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Capability Enhancement of PV Connected Grid Tied System under the Condition of Fault: A Review

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Abstract— ***The increasing integration of photovoltaic (PV) systems into grid-tied networks has introduced new challenges in maintaining system stability, reliability, and efficiency, particularly under fault conditions. Grid faults, including voltage sags, frequency deviations, and short circuits, can significantly impact the performance of PV-connected systems, leading to power quality issues and potential disconnections. This paper provides a comprehensive survey on capability enhancement techniques for PV-integrated grid-tied systems under fault conditions. Various fault detection, classification, and mitigation strategies are explored, with a focus on advanced control algorithms, fault ride-through (FRT) mechanisms, and grid-supportive functionalities. The role of modern power electronic converters, artificial intelligence-based fault diagnosis, and grid codes in enhancing system resilience is also discussed. Furthermore, the paper highlights emerging trends and future research directions in improving the fault tolerance and operational stability of PV-connected grids. The insights presented in this survey aim to contribute to the development of more robust and fault-resilient PV-integrated power systems.***

Keywords— Photovoltaic (PV) System, Grid-Tied System, Fault Conditions, Fault Ride-Through (FRT), Power Quality, Fault Detection, Grid Stability etc.

I. INTRODUCTION

I Solar power has a vast thrust in Indian sub-continent. As of February 2025, India's installed solar power capacity has reached 102.57 GW which has been achieved by installing nearly 70 solar parks to facilitate the development of these plants all- around the nation. The demand of solar energy is increasing day by day seeing to its applicability. The application oriented installation of PV system has been tabulated in table-1. From the table it can be seen that the major role of solar power generation is its grid connected operation. The grid connected operation is carried-out in two layers; one is the DC-DC conversion whose elements are MPPT technique and DC_DC boost converter. In this layer DC output voltage of the PV is regulated using MPPT and boosted to a required level using DC converter. Second layer is the conversion of DC into AC matching the grid compatibility using inverter. Inverter performs two functions of converting DC into AC and integrating the solar with the existing utility system.

It is worth noting that the grid connected PV system has two individual functionalities and system. One is the individual DC to AC PV operation and another is the large AC grid supplying to surplus consumers. Hence the grid connected operation of PV is very complicated since any abnormalities in the grid may affect the operation of PV system and vice-versa. The dc-bus voltage will increase due to the continuous operation of the dc/dc converter with the MPPT function when the faults happen in the dc/ac converter or grid side. Then the power electronic devices might be broken down due to high dc-bus voltage, as well as the PV sources. Though, a dc-bus voltage protection unit is designed in most cases, the protection performance is limited by the response time and the designed voltage tolerance.

In this work, the behavior of a PV system under a fault is studied and ride–through control scheme is analyze which is able to support the grid. Furthermore, a continuous DC supply is maintained from PV system at the time of fault at grid side. Also the proposed control scheme is able to support the grid through the injection of reactive power. The control scheme makes use of a synchronous reference frame based PI controller.

Table 1: Photovoltaic (PV) installed capacity by application (GW)

Application	28/02/2025
Solar power ground mounted	78.47 GW
Solar power rooftop	16.66 GW
Off-grid solar power	4.59 GW
Hybrid Projects (Solar Component)	2.85 GW
TOTAL	102.57 GW

Low voltage ride through capability

Low Voltage Ride through (LVRT), is the capability of PV system to stay connected in short periods of lower electric network voltage (voltage dip) as shown in figure 1. It is needed at distribution level (wind parks, PV systems, distributed cogeneration, etc.) to prevent a short circuit at HV or EHV level from causing a widespread loss of generation. Similar requirements for critical loads such as computer systems and industrial processes are often handled through the use of an uninterruptible power supply (UPS) or capacitor bank to supply make-up power during these events. Along with the updates of grid codes, the control techniques of grid-tied PV inverters are required to be upgraded as well because the operation under the low voltage faults is much different from that under the normal conditions. To be specific, the main issues need to be considered include the over current caused by the abrupt voltage drop, the sudden surge of dc-link voltage as a result of the difference between input and output power, the fault detection and the phase-locked loop (PLL) under the low voltage faults. In order to successfully complete the LVRT operation, several control methods have been proposed. The most important task of the control to stabilize the operation under the condition of LVRT is to inject the required amount of reactive power in order to maintain the voltage sag due to fault. Under such conditions strategies must be designed so that PV system must be capable of ride-through under the condition of fault.

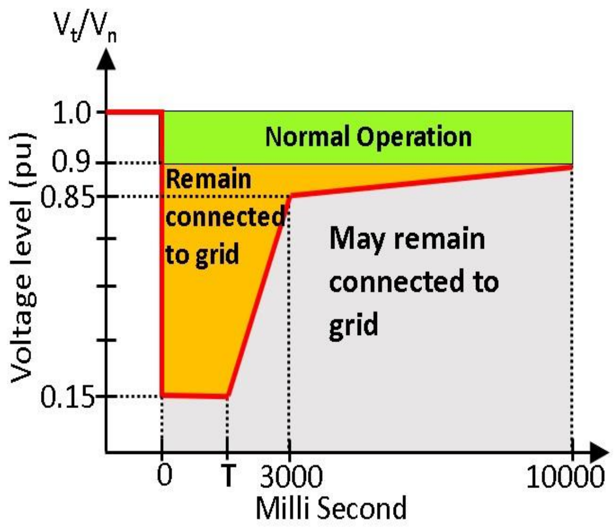

Fig. 1: LVRT capability curve

A part of the electrical energy is lost during its transmission. This puts a physical limit as to the distances of generation centers from the load centers. That is why electrical systems have evolved mainly within their own geographical jurisdiction. Although by employing a different technique, called DC transmission, it became feasible to transport electrical energy over longer distance; electrical systems predominantly remained bound to their geographical jurisdiction.

A. History of Electricity Market

P.W. Fleury & Co. performed the first official lighting demonstration in Kolkata (formerly Calcutta) on July 24, 1879. On January 15, 1897, the Indian Electric Co. was established in London, and on January 7, 1897, Kilburn & Co [41]., in their capacity as agents, were authorised to install electric lights in Calcutta. The corporation changed its name to the Calcutta Electric Supply Corporation about a month after selecting its initial name. It wasn't until 1970 that the company's headquarters were moved from London to Calcutta. After the success of bringing power to Calcutta, it was expanded to neighboring Bombay (now Mumbai). Mumbai's Crawford Market hosted the city's first electric lighting demonstration in 1882, and the Bombay Electric Supply & Tramways Company (BEST) constructed a generating station that powered the tram network in the city in 1905. At a tea estate in Sidrapong, the Darjeeling Municipality constructed India's first hydroelectric plant in 1897.The first electrical street light in Asia was switched on on August 5, 1905, in Bangalore, India. On February 3, 1925, the first electrical train in the country travelled over the Harbour Line from Bombay's Victoria Terminus to Kurla. The Government Engineering College in Jabalpur was the first organization to establish a high-voltage laboratory in India in 1947. [21] When a new solar facility was inaugurated on August 18, Cochin International Airport in India became the first airport in the world to be totally powered by solar energy.

AI in PV Connected Grid Tied System

Photovoltaic (PV) grid-tied systems with AI are more efficient, reliable, and adaptable to dynamic grid situations. Traditional PV systems include weather-related intermittency, energy waste, and grid stability issues. Optimization of energy production, storage, and distribution using machine learning, predictive analytics, and intelligent control algorithms is possible with AI.

Solar energy forecasting is an important AI application in PV grid-tied systems. AI algorithms accurately estimate solar power production using historical meteorological data, satellite photos, and real-time sensor inputs. This helps grid operators balance supply and demand, eliminating power swings and guaranteeing system stability. AI-powered Maximum Power Point Tracking (MPPT) algorithms dynamically modify operational settings to maximize solar panel energy production under different environmental circumstances. Unlike MPPT, AI-based systems adapt and learn, boosting energy efficiency.

AI-based inverters evaluate grid circumstances and automatically manage voltage, frequency, and reactive power compensation, another major improvement. Intelligent inverters improve grid stability, minimize voltage spikes, and allow two-way energy exchange in distributed energy systems. Predictive maintenance relies on AI to monitor system health, diagnose errors, and anticipate component breakdowns. This proactive strategy extends PV system component lifetime and lowers downtime and maintenance expenses.

II. LITERATURE SURVEY

Hussin Zahloul et.al (2024) Short circuit faults are a prevalent issue in power systems, causing disruptions to the grid's normal operation. Dynamic behaviors of the conventional power systems during short circuit faults have been extensively studied and understood. The bulk of ongoing research and development are focusing on the dynamic performance of grid-connected renewable energy systems under these fault conditions, due to changes in the grid code and a decrease in system inertia. The development of effective control strategies to enhance the system's reliability during fault conditions is of paramount importance. In this paper, a two-stages grid-connected photovoltaic system (GCPV) having a rated power of 2 MW was created in the MATLAB/Simulink environment. The dynamic behaviour of the presented system was evaluated in two scenarios: steady state conditions and short circuit faults. A line-to-ground short circuit fault was created at the grid side, and its effect on the PV system's operation was observed. An advanced control system was designed to maintain stability during fault conditions. The results demonstrated the efficiency of the designated control system in minimizing the effects of short circuit faults on the GCPV system's function, and restoring the system promptly after the fault was cleared. Furthermore, considering modifications in grid regulations, the low voltage ride through (LVRT) capability of the designed system was analyzed and validated according to the UK standards. The Total Harmonic Distortion (THD) level at the common coupling point was also analyzed for voltage and current, remaining below the acceptable level of 5% as specified in the IEEE Std. 519 [01].

Mohammed Alharbi et.al (2024) This paper has examined the challenges and solutions in managing grid-connected PV inverters under conditions of grid imbalance. The paper introduces a novel control scheme that efficiently attenuates the double grid frequency oscillations observed in the DC-link voltage, a common issue under unbalanced grid conditions. The proposed scheme is validated through comprehensive simulations. This strategy includes a feedback control method for regulating oscillatory components within the dq frame, thus suppressing ripples in the DC-link voltage. The integration of an MPPT controller further optimizes the efficiency of the PV array. The proposed control method demonstrates its effectiveness in maintaining sinusoidal current injections and stabilizing DC-link voltage during unbalanced grid conditions to contribute effectively to the power grid even under challenging conditions. The suggested control scheme is considered under various scenarios, including SLG faults and dynamic changes in solar irradiance. The results showed that the system could maintain a balanced grid current, constant active power, and constant DC-link voltage, highlighting the robustness and flexibility of the proposed solution [02].

Debabrata Mazumdar et.al (2024) Recent years have seen an increase in the deployment of renewable energy sources on power system networks as a result of the gradual development of renewable energy sources. In order to utilize these intermittent sources, grid integration is crucial, since weather conditions are hard to predict accurately and do not match the pattern of generation. As a result, controlling energy becomes an unavoidable challenge when the alternative energy source is connected to the grid in a distributed manner. A number of factors contribute to the problem, including sporadic sources, daytime expenses, and limitations concerning the specifications of solar panels. Therefore, a more robust control system is needed to enhance the reliability and efficiency of the renewable energy integrated power network. Thus, this manuscript presents the design, implementation, and performance of an improved fractional order PID (FOPID) controller for proposed grid-connected photovoltaic systems. To maximize the power from the photovoltaic source, the controller is designed to extract as much energy as possible. In addition to having the adaptive nature of a PID controller, the proposed FOPID controller is capable of optimizing its gain parameter according to the generator and grid side parameters being considered. The proposed study utilized grey wolf optimization (GWO) to tune the FOPID controller for tracking the quadrature axis model, DC link voltage and current regulation, and maximizing the maximum power point. Further, FOPID is used to perform the system's current control functions, and each time the error is measured, the regulating parameters are updated accordingly. This paper contrasts fuzzy logic controllers (FLC), flying squirrel search optimization (FSSO), and PSO-tuned FOPID controllers with the proposed work. The simulation's results are displayed and examined in the section on results and outcomes. The obtained results demonstrate maximum solar power output under erratic weather conditions, validating the effectiveness of the proposed controller [03].

Mansour Hajji et.al (2023) In the current work, we have developed a fault detection and diagnosis framework based on machine and deep learning techniques that are capable of diagnosing the most frequent faults in grid connected PV (GCPV) systems at many irradiance levels. The irradiance levels have been investigated to improve the power production and to maintain the operation of these systems. Thereafter, we have evaluated the applied techniques with different untrained data while covering range of irradiance (low, standard, and high) equal to 400, 1000 and 1750 W/m2 respectively.
The developed approach was able to classify the PV faults including LL fault, LG fault, Bp fault and Cn fault. The

obtained results confirmed that the developed paradigm achieved good diagnosis accuracy under different simulation conditions [04].

Bilel Dhouib et.al (2023) The dynamic modeling, control, and simulation of renewable energy sources connected to the electrical grid are investigated in this study. Photovoltaic (PV) systems and wind systems connected to the power grid via the point of common connection (PCC) were the only two systems included in our study. Simulation and control methodologies are provided. For both PV arrays, the method of extracting maximum power point tracking (MPPT) is utilized to obtain the highest power under standard test conditions (STC: 1000 W/m2 , 25 ◦C). A power electronics converter that can transform DC voltage into three-phase AC voltage is required to connect a PV system to the grid. Insulated gate bipolar transistors (IGBTs) are utilized in a three-level voltage source converter (VSC). The distribution network is connected to this three-phase VSC by way of a step-up transformer and filter. During synchronous rotation in the d − q reference frame, the suggested control for the three-level solar power system that is connected to the grid is constructed. To obtain a power factor as near to one as possible, the phase-locked loop (PLL) is employed to align the angle of the power grid voltage with the angle of the current coming from the inverter. Squirrel-cage induction generators (SCIGs), which are utilized as fixed speed generators and are linked directly to the power network, are the foundation of the wind system. Additionally, a pitch angle control approach is suggested to keep the wind turbine’s rotor speed stable. MATLAB/Simulink software is utilized to model and simulate the suggested hybrid system. Under fault scenarios such as the line to line to line to ground fault (LLLG fault), the suggested hybrid system’s dynamic performance is examined. The simulation results prove the ability to manage the small hybrid system that combines solar and wind power, as well as its dynamic performance [05].

MOATH ALRIFAEY et.al (2022) Manual feature extraction and feature selection are the main challenges of PV fault detection and classification because the huge feature database consists of different sensing signals under a noisy environment. In order to tackle the PV fault detection and classification problems effectively, a hybrid DL model is proposed in this paper through the proper combination of discrete wavelet transform (DWT), stacked autoencoders, deep equilibrium optimization algorithm (DEOA), and long short-term memory (LSTM). In contrary to most existing works, the proposed hybrid DL model is able to perform the automatic feature extraction and feature selection via SAE and DEOA, respectively, in order to determine the optimal feature subsets that can play decisive roles in detecting and classifying PV faults. Extensive performance analyses have demonstrated the excellent capability of the proposed hybrid DL model to solve the PV detection and classification problems with good accuracy and short computational time. Furthermore, the proposed hybrid DL model also shows its good robustness under noisy environments. The competitive fault detection and classification performances demonstrated by the proposed hybrid DL model are anticipated to benefit the electrical engineers in diagnosing the healthy conditions of PV plants during maintenance activities. As the extended works of current studies, it is worth examining further the performance of the proposed hybrid DL model with different datasets and different multiobjective optimization problems. The same hybrid DL model can also be applied by the decision-makers in other hazardous areas such as the nuclear and gas electrical plants to evaluate and classify the risk levels in order to prevent future failures [06].

III. EXISTING DC CONTROLLER ANALYSIS

The DC-boost voltage can always be regulated, even in the fault conditions from the DC/AC converter or grid side, thus the fault ride through performance on dc side is enhanced. In this work a continuous DC supply is maintained from PV system at the time of fault at grid side. Also the proposed control scheme is able to support the grid power flow at the time of fault.

The control scheme makes use of a synchronous reference based controller. A grid-connected PV system with 10 parallel and 10 series module of 1STH-215P array type having power rating of 20KW. The voltage of PV system is 350 V and current rating is 80 A. The performance analysis of DC controller structure system as shown in figure 2, under following three operating mode has been carried out;

1) For constant maximum irradiance.
2) Under the condition of grid fault.

The Vmp, i.e maximum voltage output of one module is 36V, and output of the system design is 370V. The DC output of the solar system is regulated by using DC-DC boost converter. The system design parameter is shown in Table-2. The PV output at constant radiance of 1000 w/m2 is presented in figure 3 (a). The output of boost converter is maintained as 650 V as shown in figure 3 (b).

The output power of the PV source is affected by the output voltage Vpv given a constant solar irradiation level. In order to maximize the system real power output P, the perturbation is introduced by employing perturb and observe MPPT. The control objective is to design a virtual control input Vref_ peak to make the output voltage Vdc track the Voltage reference Vdc. The controller is designed using abc-dq0 transform and PLL. The design controller has the capability of fault ride through, i.e. it can maintain constant DC output from the solar side when a fault is occur grid side. The output power at constant irradiance is presented in figure 3. The performance of the designed controller for the condition of grid fault is tested by introducing a fault at grid side. The PV voltage at FRT is presented in figure 5(a), with respective DC boost voltage figure 5(b). The power flow at PCC for the FRT is given in figure 6.

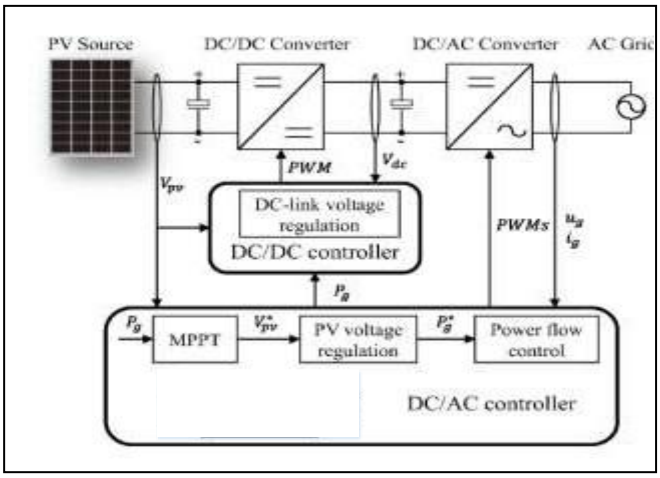

Fig. 2: System description of a grid-tied PV system with DC control structure

Table 2: Parameter & its value

Parameter	Value
Solar rating	20 Kw
Solar output voltage Vpv	370 V
Output of boost converter Vdc	650 V
Frequency	50Hz
Solar side capacitance Cpv	1µF
Boost converter inductance Ldc	3mH
Boost converter conductance Cdc	2400µF
Filter inductance Lf	10mH
Filter resistance Rf	10Ω
Filter capacitance Cf	250µF
Nominal grid voltage	415 V

IV. RECENT ADVANCEMENT IN THE CAPABILITY ENHANCEMENT OF PV CONNECTED GRID

Recent advancements in photovoltaic (PV) grid-tied systems have introduced several technologies aimed at enhancing efficiency, reliability, and integration with the power grid. Key developments include:

- High-Efficiency Solar Cells: Innovations in solar cell materials have led to significant efficiency improvements. For instance, Qcells achieved a world-record efficiency of 28.6% by integrating a perovskite top layer with traditional silicon cells. This advancement allows for greater power output from the same panel area, addressing space constraints in large-scale solar installations.

- Advanced Inverter Technologies: Modern inverters now feature high-efficiency power conversion, intelligent control, and monitoring capabilities. Utilizing advanced topologies like multi-level inverters and incorporating materials such as silicon carbide (SiC) and gallium nitride (GaN) have boosted conversion efficiencies to approximately 98-99%. Additionally, these inverters support real-time data analysis, remote management, and seamless integration with smart grids, enhancing overall system performance.

- Series Active Filters for Power Quality: To address power quality issues like voltage fluctuations and harmonics, researchers have developed series active filters for the DC side of grid-connected PV systems. Comprising inductors, capacitors, and transistor-diode pairs, these filters effectively reduce total harmonic distortion, thereby improving the stability and reliability of power supplied to the grid.

- Integration of Energy Storage Systems: Combining thermal energy storage systems (TES) with PV generation enhances grid stability by storing excess energy during peak sunlight periods for use during low production times. Technologies like molten salt thermal energy storage and phase change materials have demonstrated the potential to increase overall system efficiency and provide a more consistent power supply.

- Artificial Intelligence and Machine Learning: The application of AI and machine learning in PV systems enables predictive maintenance, performance optimization, and accurate forecasting of energy production. These technologies analyze data from various system components to anticipate failures, adjust operations for optimal performance, and enhance the integration of solar power into the grid.
- Grid-Enhancing Technologies (GETs): Implementing GETs such as Dynamic Line Rating (DLR) improves the capacity and efficiency of existing transmission infrastructure. DLR dynamically assesses the real-time capacity of transmission lines based on environmental conditions, facilitating better integration of renewable energy sources and reducing grid congestion.

V.CONCLUSION

The integration of photovoltaic (PV) systems into grid-tied networks presents significant challenges, particularly under fault conditions that can compromise system stability and power quality. This survey has provided an extensive review of various techniques aimed at enhancing the capability of PV-connected grid-tied systems during faults. Advanced fault detection and classification methods, fault ride-through (FRT) strategies, and intelligent control mechanisms have been identified as key solutions for improving system resilience. Additionally, the role of modern power electronic converters, artificial intelligence-based fault diagnosis, and compliance with grid codes has been highlighted as crucial in maintaining reliable grid operation. While significant progress has been made in improving fault tolerance, further research is needed to optimize real-time fault handling techniques, enhance the adaptability of PV inverters, and develop more efficient grid-supportive functionalities. Future advancements in artificial intelligence, machine learning, and smart grid technologies are expected to play a vital role in further strengthening the stability of PV-integrated power systems. Ultimately, a coordinated approach involving improved grid codes, advanced control algorithms, and emerging technologies will be essential to achieving a more resilient and fault-tolerant PV-connected grid.

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