RESEARCH ARTICLE OPEN ACCESS

The Power quality and power management challenges and multi-functional control solutions in three phase grid integrated solar energy distribution system: Comprehensive Review

Prashant K Shah*, Chetan D Kotwal**, Tejas M Vala***,
(Research Scholar, Electrical Engineering, Gujarat Technological University, Ahmedabad,)
*** (Electrical Engineering, Sardar Vallabhbhai Institute of Technology, Vasad,)*
**** (Electrical Engineering, Government Engineering College, Godhra,)*

ABSTRACT
Renewable energy sources are necessity in today's world due to depleted fossil fuels. Demand for various renewable sources is increased over a period of time. Solar and wind energy sources are two most promising renewable energy sources among all of these. Due to the fact that solar power is unpredictable in nature, higher penetration of their types in existing power system could cause and create high technical challenges especially to weak grids. Voltage and frequency fluctuation, and harmonics are major power quality issues for grid-connected solar systems with bigger impact in case of weak grid. This can be resolved to a large extent by having proper design, advanced fast response control facilities. Moreover, control structure complexities increase in case of combined management of power quality and power management. The multimode control algorithms with a perspective of both power quality and power management of such systems are very important. This paper provides a comprehensive review on power quality and power management challenges and solutions for solar integrated systems using various control strategies. Various Custom power devices and appropriate control techniques can be effectively used to solve power quality and power management issues. The multifunctional control is also gaining attention nowadays and custom power devices can also be used for this. The paper gives a review of the main research work reported in the literature with regard to various power quality and power management issues, their control mechanisms for three phase grid-connected solar distribution systems.
Keywords - Custom power device (CPD), Distributed static compensator (D-STATCOM), Dynamic voltage restorer (DVR), Grid integrated solar system (GISS), Phase-locked loop (PLL), Solar photovoltaic (SPV), Shunt active power filter (SAPF), Unified power quality conditioner (UPQC)

Date of Submission: 03-11-2023 Date of acceptance: 16-11-2023

I. Introduction

The availability of fossil fuels is decreasing daily. Domestic and industrial demand is causing a sharp increase in energy needs. Demand for wind and solar photovoltaic (PV) systems is rising quickly on a global scale [1]. Power generation based on renewable energy is becoming more and more popular worldwide, with solar and wind energy being the most promising options [2, 3]. Integrating wind and solar energy into the current electrical infrastructure may help to reduce overall grid stress [4]. Solar standalone systems don't feed extra power into the grid; instead, they use it to meet local demand [5]. Grid-tied systems lessen the overall load on power plants and the electrical grid by providing the grid with excess power. Grid-tied photovoltaic systems are now necessary, but they come with a lot of challenges and issues [6]. The environment conditions, such as solar radiation, weather, and other factors, have a significant impact on solar power generation [7]. The amount of PV power varies throughout the day and year due to changing environmental conditions. To extract the maximum power from the PV array, the maximum power point tracking algorithm is necessary [8]. Some of the most widely used methods for maximizing the power output of a solar array are perturb and observe, incremental conductance, fuzzy, artificial neural networks, and neuro-fuzzy [9]. Furthermore, because of distorted grid conditions, integrating solar photovoltaic renewable energy systems into the distribution grid is always difficult and may cause disturbances to grid synchronization. In grid-tied PV systems, PLLs are frequently used to synchronize the converters to the grid [10]. Several PLLs, such as SRF, IRPT EPLL, DDSRF, alpha-beta PLL, SOGI-PLL and 3M-PLL, have been developed for grid synchronization [11, 12] . Research was done on adaptive EPLL, LMS, adaptive normalized least mean fourth (NLMF), and ANF [13]. PLL-less adaptive filter techniques, like the PLL-less fast CTF technique, have also been more and more popular recently [14, 15]. Grid-tied solar system performance is hampered by a number of power quality problems, such as voltage sag, voltage swell, transients, flickers, harmonics, and power factor changes [16]. To address these PQ issues, a range of custom power devices (CPD) with appropriate control algorithms have been introduced at the point of common coupling (PCC). These CPD devices are divided into four categories: series, shunt, series-series, and shunt-series, depending on how they connect to the grid network. UPQC is a series-shunt configuration. Shunt devices include DSTATCOM and SAPF. Series devices include DVR [17, 18]. Many control mechanisms have been proposed in the literature to ensure that the active power flow in a grid-connected system is properly managed, as this is a primary and essential requirement [19-21]. The proper operation of a grid photovoltaic system depends on the selection of suitable control strategies [22]. The main purpose of a grid integrated system is to inject active power to the grid; however, grid tied systems also need to include a number of ancillary features, such as grid synchronization, PV module monitoring, load compensation, power quality mitigation, reactive power management, power factor corrections, and anti-islanding [23]. Under both normal and distorted grid conditions, a multi-objective control strategy is needed to investigate synchronization, power quality, and maximum power extraction for a grid-interfaced system. Thus, recent attention has been focused on this multifunctional system and its control design [24]. Multifunctional control for grid PV system was observed for the grid-tied solar photovoltaic system using a fundamental extraction technique [25, 26]. The phenomenon known as islanding happens when a certain part of the utility grid is disconnected from a large number of PVs that are interconnected. It causes problems with frequency and voltage control as well as power quality problems. Thus, suitable anti-islanding measures are required for PV systems that are connected to the grid [27, 28].With the rapid development of photovoltaic power generation industry, its safe and stable operation has an increasing impact on the power grid. After a short-term fault occurs, a large number of units will be disconnected and the voltage and frequency stability of the system will be reduced and even cause the interruption of power supply in some areas. Therefore, the PV generation system is expected to have the same low voltage ride-through capability as conventional units [29]. This paper gives the comprehensive overview of three phase grid connected PV distribution system in Section 2. Section 3 illustrates various power quality and power management challenges with grid connected solar system along with their possible solutions. Section 3 also briefs about Custom Power devices used for grid connected solar photovoltaic systems and various literature reported for the same. Various control schemes and their salient features are defined in section 4. Section 4 also describes about various control features to be considered while designing multifunctional control schemes for grid tied solar system. Section 5 discusses on summary and conclusion.

II. Overview of basic Grid connected three phase distribution system

The DC to AC inverter helps in controlling the power factor by injecting the sinusoidal current into the grid. The DC energy generated from the solar PV is converted into the AC power and is efficiently transferred to the electrical grid by the application of grid side inverter (GSI). Based on the configuration and types of components used, inverters can be classified into different categories. This division of categories is based on various factors, such as, number of power processing stages i.e. single stage and multi-stage, transformer and transformer less high frequency configurations, number of levels involved in the design and the type of switching used [30].

A quick and precise control system design guarantees the grid side inverter operates correctly. As a result, one of the most important components of the grid-connected PV system is the control of the grid connected solar inverter. Because they provide the control function, power converters are essential parts of PV systems for both single and multistage systems [31]. Islanded systems and grid-connected systems have differing control requirements. Both situations call for MPPT algorithms and current/voltage controllers.

The MPPT control module and the inverter control module are primary requirement for the grid PV system [32].

The inverter control module maintains correct grid synchronization, regulates the amount of active and reactive power supplied to the grid, and regulates the voltage across the DC link [33].

a. Single Stage Grid PV system

The single stage solar energy systems consist of are: (i) PV array, (ii) DC-AC converters (inverters) as shown in Fig. 1.

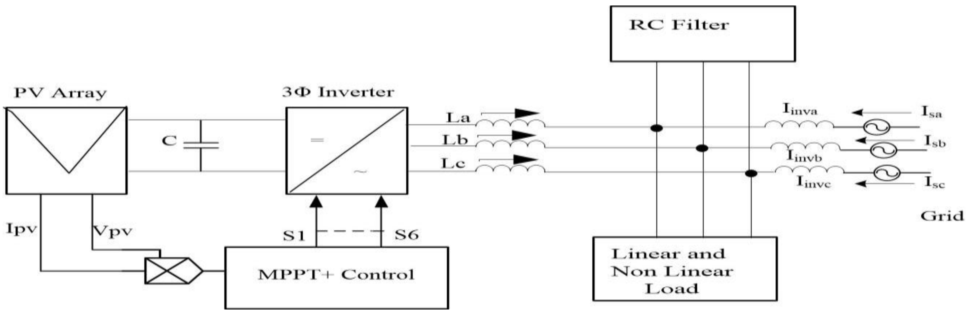

Fig. 1 Single Stage Three phase Single stage PV System

b. Dual stage grid-integrated solar system

Power circuits employed dual or multistage solar energy applications are: (i) DC-DC converters, (ii) DC-AC converters (inverters). Each stage in dual stage may consist of different power converter topologies for grid-connected systems. An inverter with more than one power processing stage is referred to as the multiple stage inverter [34].

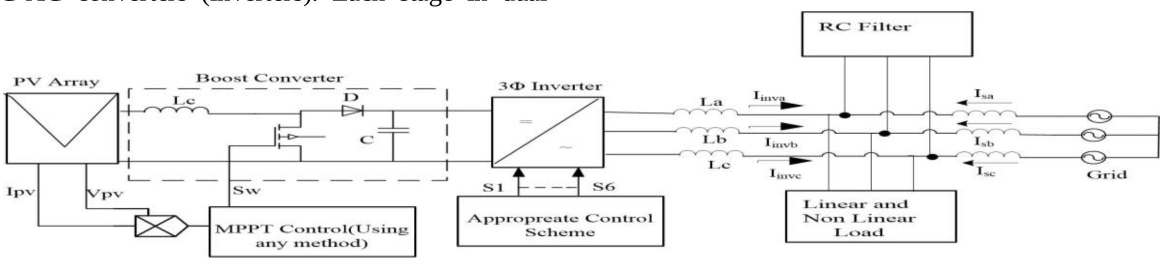

Fig. 2 Multi Stage Three phase Single stage PV System

The basic solar grid integrated system consists of a photovoltaic array coupled to a step-up dc/dc converter, a three-phase voltage source converter, grid interface inductors, and three-phase loads of different types, as shown in Fig. 2. The first stage, the solar array, is connected to the input of the step-up dc/dc converter. The following stage involves connecting a voltage source converter to the output of a DC/DC converter. The inverter's output is connected to a 50 Hz three-phase distribution grid. The inverter reduces the current harmonic content at the PCC while feeding the active power from the PV panel into the grid. The number of PV modules and their series and parallel connections determine the total power capacity of the PV array system.

c. Grid PV systems with low frequency transformer and high frequency transformers

The single stage solar energy systems consist of are: (i) PV array, (ii) DC-AC converters (inverters)

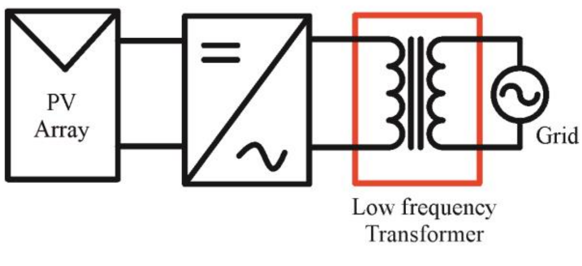

Fig. 3(a) Line-frequency transformer between the inverter and the grid

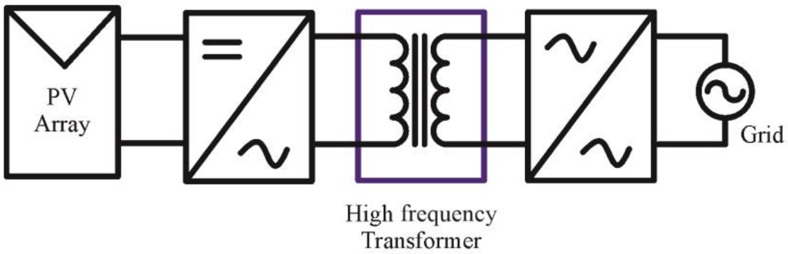

Fig. 3(b) HF-link grid-connected ac/ac inverter

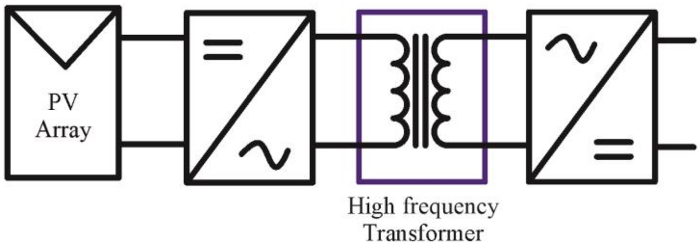

Fig. 3(c) High-frequency transformer connected between dc-ac converter and ac-dc converter

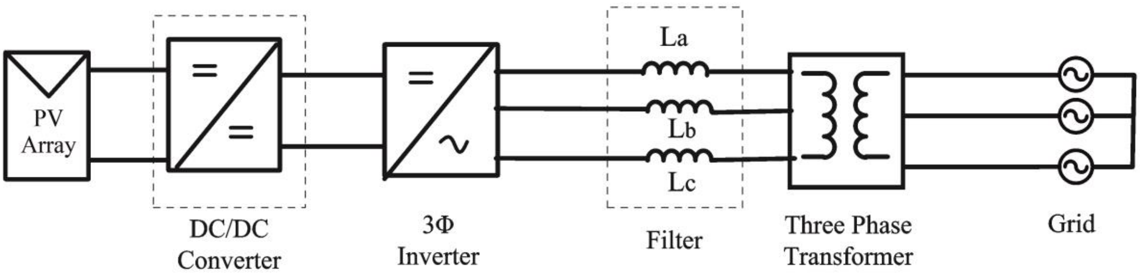

Fig. 3(d) Three phase grid PV system with transformer

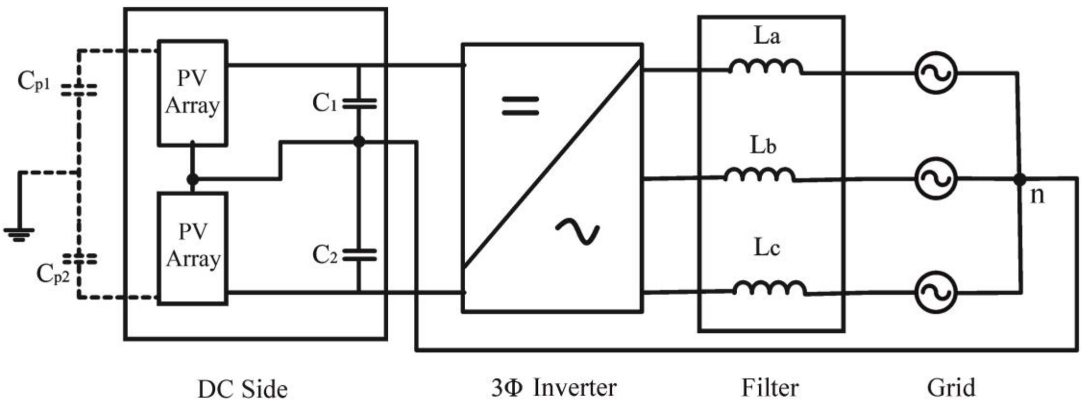

Fig. 3(e) Three phase grid PV system with transformer less configuration

Generally speaking, there are two types of grid-connected PV inverter topologies: those with transformers and those without [35]. Inverters use line-frequency transformers to provide galvanic isolation between the utility grid and photovoltaic panels. The isolation transformer assists in resolving the issue of the PV system's DC current injection into the utility grid. Given their size and weight, line frequency transformers add significantly to the total cost of a photovoltaic system. For this reason, they are regarded as a troublesome inverter component [36]. Using the high-frequency transformer built into the inverter or DC/DC converter is another way to address this issue. This lowers the system's overall cost by reducing the system's size and weight, but, the main problem with the high frequency transformer is that new conversion stages should be introduced leading in more power losses and as a consequence low efficiency. To get around these problems, transformer-less inverter topologies are created for PV applications [35, 36].

III. Challenges and possible solution for three phase grid integrated PV systems

The primary challenges for the grid integrated PV systems are power quality and power monitoring issues due to various reasons as indicated in Table1 [37].

a. Power quality issues

Due to its dependence on temperature and irradiance, solar photovoltaic has very variable output. This exacerbates PQ disturbances when coupled with a grid; this need to be minimized to provide stability and smooth synchronization. Moreover, presence of power converters and nonlinear loads in the system adds to the power quality problems. Distorted grid conditions, current and voltage harmonics also creates power quality issues. Voltage sag, voltage swell, voltage unbalance, unbalanced load, voltage interruption and notches also magnify power quality troubles in the PV integrated systems [37]. These PQ difficulties will probably increase as penetration levels rise.

b. Solution to power quality problems

Custom power devices are popularly used to solve many power quality problems under distorted grid conditions. By regulating line impedance, phase angle, current harmonics, voltage harmonics, voltage magnitude, and imbalance loads, the CPD are used in the distribution grid to maintain power quality. The various configurations of voltage source converters (VSCs) and DC link capacitors determine how these devices are set up. These devices offer reactive power support, power factor correction, voltage sag, voltage swell, flickers, and instantaneous mitigation of power quality problems. They also offer good voltage regulation. The grid supply and solar PV quality are enhanced by custom power devices. The CPD devices are categorized as follows: (a) Series connected devices (DVR), (b) Shunt connected devices (DSTATCOM and SAPF), (c) Shunt-Series connected devices (UPQC). These devices can be connected in PV based system to mitigate many power quality issues either load side or supply side [38].

3.2.1 Solution to Load Current Harmonics

The non-linear behavior of components linked to the power grid causes harmonics, which result in undesirable phenomena in the grid and associated loads. In order to mitigate the effects of the current harmonics, the simplest method is to use passive filters designed especially for the specific harmonics frequencies that need to be removed. It is preferable to use active filters to inject compensating currents in order to counteract the harmonic effect. Custom power device based solution can mitigate the harmonics caused by nonlinear load and maintains the THD of grid current under limits of IEEE-519 standard. Shunt active power filter (SAPF) can be used to solve problems related to current harmonics. There are also filters that combine active and passive technologies known as hybrid filters.

3.2.2 Solution to Voltage Harmonics, Voltage Sag, Voltage Swell

A dynamic performance of PV based inverter system using Custom power can be tested power quality improvement and power flow management thus increasing its utility under scenarios of sudden change in irradiation and fluctuations in grid voltage such as voltage sags/swells and nonlinear load. Dynamic voltage restorer (DVR) is popularly used to solve such problems.

3.2.3 Load compensation and power factor correction

A Distribution static compensator (D-STATCOM) is the power device which is implemented in shunt configuration to improve problems related to the reactive power and load compensation in grid connected distribution system.

3.2.4 Combined effect of current and voltage harmonics, sag, swell

Issues related to combined effect of current and voltage harmonics, voltage sag, voltage swell, voltage interruption is a major challenge to the grid integration system. UPQC can be effectively utilized to provide multifunctional solution to major problems related to current and voltage harmonics, unbalance voltage, load reactive power, voltage sag, voltage swell and voltage interruption. UPQC has a series and shunt inverter and associated multi-objective control for both the inverter. The Shunt inverter injects currents to ensure a balanced, sinusoidal and unity power factor PCC current except under source voltage interruption. Series inverter injects voltage with necessary phase angle to the input voltage in case of voltage swell or sag.

3.2.5 Literature review for Custom Power devices based Power quality mitigations

Table 1 summarizes various challenges and custom power devices based possible solution referred in various literature.

Table 1. Power quality Challenges in PV integrated distribution system and possible solution referred in various literatures.

Sr. No.	Challenges	CPD topologies and Solution	References
1	Voltage sag, Voltage swell	DVR	[39]
2	Power quality issues due to current harmonics injected as a result of nonlinear loads.	Appropriate passive filters, Shunt active power filters (SAPF).	[40-42]
3	Current harmonics, voltage regulation and load balancing, power factor correction	D-STATCOM	[43]
4	Power quality issues due to harmonics, unbalanced load, voltage sag, swell, unbalanced voltage, flicker, power factor correction etc.	Unified Power Quality Conditioner(UPQC), Series Active Filters	[44-46]

3.2.6 CPD topologies and salient features for grid integrated solar systems

Table 2 summarizes various custom power devices topologies and their salient features referred in literature.

Table 2. Power quality Challenges in PV integrated distribution system and possible solution referred in various literatures

Sr. No.	CPD topologies	Salient feature	Ref
1	Unified Power Quality Conditioner for Power Quality Mitigation (PV-UPQC)	The shunt compensator of the PV-UPQC compensates for the load current harmonics and reactive power. The series compensator compensates for the grid side power quality problems such as grid voltage sags/swells by injecting appropriate voltage in phase with the grid voltage.	[47-49]
2	PV-SAPF	Current harmonics elimination due to presence of nonlinear load. Total harmonics distortion of the source current can be reduced as per IEEE guidelines.	[50]
3	PV-DSTATCOM	During PV-DSTATCOM mode excess PV power is supplied to grid and during DSTATCOM mode, grid supplies power to load.	[51, 52]
4	PV-DVR	Stability against voltage swell, voltage sag, voltage interruption.	[53, 54]

c. Power Management and monitoring concerns and possible solution for grid integrated PV system

Inverter control design for grid integrated system requires power management and monitoring plans for (a) active power (b) reactive power (c) Anti-islanding (d) Power monitoring.

3.3.1 Active Power Management in grid integrated PV system

The key component for an active power control plan under different conditions, like: (i) Local nonlinear load connected to the grid without any PV power (ii) PV has grid connectivity but no local load. (iii) PV and the local load are both connected to the grid [44]. There are various concerns while designing a suitable strategy for active power management. The generated PV power varies due to environmental conditions like solar irradiance, shading effect and cloudy weather conditions. Moreover, during night PV inverter can be used to provide reactive power support to the grid. Proper control operation to maintain very good power factor is also essential. Active power injected to the grid should be free from harmonics but harmonics are injected to the grid current due to many power quality issues e.g. nonlinear load profile, high frequency switching of the power converters etc. [55].

3.3.2 Reactive Power Management in grid integrated PV system

A local load connected with the grid-interfaced photovoltaic (GIPV) system demands reactive power compensation at the distribution level. The compensation either fulfilled by the PV inverter or grid side arrangements such as capacitor bank, static VAR compensator or tap-changing transformers. Amongst both, the inverter has merit to compensate reactive power [56].

3.3.3 Anti-islanding in grid integrated PV system

When a solar system in a grid-connected photovoltaic system generates power while the grid is out, this is known as islanding. When power from a solar panel system is generated and fed into the grid, things gets risky. Utility personnel attempting to repair the grid have grave worries about their safety in this situation. Grid-connected systems must be protected against islanding. Disconnecting the solar modules during grid power disruptions is the goal. Disconnection creates safe conditions for maintenance and isolates possible issues to prevent harm to PV components. Essentially, there are two methods to solving the islanding problem: the active method and the passive method.

3.3.4 Power monitoring in grid integrated PV system

Performance of the PV systems decreases and equipment life time may reduce without proper monitoring. Various advanced monitoring techniques using artificial intelligence and machine learning are recently used for this purpose.

3.3.5 Solutions to Power management and monitoring problems in grid integrated PV system

Power management and monitoring plays an important role for the grid connected PV systems, however various challenges and associated solutions are associated with the same as shown in Table 3.

Table 3. Solutions to Power management and monitoring problems in grid integrated PV system

Sr. No.	Detail	Concern	Solution	References
1	Active Power Management	Variable environmental condition, voltage profile in solar based PV system. Power factor improvement	Various MPPT techniques. Reactive power control for load compensation	[57] [58]

		Harmonics in injected grid current due to nonlinear load profile.	using D-STATCOM Use of shunt active power filter (SAPF).	 [40, 59]
2	Reactive Power Management	Load compensation and reactive power management due to voltage sag, swell and sudden load changes.	DSTATCOM based control schemes	[60]
3	Anti-islanding	Disconnection of the solar modules during power outages of the grid.	Passive technique Active technique	[61]
4	Power monitoring	Performance of the PV systems decreases and equipment life time may also reduce without proper monitoring.	ANN, Machine learning techniques	[62]

IV. Control Strategies for Grid PV systems

Grid-tied inverters shall have the following features: (a) faster dynamic response; (b) power factor that should be almost equal to unity; (c) sufficient frequency control; (d) low harmonic output; (e) effective grid synchronization; (f) protection against under- and over-frequency and voltage fluctuations; and (g) Anti-islanding. Overall control has to be designed by looking in to above points.

a. Summary of Control Schemes and their salient features, Limitations

For three-phase grid-connected distribution systems, a variety of controllers are frequently utilized, including adaptive, predictive, non-linear, intelligent, and adaptive controllers. Table 4 summarizes the reported literature on the different grid PV controllers. These controllers are capable of controlling a wide range of parameters, such as voltage, current, power, and so on. However, grid photovoltaic systems (PV) are quite complicated and need a number of multi-objective features to function well, as Table 5 illustrates.

In accordance with grid dynamics, solar power generation uncertainty, and grid disruption, controllers can function in various modes. The weather and other environmental conditions affect the amount of solar electricity generated during the day and at night. For this reason, one or more control methods as well as suitable power converter topologies are needed for various purposes such as anti-islanding protection, load adjustment, grid synchronization, power factor corrections, and power quality. Additionally, switching between different modes according to the situation is also essential. Table4 summarizes about various control schemes, their salient features and limitations.

Table 4. Control schemes, their salient features and limitations summary

Sr. No.	Control Scheme	Control Name	Salient features	Limitations	References
1	Linear controllers	Classical controllers (P, PI, PD, PID)	The PI controller allows efficient tracking of DC signals	Tuning of parameters and its adaptabilities with uncertainty is a major drawback.	[63]
		Proportional Resonant (PR) controllers	AC signals can be tracked without steady state error by using PR controllers. PR controllers can be provided by both positive and negative harmonic compensators.	Enhanced functioning under abnormal grid conditions compared to PI controller, but sudden change in the grid voltage could additionally raise the error between the reference signal and the controlled signal which results in causing significant divergence from its expected value.	[64]
2	Non-linear controllers	Sliding mode controllers	The main advantages of this technique are simplicity and robustness and insensitivity to parameter variation and load disturbances.	The performance of the SMC is also dependent on the sampling time and suffers from distortion if an inadequate sampling time is selected. In addition, when SMC tracks a variable reference, the phenomena of chattering is observed, which is a major disadvantage of SMC.	[65, 66]
		Hysteresis controllers	Response is fast.	Control scheme has high computational complexity. It has high switching frequency which leads to undesirable harmonics.	[67]
3	Adaptive controllers	Adaptive controller	In adaptive control methods, depending on the operating conditions of the system the control action is automatically adjusted	Control scheme has high computational complexity	[68, 69]
4	Predictive controllers	Model Predictive Controllers	MPC is a kind of multivariable control technique which is based on a prediction model. It means the past information of the system and future inputs are utilized for prediction of the future output of the system.	The MPC has algorithm and needs longer time than the other controller.	[70, 71]

5	Intelligent controllers	Hybrid Neuro-Fuzzy Controllers	The non-linear nature of the photovoltaic system, the ANFIS method has advantage compared to the two PI regulation loop for grid currents.	High computational complexities and expenses.	[72, 73]

b. Multifunctional Control Strategies for grid integrated solar system

Multifunctional control systems have drawn a lot of attention from researchers because they can facilitate the integration of renewable energy sources and energy storage devices into the utility grid while also improving the quality of power supplied to customers. Given its ability to regulate active power, reactive power demand, power factor improvement, PQ enhancement, load compensation, and active power injection, multifunctional control is gaining popularity for the grid-tied solar systems [74].

Researchers can create suitable control mechanisms for multi-objective systems by implementing one or more of the control strategies listed in Table 5. A designer takes into account one or more multifunctional features when creating multi-objective grid integrated systems. Overall control is dependent on the system's control objective, which is described below.

(1) Grid Synchronization (2) Power Quality (3) Maximum Power Point Tracking Methods (4) Current and Voltage Control (5) Anti-Islanding Protection (6) Grid Support (7) Energy Storage Systems (8) Power monitoring.

4.2.1 Grid Synchronization

Synchronization of PV inverter with the grid is primary and essential requirements for any grid integrated system. It requires to match inverter signals amplitude, phase and frequency with the power grid. PLL techniques are typically utilized in this operation to carry out the grid synchronization. The PLL's basic method of functioning involves adjusting the inverter's voltage using a reference voltage that is obtained at the PCC.

Generally, conventional PLL employs synchronous reference frame, second-order generalized integrator and enhanced PLL method [10]. These PLL methods do not result in good phase angle detection under distorted and weak-grid conditions. A PLL with an adaptive notch filter is presented in [75] and adaptive feed forward PLL was introduced by [76].

4.2.2 Power Quality

Maintaining the quality of the power is the multifunctional grid integrated system's primary goal and biggest challenge. Harmonic mitigation algorithms are required by control structures for inverters in PV systems in order to generate power quality that meets IEEE 519 criteria. Harmonic distortions are common variations in voltage and current caused by frequency shifts in the electrical distribution systems. In particular, there are voltage or current variations that deviate from the typical sinusoidal fluctuations. A unique control system with many functions can be modeled with the help of customized power devices (such as DSTATCOM, DVR, UPQC, and UPLC) and their suitable topologies.

4.2.3 Maximum Power Point Tracking Methods

MPPT techniques are used to maximize the power output of a photovoltaic system. Fractional open circuit voltage, fractional short circuit current, incremental conductance, and perturb and observe (P&O) are the most often used conventional MPPT complete approaches. MPPT systems based on intelligent techniques such neural networks, simulated annealing algorithm, fuzzy control, genetic algorithms, particle swarm optimization (PSO), and firefly algorithm have been described in recent years.

4.2.4 Current and Voltage Control

Typically, a two-loop control method is used to regulate voltage and current. The decoupling of the dynamic response between the two loops is a prerequisite for this construction. There must be a faster inner loop than an outer loop. An outer loop with voltage and an inner loop make up the common structure. Although PI controllers are frequently employed in both control loops, they have drawbacks that include restricted voltage regulation, incompatibilities between control loops, and narrow stability regions. Robust non-linear controllers have been suggested as a way to enhance the two-loop strategy's performance. Recent research has examined a wide range of control strategies for two-loop controllers, such as sliding mode, droop control, adaptive controllers, PI controllers, proportional resonant controllers, and model predictive control. Either one independent control loop or one single control loop can take the place of the two-loop control strategy. Complex feedback loops are avoided in this way. Predictive control is the control method that has the best chance of combining the inner and outer loops into a single loop. The functioning of an inverter and a DC-DC converter is controlled by a predictive controller. Applying independent controllers is a hybrid strategy that combines sliding and predictive control in a grid-connected photovoltaic system. Sliding control manages the DC bus's voltage fluctuations, while predictive control controls the inverter's output.

4.2.5 Anti-Islanding Protection

System protection against islanding is required for grid-connected systems. When the grid experiences power outages, the solar modules are supposed to be turned off. In order to prevent damage to PV components, disconnecting the system creates a safe environment for maintenance to be carried out. Active and passive techniques fall into two categories for Anti-Islanding Protection. Active techniques involve applying a perturbation to the grid, whereas passive techniques involve analyzing electrical variables at the PCC.

4.2.6 Grid Support

Real-world experience demonstrates that as PV generation becomes more widely integrated into a power grid, new problems and difficulties appear. It is therefore crucial to implement grid support functions in the control loops. Grid-connected photovoltaic systems must fulfill several requirements in order to assist in stabilizing the grid during disruptions. The minimal requirements are voltage, frequency, and reactive power conditions. Numerous reliable control schemes for voltage and frequency have been proposed to address the grid's dynamics problems. The system is impacted by flexible injections of both active and reactive power, depending on the condition of the grid.

These days, it is still discovered that certain classes of PV converters and their controls have the ability to produce transient events that are entirely opposite to the responses of an inertia-filled grid, which adds to the destabilizing effect on power grids. This is one of the reasons why PV systems can provide virtual inertia (through their control strategies) to the grid. If the PV system has battery storage or even hybrid storage, a droop control system might be sufficient to support the frequency in the majority of cases. The PV inverter control systems can inject reactive power components to support voltage.

4.2.7 Energy Storage Systems

Additional energy can be stored during the day and used at night to supply critical loads or for grid support. Stored energy is important in the flexible control of power flow, because used appropriately it reduces losses, power in distribution lines, reverse energy flow and supports voltage and reactive power.

4.2.8 Photovoltaic Monitoring

To achieve better performance from PV systems and increase equipment life time, the use of monitoring and control software has become popular. Software tools are responsible for acquisition, visualization and data storage. This software can include smart functions to diagnose and estimate degradation of solar panels. Data processing techniques and intelligent algorithms are used in the diagnostic process. Data processing techniques commonly used in PV systems monitoring include neural networks and machine learning algorithms. This algorithm predicts the power generation of a PV panel in normal operation under changing environmental conditions.

Table 5 summaries for various multifunctional controls Strategy and their control objectives referred in various literatures.

Table 5. Multi-functional Control strategies and control objectives

Multi-functional Control Strategy	Component/device used	Control method for grid PV system	References
Grid Synchronization	Various PLL'S	Appropriate method for grid synchronization under distortion conditions.	[10-15][77]
Power quality	Passive filters, Active Power filters, Hybrid filters.	PV-SAPF	[78]
	Load Compensation, reactive power compensation	PV-DSTATCOM based multifunctional control.	[79]
	Voltage Harmonics, Voltage Sag, Voltage Swell	PV-DVR based multifunctional control.	[80]
	Combined effect of Harmonics due to nonlinear load, Voltage sag/Swell	PV-UPQC topology based multifunctional control offers power quality (PQ) enhancement features such as harmonic elimination, reactive power compensation, mitigation of source voltage sag/swell/distortion, grid synchronization under changing frequency conditions.	[81]
MPPT	Maximum power extraction	Conventional P&0, Incremental Conductance P&O, Intelligent algorithms	[8]
Current/voltage	Various conventional and advanced control techniques	PI controllers PR controller Predictive Droop Control Sliding Adaptive Controllers	[63-73]
Anti-islanding	Islanding techniques	Passive technique Active Technique	[82]
Energy storage	Energy storage devices	Power control	[83]
Advance intelligent PV monitoring and Power forecasting	Smart/Intelligent monitoring and controlling devices	Genetic Algorithm, Artificial intelligence, Machine learning, Neural network	[72,73]

V. Conclusion

This paper has presented a comprehensive review on recent challenges and possible solutions for solar integrated three phase distribution system. The majority of common power quality and power management issues affect grid-integrated solar systems. The review of the literature indicates that many of these kinds of problems can be satisfactorily solved by custom power devices and their appropriate control mechanisms. Paper has systematically presented the key characteristics, constraints and the overall trend in PV system. Control design for the grid-integrated solar system also needs to take into account a number of design parameters, including islanding protection, grid synchronization, power quality, active and reactive power support, maximum power point tracking, and many more. Various supported literature reviews are presented for related work in multifunctional control schemes design. The paper gives comprehensive idea to the researchers working in solar integrated three phase distribution system about holistic views and reported literature.

Acknowledgements

I am thankful to the Gujarat Technological University (G.T.U.) for providing me with an outstanding research forum and the requisite support for my research work.

References

[1] S. Dey, A. Sreenivasulu, G. T. N. Veerendra, K. V. Rao, and P. S. S. A. Babu, "Renewable energy present status and future potentials in India: An overview," *Innovation and Green Development,* vol. 1, no. 1, p. 100006, 2022, doi: 10.1016/j.igd.2022.100006.

[2] L. Tripathi, A. Mishra, A. K. Dubey, C. Tripathi, and P. Baredar, "Renewable energy: An overview on its contribution in current energy scenario of India," *Renewable and Sustainable Energy Reviews,* vol. 60, pp. 226-233, 2016.

[3] V. Khare, S. Nema, and P. Baredar, "Status of solar wind renewable energy in India," *Renewable and Sustainable Energy Reviews,* vol. 27, pp. 1-10, 2013, doi: 10.1016/j.rser.2013.06.018.

[4] R. B. Sholapurkar and Y. S. Mahajan, "Review of Wind Energy Development and Policy in India," *Energy Technology & Policy,* vol. 2, no. 1, pp. 122-132, 2015, doi: 10.1080/23317000.2015.1101627.

[5] R. K. Akikur, R. Saidur, H. W. Ping, and K. R. Ullah, "Comparative study of stand-alone and hybrid solar energy systems suitable for off-grid rural electrification: A review," *Renewable and Sustainable Energy Reviews,* vol. 27, pp. 738-752, 2013, doi: 10.1016/j.rser.2013.06.043.

[6] A. Kumar, N. Gupta, and V. Gupta, "A Comprehensive Review on Grid-TiedSolar Photovoltaic System," *Journal of Green Engineering,* vol. 7, no. 1, pp. 213-254, 2017, doi: 10.13052/jge1904-4720.71210.

[7] M. Hosenuzzaman, N. Rahim, J. Selvaraj, and M. Hasanuzzaman, "Factors affecting the PV based power generation," in *3rd IET International Conference on Clean Energy and Technology (CEAT) 2014*, 2014: IET, pp. 1-6.

[8] S. A. Mohamed and M. Abd El Sattar, "A comparative study of P&O and INC maximum power point tracking techniques for grid-connected PV systems," *SN Applied Sciences,* vol. 1, no. 2, 2019, doi: 10.1007/s42452-018-0134-4.

[9] M. Mao, L. Cui, Q. Zhang, K. Guo, L. Zhou, and H. Huang, "Classification and summarization of solar photovoltaic MPPT techniques: A review based on traditional and intelligent control strategies," *Energy Reports,* vol. 6, pp. 1312-1327, 2020, doi: 10.1016/j.egyr.2020.05.013.

[10] P. Gawhade and A. Ojha, "Recent advances in synchronization techniques for grid-tied PV system: A review," *Energy Reports,* vol. 7, pp. 6581-6599, 2021, doi: 10.1016/j.egyr.2021.09.006.

[11] M. M. de Carvalho, R. L. Medeiros, I. V. Bessa, F. A. Junior, K. E. Lucas, and D. A. Vaca, "Comparison of the PLL Control techniques applied in Photovoltaic System," in *2019 IEEE 15th Brazilian power electronics conference and 5th IEEE southern power electronics conference (COBEP/SPEC)*, 2019: IEEE, pp. 1-6.

[12] K. Jha and A. G. Shaik, "A comprehensive review of power quality mitigation in the scenario of solar PV integration into utility grid," *e-Prime - Advances in Electrical Engineering, Electronics and Energy,* vol. 3, p. 100103, 2023, doi: 10.1016/j.prime.2022.100103.

[13] P. Chittora, A. Singh, and M. Singh, "Adaptive EPLL for improving power quality in three-phase three-wire grid-connected photovoltaic system," *IET Renewable Power Generation,* vol. 13, no. 9, pp. 1595-1602, 2019.

[14] A. Khan, M. Easley, M. Hosseinzadehtaher, M. B. Shadmand, H. Abu-Rub, and P. Fajri, "PLL-less active and reactive power controller for grid-following inverter," in *2020 IEEE energy conversion congress and exposition (ECCE)*, 2020: IEEE, pp. 4322-4328.

[15] R. Kumar Agarwal, I. Hussain, and B. Singh, "Three-phase single-stage grid tied solar PV ECS using PLL-less fast CTF control technique," *IET Power Electronics,* vol. 10, no. 2, pp. 178-188, 2017.

[16] A. N. Kumar and I. J. Raglend, "Multi-objective Control of Multi-Operational Grid-Integrated Inverter for PV Integration and Power Quality Service," *Ain Shams Engineering Journal,* vol. 12, no. 3, pp. 2859-2874, 2021, doi: 10.1016/j.asej.2021.01.036.

[17] A. Chebabhi, K. Abdelhalim, F. M. K. Fellah, and A. Fayssal, "Self tuning filter and fuzzy logic control of shunt active power filter for

eliminates the current harmonics constraints under unbalanced source voltages and loads conditions," *Journal of Power Technologies,* vol. 98, no. 1, pp. 1-19, 2018.

[18] N. Gowtham and S. Shankar, "UPQC: a custom power device for power quality improvement," *Materials Today: Proceedings,* vol. 5, no. 1, pp. 965-972, 2018.

[19] M. Talha, S. R. S. Raihan, and N. A. Rahim, "PV inverter with decoupled active and reactive power control to mitigate grid faults," *Renewable Energy,* vol. 162, pp. 877-892, 2020, doi: 10.1016/j.renene.2020.08.067.

[20] L. Liu, H. Li, Y. Xue, and W. Liu, "Decoupled active and reactive power control for large-scale grid-connected photovoltaic systems using cascaded modular multilevel converters," *IEEE Transactions on Power Electronics,* vol. 30, no. 1, pp. 176-187, 2014.

[21] S. Weckx, C. Gonzalez, and J. Driesen, "Combined central and local active and reactive power control of PV inverters," *IEEE Transactions on Sustainable Energy,* vol. 5, no. 3, pp. 776-784, 2014.

[22] K. Arulkumar, K. Palanisamy, and D. Vijayakumar, "Recent advances and control techniques in grid connected PV system–A review," *International Journal of Renewable Energy Research,* vol. 6, no. 3, pp. 1037-1049, 2016.

[23] Ó. Gonzales-Zurita, J.-M. Clairand, E. Peñalvo-López, and G. Escrivá-Escrivá, "Review on multi-objective control strategies for distributed generation on inverter-based microgrids," *Energies,* vol. 13, no. 13, p. 3483, 2020.

[24] B. Boukezata, J.-P. Gaubert, A. Chaoui, and M. Hachemi, "Predictive current control in multifunctional grid connected inverter interfaced by PV system," *Solar Energy,* vol. 139, pp. 130-141, 2016.

[25] R. A. Soumana, M. J. Saulo, and C. M. Muriithi, "A new control scheme for limiting the compensation current and prioritizing power injection in multifunctional grid-connected photovoltaic systems," *e-Prime - Advances in Electrical Engineering, Electronics and Energy,* vol. 2, p. 100055, 2022, doi: 10.1016/j.prime.2022.100055.

[26] C. Jain and B. Singh, "A SOGI-Q based control algorithm for multifunctional grid connected SECS," in *2014 IEEE 6th India International Conference on Power Electronics (IICPE)*, 2014: IEEE, pp. 1-6.

[27] A. Kitamura, H. Matsuda, F. Yamamoto, and T. Matsuoka, "Islanding phenomenon of grid connected PV systems," in *Conference Record of the Twenty-Eighth IEEE Photovoltaic Specialists Conference-2000 (Cat. No. 00CH37036),* 2000: IEEE, pp. 1591-1594.

[28] M. A. Khan, V. B. Kurukuru, A. Haque, and S. Mekhilef, "Islanding classification mechanism for grid-connected photovoltaic systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics,* vol. 9, no. 2, pp. 1966-1975, 2020.

[29] T. Li, H. Fan, S. Zeng, X. Hu, Z. Meng, and Y. Zhao, "A low voltage ride-through strategy for grid-connected PV converters based on variable power point tracking method," *Energy Reports,* vol. 8, pp. 398-404, 2022.

[30] I. C. Rath and A. Shukla, "Review of three phase transformer-less PV converters," in *2019 IEEE International Conference on Sustainable Energy Technologies and Systems (ICSETS)*, 2019: IEEE, pp. 063-068.

[31] R. Dogga and M. K. Pathak, "Recent trends in solar PV inverter topologies," *Solar Energy,* vol. 183, pp. 57-73, 2019, doi: 10.1016/j.solener.2019.02.065.

[32] N. Zinelaabidine, M. Karim, B. Bossoufi, and M. Taoussi, "MPPT algorithm control for grid connected PV module," in *2017 International Conference on Advanced Technologies for Signal and Image Processing (ATSIP),* 2017: IEEE, pp. 1-6.

[33] R. Mechouma, B. Azoui, and M. Chaabane, "Three-phase grid connected inverter for photovoltaic systems, a review," in *2012 First International Conference on Renewable Energies and Vehicular Technology*, 2012: IEEE, pp. 37-42.

[34] R. N. Yogesh and A. Thorat, "A review on photovoltaic module based grid connected power inverter," in *2013 International Conference on Power, Energy and Control (ICPEC)*, 2013: IEEE, pp. 272-276.

[35] S. Chakraborty, M. Razzak, M. S. U. Chowdhury, and S. Dey, "Design of a transformer-less grid connected hybrid photovoltaic and wind energy system," in *2014 9th International Forum on Strategic Technology (IFOST)*, 2014: IEEE, pp. 400-403.

[36] H. Xiao, "Overview of transformerless photovoltaic grid-connected inverters," *IEEE Transactions on Power Electronics,* vol. 36, no. 1, pp. 533-548, 2020.

[37] H. K. Khyani and J. Vajpai, "Integration of solar PV systems to the grid: issues and challenges," *International Journal of Engineering Research & Technology (IJERT), ETRASCT,* vol. 2, no. 3, pp. 393-397, 2014.

[38] A. N. Deshmukh and V. K. Chandrakar, "Power quality issues and their mitigation techniques in grid tied Solar Photovoltaic Systems-A review," in *2021 International Conference on Computer Communication and Informatics (ICCCI)*, 2021: IEEE, pp. 1-6.

[39] S. Mishra, S. Bhuyan, and P. Rathod, "Performance analysis of a hybrid renewable generation system connected to grid in the presence of DVR," *Ain Shams Engineering Journal*, vol. 13, no. 4, p. 101700, 2022.

[40] W. U. Tareen, S. Mekhilef, M. Seyedmahmoudian, and B. Horan, "Active power filter (APF) for mitigation of power quality issues in grid integration of wind and photovoltaic energy conversion system," *Renewable and Sustainable Energy Reviews*, vol. 70, pp. 635-655, 2017.

[41] R. A. Soumana, M. J. Saulo, and C. M. Muriithi, "A new control scheme for limiting the compensation current and prioritizing power injection in multifunctional grid-connected photovoltaic systems," *e-Prime-Advances in Electrical Engineering, Electronics and Energy*, vol. 2, p. 100055, 2022.

[42] R. Boopathi and V. Indragandhi, "Comparative analysis of control techniques using a PV-based SAPF integrated grid system to enhance power quality," *e-Prime-Advances in Electrical Engineering, Electronics and Energy*, vol. 5, p. 100222, 2023.

[43] D. Nair, M. Raveendran, A. Nambiar, N. P. Mohan, and S. Sampath, "Mitigation of power quality issues using DSTATCOM," in *2012 International Conference on Emerging Trends in Electrical Engineering and Energy Management (ICETEEEM)*, 2012: IEEE, pp. 65-69.

[44] P. K. Shah, C. D. Kotwal, A. K. Giri, and B. Chitti Babu, "Study of multi-objective photovoltaic grid connected system using SOGI-FLL and NL-SOGI-FLL-APF based DQ hysteresis method," *Electrical Engineering*, vol. 105, no. 5, pp. 2735-2749, 2023, doi: 10.1007/s00202-023-01817-3.

[45] T. Koroglu, K. C. Bayindir, and M. Tumay, "Performance analysis of multiconverter unified power quality conditioner with an EPLL-based controller at medium voltage level," *International Transactions on Electrical Energy Systems*, vol. 26, no. 12, pp. 2774-2786, 2016.

[46] M. Gayatri and A. M. Parimi, "Mitigation of supply & load side disturbances in an AC Microgrid using UPQC," in *2016 IEEE 6th International Conference on Power Systems (ICPS)*, 2016: IEEE, pp. 1-6.

[47] O. O. Osaloni and A. K. Saha, "Distributed Generation Interconnection with Improved Unified Power Quality Conditioner for Power Quality Mitigation," in *2020 International SAUPEC/RobMech/PRASA Conference*, 2020: IEEE, pp. 1-6.

[48] S. K. Dash, S. Mishra, and P. K. Ray, "Photovoltaic tied unified power quality conditioner for mitigation of voltage distortions," in *2016 International Conference on Computer, Electrical & Communication Engineering (ICCECE)*, 2016: IEEE, pp. 1-5.

[49] S. Devassy and B. Singh, "Design and performance analysis of three-phase solar PV integrated UPQC," *IEEE Transactions on Industry Applications*, vol. 54, no. 1, pp. 73-81, 2017.

[50] R. Belaidi, A. Haddouche, M. Fathi, M. M. Larafi, and G. M. Kaci, "Performance of grid-connected PV system based on SAPF for power quality improvement," in *2016 International Renewable and Sustainable Energy Conference (IRSEC)*, 2016: IEEE, pp. 542-545.

[51] A. Ram, P. R. Sharma, and R. K. Ahuja, "Enhancement of power quality using U-SOGI based control algorithm for DSTATCOM," *Ain Shams Engineering Journal*, p. 102296, 2023.

[52] B. Singh, M. Kandpal, and I. Hussain, "Control of grid tied smart PV-DSTATCOM system using an adaptive technique," *IEEE transactions on smart grid*, vol. 9, no. 5, pp. 3986-3993, 2016.

[53] A. Kiswantono and E. Prasetyo, "Mitigation voltage sag/swell and harmonics using DVR supplied by BES and PV System," in *2018 Electrical Power, Electronics, Communications, Controls and Informatics Seminar (EECCIS)*, 2018: IEEE, pp. 36-41.

[54] M. Ramasamy and S. Thangavel, "Photovoltaic based dynamic voltage restorer with energy conservation capability using fuzzy logic controller," in *2012 International Conference on Emerging Trends in Science, Engineering and Technology (INCOSET)*, 2012: IEEE, pp. 485-492.

[55] I. Hussain, "Active Power Control of Grid Tied SPV System with DSTATCOM Capabilities," *International Journal of Emerging Electric Power Systems*, vol. 18, no. 3, 2017.

[56] A. A. Jeman, N. M. Hannoon, N. Hidayat, M. M. Adam, I. Musirin, and V. Vijayakumar, "Active and reactive power management of

grid connected photovoltaic system," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 13, no. 3, pp. 1324-1331, 2019.

[57] A. Hassan, O. Bass, and M. A. Masoum, "An improved genetic algorithm based fractional open circuit voltage MPPT for solar PV systems," *Energy Reports*, vol. 9, pp. 1535-1548, 2023.

[58] S. Sreejith, U. Bose, K. M. D. S. Vachana, and V. Jyothi, "Application of D-STATCOM as load compensator for power factor correction," in *2014 International Conference on Control, Instrumentation, Communication and Computational Technologies (ICCICCT)*, 2014: IEEE, pp. 595-600.

[59] D. Li, T. Wang, W. Pan, X. Ding, and J. Gong, "A comprehensive review of improving power quality using active power filters," *Electric Power Systems Research*, vol. 199, p. 107389, 2021.

[60] P. Afsher, K. Shyju, and M. Kumar, "An enhanced operation of PV-DSTATCOM," in *2020 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, 2020: IEEE, pp. 1-6.

[61] A. Ahmad and L. Rajaji, "Anti islanding technique for grid connected residential solar inverter system," 2013.

[62] V. S. B. Kurukuru, A. Haque, M. A. Khan, S. Sahoo, A. Malik, and F. Blaabjerg, "A review on artificial intelligence applications for grid-connected solar photovoltaic systems," *Energies*, vol. 14, no. 15, p. 4690, 2021.

[63] S. P. Sunddararaj, S. S. Rangarajan, U. Subramaniam, E. R. Collins, and T. Senjyu, "Performance of P/PI/PID Based controller in DC-DC Converter for PV applications and Smart Grid Technology," in *2021 7th International Conference on Electrical Energy Systems (ICEES)*, 2021: IEEE, pp. 171-176.

[64] M. K. Mishra and V. N. Lal, "Modified proportional resonant current controller with MPPT for three phase single stage grid integrated PV system," in *2020 IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2020: IEEE, pp. 3293-3297.

[65] M. Kermadi, Z. Salam, and E. M. Berkouk, "An adaptive sliding mode control technique applied in grid-connected PV system with reduced chattering effect," in *2017 IEEE Conference on Energy Conversion (CENCON)*, 2017: IEEE, pp. 180-185.

[66] S. S. Pradhan, R. Pradhan, and B. Subudhi, "Design of sliding mode controller for three phase grid connected photovoltaic system," in *2016 International Conference on Signal Processing, Communication, Power and Embedded System (SCOPES)*, 2016: IEEE, pp. 1317-1322.

[67] S. K. Sharma and V. Gali, "Development of modified hysteresis current controller switching scheme for multifunctional grid-tied photovoltaic inverters," in *2021 1st International Conference on Power Electronics and Energy (ICPEE)*, 2021: IEEE, pp. 1-6.

[68] N. B. Perumallapalli, B. C. Babu, R. Peesapati, and G. Panda, "Three-phase grid-tied photovoltaic system with an adaptive current control scheme in active power filter," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, pp. 1-25, 2020.

[69] T. K. Roy, M. A. Mahmud, A. M. T. Oo, and M. E. Haque, "An adaptive direct power controller for three-phase grid-connected photovoltaic systems with parametric uncertainties," in *2017 11th Asian Control Conference (ASCC)*, 2017: IEEE, pp. 2686-2691.

[70] Z. Sun, W. Zheng, and H. Du, "A Simplified Model Prediction Control Method for PV Grid-Connected Inverter," in *2019 IEEE Innovative Smart Grid Technologies-Asia (ISGT Asia)*, 2019: IEEE, pp. 3525-3530.

[71] A. Gopakumar and A. Vijayakumari, "Model predictive current controller for grid connected PV inverter," in *2017 International Conference on Circuit, Power and Computing Technologies (ICCPCT)*, 2017: IEEE, pp. 1-6.

[72] O. Oubrahim and M. Ouassaid, "Performance improvement of grid connected pv system using neuro-fuzzy controller," in *2020 International Conference on Sustainable Energy Engineering and Application (ICSEEA)*, 2020: IEEE, pp. 1-6.

[73] J. R. Vazquez, A. D. Martin, and R. S. Herrera, "Neuro-fuzzy control of a grid-connected photovoltaic system with power quality improvement," in *Eurocon 2013*, 2013: IEEE, pp. 850-857.

[74] P. Shukl and B. Singh, "Multifunctional control of weak grid intertie solar PV system with synchronization capability," in *2020 International Conference on Power, Instrumentation, Control and Computing (PICC)*, 2020: IEEE, pp. 1-6.

[75] H.-Y. Jung, Y.-H. Ji, C.-Y. Won, D.-Y. Song, and J.-W. Kim, "Improved grid-synchronization technique based on adaptive notch filter," in *The 2010 International Power*

Electronics Conference-ECCE ASIA-, 2010: IEEE, pp. 1494-1498.

[76] A. C. Kathiresan, J. PandiaRajan, A. Sivaprakash, T. Sudhakar Babu, and M. R. Islam, "An adaptive feed-forward phase locked loop for grid synchronization of renewable energy systems under wide frequency deviations," *Sustainability*, vol. 12, no. 17, p. 7048, 2020.

[77] S. Golestan, J. M. Guerrero, and J. C. Vasquez, "DC-offset rejection in phase-locked loops: A novel approach," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 8, pp. 4942-4946, 2016.

[78] S. M. Bagi, F. N. Kudchi, and S. Bagewadi, "Power quality improvement using a shunt active Power filter for grid connected photovoltaic generation system," in *2020 IEEE Bangalore Humanitarian Technology Conference (B-HTC)*, 2020: IEEE, pp. 1-4.

[79] S. K. Sahoo, S. Kumar, and B. Singh, "VSSMLMS-based control of multifunctional PV-DSTATCOM system in the distribution network," *IET Generation, Transmission & Distribution*, vol. 14, no. 11, pp. 2100-2110, 2020.

[80] T. Noohu and A. Thasneem, "Novel Dynamic Voltage Restorer with Multi-Functional Capability," in *2019 2nd International Conference on Intelligent Computing, Instrumentation and Control Technologies (ICICICT)*, 2019, vol. 1: IEEE, pp. 797-803.

[81] A. A. Dongre, A. K. Dubey, and J. P. Mishra, "Solar PV-Supported Multi-functional UPQC for Three-Phase System Using VCO-less-FLL," *Arabian Journal for Science and Engineering*, vol. 48, no. 5, pp. 6341-6359, 2023.

[82] S. B. Jinjala and B. N. Vaidya, "Analysis of Active and Passive Method for Islanding Detection of 3-Phase Grid Connected PV System," in *2018 2nd International Conference on Trends in Electronics and Informatics (ICOEI)*, 2018: IEEE, pp. 592-597.

[83] V. Narayanan, S. Kewat, and B. Singh, "Control and implementation of a multifunctional solar PV-BES-DEGS based microgrid," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 9, pp. 8241-8252, 2020.