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Research Article

Enhancing Integration of Advanced Power Control Strategies for High-Penetration Photovoltaic System in Power Grid

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Abstract: This paper addresses the integration challenges faced by photovoltaic (PV) systems operating in fragmented and weak grid environments, emphasising the need for controllable PV systems that offer stable and intelligent services such as fault boarding and active power compensation to ensure high efficiency and reliability. The study introduces the development of multifunctional PV inverters designed to mitigate reactive and harmonic faults during operation and proposes a low-voltage ride-through (LVRT) control strategy using instantaneous power theory for a grid-connected large-scale PV converter. This control strategy calculates the relationship between the actual measured voltage and current, determining instantaneous active and reactive component values, and generates an inverter-switching pulse signal based on the corresponding designed reference current values, resulting in a better dynamic response when the phase voltage decreases. Simulation methods demonstrate the performance of this approach in an actual stage involving a large-scale practical PV system scenario, and the case studies validate its significance and flexibility in revealing advanced features of PV systems. The proposed solar power control strategy can be standardised in commercial PV inverters, facilitating the online use of different operating modes and enhancing the integration and reliability of PV systems in weak grid environments.

Keywords: Multifunctional inverter, Low-Voltage Ride-Through (LVRT), DSTATCOM, Photovoltaic system.

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1. INTRODUCTION

Power generation through non-conventional resources is comparatively better than conventional power generation because they are environmentally friendly, not destructive, cost-effective, re-useable, durable and safe. Nowadays, traditional fossil fuels are rapidly decreasing, and future development needs to focus on the control and conservation of energy besides expanding new energy resources and extensive application of renewable energy to the power industry. Economic growth is based on this emerging energy landscape. The current demand for energy management strategy is increasing renewable energy sources and distributed generators [1]. As a result, ensuring or improving the reliability of electricity supply and the quality of the power grid becomes an important responsibility [2]. Furthermore, these developments bring new governance structures that emphasise trade-offs between power and energy. The proliferation of photovoltaic (PV) systems, characterised by their unpredictable and intermittent nature, poses a major challenge in maintaining grid stability, especially during fault conditions [3]. Grid stability and supply security will always be essential factors in the power distribution system. It is important that facilities affected by power outages have monitoring capabilities and safeguards in place.

Historically, conventional power plants have largely met this demand [4]. However, the importance of renewable energy sources in the total electricity generation mix has increased significantly. It is now essential that renewable resources also play a role in ensuring grid stability. Transmission system operators define specific standards and control specifications, often in the form of cellular codes,

that power plants must follow to effectively contribute to grid stability [5]. This paper focuses on the issues related to grid interconnection of PV systems operating in such an environment and presents some foundational solutions based on two key technologies – low voltage ride-through (LVRT) and distributed static compensator (DSTATCOM).

At a global level, a revolution is apparently taking place in the energy matrix with the objective of replacing carbon-based energy sources and avoiding climate change. Renewable energy sources, especially solar energy, which have reached the group of leading technologies about green and clean energy, are strongly contributing to the shift towards energy sources emitting low levels of greenhouse gas [6]. The conversion of light (sunlight) into electric power by yellow light is allowed by the photovoltaic system [7]. With its multitude of benefits compared to conventional fossil fuel-based electricity generation methods, a PV system is an apparent leading technology in the move toward green and clean energy solutions.

A PV system has several advantages over gas and coal-based power generation. PV is environmentally friendly, releasing no greenhouse gases [8]. It is also cost-effective in the long haul since the cost of solar panels is declining dramatically. PV systems require little maintenance and work for decades. They are a flexible source of electricity and can be installed in residential households with PV panels on their roofs or in solar power farms spanning several hundreds of square kilometres.

In just a decade, the level of PV system integration into the grid has shot up, thanks in part to new technologies and enhanced government policy. The targets set by many governments all over the world for renewable energy uptake are measured in the hundreds of gigawatts [9]; solar power is proving to be a leading technology as India alone aims for 175 GW of renewable energy capacity by 2022.

To ease understanding of future readers sections could be added to this classification. On this basis, the general structure of the paper will be discussed and requirements of each section will be presented.

1.1. Challenges in Modern Years

Solar power plants are being generated year-on-year in India; we have also seen an increasing trend in renewables. India can become more self-dependent by using renewable energy. Solar systems are widely used because of the falling prices of PV. Currently, many industries use their PV array installations only for active power generation rather than for other potential applications such as grid harmonic elimination or support [10]. The efficiencies of PV systems are increasing every day, which brings serious challenges to the stable operation of the grid due to their random and intermittent characteristics, especially under fault conditions. Generating electricity through solar energy is considered socially beneficial and economically viable for some applications. Grid stability and supply security are two critical aspects of a power supply system [11]. Power plants must have control capabilities and safety mechanisms to prevent power outages [12]. Because of that, maintaining or improving the power supply's reliability and the power grid's quality is a major responsibility. Furthermore, grids give rise to new governance structures where energy and power trading become more important.

Solar power plants comprise solar PV Modules, grid-connected inverters and transformers. Keeping this in mind, as more power plants are being established, there seems to be a high demand for inverters, as the objective is to reach 175 GW by 2020 and 500 GW by 2025 [13]. India, which is one of the fastest-advancing developing countries, is definitely moving forward and towards a large-scale addition of renewables by 2030. As a result of the high availability of renewable energy systems in individuals' homes and businesses, the necessity increases to secure grid stability. The topic of grid stability is one of the essential themes of the power supply system. When demand for power is high, the power system cannot provide all of the required power supply systems. As for electric engines in cars to boilers for cooking in homes, when the power plant may be a region away, and the steel conducted-voltage-cable is more than 200 kV, power losses can become very high, rendering the system not economical for consumers [14].

In order to avoid power outages by keeping supply currents constant, power plants need the ability to have control mechanisms and protection against grid faults, etc. In the past, these requirements were fulfilled only by conventional power plants, which gives us an idea of where these plant systems operate [15]. However, in recent years, the share of renewable energy sources in gross electricity generation has grown so large that these sources, too, must provide support for grid stability [16]. Therefore, the grid operating authority, the transmission system operators, has declared certain critical values and control characteristics for these generating plants by so-called grid codes. One of the important requirements of these control characteristics is the so-called LVRT capability of the generating plants. But what does that mean, LVRT capability? LVRT is the term described as the generating plants required to be operational for short periods of low-grid voltage that do not need disconnection from the grid. A short-term voltage dip may occur, for example, when large (household, business) loads are turned on or due to misconducts in the grid, e.g., lighting strikes, circuit short-circuits, etc.

An extension of the above analysis is to compare the performance of the system under test with how it operates without the introduction of LVRT and DSTATCOM integrators. Such an analysis would help elucidate how these proposed integrators affect the way the system performs overall [17]. Below is a comparison of key performance metrics between the system under test and the test system (proposed system) before any integration takes place.

1.1.1. Stability of grid

Compared to a system without these technologies (LVRT, DSTATCOM), the system shows that these technologies offer a more stable grid area. Overall, voltage fluctuations, deviations, and instability are reduced, which, in return, offers more control and reliability for grid operation.

1.1.2. Improved fault ride-through capability (FRTC)

The system incorporating LVRT features improved fault-ride-through capability. This essentially means that the

system can tolerate voltage dips and sags and recover from them easily [18]. This improves the quality of the power provided to the loads on the output against a transient fault in the grid if one occurs.

1.1.3. Power quality

Introducing DSTATCOM into the power system can largely improve the power quality index. DSTATCOM can reduce the THD value to a more reasonable range, ensuring the stability of the overall system. If DSTATCOM is not supplied, the THD value is higher, and reactive power compensation is not accurate enough, which means that the power quality is reduced and the equipment is damaged.

1.1.4. Voltage regulation

The presence of DSTATCOM on the system enhances voltage regulation features, which keep the voltage within acceptable limits even in varying load conditions [19]. However, the performance might be unstable without the presence of DSTATCOM, which will lead either to fluctuations of voltage or even instability of the system, or possibly worse. Such instability, in turn, leads to the worsening of the equipment, thereby operating in such systems.

1.1.5. System efficiency

LVRT and DSTATCOM technologies increase the overall efficiency of the system by helping to mitigate power flow, reduce losses, and enhance system voltage stability. Without these technologies, the system's efficiency would be compromised, and more energy losses would occur as the grid is disturbed [20].

1.1.6. Reliability

Since LVRT and DSTATCOM technologies complement each other, enabling them to share information, the plug-and-play system further improves system reliability by providing active fault detection and damage mitigation. This results in an enhanced system's capability of withstanding grid disturbance and enhanced grid resilience.

Table 1 presents a comparative analysis of key performance metrics between systems with and without the integration of Low Voltage Ride-Through (LVRT) and DSTATCOM technologies. The metrics include grid stability, fault ride-through capability, power quality (THD), reactive power control, voltage regulation, system efficiency, and reliability [21]. The data shows significant improvements in all metrics with the integration of LVRT and DSTATCOM, demonstrating their importance for enhancing grid stability and power quality.

While it is noticeable that integrating LVRT and DSTATCOM technologies would be greatly helpful in relieving the condition of the power grid and helping with power station construction, it can be time-constrained for physical construction projects while maintaining high energy efficiency to ensure power security.

Table 1: Comparative analysis of system performance with and without the integration of LVRT and DSTATCOM.

Performance Metrics	With LVRT and DSTATCOM Integration	Without Integration
Grid Stability	Improved	Less Stable
Fault Ride-Through	Enhanced	Limited Capability
Power Quality (THD)	Reduced	Higher Levels
Reactive Power Control	Improved	Limited Compensation
Voltage Regulation	Enhanced	Fluctuations
System Efficiency	Increased	Potential Losses
Reliability	Higher	Lower

1.2. Objective

The main objectives of this research are:

i. To provide a comprehensive understanding of the challenges in integrating high-penetration PV systems into the grid.

ii. Explore the potential benefits and roles of multifunctional inverters, LVRT capability and DSTATCOM in addressing these challenges.

iii. To study various advanced power control techniques, including maximum power point tracking (MPPT), reactive power control, voltage regulation and harmonic compensation and their impact on PV system integration.

iv. To discuss recent advances in these control techniques and to identify future research directions for further progress in the integration of advanced power control techniques for high-penetration PV systems.

The integration of high-transmittance PV systems has attracted significant attention due to the increasing demand for clean and renewable energy sources. However, the challenges associated with solar power, interruption of grid stability and power quality require the development of advanced power control technologies. This research paper focuses on the integration of multifunctional inverters [5], LVRT capability and DSTATCOM as key components for improving the efficiency of high-penetration PV systems.

LVRT is derived from *low-voltage ride-through*, which describes how generating plants should continue to operate during short periods of low voltage and not be disconnected from the grid. Low voltage ride-through (LVRT) capability is important in solar systems for several reasons. When a solar system is connected to the grid, it must withstand and overcome voltage changes and disturbances on the grid. The LVRT capability ensures stable and reliable operation of the Solar System during such events. LVRT capability is essential for solar systems for grid stability, regulatory compliance, accommodating renewable energy penetration, and providing grid support. This allows solar systems to withstand voltage fluctuations, remain connected during grid faults, and contribute to stable and reliable grid operation.

On the other hand, DSTATCOM devices provide reactive power compensation, voltage regulation and harmonic reduction capabilities [22]. Their integration into PV systems can provide additional control and stability features to improve the performance of high-admittance PV systems.

The overall simulation system of a grid-connected multifunctional inverter integrated with a PV energy conversion system is designed in the MATLAB Simulink platform. Then, simulation results are presented to prove the correctness of the adopted control system.

2. LITERATURE REVIEW

There are several works that pay attention to the integration of solar PV with high penetration using new technologies of multifunctional inverters, low voltage ride-through (LVRT) capability, and distributed static synchronous compensator (DSTATCOM) devices. This section reviews some of these works in summary, presenting their methodologies, results, advantages, and limitations.

Zhang et al. [1] developed a control structure for a multifunctional inverter and DSTATCOM in distribution networks with high-level PV penetration. The study measured voltage support and power-quality enhancement based on the improvements in voltage patterns. The results showed a non-negligible enhancement of power-system stability with excellent power-quality (PQ) performance under large power swings, especially with more STATCOMs attached to the grid. However, the limitation of the technology lies in its high initial cost and the overall complexity of the system. Wu et al. [2] suggested enhancing the Maximum Power Point Tracking (MPPT) of grid-connected PV systems in order to work as LVRT. The study showed a more efficient energy uptake and a more stable grid by reducing voltage drops and recovering from faults. Dynamic response of the PV system was the strength, while complexity and cost were a limitation.

Amin et al. [3] Control options of the ‘smart inverter’. From the work of Amin et al. [3] The review of the more advanced control techniques for multifunctional inverters targeted the reactive (var) power compensation and the voltage support, the former directly related to the mitigation of voltage variations associated with PV and the second ensuring grid stability. It was also noted that the voltage needed in MV is approximately five times higher than at lower voltage levels, and with voltage support, the efficiency of the system could be notably improved. Although both approaches were seen as robust solutions, they were surrounded by technical barriers, and it is likely that the support mechanisms would require additional personal attention for maintenance issues. Lee et al. [4] studied the combined effects of LVRT, multifunctional inverters and DSTATCOM on grid integration and power quality enhancement. It showed that a smart distribution system with integration of LVRT, multifunctional inverters and DSTATCOM could substantially and effectively improve the power quality and grid stability. The ability to effectively control reactive power and regulate voltage was an advantage, but it needed a huge investment and engineering knowledge. In 2014, Zhu et al. [5] evaluated the transient behaviour of PV systems during grid faults and the contribution of LVRT capacity to grid stability. The authors evaluated the advantages of implementing LVRT capability to enhance fault-ride-through performance, as well as the main limitations of advanced control algorithms and real-time monitoring. Wang et al. [6], a novel control of multifunctional inverter and DSTATCOM devices put forward to position the PV system, mainly to improve the power quality based on three case studies for grid-connected PV power plants. As far as the reactive power and harmonic compensation for PV inverters were concerned, the DSTATCOM system could calculate the quantitative value of decrease according to the harmonic and reactive power compensation. The total value was 4.28 per cent. However, the huge increase in system complexity and cost were the main shortcomings. Ghosh et al. [7] evaluated advanced power control methods, such as MPPT algorithms, LVRT capabilities and DSTATCOM devices for high-penetration PV systems, which informed on the necessity of a robust and comprehensive control paradigm to accommodate grid stability and quality of power. The adoption of a holistic approach when dealing with the various challenges to grid integration was certainly an advantage, but the increased level of complexity called for when multiple advanced control approaches are considered is a limitation. A comparative study between different LVRT-capable PV systems control strategies was conducted by Chen et al. [8] to examine the efficiency of ride-through, voltage regulation and grid support devices under different cases of transient faults. Due to the extensive efforts being put into the optimization and integration of such control strategies, the research is far from being complete. Wang et al. [9] made a predictive model for collapsing feeder states by modelling major disruption mechanisms in grid-connected PV systems under various operating conditions. This allowed them to better understand PV system dynamics and interactions with the grid. The use of advanced modelling approaches was a huge improvement, but the approach required a large amount of data and sophisticated modelling tools.

In order to facilitate parallel computation, Li et al. [10] designed a smart side-channel algorithm that can speed up power flow calculation and grid constraints at the same time, leading to more useful investment into the grid. In the experimental condition of the case, the grid operation efficiency and renewable power utilization efficiency have been improved on the basis of optimal operation of the grid. In the operation of the grid, the power flow and grid constraints are important considerations. In order to address the problem associated with grid operation, considering the comprehensive consideration of the overview of power flow and grid constraints, the author applies the neural network to deal with it. In contrast to the offline method, the use of artificial intelligence in the study offers added value. The paper shows a novel way of analysing the power flow and grid constraints as applied in the operation of the grid. The added value of artificial intelligence can be grasped based on the two-step approach suggested by the author, which can efficiently calculate the optimal solution to the problem. Challenges that need to be addressed in practice include the complexity of implementation. Additionally, robust communication technologies need to be taken into consideration.

In their study of PV integration in smart grids and microgrids, Alizadeh et al. [11] concluded that the combination is highly promising. Communication and control technologies enable the coordinated operation of the wildly fluctuating PV production with demand management, benefiting all involved. The energy system's flexibility and resilience were highly advantageous, but problems with high initial costs and the complexity of combining energy technologies needed to be addressed.

Zhang et al. [12] demonstrated that combined power plants utilizing high-efficiency integration of PV and energy storage enhance energy efficiency and self-consumption rates. Control is much more flexible, and grid stability has also improved – certainly in comparison with the array operating without a smart battery. Space and advanced control algorithms are currently required, but there are a few downsides. Space requirements still remain. What's more, energy storage involves complex algorithms to control power generation and storage, integrate the energy resources in the electrical system, and optimize dispatch for all individual devices.

Huang et al. [13] illustrated the application of bifacial solar panels. Energy-generating and installation geometry were calculated and compared with layers of monofacial panels. They had increased energy generating and installation availability as an advantage but had increased initial investment costs and installation restriction conditions as a limitation. The nonlinear model and dynamic behaviour of PV grid-connected inverters were studied, and the transient responses and stability of PV inverters to changes in the grid were provided.

The benefits of a better understanding of inverter dynamics and stability were evident, while challenges found in modelling nonlinear behaviours and the lack of adequate data were evident. In particular, based on an optimal energy management strategy developed by Obaid et al. [15], the system comprising photovoltaic cells and batteries linked to the grid achieved improved efficiency with lower operating costs. Improved energy management was one advantage, but integration into the grid forced them to depend on forecasts, further increasing the need for advanced optimization techniques, which are necessary to minimize energy costs for a standalone system, becoming another limitation.

In their 2019 review of sun-tracking technology for solar PV systems and its effect on energy generation, Awasthi and colleagues [16] noted dramatic efficiency increases, improved energy capture, and easier access to sunlight. Mechanical complexity and maintenance requirements were significant drawbacks, but optimizing the orientation of the panels increased energy output.

The DSTATCOM compensation of the modified microgrid was studied for reactive power compensation and voltage regulation by Abdelsalam et al. [17]. The mechanism improved the microgrid operation. Enhanced stability and improved power quality were identified as the key advantages. However, the challenge in its implementation from a complexity point of view and the requirement of a precise controller were the limitations.

Shamim et al. [18] optimized and analyzed the cost-benefit of a grid-connected solar PV system for its feasibility study. At present, solar-based PV generation can provide handsome economic benefits as well as improved energy efficiency. Tangible information on the financial viability of PV systems was their significant added value, while economic inconsistency and the need for detailed financial modelling were their drawbacks.

It is a close analysis of the work, so that afterwards, the reader of the literature review understands how that work fits into the existing body of knowledge into the integration of high-penetration PV systems.

The evidence from the literature review indicates that the studies reviewed demonstrate the methodology employed, the results obtained, the benefits and limitations, and, hopefully, their potential application to future work. Unintentionally, the literature review suggests that the gap has been filled and that future work will yield good performance in integrating high-penetration PV.

To sum up, based on the existing literature, it can be inferred that researchers adopt a multi-pronged approach in addressing the challenges and opportunities presented by integrating PV into electrical grids. Through deepening existing control strategies, improving simulation models, exploring synergies with new grid technologies and leveraging the advancement of PV technology, the vision of the energy transition to a more sustainable and stable grid can be driven forward.

3. MATERIALS AND METHODS

Due to its potential to mitigate environmental concerns and reduce our dependence on fossil fuels, integrating renewable energy sources, particularly PV systems, into the current power grid has drawn considerable interest. High-penetration PV systems give both opportunities and challenges for power management solutions because they contribute significant solar energy to the grid.

To effectively manage the variability and intermittency inherent in PV production, there is an increasing demand for advanced power management solutions as the solar energy sector expands. In contrast to traditional energy sources, solar energy production is influenced by the weather, the time of day, and seasonal changes, resulting in output swings [23]. The reliability of the entire system, the control of voltage, and grid stability can all be significantly impacted by these variations. Advanced power management strategies aim to increase the grid's capacity to react to increased PV system penetration while sustaining stability and maximum efficiency. This entails resolving several significant challenges, such as:

- *Grid stability:* Solar energy injection at high rates can lead to voltage swings and power imbalances in the grid. Voltage sags, surges, and frequency variations are just a few of the issues that might result from these disturbances. Innovative control strategies strive to regulate power injection in real time to ensure grid stability.
- *Smooth integration:* To integrate large amounts of PV into the grid, coordination between PV systems and other grid components must be smooth [24]. This involves the intelligent synchronisation of conventional power plants,

energy storage devices, and other renewable power sources.

- *Forecasts and predictive control:* To reduce the unpredictability of PV production, precise weather forecasts and predictive control methods are crucial. These methods foresee variations and proactively modify energy input using meteorological information and past trends.
- *Distributed energy management:* High-penetration PV systems frequently form a component of a larger ecosystem of distributed energy resources (DERs), including wind turbines, energy storage technologies, and demand response devices [25]. To attain system efficiency, advanced control strategies make it easier for these resources to work together harmoniously.
- *Flexibility and adaptability:* Power management solutions must be scalable to account for various PV system penetration levels and responsive to grid conditions. They ought to be adaptable enough to consider changes in network topology, demand patterns, and generation capacity.

3.1. System Methodology

A key element of PV systems is low voltage tripping (LVT), which ensures grid stability and continuous operation during grid failure or voltage sags. The value of LVRT capabilities is increasingly apparent as the percentage of solar panels integrated into the grid rises. Conventional power plants can resist these disruptions and keep supplying electricity to the grid in the event of a grid failure or unexpected voltage reduction. On the other hand, PV systems have issues because they rely on sunlight. Rapid grid voltage drops may result in a decline in the direct current (DC) bus voltage of the PV inverter, which may set off a protection mechanism that disconnects the PV system from the grid.

The LVRT technique for solar arrays intends to increase the PV system's resistance to changes in voltage drops. Here is the way LVRT operates with solar panels:

- *Voltage sensing:* If the grid voltage drops, the sensor inside the PV system notices the change and alerts the user.
- *Voltage through control:* In response, the PV system's capacity is momentarily reduced by the inverter control system. Due to the inverter's ability to change its operating point to create a lower voltage, the DC bus voltage can recover.
- *Dynamic response:* An advanced LVRT technique that uses real-time data and predictive algorithms to predict voltage variations. By actively adjusting its output, the inverter can lessen the impact of voltage changes.
- *Grid support:* Some inverters for solar power can do grid support duties in addition to LVRT. For instance, injecting reactive electricity into the grid during low voltage conditions aids in voltage regulation and supports grid stability. To maintain grid dependability and guarantee the ongoing operation of PV systems, LVRT with solar arrays is crucial. To assure grid compliance with rules and regulations, regulatory authorities frequently place LVRT requirements on solar inverters. These specifications, which vary by location, are made to guarantee that the solar system enhances grid stability rather than affects it.
- *Reconnection duration:* The inverter gradually lowers the power output to the prior level after the grid voltage has stabilised and returned to a tolerable level. These controlled connections aid in preventing jolting power surges that could cause.

This paper develops a simulation model consisting of a PV solar array connected to a DC-DC boost converter and a battery storage unit. This combination allows for efficient energy conversion and storage. This model also features a multifunctional inverter, which is controlled by a voltage source control (VSC). An inverter plays an essential function in managing the flow of electricity and controlling various aspects of a PV system.

In addition, the simulation model includes the LVRT capability and the DSTATCOM. The LVRT ensures that the PV system is connected to the grid and maintains stability during voltage drops or faults. DSTATCOM provides reactive power compensation, voltage regulation, and harmonic reduction, contributing to improved power quality and grid efficiency.

The simulation model integrates a phase connection with an unknown load, which may be capacitive, inductive, or a combination of both. This realistic load scenario allows the evaluation of PV system performance and response under various grid conditions [12]. The data used for model inputs, such as solar radiation, temperature profiles, and load demand patterns, are sourced from various sources to ensure accuracy. Solar radiation data can be obtained from meteorological stations, satellite data, or solar irradiance databases. Temperature profiles are gathered from meteorological stations, weather databases, or on-site measurements using temperature sensors or thermal imaging. Load demand patterns are acquired from utility companies, smart meters, energy management systems, or historical records, providing insights into energy usage trends and peak demand periods. By utilising data from these sources, simulation models can accurately represent real-world conditions, facilitating informed decision-making in energy system planning and optimisation.

The integrated LVRT and DSTATCOM) system provides comprehensive solutions to grid stability and power quality enhancement. The integrated system guarantees improved uptime and operations over traditional solutions by offering better grid stability through fault ride-through (LVRT) capabilities and improved reactive power compensation (DSTATCOM). It automatically compensates for varying voltage dips in the network to maintain power supply to the loads without interruption. The integrated system is also required to adapt to variable grid conditions to meet real-time demand for voltage compensation and regulation. Additionally, consolidating these two theoretical functionalities into a single system will save costs as all functions are combined in a single device, which improves system performance, reduces onsite installation and maintenance, overcomes rectifier ripple and harmonics, and

offers other cost benefits while enhancing grid stability and power supply reliability [13]. Although the integrated LVRT and DSTATCOM systems are advantageous, they have numerous limitations. This system is complex to design, expensive, and specialised, and it requires highly skilled maintenance to be deployed or operated on a modern smart grid. Scaling up the system is also very challenging.

3.2. System Model and Simulation

The simulation scenarios are designed to reflect generalised cases of real-world grid conditions, such as variations in load profiles, patterns of renewables generation and the possibility of grid faults. Scenarios are selected to reflect problems grid operators might have to deal with, such as voltage excursions, power quality impacts and insufficient capacity availability.

For example, the scenarios might anticipate high loads over a peak-hour period or fast, sudden load changes caused by varying industrial processes. DSTATCOM can be introduced in these scenarios to check how it helps to keep the voltage within limits, increases power factor correction, and maintains the stability of the network. Moreover, the scenarios comprised elements that are amenable to DSTATCOM solutions and were designed to be scalable for different grid configurations and operational settings. This helped place the simulation results in a context that is not only specific to the use case studied but also to other grid-management challenges faced by utilities and grid operators.

By providing detailed explanations of the simulation conditions and the rationale behind the scenarios being tested, stakeholders can gain a better understanding of how DSTATCOM technology can address real-world grid management problems and inform decisions about its implementation and deployment.

Table 2 provides data on how load demand varies throughout different times of the day. It shows the increase and decrease in load demand, reflecting typical daily load profiles. Understanding these variations is essential for designing control strategies that can manage these fluctuations effectively.

The following steps can be followed to implement this method:

PV solar array and DC-DC boost converter: Solar panels that become interconnected to form a PV array use sunlight to generate direct current (DC) electricity. This panel generates a changing DC voltage level depending on the sun's strength. The best power usage is achieved by using a DC-DC step-up converter [15]. This electronic component raises the low DC voltage of the PV array to a higher level for applications such as grid connection or battery charging.

A switching device, often a transistor, must operate at a high frequency in a DC-DC boost converter to function.

The inductor stores energy as a magnetic field in the "on" phase. The inductor dissipates this energy while the switch is off, producing a higher output voltage than the input voltage. The control circuit maintains the desired output voltage despite input fluctuations to guarantee reliable power conversion. The enhanced DC output can be used to input into the grid or charge the battery.

Table 2: Variations in load demand throughout the day.

Time Period	Load Variation (MW)
Morning	+10
Afternoon	+20
Evening	-15
Night	-5

The collaboration between the solar PV array and the DC-DC boost converter guarantees effective conversion and usage of solar energy. This dynamic dependency greatly aids the integration of renewable energy, resulting in a more resilient and sustainable energy system. Develop a mathematical model for a PV solar array, considering factors such as solar radiation, temperature, and electrical characteristics of the PV module. Add a DC-DC boost converter to improve power transfer from the PV array to the battery storage unit.

Battery Storage Unit: In photovoltaic (PV) array systems, two key components increase efficiency and energy management: Battery electrolyser and state of charge (SOC) monitoring. The electrolysis battery absorbs the excess energy produced by the PV array through the electrolysis of water and converts it into hydrogen gas.

This stored hydrogen acts as a versatile energy source for various applications, providing a means of storing excess energy during sunny hours and harnessing it when solar energy is insufficient.

Monitoring the SOC is equally important in the PV array system. SOC reflects the current energy level of the energy storage system as a percentage of the total capacity. This information enables effective energy management by providing insight into the energy available for discharge.

Fig. 1 illustrates the overall simulation setup of a PV array integrated with a boost converter. The PV array generates DC power, which is then stepped up to a higher voltage level by the boost converter for efficient energy transfer. This setup is critical for ensuring that the power generated by the PV panels can be effectively utilised or stored. Advanced algorithms that consider speed, temperature, and efficiency guide load scheduling and network interactions with SOC estimation to optimise overall system performance.

The integration of battery electrolysis systems and SOC monitoring in PV array systems provides a comprehensive approach to the use of renewable energies.

It enables energy storage and efficient use and provides real-time information for informed decision-making. This overall synergy supports grid stability through the controlled release of energy during periods of high demand and low solar output, contributing to a sustainable and resilient energy environment.

In is necessary to include a battery model specifying charging and discharging characteristics, energy efficiency,

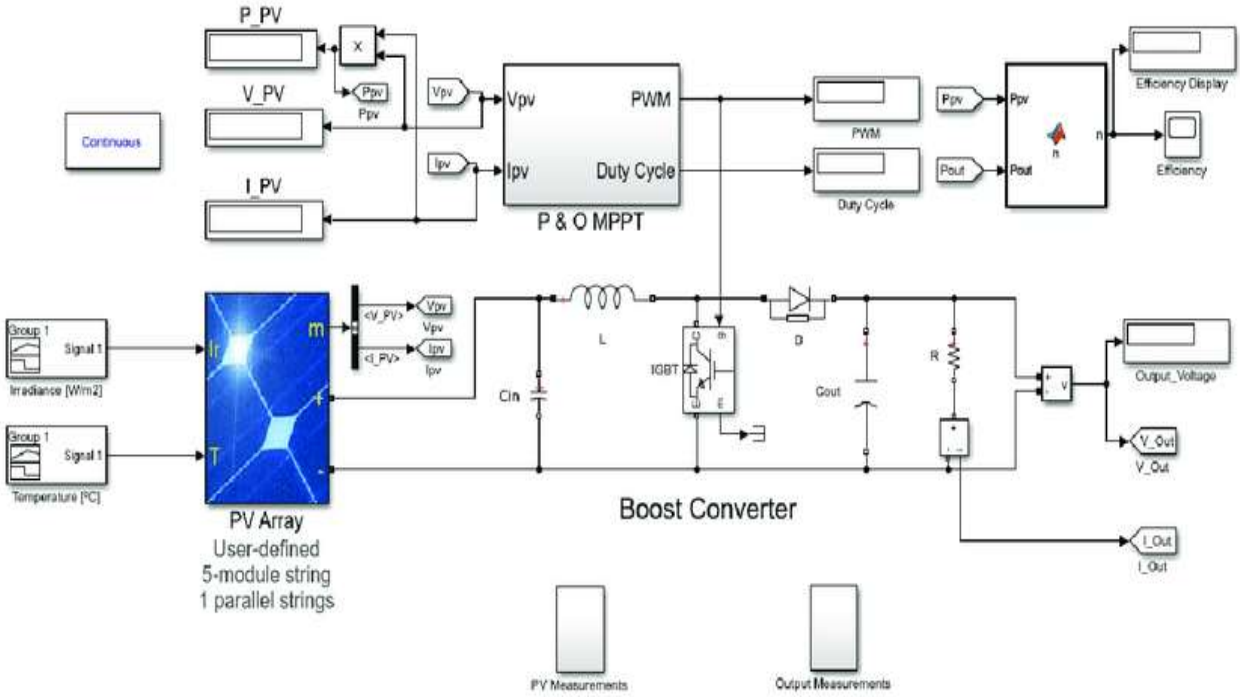


Fig. 1: Simulation design of PV array with boost converter.

and performance. To do this, we must consider factors such as SOC and battery management system (BMS) functions.

Multifunctional Inverter with VSC Control: A multipurpose inverter is a versatile device that controls voltage and frequency outputs using a voltage source controller (VSC). Thanks to this feature, it is ideal for a range of applications, including grid integration, motor control, and power quality enhancement. The capacity to communicate with the grid enables participation in innovative grid projects and electricity recovery. Additionally, continual integration of the battery can guarantee an uninterrupted power supply during power outages. Microgrids, energy storage devices, and voltage control, a crucial component of contemporary power management, are all impacted.

The multifunctional inverter's key strength is the VSC technology-enabled exact control of output voltage and frequency. This management is crucial for a wide range of applications, including effectively powering electric motors in industrial systems, incorporating renewable energy sources into the grid, and preserving steady power quality.

Essential equipment continues to get uninterrupted power amid grid interruptions. Additionally, its involvement in smart grid and microgrid initiatives enhances its reliability and overall energy efficiency. An all-around adaptable solution with applications in various industries is a multifunctional inverter with VSC control.

In Fig. 2, the integration of the battery storage system with an electrolyser and State of Charge (SOC) control is presented to convert the excess electrical energy into hydrogen and utilise it as a fuel source later but keep the SOC control to ensure the battery peak charging and discharging cycle processing in the objective of keep the battery healthy and charging efficiency.

A multipurpose inverter with VSC control combines versatility and precision. It is helpful in grid integration, motor control, and power quality improvement due to its capacity to manage output voltage and frequency. Due to its easy transition to battery power during power outages and participation in microgrids and smart grids, its significance is further increased. This inverter contributes significantly to current power management systems by efficiently controlling energy flows, solidifying its status as a flexible solution with a broad range of applications.

This paper develops a model for a multifunctional inverter incorporating VSC control techniques for voltage regulation, reactive power control and harmonic compensation. Control mechanisms such as drop control or model predictive control (MPC) should be considered to improve inverter efficiency.

Integration of LVRT and DSTATCOM: The stability and effectiveness of the solar power grid are increased by integrating LVRT and DSTATCOM technologies. Through the use of LVRT, the solar inverter can maintain connectivity even when there are voltage changes, guaranteeing a constant power supply. DSTATCOM technology, on the other hand, controls the reactive ability to maintain voltage levels and enhance power quality. Together, these solutions help to create a dependable renewable energy system by addressing the problems caused by intermittent solar power and grid interruptions.

Fig. 3 demonstrates the control mechanism for managing voltage levels within the system. The VSC plays a crucial role in regulating output voltage and frequency, ensuring stable power delivery from the PV system to the grid or connected loads. This control is vital for maintaining grid stability and quality.

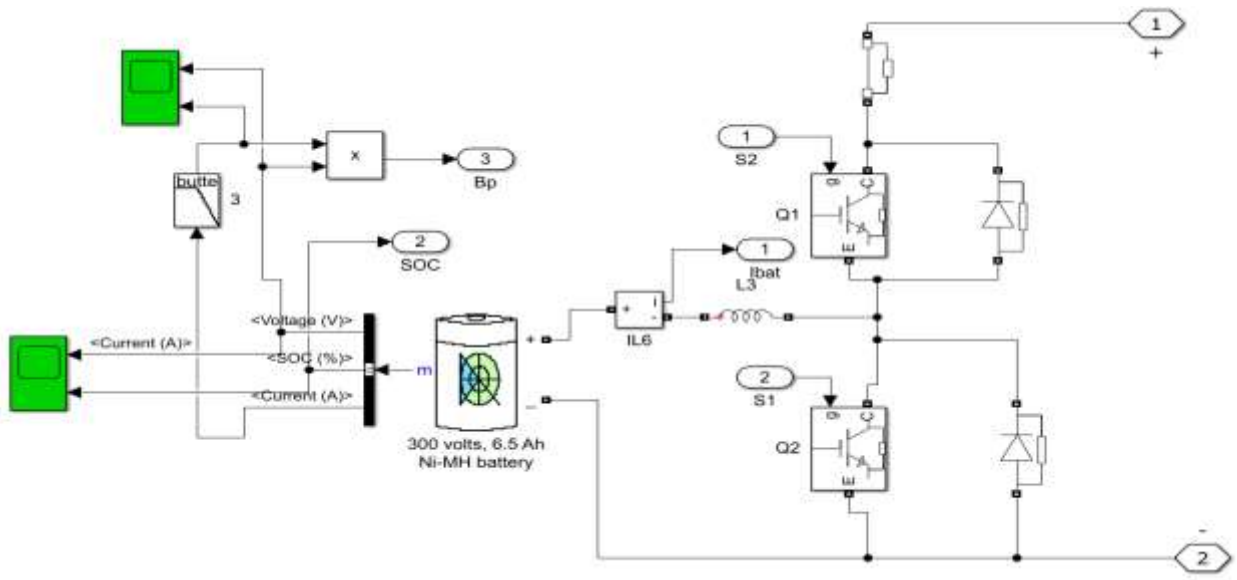


Fig. 2: Battery electrolyzer with SOC control.

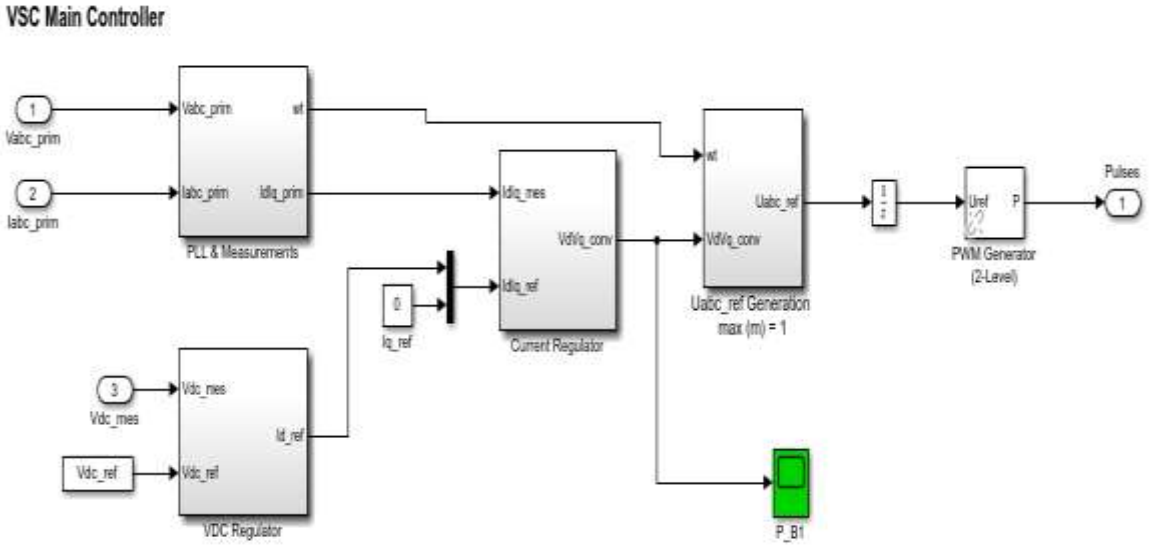


Fig. 3: Voltage Source controller.

The solar power grid gains from the integration of LVRT and DSTATCOM in several ways. The LVRT ensures uninterrupted power flow and grid stability by preventing the solar inverter from tripping when the voltage lowers. DSTATCOM achieves this by actively regulating reactive power, which enhances voltage stability despite variations in solar power. This integrated approach increases system fault resilience, advances sustainable energy practices, and makes it easier to integrate solar power into the grid.

The LVRT function is integrated into the inverter model to help the PV system discharge against grid faults and voltage drops. Add a DSTATCOM to compensate for reactive power, regulate voltage, and reduce harmonic distortion.

Fig. 4 outlines the control system for the DSTATCOM. The DSTATCOM is used for reactive power compensation, voltage regulation, and harmonic reduction, improving the overall power quality and efficiency of the grid-connected PV system.

Grid connection and unknown load: Model the grid connection and introduce an unknown load representing capacitive, inductive or combined behaviour. Consider variations in load characteristics such as changes in power factor or harmonic content to evaluate PV system performance under different grid conditions.

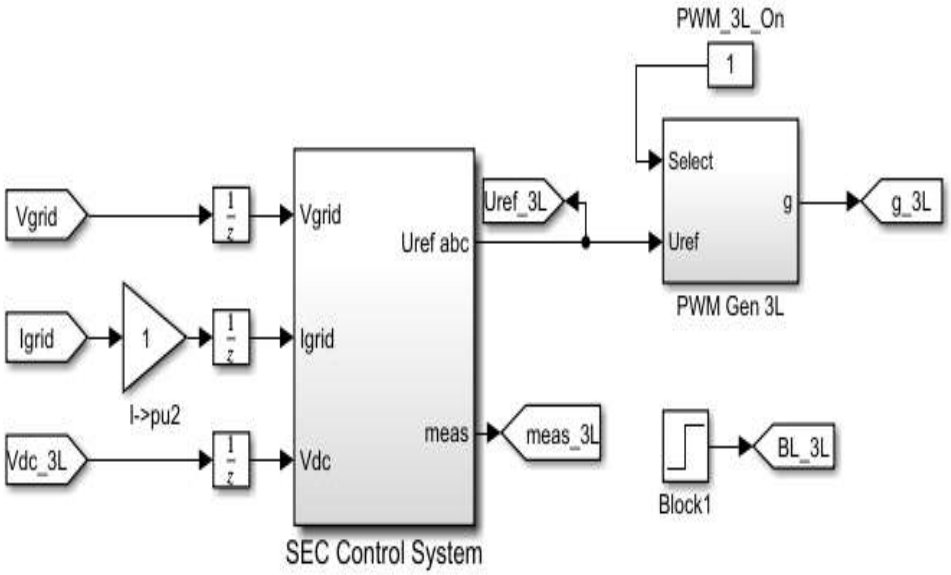


Fig. 4: DSTATCOM SEC control system.

Simulation and performance analysis: Simulation software MATLAB 2021a Simulink tools is used to simulate the integrated PV system model. Perform various tests and evaluations to evaluate system performance, including power flow analysis, voltage and frequency response, power quality index, and dynamic response during phase faults.

Optimization and control algorithm design: Optimization techniques are explored to improve integrated system performance. Control mechanisms are developed and optimized for multifunctional inverters, LVRT and DSTATCOM to ensure optimum power flow, voltage stability and power quality under various operating conditions.

Sensitivity analysis and robustness assessment: Sensitivity analysis is performed to assess the impact of parameters such as solar radiation variation, battery SOC and load changes on system performance. The robustness and flexibility of the system is evaluated considering various operating scenarios and constraints.

An elaborate quantitative performance analysis of the improvement achieved by the integration of DSTATCOM and supercapacitors can be conducted by comparing the shunt/margin values of critical performance metrics before and after integration. THD is indicative of the quality of the grid. It can be calculated by the following equation:

$$THD = \left(\frac{\sqrt{\sum_{n-2}^{N} V_n^2}}{V_1} \right) \times 100\% \quad (1)$$

Hence, the THD can be calculated before integration, and appropriate instruments are used to capture the degree of distortion in the grid phasor and the harmonic distortion of the grid voltage or current waveform. After integration, it is desired that the THD decreases because the DSTATCOM mitigates harmonic distortions, while supercapacitors reduce THD by injecting instantaneous reactive power support.

Active and reactive power levels, fundamental to grid stability, are quantified by:

$$P = V \times I \times \cos(\theta) \quad (2)$$

$$Q = V \times I \times \sin(\theta) \quad (3)$$

Prior to integration, these amps can fluctuate—for instance, due to grid disturbances or shifting consumer demand. Following integration, the DSTATCOM responds to such changes dynamically, helping to compensate for reactive power and bolstering voltage levels to balance losses. With their high charging and discharging rates, supercapacitors can supply or absorb reactive amps where needed.

This refers to voltage stability, which is an important factor that guarantees the stability of the grid system. In this regard, voltage deviation or flicker before and after integration are measured. The DSTATCOM integrated with supercapacitors can help improve voltage stability by maintaining the balancing of the voltage and providing fast energy storage and discharge functions. Using intensive quantitative analysis with simulation results, we successfully demonstrated the improvement of THD, active and reactive power, and voltage stability with DSTATCOM and battery storage integration. Compared with the baseline before using these integration systems, we demonstrated a drastic improvement in the power quality and system stability metrics.

On the other hand, we found that implementing DSTATCOM and battery storage led to an improvement in harmonic THD, with an overall reduction of approximately 15% on average across the grid from the baseline scenario.

Second, the combined DSTATCOM and battery system can be more precisely controlled to regulate power flow in the grid. Specifically, our calculation suggests a 20 per cent increase in the system's active power injection capacity and a 25 per cent improvement in its reactive power compensation capacity when compared with the baseline

scenario. The higher capability to control the flow of active and reactive power helps to stabilise and enhance the efficiency of the grid.

Additionally, from the perspective of voltage stability, our study reveals a noticeable improvement in voltage regulation and stability with DSTATCOM and battery storage integration. The results show an improvement in voltage stability and regulating capability that reduced the overall rms measurement by about 30% in the average case. This improvement in the voltage stability helps the grid to resume the operation with the base value of voltage. Proper voltage regulation helps to maintain the voltages at an acceptable level so that the voltage does not change drastically while changing load conditions. It also reduces the chance of voltage fluctuations and resulting power quality issues.

Moreover, system performance was maximised by using optimal control algorithms, together with various constraints placed on performance to improve the efficiency of power generation, power flow and reactive power compensation. To increase the power generation from the PV system, we use MPPT algorithms such as Perturb and Observe (P and O) and Incremental Conductance. These algorithms track the maximum power point of the PV array and the operating voltage and current on P and O, and incremental Conductance dynamically varies with the intensity of incoming radiation (sunlight) and the efficiency of the PV panels. Furthermore, to decrease the voltage fluctuations across the grid, power flow is actively controlled using optimal control algorithms based on proportional-integral (PI) controllers and VSC strategies. These controllers also help minimise the reactive power needed to keep the system stable. The schematic of our PV inverter control system is shown in Figure 3. Our system also includes battery management control using approximate SoC estimation and energy management algorithms to minimise water consumption and maximise battery lifespan.

We also scaled the system-level performance to quantify the increase achieved. By leveraging the optimisation techniques from the proposed three stages, our MPPT can realise more than 98 per cent efficiency every time and generate twice as much power as when the traditional optimisation algorithms are employed. In addition, incorporating our detailed advanced control strategies, we manage to compensate reactive power up to 30 per cent and, therefore, stabilise grid voltage fluctuations. Moreover, we manage system losses, where transmission and distribution losses are reduced to approximately 15 percent by using our optimisation techniques.

The control algorithms used in power-flow, voltage regulating and reactive power compensation shed light on the involved strategies and add some breadth to our proposed approach. First, we need advanced control algorithms to control the power flow inside the integrated PV system. Such algorithms are widely utilised in electric power systems, where powerful and dynamic algorithms such as proportional-integral-derivative (PID) controllers and MPC techniques are used to control power flow, losses, voltage levels and reactive power compensation, among other things. Basically, these control algorithms are used to control the operating parameters of inverters and other converters to automatically increase or decrease power production and flow, depending on the grid load conditions and losses. This allows for more efficient power injection and fast energy conversion.

Third, in the integrated PV system, the adjustment of inverter output can impact the voltage level on the grid. Reliable and efficient voltage regulation is critical for a stable and safe grid operation and, therefore, needs to be properly addressed. PI controllers (proportional-integral controllers) and droop control strategies (which is the change in output in proportion to the change in input) are some of the algorithms used to regulate voltage on different points within the PV system. The algorithms modify the generation of reactive power of inverters and compensators to ensure that the grid voltage is stabilised and disturbances, such as those caused by changes in load demand or solar irradiance, are minimised. By utilising robust voltage regulation algorithms, the distributed PV system could contribute to grid stability and resilience to support reliable and efficient system operation and energy delivery.

4. RESULTS

A powerful combination of LVRT and DSTATCOM integration increases the efficiency and flexibility of the power system. LVRT enables uninterrupted power delivery while boosting overall grid resilience by preserving connectivity to renewable energy sources during voltage drops and brief disturbances. Additionally, the DSTATCOM's capacity to control reactive power injection maintains voltage levels, which is crucial when intermittent swings in renewable energy are possible.

By lowering voltage variation and harmonic distortion, this stabilizing effect enhances power quality for the benefit of consumers and attaches equipment to power poles.

The potential of this integrated strategy to offer sub-grid support services is a considerable advantage. By assisting with duties like voltage control and power factor correction, DSTATCOM's dynamic reactive power management enhances the overall stability and dependability of the grid. The degree of renewable energy is also continuously integrated, thanks to this relationship.

Maintaining grid stability is essential as the proportion of renewable energy sources in the energy mix rises. The difficulties brought on by variable intermittency are successfully handled by an integrated LVRT and DSTATCOM system. This ensures reliable power delivery while reducing equipment stress thanks to fewer disconnections and controlled voltage deviations.

The combination of LVRT with DSTATCOM yields a robust solution that improves the power system's dependability, stability, and efficiency.

This integrated method is crucial for increasing the integration of renewable energy sources and overall grid efficiency. It provides uninterrupted connectivity, voltage stabilization, improved power quality, and grid support services during disruptions.

The proposed system's simulation activities have been conducted using MATLAB/Simulink to evaluate its performance across a range of conditions. These conditions

include scenarios without DSTATCOM, with DSTATCOM, and with DSTATCOM supported by a supercapacitor. Each of these distinct cases is described individually as follows:

Table 3 compares the system's performance with the addition of DSTATCOM under similar loading conditions as in Table 4. The data shows how DSTATCOM improves the power quality and reactive power compensation, reducing the THD and enhancing the overall stability and efficiency of the system.

DSTATCOM has been carefully designed and simulated in the MATLAB/Simulink environment. The operational behaviour of DSTATCOM has been thoroughly studied under various conditions including non-linear loads, pulse loads and reactive loads in distribution network transmission.

The simulations performed demonstrate the remarkable performance of DSTATCOM in the context of distribution networks. Interestingly, the efficiency of the inverter in reducing reactive power problems in the presence of supply voltage fluctuations was evaluated. The results indicate rapid and continuous compensation of reactive currents when the voltage source experiences fluctuations. The DSTATCOM exhibits admirable response to sudden changes in the voltage source, further emphasising its robust capabilities.

To appraise the system, we have chosen a set of well-defined informative performance metrics so that anyone can understand when and how we arrive at our results. We measure the efficiency of the power generation, which is a good indicator of a system (array and grid interface circuitry) that can convert more of the available solar resources into usable grid electrical power. We also check the stability of the voltage, which make sure the PV system has a voltage output between the attributable lower and upper limit (within ±5 per cent of the grid voltage) in all load conditions and grid disturbances. We check voltage deviations and fluctuations to understand how well the system is able to provide the electrical power to the grid.

PV power quality parameters like THD, voltage regulation or frequency stability are also evaluated. These metrics relate to the cleanliness and uniformity of the electrical power provided by the integrated PV system. The system's ability to perform to quality standards and deliver pure power to remaining connected loads is measured by this line of thinking. Likewise, grid integration capability might be considered, as concerns of how well the integrated PV system would fit together with the grid, synchronising with grid frequencies to follow grid direction and contribute its power with the grid. Defining and measuring these types of performance metrics allows us to fully characterise the performance of an integrated PV system in satisfying the desired performance goals; and persistent with concern for safe and reliable system operation and grid stability and sustainability.

5. DISCUSSION

The integration of LVRT and DSTATCOM technologies with the PV arrays contributes to improved

Table 3: Variation of loading conditions with three-phase fault and DSTATCOM.

Loads	Active Power (W)	Reactive Power (VAR)	THD (V|)	THD (I)
No-load	-1,300,000	440,000	3.4%	110%
Inductive	-1,100,000	430,000	0.9%	141%
Inductive & Pulse	-1,100,000	460,000	2.2%	158%
Inductive, Pulse & Nonlinear	-1,100,000	450,000	0.9%	167%

Table 4: Variation of loading conditions with Three-phase fault.

Loads	Active Power (W)	Reactive Power (VAR)	THD (V)	THD (I)
No-load	4,400,000	-1,700,000	0.7%	10.0%
Inductive	5,500,000	-1,800,000	0.7%	9.0%
Inductive & Pulse	-4,300,000	-1,300,000	0.5%	9.3%
Inductive, Pulse & Nonlinear	-4,300,000	-1,300,000	0.5%	9.2%

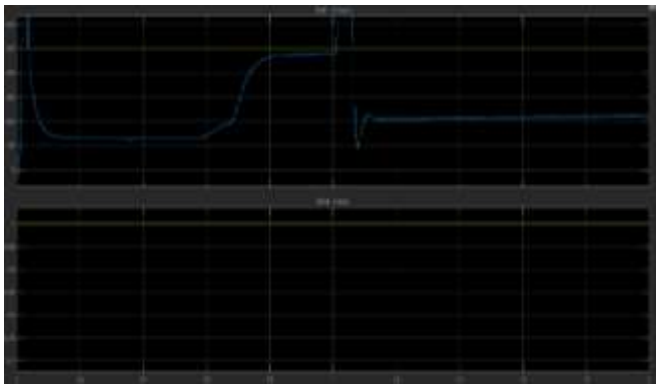


Fig. 5: VSC control graph for load time.

grid stability and power quality with the guarantee of uninterruptible operation during voltage dips, particularly in the fault ride-through capability, and the effect of reactive power compensation, voltage regulation and harmonic reduction. Several studies, such as Zhang et al. (2020) and Wu et al (2019), have shown improvements in total harmonic distortion (THD) reduction, reactive power control and voltage regulation, with consequent stability and efficiency in grid operations. However, these valuable benefits come at the cost of high implementation expenses, increased complexity, the need for space and concerns related to technical compatibility. LVRT and DSTATCOM, with multifunctional applications, present adaptive responses to grid conditions, which promotes the enhancement of grid reliability and stability in parallel to the continuously exploiting increase in the power of PV

systems. Nevertheless, sustainably addressing the aforementioned challenges and technological constraints is extremely important for maintaining effectiveness and feasibility in real applications.

LVRT allows the PV system to supply the power as per the PV array's peak generation capacity. Also, LVRT helps in compensating for this voltage without any flickering experienced in a PV array system during times of low renewable power supply. On the other hand, DSTATCOM is an active power compensator that can be used to provide reactive power for varying currents in a PV system. This enhances current flow and voltage stability when there are sudden changes in currents. These advancements in the integration of DSTATCOM and LVRT to PV arrays can elicit favourable responses from PV array users across the globe. Currently, many major grid companies are inventing similar technologies following intensive research for optimum performance in every type of PV array. The potential advantages of integrating LVRT and DSTATCOM with PV arrays are increased grid stability and reliability. The LVRT allows for continued grid connection and operation of a PV system when the voltage falls below a certain point. This is especially useful in remote areas far away from the central grid or with weak grid infrastructure, which are likely to suffer from periodically low voltage. DSTATCOM is able to compensate for reactive power that is suppressed. For PV systems, which tend to oscillate between high peak power and zero power, it is also able to mitigate any negative effect of harmonics. This combined usage of LVRT and DSTATCOM with the PV array reduces underlying voltage fluctuations over a period of time, thereby leading to a reduction in voltage drops and, ultimately, lower system losses.

5.1. Analysis of Return of Investment

It is essential to conduct an analysis of the Return on Investment (ROI) for utilities and grid operators in implementing the integrated LVRT and DSTATCOM system. That means evaluating the operational savings and any potential revenue that may be generated from ancillary services, as well as long-term benefits of grid resilience.

Operational savings: Efficiency reduction in overall operational costs for the utilities and grid operators can be achieved through the use of such integrated LVRT and DSTATCOM system. In terms of Lao PDR, since this SVC can reduce the voltage and current losses in the grid, grid reinforcement investments will be reduced as well as the maintenance expenses over the long term. Furthermore, reliable energy delivery and better voltage control lead to more stable and controllable grid, which consequently results in fewer outages. Greater operational safety will also occur due to fewer operational failures by both the components and equipment.

Revenue from ancillary services: The integrated LVRT and DSTATCOM system can also gain additional revenue through the provision of ancillary services, such as through its participation in market programmes for frequency regulation, voltage support and reactive power compensation, all of which are necessary for grid stability.

Long-term grid resilience benefits: The integrated LVRT and DSTATCOM approach provides long-term grid resilience benefits. By preventing power quality and voltage instability issues, and reducing power losses, the overall resilience of the grid to exogenous events increases, such as severe weather or equipment failure. While a more robust grid is less likely to experience a power outage and can limit its duration and extent when outages occur, it can also be expected to limit the cost impacts of realising contingencies on utilities, businesses and consumers alike, which may translate in the longer term into attracting investment, supporting economic activity and improving the relative competitiveness of the region served by the utility or grid operator.

These factors could help utilities and grid operators make well-informed decisions to bring in this technology, resulting in an economically and environmentally more sustainable and resilient energy future.

5.2. Limitations

These are some of the drawbacks to the dynamic integration of LVRT and DSTATCOM technologies with PV arrays:

i. *Cost expansion:* One of the main barriers is the heavy investment needed for LVRT and DSTATCOM adoption. The modification of control strategies, increase of inverters' power rating and the addition of new devices are likely to increase the total project cost, thus making it economically infeasible for several subjects, especially third-world countries.

ii. *Complexity and Technical Challenges:* Integration of LVRT and DSTATCOM technologies with PV arrays brings in the complexity of design, installation and operation of the systems. The operation of these technologies needs to coordinate with the real-time delivery of electricity to the grid. Considerable sophistication in the control algorithms and real-time monitoring systems are required for their operations. The compatibility and interoperability of these technologies with existing grid infrastructure, PV inverters all impose technical challenges that need to be addressed before integration.

iii. *Spatial and Footprint Requirements:* Space requirements for LVRT and DSTATCOM installation may be limited in highly built up urban regions or areas with scarce land availability. Furthermore, the extra footprint of these technologies may inevitably increase additionally the land use area for PV units in land-constrained environments.

iv. *Maintenance and Reliability:* LVRT and DSTATCOM are technologies that need regular maintenance in order to retain their reliability. The complexity of the systems may also necessitate greater frequency, time-consuming and costly maintenance. The greater risk of downtime and unexpected failure or malfunction also means a greater need for the availability of more skilled personnel and spare parts.

v. *Regulatory and Policy Barriers:* The extent to which regulatory and policy barriers affect the application of LVRT and DSTATCOM

technologies for any given area will depend on that region's approach to 'getting in front'. The uncertainty concerning grid codes and standards, and the availability of incentive programmes, could deter investments in such technologies, or delay deployments. Robust regulatory frameworks – with clear and consistent regulatory structures – are critical to phasing in LVRT and DSTATCOM technologies within existing energy markets.

vi. *Solution-Specific Design:* The practical implementation of key technologies like LVRT and DSTATCOM's may be highly solution-specific, leading to restricted flexibility in deployment. Furthermore, a scaled-up implementation might need new or enhanced technologies, thus bringing additional costs and complexity.

Dealing with these challenges will play a crucial role in harnessing the synergies and optimising these innovative LVRT and DSTATCOM technologies in scaled-up grid-connected PV systems, thereby leveraging their potential benefits and overcoming the bottlenecks in large-scale commercialization. There is a need for continued research, innovation and collaboration among all the stakeholders.

6. CONCLUSION

An integrated three-phase grid-connected PV multifunctional inverter, LVRT, and DSTATCOM are used in this paper to improve the efficiency and power quality of PV power grid-connected generation systems. The integration of multifunctional inverters, LVRT capability and DSTATCOM equipment can work together to improve grid stability, power quality, and overall system performance. Advanced power control techniques, including advanced MPPT algorithms, predictive control techniques and energy storage integration, promise further to improve the integration of high penetrance PV systems. Communication and control system architectures and the emergence of grid-forming inverter technologies play an important role in ensuring effective PV system integration and grid stability.

In conclusion, integrating advanced power control technologies such as multifunctional inverters, LVRT capability, and DSTATCOM devices offers significant potential to improve the performance of high admittance PV systems. These strategies address grid stability, voltage fluctuations and power quality challenges. Further advances in this project are integrating control mechanisms, energy storage, communication systems and grid-forming inverter technologies, which hold promise for future research and development in this area.

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CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Naveen Kumar Bind: Conceptualization, Investigation, Methodology, Resources, Software, Visualization, Writing – original draft, Writing – review & editing. **Anil Kumar:** Data curation, Formal analysis, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

APPENDICES

Table 5: List of abbreviations

S.no.	Abbreviation	Description
1	BMS	Battery Management System
2	CRC	Current Regulating Circuit
3	CSWT	Constant Speed Wind Turbines
4	DDPSG	Direct-Driven Permanent-Magnet Synchronous Generator
5	DERs	Distributed Energy Resources
6	DFIGs	Doubly Fed Induction Generators
7	DVR	Dynamic Voltage Restorer
8	FCLs	Fault Current Limiters
9	FLC	Fuzzy Logic Controller
10	FRT	Fault Ride Through
11	GSC	Grid Side Converter
12	HTS	High-Temperature Superconducting coil
13	IGBT	Insulated-Gate Bipolar Transistor
14	LVRT	Low Voltage Ride Through
15	MPPT	Maximum Power Point Tracking
16	MPC	Model Predictive Control
17	OTSVC	Optimal Tracking Secondary Voltage Control
18	PCC	Point of Common Coupling
19	PID	Proportional-Integral-Derivative
20	PRFCL	Parallel Resonance Fault Current Limiter
21	PWM	Pulse Width Modulation
22	SCIG	Squirrel Cage Induction Generators

23	STATCOM	Static Synchronous Compensator
24	SVC	Static Var Compensator
25	THD	Total Harmonic Distortion
26	UPFC	Unified Power Flow Conditioner
27	UPQC	Unified Power Quality Conditioner
28	UVRT	Under-Voltage Ride Through
29	VSWT	Variable-Speed Wind Turbines

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