

Examining Power Quality Challenges in Photovoltaic-Grid Integration: A Critical Review

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Abstract: With the massive growth of photovoltaic (PV) installations worldwide, the impact of integration between PV and the grid is becoming a serious issue and requires immediate attention. This is due to the intermittent power that the PV itself generates. The quality of the power can affect the stability of the system, the protection equipment, and the energy efficiency, which imposes a financial issue. This literature review will present the most frequently encountered problems when PV integrates with the grid, namely power quality issues, particularly on the distribution network. Problem-solving will also be presented as a reference for future PV development. It discusses several ways to handle power quality problems, depending on the factors influencing power quality. One of the proven ways is to use a modern inverter equipped with features that suit the system's needs. However, the discussion in this paper is limited to the issues of power quality and voltage generated by PV integrated into the grid. Future studies can discuss other technical issues, such as protection, feeder losses, and other problems that may arise in the future.

Keywords: photovoltaics, power quality, grid-connected.



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1. Introduction

In recent decades, the growing concern for climate change and the energy crisis has stirred many countries to take a massive step toward combining renewable energy into the existing grid. One of the renewable energies, photovoltaic (PV), is taken into higher consideration because of the improved technology in solar PV that results in cost reduction [1], [2]. As a result of the drop in the price of solar PV coupled with supporting energy policies, there has been an increase in solar PV installations in the last decade. Figure 1 shows the significant growth of PV installed between 2010 and 2021 across the world [3]. In this period, there has never been even the slightest decrease in PV installations. Over one million GW of PV were installed. Figure 2 shows ten countries with the highest installation of PV around the globe [3]. China has the highest number of PVs. It accounts for 327,591 GW, which is around 31.6% of the total number of PV installations around the world. This PV system can be divided into two categories: off-grid and on-grid. Off-grid systems, as the name suggests, are separate from the main grid and mostly exist in rural areas or on the islands. Meanwhile, on-grid systems are connected to the main grid and are illustrated as having the most installed PV capacity [4].

Figure 1. PV installation across the globe between 2010-2021.

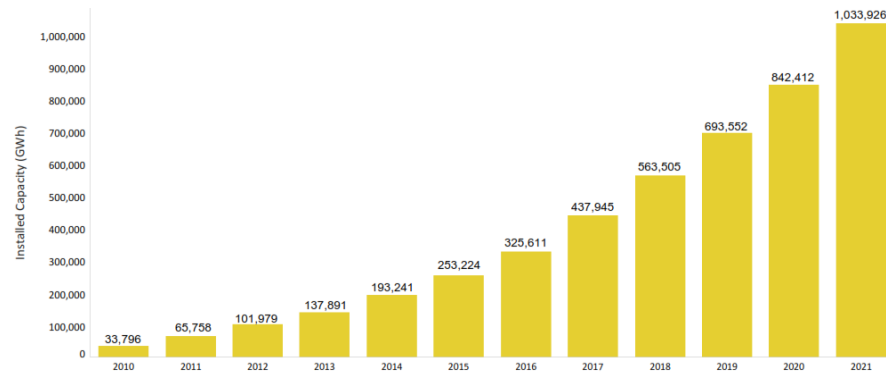
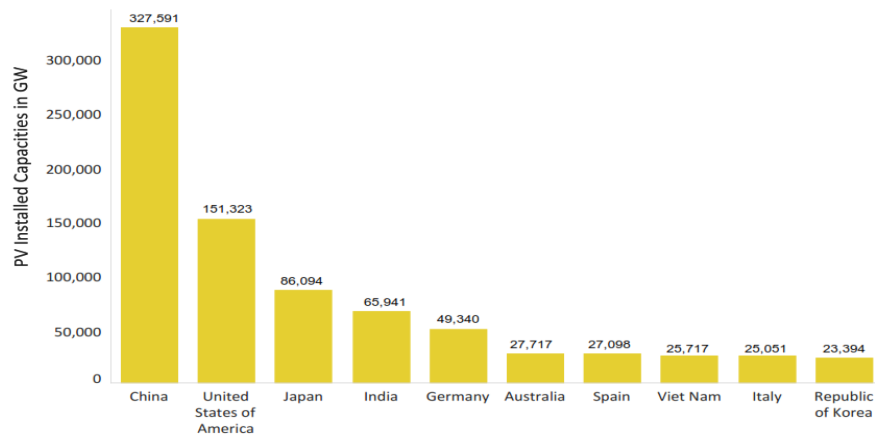


Figure 2. Top 10 countries with PV installation in the world.



Unfortunately, the interconnection of solar PV to the grid has some obstacles, such as voltage and power quality issues. Power fluctuation, for instance, occurs due to PV solar irradiance caused by cases where the sun is covered by clouds, which may occur for minutes or hours [5]. This fluctuation can lead to an unstable system and damage the power quality [6]. Moreover, power fluctuations can result in power swings in lines, voltage fluctuations, and voltage flickers [5]. Table 1 illustrates the reported occurrences of power quality concerns.

Table 1. Previous studies on power quality issues.

No	Category	Causes
1	Voltage fluctuations/voltage flicker	<ul style="list-style-type: none"> • Differences in solar PV generation [7] • Abrupt change in voltage [4]
2	Voltage unbalance	The loading of the phases is changed drastically [4]
3	Harmonic disturbances	<ul style="list-style-type: none"> • The use of power inverter without filter [8] • The use of DC to AC current inverter [8] • Equipment nonlinearity [9]
4	DC offset	Inverter as a source of DC [7]
5	Frequency fluctuation	Unbalance between power consumption and production [4], [8]
6	Overvoltage/under voltage	<ul style="list-style-type: none"> • No load at LV network [4] • Insufficient provision of reactive power [8] • The peak PV generation abruptly declines [4]
7	Power fluctuation	Variation in solar irradiation [8]

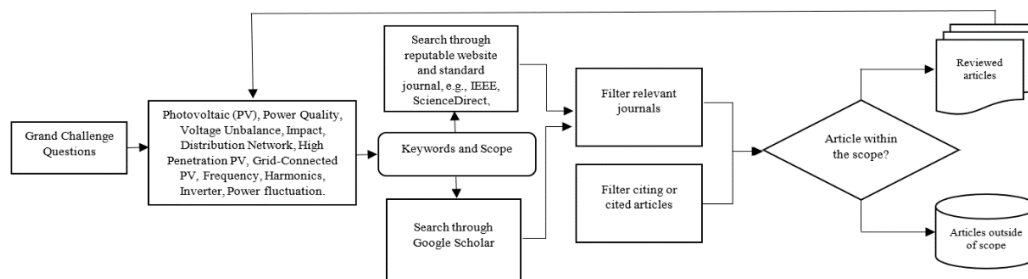
Before going into more depth, this literature review is organised into six sections. Section 2 illustrates the methodology that was used. Section 3 explores the PV system architectures that are integrated into the grid, including the positive and negative implementations of the PV architecture. The details of power quality issues are then discussed in Section 4. Section 5 looks into the reported case study of power quality issues. Finally, the discussion and conclusion are presented in sections 5 and 6, respectively.

2. Methods

Taking into account the rapid growth of the use of solar PV, as seen in Figure 1, and the power quality issues that were frequently discovered by earlier research, a more extensive literature review was conducted using the methodology illustrated in Figure 3, which drew inspiration from [4]. The initial step is to identify the "Grand Challenge" questions, which became the critical question. The primary inquiries encompassed the following:

1. What is the significance of power quality in ensuring the dependability of systems that incorporate a substantial amount of PV?
2. What power quality challenges will high PV penetrations impose in the future?
3. What advancements are feasible to resolve the forthcoming energy quality challenges?

Figure 3. Literature review flowchart.



The keywords were defined in light of these three inquiries, which serve as a guide for locating the pertinent journal. Google Scholar was used to conduct searches for newspapers, journals, reports, and international standards. Furthermore, scientific research was acquired from preeminent institutions specialising in solar energy and power systems. In addition to Hindawi, the National Renewable Energy Laboratory (NREL), IEEE, ScienceDirect, Elsevier, and the European Association for the Development of Renewable Energies, Environment, and Power Quality (EA4EPQ) were used to conduct the research for relevant materials. Supplementary information, including the utilised background data, was acquired from the International Renewable Energy Agency's (IRENA) website, which is revised yearly.

Subsequently, a preliminary evaluation of journals, reports, and publications was conducted through a cursory examination of their abstracts, conclusions, and headings. These were then categorised as "resources that may be required." 65 publications that corresponded to the keywords were then located. 33 of those publications contributed to the subject matter of this literature review. The subsequent task was to conduct an analysis of the negative impact or influence caused by high penetration PV from the power quality perspective. The identified issues were systematically categorised according to their root causes, as illustrated in Table 4 of Section 5.

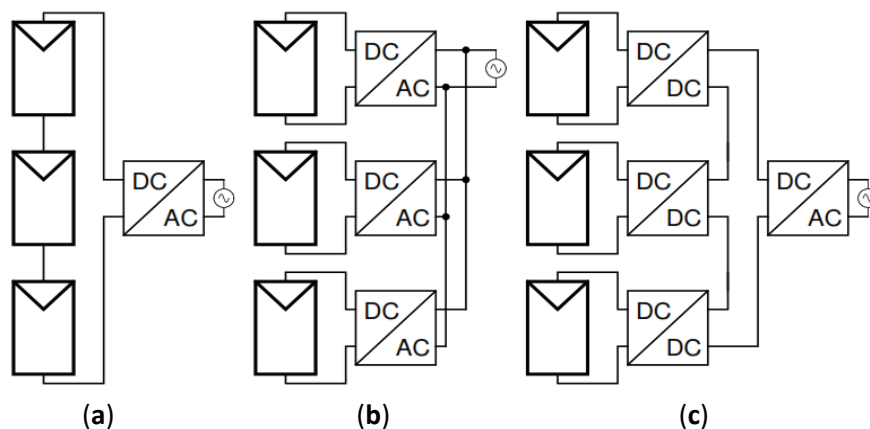
It is important to acknowledge that the scope of this literature review was restricted to power quality concerns alone. It excluded discussions on communication, society, and the environment. Slightly more attention was devoted in Part 2 to the architectural issues of PVs, which entailed shading that can degrade power quality. The result and discussion section provided a brief discussion of the economic aspect. It is important to know that the "Grand Challenge" was added to power quality issues, which explored future enhancements in this area.

3. PV System Architectures

High-penetrated grid-connected photovoltaic systems, referred to as a megawatt-scale distributed generation type, are developing quickly. To integrate a solar PV array with the grid, a power electronic interface must be established between the array and the grid [2]. A power-conditioning unit and a series/parallel combination of PV arrays are the primary components of a PV system connected to the grid. While the second component maintains the highest level of PV operation efficiency by converting DC electricity to AC power, the first component turns sunlight directly into DC power [8]. Due to array shading, dirt build-up, or manufacturing in residential PV applications, many PV installations have current mismatches across various panels [10].

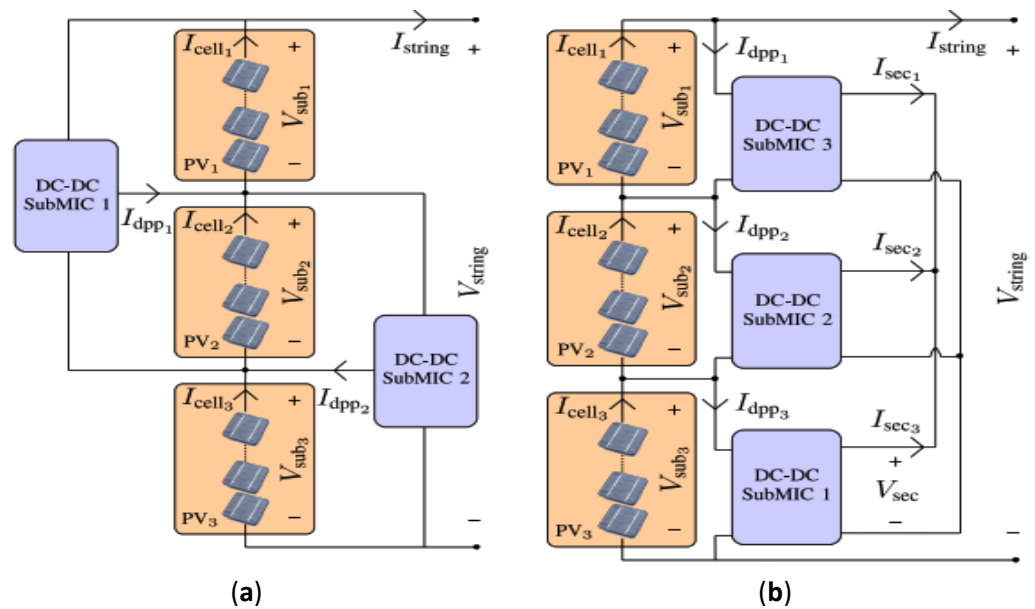
Figure 4 shows examples of current PV power processing architectures. Figure 4 (a) portrays the most popular PV system, which links a central inverter and all of the modules in series. This architecture is known as the typical bulk conversion technique [10], [11]. Only when the maximum power point (MPP) and current levels are adequately matched can this strategy be considered efficient and successful [11]. As a result, power will be lost if there is only one cell with partial shade. Several ideas have been put forward to use full power processing (FPP) distributed power electronics to cut down on these losses caused by mismatches [12], such as microinverters as seen in Figure 4 (b), have been put forth to use full power processing (FPP) distributed power electronics to lessen these mismatch-related losses [12]. This technique is referred to as the panel-panel inverter or micro-inverter concept. Micro-inverters often have lesser efficiency than high-voltage string-level inverters, even though this method may boost the system's overall energy capture [10]. The concept of DC optimizers is shown in Figure 4 (c). This architecture allows for separate maximum power point operations for each panel as well as localised control over panel voltage and current, enhancing the system's overall energy extraction in the process [11].

Figure 4. PV system architectures: (a) Series string architecture; (b) Micro-inverter architecture; (c) Cascade DC-DC optimiser architecture.



More recently, several differential power processing (DPP) architectures have been proposed [13], [14]. These DPP architectures can be classified into two groups: PV-to-PV DPP architectures, as shown in Figure 5 (a), and PV-to-bus DPP architectures, shown in Figure 5 (b) [12]. The "full power processing" architectures of the front-end DC optimisers and micro-inverters allow them to process all of the power produced by their associated PV module, even in the presence of shadowing. For this category, Figure 5 (a) is a representative example. When the currents produced by the PV modules are not equal, mismatch losses happen. As long as the modules' symmetry is restored, these losses can be prevented [15]. PV-to-bus architecture with isolated ports is shown in Figure 5 (b). This PV module architecture uses subMICs in place of bypass diodes. Each subMIC's primary side is directly connected to each substring in parallel, replacing the corresponding bypass diode. The subMICs are implemented as dc-dc converters with isolation because the secondary side is connected in parallel across the module's output [13].

Figure 5. DPP architectures: (a) PV-to-PV shuffling converters; (b) Isolated port PV-to-bus.



4. Power Quality Issues in High PV Penetration

Power quality (PQ) in the distribution system is essential because abrupt changes and devices that don't work in a straight line can disrupt the voltage-current waveform at the system's central point [16]. The electric equipment can experience malfunctions or damage during operation due to variations in voltage, current, and wave shape, resulting in inaccurate outcomes [17]. Studies reported on PQ issues can be seen in Table 1 and explored in the following sections:

4.1. Voltage fluctuations/voltage flicker

Flicker is defined by IEEE Standard 1453-2015 [18] as "the subjective impression of fluctuating luminance caused by voltage fluctuations." To prevent power outages and other- worst-case scenarios, the grid should accommodate the intermittent nature of solar PV to ensure a steady supply of electricity [19]. Electric arc furnaces, ovens, and any other large-draw variable loads are the sources of voltage flicker [20]. Usually, it causes unpleasant variations in lighting intensity.

4.2. Voltage unbalance

Voltage unbalance is a serious issue in power systems. Even without PV penetration, there may already be an imbalance due to unequal impedances and load cross-phases [4]. In general, distribution suppliers are responsible for providing loads throughout the network to address the imbalance caused by unequal power consumption among consumers, which results in voltage level disparities at the customer end.

The variations in voltage unbalance definitions have been examined in several researches. Three definitions of voltage unbalance—IEEE 1159, IEEE 141-1993, and NEMA—are quantitatively compared in [21]. Table 2, which contains numerical comparisons, reveals that there are still some discrepancies, even if these publications conclude that voltage unbalance definitions accord quite well to unbalances below 5% [22].

Table 2. Numerical comparison for low and high frequency of voltage unbalance.

Operation for low-frequency conditions	Operation for high-frequency conditions
$p = \min_{f < 60 - db_{UF}} \left\{ p_{pre} + \frac{(60 - db_{UF}) - f}{60 \cdot k_{UF}}; p_{avl} \right\}$	$p = \max_{f > 60 + db_{OF}} \left\{ p_{pre} - \frac{f - (60 + db_{OF})}{60 \cdot k_{OF}}; p_{min} \right\}$

4.3. Harmonic disturbances

Harmonic distortion in the current and voltage waveforms has emerged as a significant concern due to the widespread integration of solar photovoltaic systems into the electrical infrastructure [23]. Harmonic disturbances typically result from the inverter switch delay, which distorts the waves [24]. The metric frequently employed to quantify the extent of the distortion is known as total harmonic distortion (THD). THD is defined as the ratio of the root mean square (rms) magnitude of the harmonics (excluding the fundamental component) to the RMS value of the fundamental component. The term for THD measured in current can be represented as equation (1).

$$THD_i = \sqrt{\sum_{n=2}^{\infty} I_n^2} / I_1 \tag{1}$$

The industry proposes many standards, such as IEEE standards, which establish harmonic limitations by considering voltage levels and the ratio between the maximum short-circuit current (I_{sc}) and the maximum demand current (I_L) rather than relying on predefined harmonic distortion limits [25]. The current distortion limitations, which vary according to the I_{sc}/I_L ratio, are provided in Table 3 [26].

Table 3. Individual harmonic limits (%).

I_{sc}/I_L	2≤h<6		6≤h<11		11≤h<17		17≤h<23		23≤h<35		35≤h≤50		TDD
	Odd	Even	Odd	Even	Odd	Even	Odd	Even	Odd	Even	Odd	Even	
<20°	4.0	2.0	4.0	4.0	2.0	2.0	1.5	1.5	0.6	0.6	0.3	0.3	5.0
20<50	7.0	3.5	7.0	7.0	3.5	3.5	2.5	2.5	1.0	1.0	0.5	0.5	8.0
50<100	10.0	5.0	10.0	10.0	4.5	4.5	4.0	4.0	1.5	1.5	0.7	0.7	12.0
100<1000	12.0	6.0	12.0	12.0	5.5	5.5	5.0	5.0	2.0	2.0	1.0	1.0	15.0
>1000	15.0	7.5	15.0	15.0	7.0	7.0	6.0	6.0	2.5	2.5	1.4	1.4	20.0

4.4. DC offset

Transformer-less photovoltaic inverters are used in the integration of PV into the grid (TLPVIs). Even though TLPVIs are very efficient, lightweight, and cost-effective, there have been reports of negative impacts on the distribution transformer [27]. An inadequate DC part can cause a lot of DC to flow into the grid, which can be problematic as it can cause the transformer to overload, the relay to fail, the capacitor to overheat, the AC current to ripple and have harmonics, and to trigger the need for more reactive power to rise [7], [28].

4.5. Frequency fluctuation

The most significant aspect influencing LSPV incorporation into the system is frequency variation. The main concern is that the PV system is a static source with no inertia. When more conventional generation units are replaced with LSPV, the effective inertia of the bulk power system will be lowered. As a result, the system is unable to cope with power outages and frequency fluctuations [24]. Another big problem with frequency changes is that converter-interfaced (CI) technologies like PV don't naturally respond to changes in frequency in the network and can't control reactive or effective power [27].

4.6. Overvoltage/under voltage

PV systems are usually designed to operate near unity power factors to fully utilise solar energy [5]. Regardless of whether a photovoltaic (PV) system is to blame for the occurrence of overvoltage and undervoltage problems, these problems remain a concern [29]. High distribution voltage or light loads may cause overvoltage on a system with high PV penetration [20]. Meanwhile, a gradual decrease in peak PV generation due to cloud movement or other factors may lead to an undervoltage condition. It is unlikely that PV will cause overvoltage or undervoltage issues in the transmission system [4].

4.7. Power fluctuation

PV system output power fluctuation is one of the primary variables that could lead to serious operational issues for the utility network. Cloud movement-induced variations in sun irradiation are what cause this phenomenon. Power swings in lines, excessive and insufficient loading, unacceptably large voltage fluctuations, and voltage flickers can all result from power fluctuations [8].

5. Case Study of High PV Penetration and Potential Power Quality and Voltage Issues

Since PV has become one of the most promising renewable energies, several countries have projections of future PV installations. It is common knowledge that every nation has a unique voltage level. Numerous accounts of stakeholders' experiences in businesses that have effectively included PV in their networks have been published. Table 4 presents the results of additional research and analysis on the effects of aggregated rooftop PV installations.

Table 4. Previous studies on power quality issues.

Location	PV size	Reported power quality issues	Mitigation methods used
Germany [30]	31 GW	50.2 Frequency risk	<ul style="list-style-type: none"> • Central voltage control strategies • Decentralized voltage control strategies • Local voltage control strategies
Austria [31]	101 kWp	RMS event	Change the adjustment of coupling protection
Carlsbad, New Mexico [29]	10 MW	Voltage fluctuation, High voltage, Reverse power flow	<ul style="list-style-type: none"> • Regulate power factor • Add remotely control capacity bank • Energize incrementally for the inverters
Fort Collins, Colorado [29]	5.2 MW	Generate more power and export power back to the utility system	<ul style="list-style-type: none"> • Energize incrementally for the inverters • Set the inverters to absorb 100/150 kVAr
Miami, Florida [32]	1.1 MW	Power ramps, Harmonic distortions	<ul style="list-style-type: none"> • Applying controllable inverter in output voltage • Applying pulse width modulation (PWM)
Kaua’i Hawaii [29]	1.2 MW	Over frequency	Increase set point of over frequency
Fontana, California [29]	2 MW	In the substation, there were no instances of reverse power transmission	Capacitor bank control setting

6. Results and Discussion

The world's rapid growth of solar PV is in line with the high amount of solved PV installation problems. Many factors can affect power quality, such as frequency, voltage rising, harmonic, active and reactive power influences, etc. It can be a severe problem when PV integrates with the grid.

The inverter can resolve a frequency issue in the distribution system by implementing a local voltage control strategy. The PV inverter's active and reactive power controls on the distribution side can mitigate substantial voltage increases caused by high solar irradiation. This will be of tremendous economic and technical benefit, as the implemented inverter can regulate both active and reactive power. A case in point is the PV problem in Germany, which encompassed a capacity of 31 GW [30]. This approach has demonstrated the effectiveness and simplicity of the implementation due to its lack of reliance on supplementary infrastructure, including communications and information systems. Undoubtedly, considering this approach does not necessitate supplementary infrastructure, it can be deemed more cost-effective.

A solution to the issue of voltage fluctuations is to modify the power factor. By incorporating a power factor adjustment apparatus, such as a capacitor or an inverter with a power factor controller, it is possible to modify the power factor. A power factor enhancement could potentially establish a stable and satisfactory voltage system. Thus, this method is entirely feasible in theory. In the context of projects in New Mexico [29], this approach was effectively implemented to resolve voltage issues by installing a power factor-controlling inverter. Furthermore, an alternative approach to managing voltage fluctuations involves modifying the voltage on the distribution side using an on-load tap changer (OLTC). The distributed transformer carries out the process of aligning the distributed transformer with the pre-existing OLTC. Nevertheless, implementing OLTC on distribution transformers is uncommon due to the substantial cost and maintenance requirements associated with such transformers. However, this approach is utilised in a project located in Fort Collins, Colorado [29], to manage voltage fluctuations.

Managing harmonic distortion is possible using sophisticated inverters equipped with output voltage regulator functionalities. Contemporary inverters are outfitted with output voltage regulators that can influence harmonic values. By optimally maintaining the quality of the output voltage, the harmonic value of the system will be enhanced. Furthermore, the implementation of pulse width modulation (PWM) has proven to be highly advantageous in addressing harmonic distortion. Similar to output voltage regulators, the PWM method necessitates a signal management-capable inverter. The construction in Miami, Florida, serves as an example [32]. Harmonic distortion in a photovoltaic system with a capacity of 1.2 MW was eliminated by combining inverters with output voltage adjustment and PWM. The involvement of an engineer in the planning and selection of the inverter type is critical in this situation due to its significant economic and technical implications.

When the issue with the inverter occurs, it generates more power back to the utility system, and incrementally energising the inverters is implemented. The power supply is managed by the power management principle and consideration of the system's condition. Consider Fort Collins, Colorado [29] as an illustration. By monitoring the current in the system, energy is progressively supplied to the inverter in this effort. From an economic standpoint, this approach requires no expenditure but rather the engineer's capability to compute the power flow.

Power quality, however, is essential and will continue to be a focal point. This is a result of using renewable energy sources, particularly solar energy, which is expanding quickly globally. Given the intermittent nature of solar energy and how closely it relates to power quality, this is a very intriguing subject for further research. As a result, there will be plenty of fresh concepts and approaches that can effectively and efficiently address the power quality issue.

Moreover, it is anticipated that the load will rise gradually in the future with a range of load variations. Undoubtedly, this load variance presents a particular difficulty in resolving power quality issues. The difficulty of power quality will be greater if additional renewable energies like hydro, wind, and tidal are used in the same system.

Furthermore, the resolved power quality issue can now serve as a model. Although, the equipment supporting it, including the feature-rich inverters, still has to be improved. Because of this, the engineer's involvement is crucial when developing the inverter to meet system and load requirements. A device that can precisely measure and regulate the output voltage, power factor, and frequency in a single inverter can be developed based on the solution to the power quality issue covered in this literature review. This eliminates the need for additional equipment, which can be costly and take up space. For instance, data management and AI integration can be established. It will be simpler to detect changes in the system load using AI and data management, enabling prompt and accurate problem-solving.

In summary, the power quality issue can be addressed through diverse approaches contingent upon its underlying cause. The frequency-induced power quality issues can be mitigated through local voltage controls, while voltage fluctuations can be corrected by implementing power factor settings. Additionally, inverters with output voltage regulator capabilities can effectively address the harmonics issue. Incrementally energising the inverters may also provide a solution to the power quality issue that arises from increasing power generation and exporting it back to the utility system.

7. Conclusion

This literature review outlines the variables that impact power quality when photovoltaic penetration is high. It provides discussions on several problem-solving techniques along with examples of actual projects. Regarding frequency issues, the inverter's local voltage control and power factor adjustments can help reduce voltage variations. By controlling the output voltage, an inverter may compensate for the distortions in the harmonic. Future power quality issues that could jeopardise electrical systems, such as blackouts, require equipment advancements such as complicated inverter creation in addition to power quality enhancement support features. Another option is to combine artificial intelligence (AI) and data management with the electrical system to monitor the PV when shade or other undesirable events occur. Decisions can be made quickly, accurately, and effectively, preventing an interruption to the electrical system.

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