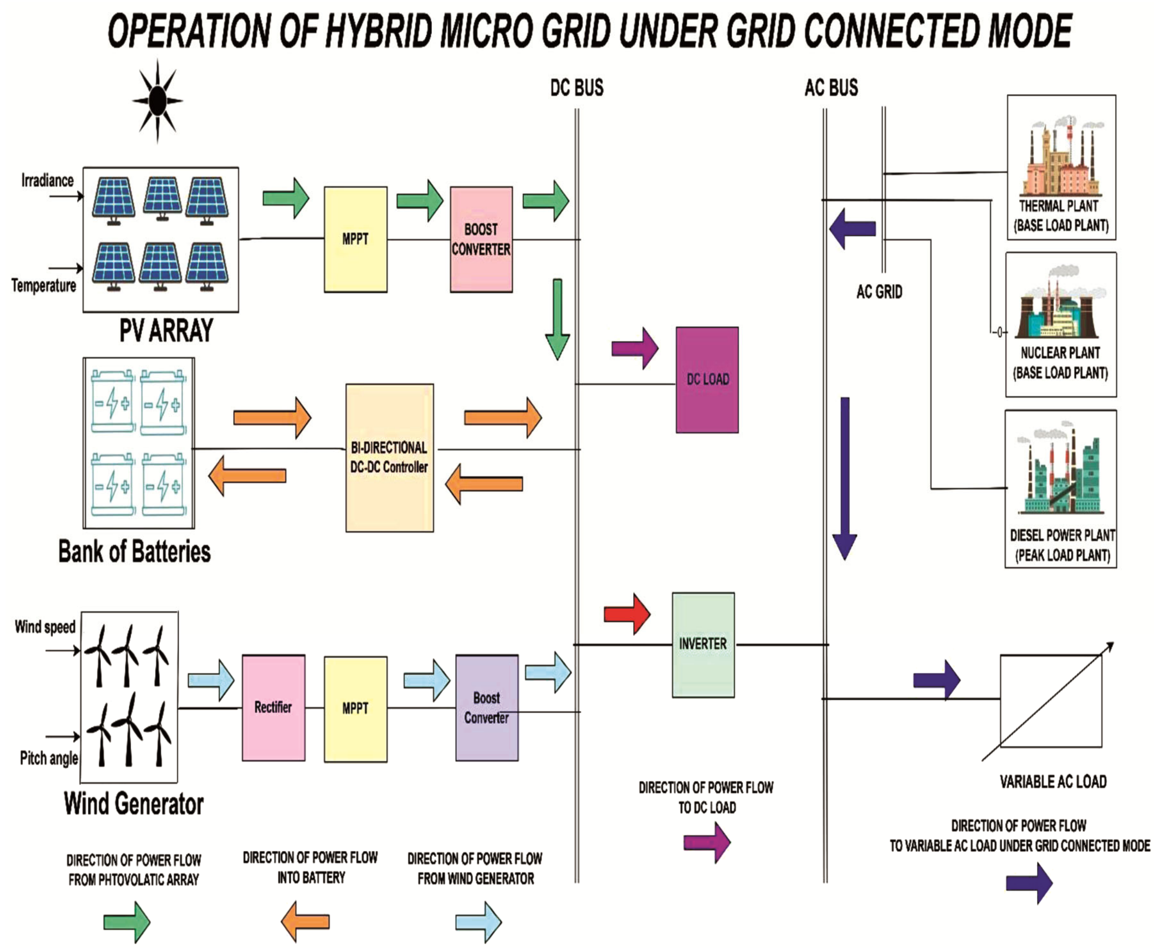

Fig. 1 — Grid-connected mode operation of Hybrid microgrid

parameters derived from the surrounding environment that must be considered for optimal functionality. These essential parameters include irradiance, temperature, wind speed, and pitch angle, each playing a critical role in the system's overall effectiveness and efficiency. Specifically, irradiance and temperature levels directly affect the output characteristics of the photovoltaic panel, thereby influencing its energy generation effectiveness. In contrast, wind speed and pitch angle are crucial factors that influence the performance output of the wind generator, ultimately affecting the energy yield from this component as well. In summary, understanding and monitoring these four input parameters is essential for maximizing the operational efficiency of the Hybrid Microgrid, ensuring that both photovoltaic and wind energy systems function at their best potential.

In the intricate scenario characterized by fluctuating irradiation levels, it is essential to note that, of the four critical parameters under consideration, only one parameter can vary at different stages and levels. This parameter is identified as irradiance, a crucial input for photovoltaic cells or arrays. Meanwhile, the other three input parameters relevant to the operation of the hybrid microgrid—namely temperature, wind speed, and pitch angle—were meticulously maintained at constant values throughout the simulation period, ensuring a controlled environment for the analysis. Concurrently, the hybrid microgrid is subjected to various stages characterized by variable conditions, allowing for a comprehensive assessment of its performance under such scenarios. Additionally, the electrical load of the hybrid microgrid encounters multiple phases of these fluctuating conditions, which is crucial for understanding how the system responds to shifts in demand and supply dynamics.

This rigorous approach enables researchers to evaluate the interplay between varying irradiance and

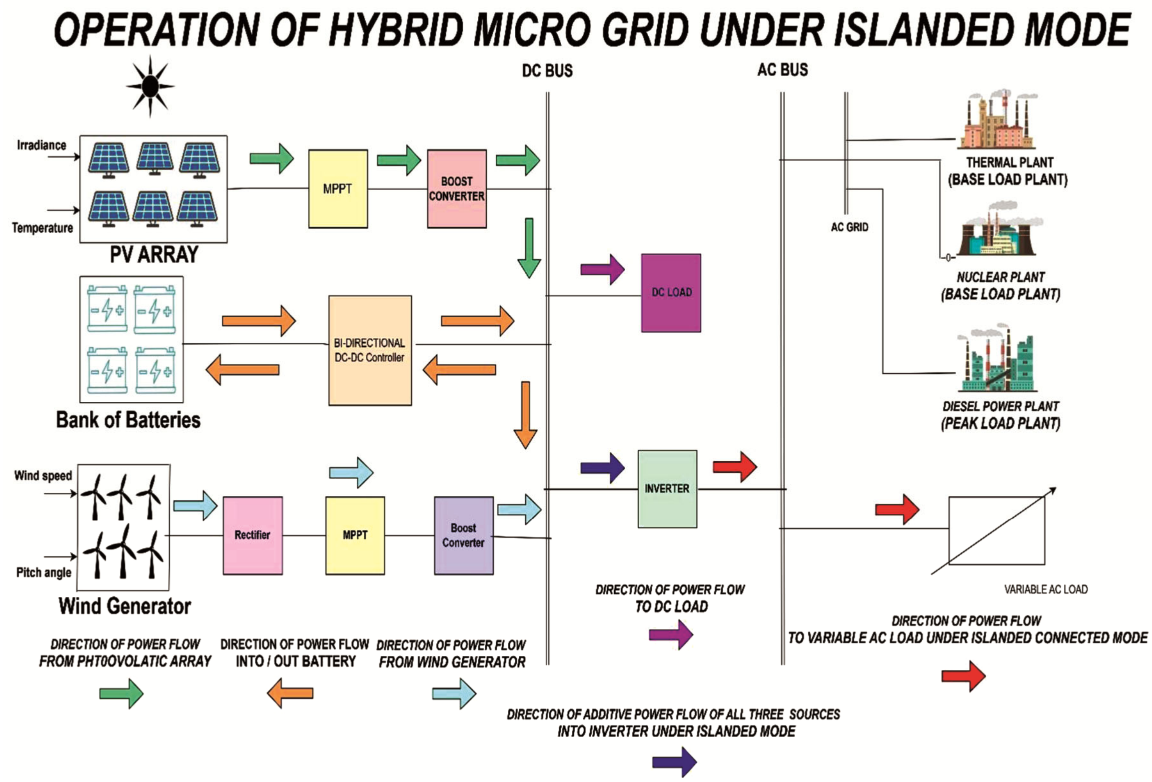

Fig. 2— Islanded mode operation of Hybrid microgrid.

steadfast parameters, providing insights into the hybrid microgrid's operational efficiency and stability. Ultimately, this methodical examination of the hybrid microgrid's behavior in response to constant and variable parameters is crucial for optimizing its design and functionality in real-world applications.

Figure 3 shows that one of the four significant parameters will be adjusted. In contrast, the other parameters—specifically temperature, wind speed, and humidity—will remain constant. The variable parameter, irradiance, will change from 800 W/m² to 1200 W/m². This modification of irradiance can be categorized into three distinct groups, as detailed below.

The photovoltaic (PV) panel goes through three operational stages regarding irradiance: the first stage, called "FSVOIR," operates below optimal conditions; the second stage, "SSVOIR," functions at rated conditions; and the third stage, "TSVOIR," exceeds optimal levels. A table will summarize the abbreviations for these stages of variable irradiance operation.

Where,

“FSVOIR” expanded as First Stage Variable Operation of Irradiance.

“SSVOIR” expanded as Second Stage Variable Operation of Irradiance.

“TSVOIR” expanded as Third Stage Variable Operation of Irradiance.

Table 1 explains the various stages of irradiance under different irradiation conditions: FSVOIR operates under less than rated or optimal conditions, SSVOIR operates at rated or optimal values, and TSVOIR operates above rated values value.

As an integral component of the proposed approach, the hybrid microgrid will operate in various operational modes. These modes will include both the Islanded mode and the grid-connected mode, with consideration given to the level of irradiation.

Concerning the Fig.4, it becomes evident that we can discern the diverse behaviors exhibited by the traditional grid system, which subsequently facilitates the operation of a hybrid grid across multiple variable modes. These various operational modes can be systematically categorized into four distinct classifications, namely the initial stage of variable grid operation, which is denoted or symbolized by the acronyms “FSVOG,” “SSVOG,” “TSVOG,” and “FTSVOG.”

Where

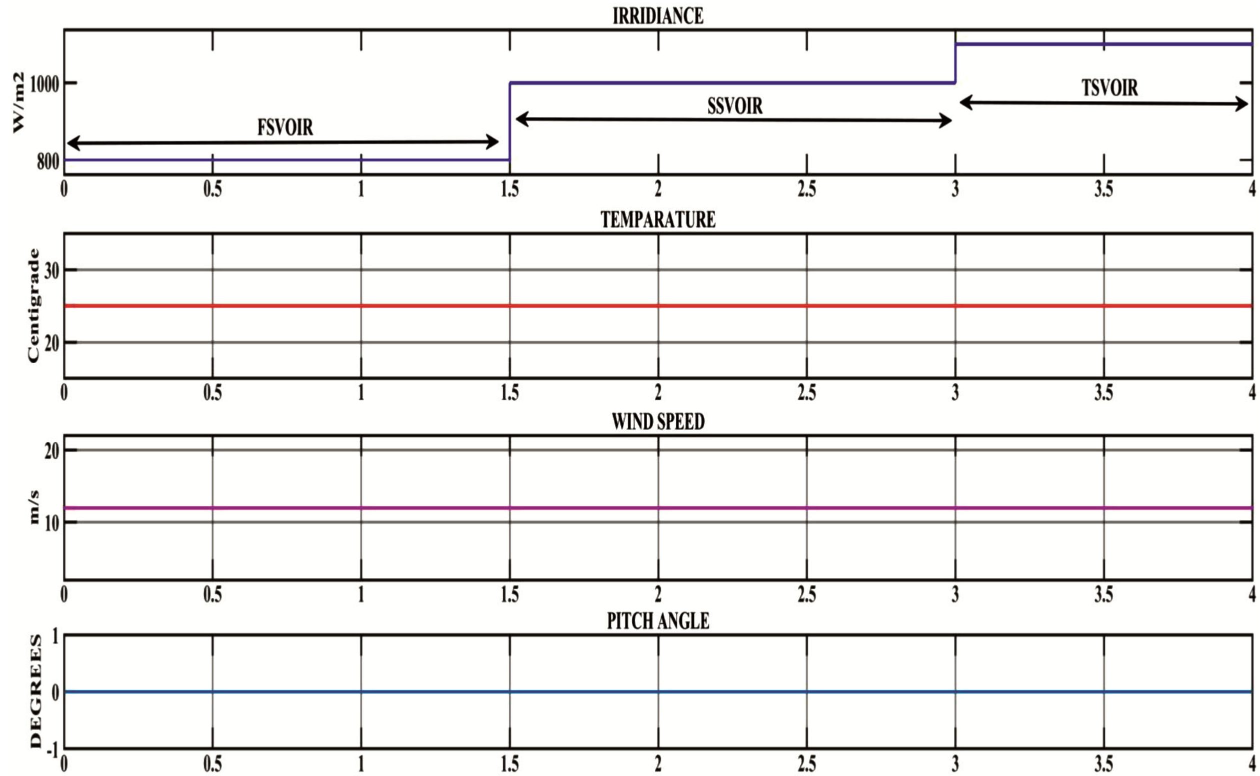

Fig. 3 — Behavior of irradiance, temperature, wind speed, and pitch angle under variable irradiation

Table 1 — List of various stages of variable irradiance

S.No	Abbreviated Title Denoted By	Level of Irradiation intensity.	Proportion of each stage's duration within the overall simulation timeframe.
1	FSVOIR	Less than rated/ Optimal value	37.5%
2	SSVOIR	Rated value/ Optimal value	37.5%
3	TSVOIR	More than rated/ Optimal value	25%

FSVOG expanded as the First stage of the grid's Variable Operation. In this mode, the Grid is connected or active.

SSVOG expanded as the Second stage of the Variable Operation of the Grid. In this mode, the Grid is disconnected or inactive.

TSVOG was expanded to the Third stage of the Variable Operation of the Grid. In this mode, the Grid is in connected or active mode.

FTSVOG was expanded to the Fourth stage of the grid's Variable Operation. In this mode, the Grid is disconnected or inactive.

With reference to Table 2, it describes the various stages of irradiance under different operational conditions of the Conventional Grid: FSVOG operates in grid-connected mode for 18.75% of the total simulation duration, SSVOG operates in rated islanded mode for 37.5% of the total simulation duration, TSVOG operates in grid-connected mode for 37.5% of the total simulation duration, and FTSVOG operates in rated islanded mode for 6.25% of the total simulation duration.

The load in this situation reveals an extensive and noteworthy level of variability, which undoubtedly plays a vital role in shaping the overall variation in the methodology currently under discussion and examination.

As shown in the Fig.5 before this discussion, the power connected to the load experiences significant fluctuations that can be directly attributed to changes in the load current. At the same time, the voltage remains stable and unchanged throughout the entire process.

This observation indicates that the magnitude of the load transforms various operational phases, reflecting the inherently dynamic and ever-changing

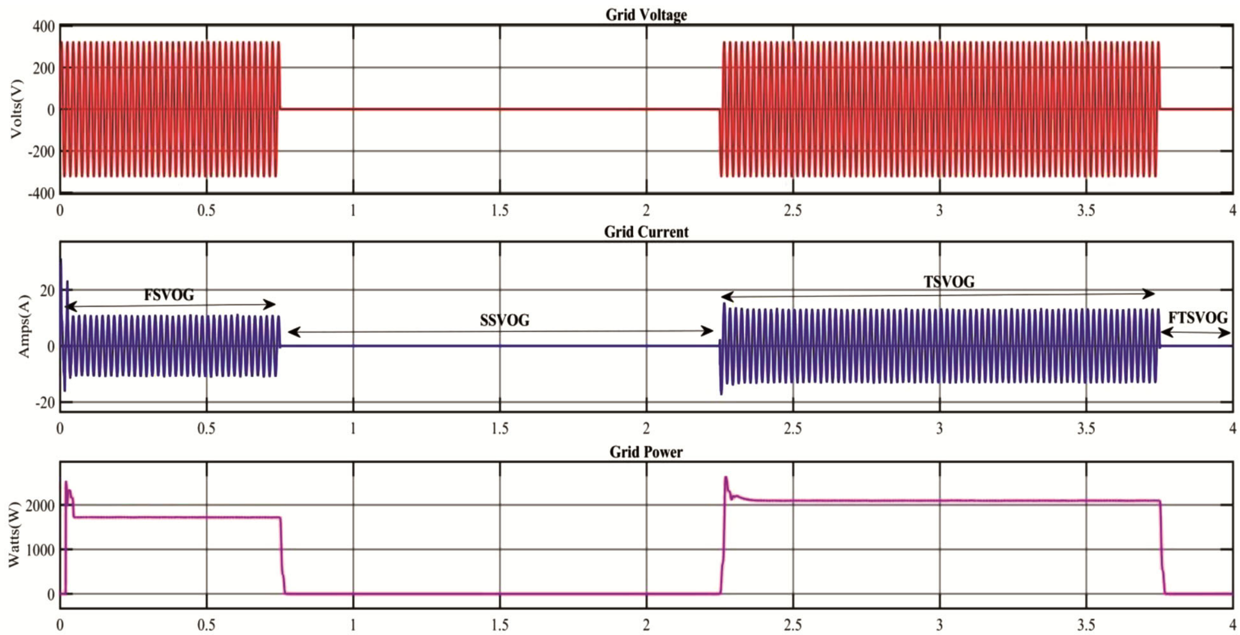

Fig. 4 — Behavior of Grid Voltage, Grid Current, and Grid Power Under Variable Grid Operation

Table 2 — List of various stages of variable operation of Grid

S.No	Abbreviated Title denoted by	Mode of operation of Conventional Grid	Proportion of each duration within the overall simulation timeframe
1	FSVOG	Grid-connected	18.75%
2	SSVOG	Islanded	37.5%
3	TSVOG	Grid-connected	37.5%
4	FTSVOG	Islanded	6.25%

nature of the system being analyzed. Therefore, it is crucial to recognize that the load's variability is not just a significant characteristic of the proposed approach but also an essential element in understanding the broader implications and complexities of load management within electrical systems.

Reflecting on the thorough examination conducted earlier, we have meticulously categorized each unique stage related to load variations into a comprehensive framework comprising three clearly defined phases. We have systematically identified the initial stage of load variation as the preliminary stage, along with the intermediary stages known as “FSVOL,” “SSVOL,” and “TSVOL.”

With reference to Table 3, it outlines the various stages of load conditions under different irradiation scenarios. In FSVOL, the load operates at rated or optimal load conditions for 25% of the total simulation duration. In SSVOL, the load operates at less than rated or optimal load conditions for 25% of the total simulation duration. In TSVOL, the load operates at greater than rated or optimal load conditions for 50% of the total simulation duration.

Where,

FSVOL is the First Stage of the Load's Variable of Operation.

SSVOL is the Second Stage of the Load's Variable of Operation.

TSVOL is the Third Stage of the Load's Variable of Operation load.

The total simulation duration is divided into eight distinct segments for a detailed analysis of hybrid microgrid behavior under various conditions. Which are systematically labeled as Part A, Part B, Part C, Part D, Part E, Part F, Part G, and Part H. Each of these carefully structured segments has been diligently organized under the dynamic transitional phases that involve at least one variable, which may include fluctuations in Irradiance, variations in Grid conditions, and changes in Load demands, thereby ensuring a thorough analysis of the microgrid's

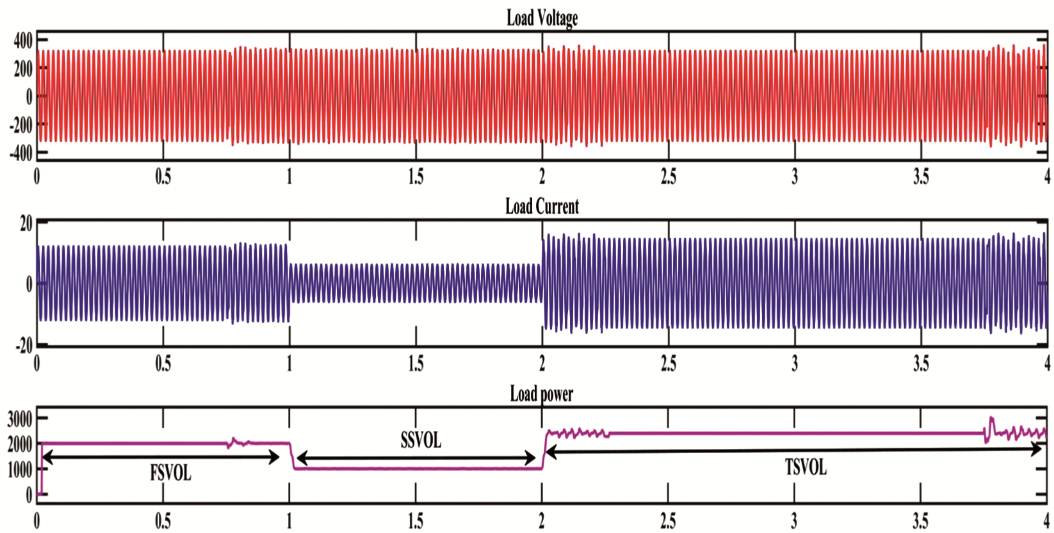

Fig. 5 — Behavior of AC Load Voltage, AC Load Current, and AC Load Power Under Variable Load Operation

Table 3 — List of various stages of operation for the operation of variable Load

S. No	Abbreviated Title denoted by	The level of Load maintained at	Proportion of each stage's duration within the overall simulation timeframe
1	FSVOL	Rated value/ Optimal value	25%
2	SSVOL	Less than rated/ Optimal value	25%
3	TSVOL	More excellent than rated/ Optimal value	50%

performance as it adjusts to a wide range of changing conditions.

Figure shows, the simulations that are meticulously crafted and closely associated with Parts A through H—namely Part A, Part B, Part C, Part D, Part E, Part F, Part G, and Part H—will, when considered collectively as a whole, represent a significant proportion of the overall duration of the comprehensive simulation process, specifically delineating Their contributions account for 18.75%, 6.25%, 12.5%, 12.5%, 6.25%, 18.75%, 18.75%, and 6.25% of the entire timeline, respectively. This highly meticulous and carefully structured arrangement will facilitate a thorough analysis of each phase within the simulation framework. Still, it will also yield invaluable insights into the intricate ways that each segment distinctly contributes to the overarching dynamics and interrelated functionalities of the entire system as a cohesive whole.

The Part-A Simulation represents 18.75% of the total simulation duration, focusing on variable operations related to irradiance, grid, and load through the FSVOIR, FSVOG, and FSVOL stages. During this phase, the irradiance levels for the PV panels were suboptimal, the hybrid microgrid operated in a grid-connected mode, and the load maintained optimal performance, supported by the traditional grid, and enhanced by MPPT-controlled solar and wind generation. Throughout the simulation, the battery, initially charged to 50%, was replenished despite unfavorable charge current flow, ensuring that the load received a consistent power supply.

Figure 7 illustrates the dynamics of voltage, current, and power derived from solar energy throughout the entire simulation. In this investigation, the dual maximum power point tracking (MPPT) enabled hybrid microgrid demonstrates the ability to extract stable power during most of the simulation period, especially under fluctuating load conditions.

The Part-B Simulation represents 6.25% of the total duration, with variable operational irradiance, grid, and load modeled as FSVOIR, SSVOG, and FSVOL, respectively. This indicates that while the irradiance and load stages remain stable, the SSVOG stage is subject to modifications, resulting in the disconnection of the conventional grid and transitioning the hybrid microgrid to islanded mode. In this configuration, the inverter, powered by the battery and supplemented by renewable energy sources, ensures stable power delivery despite minor

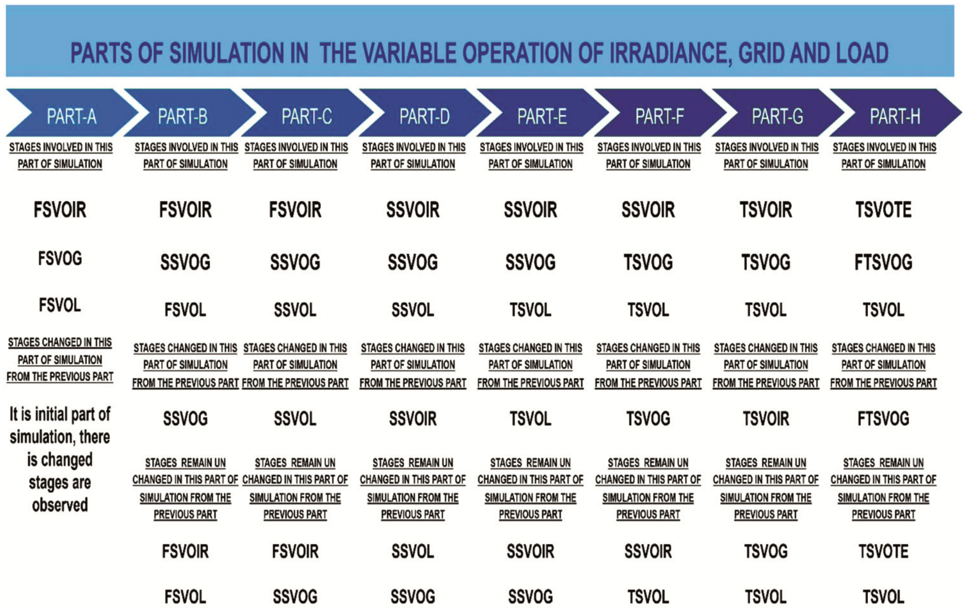

Fig. 6 — Parts of simulation along with various Stages involved in it

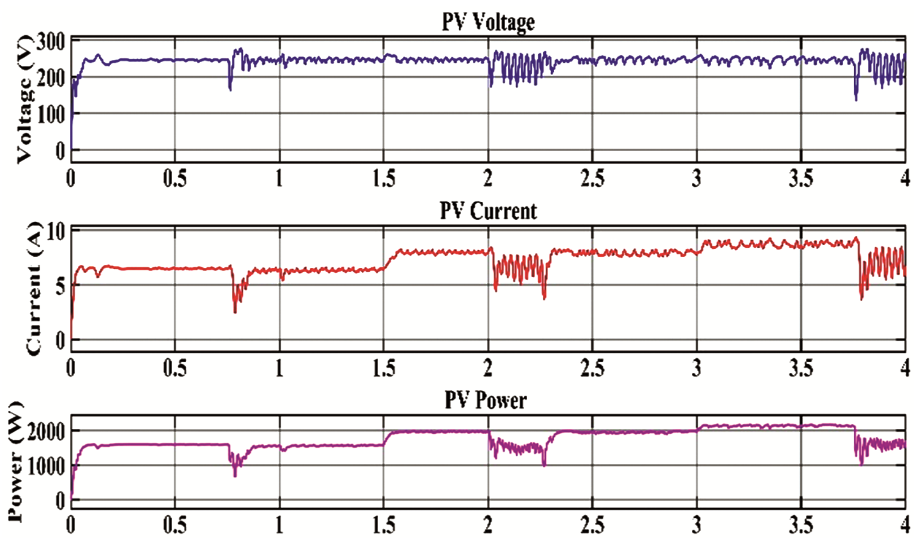

Fig. 7 — Behavior of PV Voltage, PV Current and PV Power

oscillations caused by abrupt grid disconnections and MPPT operations.

The Part-C Simulation lasts between 1 and 1.5 seconds, accounting for 12.5% of the total simulation time. During this phase, the grid and load functions are evaluated under FSVOIR, SSVOG, and SSVOL conditions, with variable operational irradiance levels. The inverter supplies the load from batteries charged by wind and photovoltaic energy, ensuring a steady and smooth power supply even when the load operates below optimal capacity.

The Part-D Simulation accounts for 12.5% of the total simulation duration, where varying operational irradiance affects grid and load performance under SSVOIR, SSVOG, and SSVOL conditions. During this phase, optimal irradiance values are maintained while the inverter, powered by battery storage replenished by wind and photovoltaic sources, supplies power to the entire load. Consequently, any increase in irradiance redirects power to the battery, ensuring a consistent and stable power supply to the load without fluctuations.

The Part-E Simulation accounts for 6.25% of the total duration, managing grid and load under SSVOIR, SSVOG, and TSVOL during various operational irradiance phases. This phase introduces a

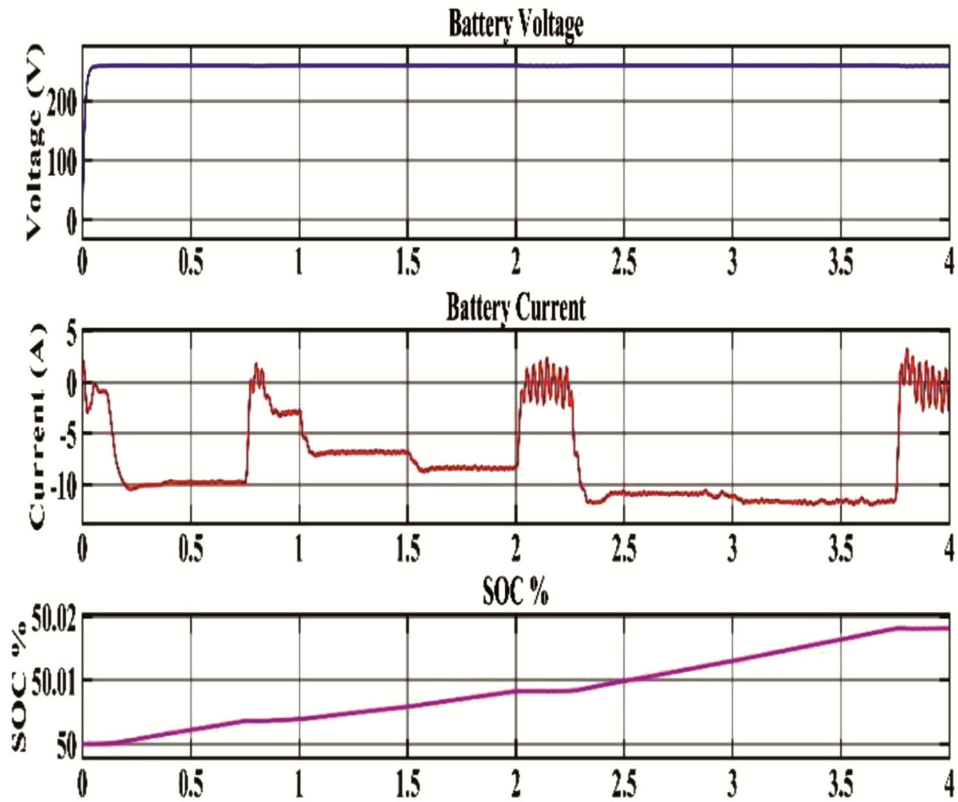

Fig. 8 — Behavior of Battery Voltage, Battery Current and State of Charge of Battery

modified TSVOL stage, where the load operates beyond its optimal capacity, supplied entirely by an inverter connected to batteries that are recharged by wind and PV energy. A sudden increase in load may lead to transient conditions, but the MPPT operations of renewable sources effectively stabilize oscillations, resulting in a steady-state, non-transient power output.

The Part-F phase accounts for 18.75% of the total simulation duration, during which the operational stages of variable irradiance maintain a consistent SSVOIR, TSVOG, and TSVOL for the grid and load, respectively. Notably, the TSVOG stage, which signifies variable grid operations, indicates that the hybrid microgrid operates in a grid-connected mode, with the conventional grid supplying all load requirements. Meanwhile, power generated from MPPT-controlled photovoltaic and wind systems is directed to the battery, enhancing its state of charge. At the same time, the load is adequately supported by the available power from the conventional grid.

Figure 8 illustrates the electrical responses of current, voltage, and percentage state of charge (% SOC) throughout the entire simulation. This figure indicates that as the percentage of SOC (State of Charge) stays above the 50% threshold, this condition supports enhancing the battery's longevity.

The Part-G Simulation constitutes 18.75% of the total duration and features variable operational irradiance, grid, and load, referred to as TSVOIR, TSVOG, and TSVOL, respectively. In contrast, the grid and load parameters remain constant. During this phase, irradiance exceeds optimal thresholds, enabling the conventional grid to stay operational. This ensures that the hybrid microgrid functions in grid-connected mode and that the traditional grid supplies all loads.

The increased power generation from MPPT-controlled photovoltaic systems, combined with the nominal output from the wind generator, enables better battery charging, enhancing the state of charge. Meanwhile, the load consistently receives power without fluctuations, ensuring a steady energy supply.

Figure 9depicts the dynamics of DC bus voltage, DC load current, and DC load power. From this figure, utilizing a dual MPPT-enabled hybrid microgrid allows for a significantly smooth power output to the DC load throughout most of the simulation.

The Part-H Simulation constitutes 6.25% of the total simulation duration, during which the variable operational irradiance, grid, and load are identified as

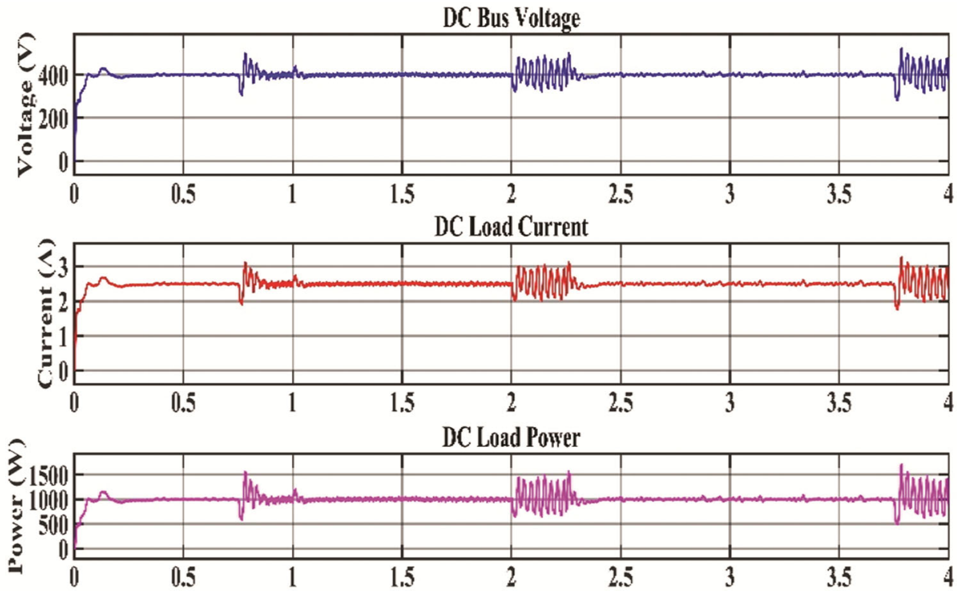

Fig. 9 — Behavior of DC Bus Voltage, DC Load Current, and DC Load Power

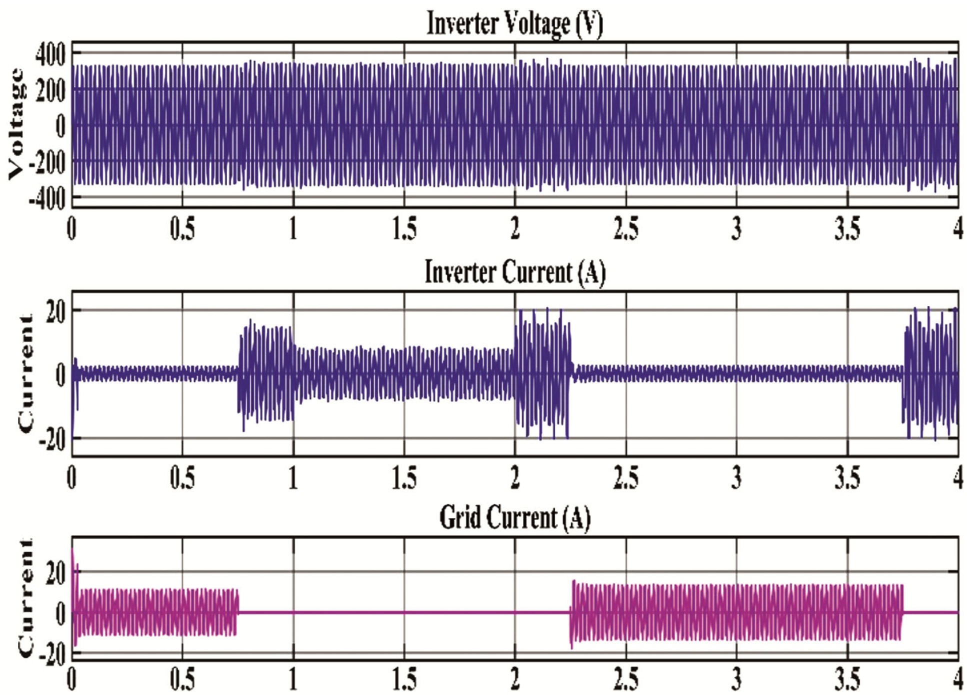

Fig. 10 — Behavior of Inverter Voltage, Inverter current and Grid Current

TSVOIR, FTSVOG, and TSVOL, respectively. The grid operation, denoted by FTSVOG, is variable, while the irradiance and load stages remain constant. Consequently, the conventional grid disconnects, allowing the hybrid microgrid to operate in islanded mode, where battery-powered inverters supply the entire load. During this transition, brief fluctuations in load power occur due to the sudden disconnection from the grid, influenced by the MPPT operation of PV and wind systems, but ultimately stabilize to provide consistent power to the load.

Figure 10 illustrates the characteristics of inverter voltage, inverter current, and grid current. The previous analysis shows that the dual maximum power point tracking (MPPT) enabled hybrid microgrid can modulate the inverter current during off-grid conditions (islanded mode) based on the demands of variable loads.

6 Summary of the Variable analysis concerning Irradiance, Grid, and Load Operations

According to Table 4, the comprehensive amalgamation of results from each phase of the simulation clearly shows that the dual maximum power point tracking (MPPT) enabled hybrid grid can optimize energy extraction from renewable sources, thereby enhancing the stability of the existing conventional alternating current (AC) grid.

Table. 4 — Outcomes of all the parts of the simulation.

PART OF SIMULATION	STAGES INVOLVED	CHANGED STAGE	STATUOF IRRADIANCE	GRID	LOAD	PV&WIND POWER	BATTERY	OUTCOME
PART-A	FSVOIR FSVOG FSVOL	Initial Phase of the Simulation	Less than optimal value	Active (connected to the grid mode)	At the optimal value	They are both feeding batteries.	The charging current and %SOC are increasing.	Since it operates in grid-connected mode, the microgrid will draw the required power for the load from the grid.
PART-B	FSVOIR SSVOG FSVOL	SSVOG	Unchanged	In-active (islanded mode)	Un changed	Both are feeding load along with the battery.	Discharging current increased and % soc is decreasing	As the microgrid operated in an islanded mode, there was a small amount of duration. Finally, the load will get the required power
PART-C	FSVOIR SSVOG SSVOL	SSVOL	Unchanged	Un changed	Less than the optimal value	Both are feeding load along with the battery, mainly fed by the wind and PV.	Discharging current is reduced, and % SOC is increasing.	As the grid is in islanded mode, almost zero oscillations occurred due to the decrease in load. Finally, the load will receive the required power.
PART-D	SSVOIR SSVOG SSVOL	SSVOIR	At optimal value	Un changed	Un changed	Both the wind and PV feed loads are balanced against the battery. The power feeding from the battery to the load is almost negligible.	Dis-charging current reduced, and %soc is increasing	In the microgrid operating in islanded mode, nearly zero oscillations occurred due to a decrease in load. Finally, the load will get the required power.
PART-E	SSVOIR SSVOG TSVOL	TSVOL	Unchanged	Un changed	More than optimal value	Both are feeding loads with the help of the battery, which is mainly loaded by the wind and PV. In this part, considerable feeding from the battery is observed.	The discharge current increased considerably, and the rate of %SOC was slightly reduced.	Asthe microgrids were in islanded mode, a sudden increase in load caused a small number of oscillations produced by MPT techniques. Finally, the load will get the required Power
PART-F	SSVOIR TSVOG TSVOL	TSVOG	Unchanged	Active (grid-connected mode)	Un changed	Both are feeding batteries.	Charging current slightly and %SOC is also increasing	As the microgrid is operated in grid-connected mode, the load will get the required power
PART-G	TSVOIR TSVOG TSVOL	TSVOIR	More than optimal value	Un changed	Un changed	Both are feeding batteries.	Due to the high availability of irradiance, the rate of charging current slightly increased, and the rate of %SOC is considerably increasing	The load will get the required power as the microgrid is operated in grid-connected mode.
PART-H	TSVOIR FTSVOG TSVOL	FTSVOG	Un-changed	In-active (islanded mode)	Un changed	Both powers supplement the load, along with the battery, which is primarily powered by the wind and PV. The battery's feeding to the load is almost negligible.	Discharging current rapidly increased. The rate of increase % SOC in considerable.	Due to island mode operation and sudden feeding, the load is high. Considerable oscillations were produced using the MPPT techniques. Finally, the load will get the required power.

Table 5 — The scenario of Peak Demand and Peak met in India in recent years[52]

Financial year	Peak Demand (MW)	Peak Met (MW)	Peak Shortage (MW)	Peak Shortage (%)
2019-20	183804	182533	1271	0.7
2020-21	190198	189395	802	0.4
2021-22	203014	200539	2475	1.2
2022-23	215888	207231	8657	4.0
2023-24	243271	239931	3340	1.4

7 Comparison of Current Results with Previous Studies or Industry Standards

The data presented in Table 5 indicates a rising trend in peak demand, accompanied by fluctuations in peak met and shortages, signaling challenges in meeting electricity demand. The significant shortages in 2022-23 underscore the need for enhanced capacity and infrastructure to meet the growing energy demands.

The data presented in the table above indicates a rising trend in peak demand, accompanied by fluctuations in peak met and shortages, signaling challenges in meeting electricity demand. The significant shortages in 2022-23 highlight the need for improved capacity and infrastructure to address the growing energy requirements.

The escalating disparity between the supply of electrical energy and the corresponding demand in India can be attributed to persistent population growth and swift industrialization. This deficiency may be addressed by augmenting the proportion of renewable energy sources within India's overall energy portfolio[53].

This is accomplished not merely by amplifying the installed capacity of renewable energy sources but also by harnessing the utmost energy potential from these sources through the innovative use of MPPT techniques. This visionary approach will empower the Indian energy sector to deliver sustainable energy across India's vast expanse, reaching even the most remote regions, including rural areas.

The ability of Maximum Power Point Tracking (MPPT) to enhance photovoltaic (PV) systems in harnessing energy is primarily attributed to their capacity to adapt to changing load conditions and improve energy collection. MPPT techniques are designed to continuously adjust the operational point of PV systems to ensure maximum power output, even in the face of changing environmental conditions such as fluctuations in solar irradiance and temperature.

The enhancement of energy collection in MPPT-equipped wind turbines can indeed be attributed to their ability to quickly adjust to changing load conditions. This agile adaptation is crucial for increasing power output and efficiency, especially during variable wind patterns. MPPT strategies, when combined with adaptive control mechanisms, enable wind turbines to respond quickly to changes in wind speed and load demands, thereby maximizing energy capture.

8 Impact of this Study on Existing Hybrid Microgrids

Hybrid microgrids encounter significant stability challenges due to the integration of renewable energy sources, which are inherently variable and intermittent. These issues are exacerbated by the need to manage both AC and DC systems within a single grid, resulting in challenges to power system stability, including voltage stability and grid stability issues. The transition between grid-connected and islanded modes introduces additional complexity to stability, along with the dynamic behaviour of power converters and the utilization of inverter-based resources. To tackle these challenges, systems equipped with Maximum Power Point Tracking (MPPT) can play a vital role by optimizing the power output from renewable sources and improving the overall stability of hybrid microgrids.

9 Conclusion

The findings indicate that the AC Load can successfully utilize power from a hybrid microgrid, supported by a dual MPPT-enabled photovoltaic array and a PMSG wind generator. Notably, the hybrid microgrid reliably accommodates both AC and DC loads, even in islanded mode. This demonstrates an improvement in the stability of the conventional power grid. However, the variety of converters and the non-linear characteristics of traditional energy sources result in minor, temporary oscillations. This presents an opportunity for future enhancements. In practical applications, this dual MPPT-enabled hybrid microgrid has the potential to provide high-quality, sustainable power across India, particularly benefiting the rural population, which accounts for approximately 70% of the country's population.

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