Recent Research Trends for Performance Enhancement of Grid-Connected Photovoltaic Systems

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***Abstract*-- Nowadays, clean energy generated from renewable energy sources (RESs) is becoming more and more important in electricity generation. Traditionally, fossil resources are not a sustainable option for the future and contribute to environmental pollution, global warming, climate change, greenhouse effect and damage to the ozone layer. To prevent these problems, by replacing the use of fossil fuel by RESs. Among RESs, photovoltaic (PV) energy is the most used due to its sustainability, local availability, environmentally friendly nature, and the gradual decrease in the cost of its installation. This paper presents a review for the most recent research trends that attract the attention of researchers and manufacturers for performance enhancement of grid-connected photovoltaic systems.**

***Index Terms*-- Renewable Energy Sources, Photovoltaic System, Converters, Controllers, Maximum Power Point Tracking, Storage System.**

I. Introduction

SOLAR radiation is a free resource available anywhere on Earth, to a greater or lesser extent. Due to the depletion of fossil fuels and the growing demand for electricity, renewable energy such as solar energy has become a promising alternative because of its sustainability, local availability, and environmentally friendly nature. It is currently a favorable choice in many countries and regions. The global installed solar-power industry is about 942 GW in 2021, with more than 20% increase compared to 2020 as shown in Fig.1 [1].

The photovoltaic (PV) system converts sunlight to electricity directly when photons of the sunlight hit on the PV array. It produces new electron-hole pairs when light shines on the P-N knot of the semiconductor, under the function of the electric field in the P-N knot, the electron-hole will flow to P-zone from N-zone, and the electrons flow to N-zone from P-zone and produce electric current after connected to the circuit as shown in Fig. 2 [2].

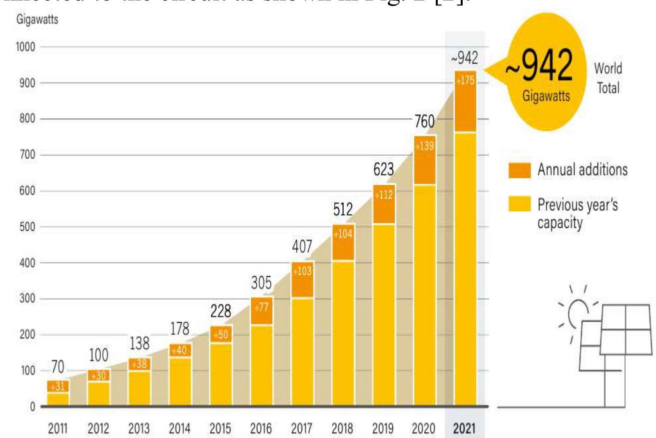

Fig. 1. Solar PV Global Capacity and Annual Additions, 2011-2021 [1].

The building blocks of a grid-connected photovoltaic (PV) system are shown in Fig. 3. The system is mainly composed of PV arrays, which convert the sunlight to DC power, and a power conditioning unit that converts the DC power to AC power (DC-DC and DC-AC converters).

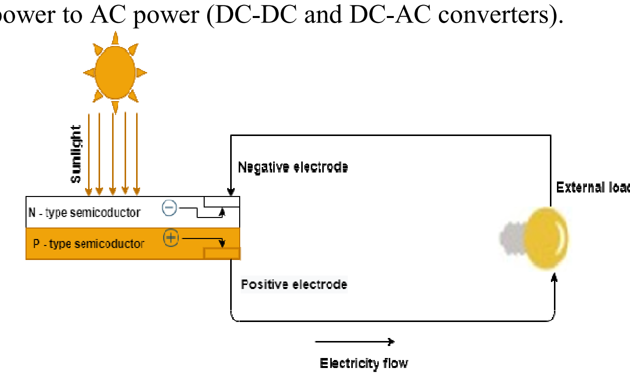

Fig. 2. Principle of a PV cell.

The generated AC power is injected into the grid and/or utilized by the local loads. In some cases, storage devices are used to improve the availability of the power generated by the PV systems and reduced its output fluctuations.

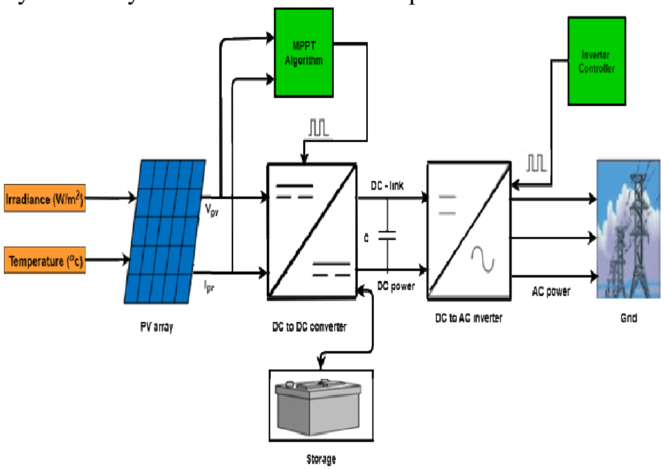

Fig. 3. Main components of grid-connected PV system.

II. Literature review

Integration of PV systems into the public grid has taken the attention of researchers and manufacturers in the recent years due to its advantages over the other types of renewable energy resources. Here, the attention to the grid-connected PV systems is drawn mainly to the following:

A. Control of DC-DC converter

The right choice of control of the DC-DC converters to meet the different requirements for any application has a great influence on the optimum performance, especially in grid-connected PV systems. Practically, the conventional boost converters cannot provide a higher voltage gain and require a high current which leads to high conduction and switching losses [3]. Therefore, for achieving a higher gain ability with a higher efficiency a lot of research has been done in the literature. O. Abdel-Rahim and H. Wang [4] proposed a new high boost converter with a model predictive control (MPC) based on MPPT algorithm with an optimum number of sensors.

A. Mirzaei and M. Rezvanyvardom [5] introduced a soft-switching full-bridge interleaved Flyback DC-DC converter with high gain in which the output current ripple reduced, and more power supplied to the load. S. Seo and H. Choi [6] proposed a fractional order PID-type control algorithm for a boost DC-DC converter. In the study, it was verified that the proposed PID can give a less overshoot and faster recovery time compared to the conventional integer order controller under input voltage variations or abrupt load. S. Mouslim, et al [7] presented a study which is based on the modelling of a SEPIC converter in continuous conduction mode. This converter is subjected to disturbances such as the variation of input voltage. The obtained results were used to design the PID controller to regulate the output voltage and compare them with fuzzy logic controller to prove the validity and efficiency of the two models.

C. Wang, et al [8] investigated the discretization effects of the zero-order holder on DC–DC buck converters under the direct ON/OFF control of sliding mode (SM). H. Komurcugi, et al [9] presented an indirect SM control of DC -DC converter. The proposed SM method employs a sliding surface function based on the input current error only. The performance of the SM method is investigated in terms of the voltage regulation under abrupt changes in the input voltage and load resistance on a prototype converter, operated in buck and boost modes. M. Kanzian, et al [10] proposed a digital SM control method for interleaved DC–DC converters. Constant switching frequency and interleaving were attained through dynamically adjusting the hysteresis width of the control signals generating comparators. G. Gkizas [11] presented and analyzed the design and robust control synthesis of a two-stage cascaded DC–DC boost converter. The systematic approach was used for selecting the circuit’s component values, in which they were optimized based on an optimization framework and assisted the use of quantitative measures that reveal the damping and ripple across passive elements.

P. Rani, et al [12] proposed an energy management technique for a three-input series connected non-isolated converter connected to the grid using fuzzy logic control. The proposed fuzzy logic control decides the quantum of power, which each source must supply, depending upon the availability of power. The PI controller is used for voltage and current control. S. Li and B. Fahimi [13] introduced a mathematical model based on the system's state-space model for controlling the resonant half-bridge DC–DC converter, which captures its steady-state behaviors for both continuous conduction mode and discontinuous conduction mode operations. P. Azer and A. Emadi [14] presented a generalized state space average model (GSSAM) for multi-phase interleaved buck, boost, and buck-boost converters. The GSSAM can model the switching behavior of the current and voltage waveforms and can be used for the converters with dominant oscillatory behavior such as resonant converters, high current ripple converters, and multi-converter systems.

B. Control of DC-AC inverter

In the renewable energy field, numerous studies have been introduced an interconnection between the RESs and the public grid through DC–AC inverters. These inverters are used to deliver the required active power and reactive power into the grid., and thereby are critical in the application of solar energy. M. Manoharan, et al [15] presented a novel finite control set model predictive control (MPC) algorithm suitable for high-voltage single-stage central inverter connecting photovoltaic system to the grid.

The proposed algorithm results in better THDs compared with previous schemes.

M. Kalashani, et al [16] presented robust nonlinear super twisting algorithm-sliding mode (SM) controllers for islanded and grid-connected operations of single-phase inverters interfaced with distributed energy resources (DERs). The presented SM controllers were robust against external disturbances, parametric uncertainties, and variations in loading conditions. Y. Zhu and J. Fei [17] proposed a disturbance observer-based fuzzy SM control strategy for a single-phase PV grid-connected inverter. The disturbance observer was designed to estimate the disturbances that may affect the control performance of the inverter and the SM controller was employed to control the output voltage of the DC–AC inverter, and a fuzzy system was used to approximate the upper bound of the observation error between the actual disturbance and its observation value to improve the performance of the control system.

S. Nirmal, et al [18] implemented two control techniques, the phase shift control (PSC) and Proportional Resonant Control (PRC) for single-phase inverters. In the PSC method, the inverter injects the desired real power into the grid by controlling the phase angle between converter and grid voltages. While, in the PRC method outputs a current reference created by the resonant controller using a communication network. H. Goh, et al [19] proposed an adaptive control algorithm for grid-connected PV inverters to suppress the resonance condition that may arise between grid-connected PV inverters and the distribution network. The proposed method utilizes a self-tuning PI controller approach which is capable of successfully suppressing resonant excitation over a wide range of grid operating conditions while maintaining excellent low-order harmonic performance and lower THD.

A. Mohamed, et al [20] presented an adaptive controller for grid-tie DC-AC inverter in grid-connected PV power system supplying a pulse AC load. The presented controller oversees the dc-bus voltage, managing the injected power to the grid, and minimizing the injected harmonics. The controller revealed stable and fast transient response with minimum steady-state error in comparison with the classical PI controller. Y. Dai, et al [21] presented a novel finite-time adaptive fuzzy control method for investigating the problem of smoothing power control of PV inverter in islanded systems.

P. Deepamangai and P. Manoharan [22] presented a robust control technique, such as an H∞, for a grid-connected quasi-admittance source inverter (QYSI). The QYSI reduced the voltage stress and start-up inrush current and increased the voltage gain. The H∞ controller was proposed to enhance the stability margin and reliability of the system. The proposed technique was compared with a proportional resonant controller (PR) showing superior results. B. Sahoo, et al [23] proposed a repetitive control (PC) approach for the reduced switch seven-level cascaded inverter (RSCI) for active and reactive power control. The performance of the PC for the RSCI was tested on a grid-connected system integrated with PV and battery energy sources. The obtained results indicated better performance of the proposed inverter topology and control strategy compared to NPC inverter with PI controller in terms of better voltage level, reduced switches, steady-state error and minimized harmonic level.

C. LVRT capability of grid-connected PV systems

Owing to the susceptibility of grid-connected PV systems against grid faults. Many countries have now implemented grid codes to secure and regulate the operation of the PV systems from exposure to grid faults. Fundamentally, the low-voltage ride-through (LVRT) control strategies for grid-connected PV systems under abnormal conditions [24], [25] should (1) quickly identify the voltage faults; (2) compute active and reactive power references; (3) provide overcurrent protection; (4) regulate the DC link voltage and (5) control the boost converter. Y. Zhang, et al [26] introduced a sliding-mode (SM) strategy to improve response speed of the PV system under LVRT condition. The SM strategy showed that the inverter not only maintains the benefits under the normal working condition, but also attains a faster response and a wide-range regulation ability while operating under the LVRT condition. B. Han, et al [27] proposed a control strategy for a Cuk LVRT capability. The repetitive controller (RC) was used to achieve zero steady-state tracking error during the grid disturbance. A nominal duty ratio was employed as a feedforward control input to alleviate the burden of a feedback controller. a PR controller was used in parallel with an RC to reduce the tracking error under voltage sag.

M. Khan, et al [28] presented a dynamic voltage support scheme for achieving LVRT with a grid-connected PV inverter during the voltage sag fault by formulating an additional reactive active current control mode which provides a stable operation of the system and achieves a higher effectiveness at the point of common coupling in low-voltage networks. The control strategy achieves LVRT within the time limits of grid standard during symmetrical faults. A. Haidar and N. Julai [29] proposed a control strategy for the DC-link of grid-connected PV systems with reactive power support to enhance the LVRT during grid faults. The control strategy investigated the ability of the PV inverter to remain connected and ride through the grid faults by selecting the optimal value of the crowbar resistor with the VAR to enhance the LVRT during the fault conditions.

H. Mei, et al [30] proposed a LVRT control strategy based on the PV grid-connected system with modular multilevel converter to overcome the problem of the voltage asymmetry drop in the power grid. On the DC side of the PV system, the fixed power control was realized through model predictive control (MPC) method and maintaining the AC-DC power balance. Meanwhile, on the AC side, the circulating current component under grid-side asymmetric faults was analyzed and suppressed. E. Bighash, et al [31] presented a fast and robust current controller based on the MPC for single-phase PV inverters to deal with the LVRT operation. The results of the proposed controller were compared with the classical PR controller to confirm its effectiveness.

A. Alhejji and M. Mosaad [32] introduced an adaptive reference PI controller for the PV inverter to enhance the system performance through supporting LVRT capability, and smoothing the PV generated power fluctuations during three-phase faults taking place at point of common coupling (PCC). J. Roselyn, et al [33] proposed an intelligent fuzzy based real and reactive power control of inverter for effective LVRT capability during grid faults. S. Islam, et al [34] presented a design and analysis of a proportional resonant (PR) controller with a resonant harmonic compensator and a fault-ride through strategy for a three-phase, grid-connected PV system under normal conditions and asymmetrical faults. The obtained results were effectively validating the stable, ripple-free, and robust response compared to other configurations.

Z. Hassan, et al [35] presented a review on various controllers related to the LVRT control strategies in the grid-connected PV systems. The main objective was to discuss the capabilities of the controllers to deliver the required active or reactive current compensations to support the power grid during the grid faults.

D. MPPT topologies for PV systems

The maximum available power drawn from a PV array depends on its electrical properties and the atmospheric conditions at the installation site. The PV panels produce a maximum power by maximum power point tracking (MPPT) algorithm when operated at the knee of their characteristic I-V curve. The MPPT can be used to increase the system efficiency by fully utilizing the PV panels. Typically, power electronic devices are used to vary the magnitude of the impedance seen by the PV array such that the output voltage of the PV array corresponds to the Maximum Power Point (MPP) voltage of the PV array calculated by the MPPT algorithm. A reliable control always tracks the MPP in all environmental conditions and force the system to run on optimum conditions.

There is a significant amount of literature discussing the numerous types of MPPT algorithms used in maximizing the energy from PV arrays in the last two decades including conventional algorithms such as perturb and observe (P&O) [36]–[39], incremental conductance (INC) [40], [41], fractional open-circuit voltage (FOCV) [42] and fractional short-circuit current (FSCC)[43] . The intelligent methods such as fuzzy logic controller (FLC) [44]–[48], artificial neural network(ANN) [49], [50], genetic algorithm (GA) [51]. Biologically inspired algorithms such as ant colony (AC) [52], artificial bee colony (ABC) [53], and particle swarm optimization (PSO) [54] were also implemented.

A scheme-based review of MPPT techniques presented a new perspective in their classifying based on their principal schemes with respect to deployment of the sensed PV arrays' terminal voltage (V) and current (I), irradiance (λ), and temperature (T) [55]. These methods can be chosen based on performance parameters such as complexity, convergence rate, speed, soft cost, sensor requirement, and reliability. Also, hybrid MPPT methods have been proposed [56]–[59]. In general, MPPT techniques generate a positive or negative reference signal according to the operational state of PV systems. The predicted value defines the trajectory of systems. Most of the techniques have stability and accuracy under stable conditions but suffer in case of rapidly changing climatic or loading conditions.

E. Performance of grid-connected PV systems under partial shading conditions

Partial shading occurs in the PV array, not only due to the surrounding buildings and trees but also because of the clouds as well as the dust and aging of PV cells. Under partial shading conditions, solar irradiance, temperature, and the efficiency of the PV array can be more incompatible. Every single PV panel works under different working conditions, which can lead to mismatching problems. In severe cases, it will significantly reduce the power output of solar PV plants and aggravate the hotspot effects of the PV panel. To mitigate the effect of partial shading conditions while improving the efficiency of the PV system, many MPPT technologies under partial shading conditions have been proposed. While conventional MPPT algorithms such as perturb and observe [60], hill-climbing [61], incremental conductance [62] may simply stuck to one of the local maxima. Different techniques based on artificial intelligence, such as fuzzy logic control [63]–[65] and artificial neural network [66] have been used to track MPPT. However, these methods require massive training and broad experience in a complex environment.

Alternatively, recent studies have exhibited a special interest in the bio-inspired MPPT algorithms, particularly swarm intelligence-based algorithms that have given better results than evolutionary algorithms such as particle swarm optimization [67]–[70], grey wolf optimization technique

[71], salp-swarm optimization [72]–[75], cuckoo search algorithm [76], artificial bee colony [77], firefly algorithm [78], and ant colony optimization [79] have tested and evaluated under partial shading conditions. Moreover, to enhance their performances and eliminate their drawbacks, several studies have integrated these algorithms into hybrid optimization methods, particularly by collaborating the optimization ability of various searching mechanisms or into a combined form of at least two techniques to compensate for the shortcomings of one technique by the performances of another [80]–[86].

F. Transient stability of grid-connected PV systems

The transient stability is the property of a power system to recover its normal operating condition following sudden and severe faults in the system [87]. The stability study is extremely important for maintaining the continuity of the power flow and properly controlling the power systems integrated with RESs. M. Yu, et al [88] proposed an adaptive control scheme to achieve transient stability enhancement for PV plants. The control scheme is designed based on the transient stability mechanism and relations between the droop factors and transient stability. The stability enhancement was implemented by increasing the reactive droop factor and reducing the active droop factor to raise the power angle curve during the transient period, which ensures the PV plant recover after the transient events.

S. Obuz, et al [89] proposed a robust partial differential equation-based control strategy, which can optimally control both distributed energy storage systems and PV power plants to enhance the transient stability of the smart grid. The grid-scale solar PV generators can be used to provide support for stabilization by curtailing its power output. The cost of this curtailment was modeled as an opportunity cost. A. Saidi [90] investigated the influence of PV integration on the voltage stability of the 53-bus power system. The efficiency and quality of voltage in PV system degrades due to instability of voltage in the grid connected system. The voltage regulation control technique using the STATCOM module to resolve the drop and the effect aspects on the voltage in the power system was proposed. The obtained results demonstrated the efficiency of the proposed control technique for enhancing the power system quality based on the Tunisian grid code.

O. Zevallos, et al [92] proposed a control scheme for PV inverters that improves the transient stability of a synchronous machine connected to the grid and supports the voltage stability through the injection of reactive power. The control scheme makes the PV inverter’s dc-link capacitors absorb some of the kinetic energy stored in the SM during momentary cessation and reduce the rotor angle oscillations within the first few cycles of the fault, effectively ensuring the SM’s transient stability. Q. Zhang, et al [92] carries out a comprehensive investigation of PV inverters stability problems on weak grid condition. The stability problems are mainly the control loops instability and inverter output voltage instability. The control loops cover the current loop and dc voltage loop where the factors influencing the stability of dc-link voltage were revealed. The voltage stability problem caused by reactive power compensation was highlighted.

J. Shair, et al [93] investigated the emerging power system stability issues under a high share of RESs. The authors also discussed the validity and limitations of the existing classical and extended power system stability classifications proposed by different IEEE/CIGRE Working Groups. Also several studies have also been carried out on the effects of solar PV integration on the voltage stability of a power system [94]–[96].

G. Dynamic stability of grid-connected PV systems

There is a lot of scope of research on the issues and challenges of the high penetration of PV systems into the power system. However, some of the issues related to the dynamic stability of grid-connected PV systems that need to be addressed. Unlike conventional synchronous generators, the PV array is interacted with the public grid through power electronic converters, and its power output is fluctuant due to the solar irradiance and temperature which may cause the negative damping of electromagnetic modes in the grid-connected PV system [97]. Precisely, PV system may cause a harmful effect on the system due to the following reasons: (1) the power output of MPPT mainly depends on the variant solar irradiance and temperature, which introduces frequent fluctuation into the power system; (2) the parameters of PV controllers may lead to decrease the damping torque of the connected system [98].

Recently, there is an increasing interest to analyze the impact of high penetration PV systems on power system small signal stability. Various probabilistic analysis methods have been used to study the small-signal stability analysis (SSSA) of a grid-connected PV system. S. Liu, et al [99] investigated the impact of the stochastic PV generation on the dynamic stability of grid-connected PV systems by using the probabilistic SSA approach. With the knowledge of the statistics of solar irradiance data, the probability density function (pdf) of the real part of the critical eigenvalue was approximated by Gram–Charlier expansion method (GCEM). The proposed analytical method was verified and compared with analytical approach and the Monte Carlo method (MCM) of a grid-connected PV system with real solar irradiance data. Y. Zhou, et al [100] studied the potential applications of stochastic response surface method

(SRSM) in the probabilistic SSSA of the power system with probabilistic uncertainties in correlated photovoltaic and loads. The proposed SRSM was used to estimate the critical damping ratio as a function of independent standard random variables from correlated loads and irradiance.

G. Wanga, et al [101] proposed a data-driven polynomial chaos expansion method for the SSSA. The proposed method is used for assessing the impact of uncertain solar irradiance on the stability margin of a grid-connected PV system. The stability margin was characterized by the critical mode damping ratio. J. Shukla, et al [102] presented probabilistic stability constrained optimal configuration model to simultaneously consider uncertainties with correlation and small-signal stability for distribution systems in the presence of PV-based distributed generation. The objective is to minimize power loss, the number of switching operations, and maximize the voltage stability margin while maintaining the constraints of bus voltage and preserving the small-signal stability of the constrained distribution system. C. Yan, et al [103] proposed a probabilistic collocation method (PCM)-based on probabilistic SSSA for a power system consisting of wind farms and PV farms. Compared with the conventional MCM method, the proposed method met the accuracy and precision requirements and greatly reduced the computation. The effects of increasing the renewable energy penetration on the probability of small signal stability were determined by reducing the output of synchronous units and shutting off part of the synchronous.

H. Shahsavari and A. Nateghi [104] presented a mathematical approach to study the effect of high infiltration of a PV power plant on the small-signal stability of a power network and design of optimal fractional order PID controller for improving the probabilistic small-signal stability of the power systems, taking into consideration the uncertainty of system operating conditions. Q. Wang, et al [105] proposed a matrix variables-based modeling method for the large-scale distributed PV grid-connected system to simulate dynamic characteristics and study the system's small signal stability. The small signal stability has been studied using the eigenvalue analysis and root locus methods. The analysis and simulation results indicated that the total output power of the PV arrays, the control parameters of the PV inverter and the phase-lock loop, and the AC system have a great impact on the small signal stability of the system.

H. Fluctuations of grid-connected PV systems' output power

The intermittent nature of PV generation can cause rapid fluctuations in the output of PV systems, which can significantly affect the voltage levels in a grid-connected with high penetration of PV systems. These voltage fluctuations may lead to violation of the existing power quality standards which can cause damage to electrical appliances connected to the grid [106]. The energy storage system (ESS) is a flexible regulated device that can be used to solve problems caused by the PV systems [107].

Y. Sun, et al [108] introduced grid-connected fluctuation requirements of different countries, summarizes the EES types, and analyzes their topological structure to suppress the fluctuation of RESs. Then, various mitigation strategies were described, which aims to ensure that RESs output meets the grid-connected requirements. Different smoothing techniques have been conducted to mitigate the fluctuation in PV output power, mainly under three classifications: (i) moving average (MA) and exponential smoothing based methods such as simple MA [109], symmetrical MA [1110], and both MA and exponential methods were analyzed in [111], (ii) filter-based methods such as low pass filter (LPF) [112], Kalman filter [113], fuzzy based filter [114], and least square estimator (LSE) filter [115], and (iii) ramp-rate based algorithms [116]–[118].

I. Volt-Var support for the grid due to of PV systems integration

Electric Power Research Institute [119] has recently given protocols for inverter-based reactive power compensation methods. Furthermore, it is suggested that PV inverters can be oversized to allow more reactive power compensation capacity and the additional cost can be offset by the reduction of capacitor banks' investment. As PV inverters can provide fast and flexible VAR support with the marginal operating cost, the Volt-VAR control (VVC) based on the PV inverters is highly promising [120]. According to the control architectures, VVC can be divided into three categories: i) decentralized, ii) centralized, and iii) distributed [121].

In decentralized or local control, which can be further divided into Q-V, P-V and Q-P strategies, the power inverters can response to local voltage measurement at the point of common coupling (PCC) rapidly for local VVC. In Q-V or P-V strategy, the reactive or real power output of the inverter is dependent on the bus voltage, such as droop control [122]. While in Q-P strategy, the reactive power output of the inverter is a function of its real power output, which can track the voltage fluctuation caused by PV generation intermittency [123]. J. Pedram and A. Dionysios [124] introduced a PCC voltage droop control based VVC with its stability issue in distribution networks

By contrast, centralized control aims to provide an optimal solution to VVC. Y. Xu, et al [125] presented a multi-time scale coordinated VVC scheme for high renewable-penetrated distribution networks. C. Zhang, et al [126] proposed a three-stage VVC scheme based on robust optimization, which includes mechanical devices scheduling, inverter output dispatch, and real-time droop control. However, the central controller suffers extensive computation and communication burdens. Furthermore, the central controller needs to gather all the system information, which may not be always available in power distribution networks.

In recent years, the distributed control has shown its merits to overcome those limitations discussed above. The control and optimization objectives can be achieved in a distributed way with peer-to-peer communications, which have good plug-and-play capability and expendability [121]. G. Mokhtari, et al [127] proposed a discrete-time consensus control of PV inverters to address voltage rise issues in low-voltage networks. Y. Wang [128] introduced a decentralized and distributed hybrid control scheme for PV inverters for both network voltage fluctuation and violation issues.

III. CONCLUSION

This paper reviews the most recent research trends for performance enhancement of grid-connected PV systems. Integration of such systems into the public grid has taken the attention of researchers and manufacturers due to its advantages over the other types of RESs. The attention is drawn mainly to the following research points:

- Enhancing the controlling of DC-DC/DC-AC converters.
- Investigating and enhancing the low-voltage ride through capability of grid connected PV systems.
- Studying the dynamic and transient stabilities of grid connected PV systems.
- Investigating the Volt-Var support for the grid due to integration of PV systems.
- Investigating the MPPT for PV systems under normal and abnormal conditions with varying temperature and radiation.
- Studying the fluctuation of output power of grid connected PV systems and their impact on the performance of the electric networks.

Many techniques and methods have been introduced, as stated in the literature review, to study and investigate the forementioned research points.

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