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Power quality Effects, Sources, and Mitigation Approaches in grid-connected solar photovoltaic system: A Comprehensive overview

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ABSTRACT
However, solar PV systems come with their own set of challenges, including high initial costs and lower reliability, especially from the perspective of residential users. Additionally, power quality is a significant concern in grid-connected solar PV systems, particularly at the consumer end. Non-linear loads on the consumer side can introduce harmonics into the power system, increasing the demand for reactive power. Common power quality issues include voltage sags, swells, flicker, harmonics, interference, and voltage imbalance. This paper reviews various power quality issues associated with grid-connected solar PV systems, explores their causes, and summarizes potential mitigation strategies. In the context of solar energy, key challenges include high initial costs and lower reliability, especially for residential users. For grid-connected solar photovoltaic (PV) systems, power quality is a significant concern, particularly at the consumer level. Non-linear loads on the consumer side can introduce harmonics into the power system, increasing the demand for reactive power. Common power quality issues include voltage sags, swells, flicker, harmonics, interference, voltage imbalance, and low voltage ride-through. This paper provides a comprehensive review of these power quality issues, their causes in grid-connected solar PV systems, and summarizes various mitigation strategies.
Keywords- Grid integrated Solar PV system, Power Quality problems, voltage sag, swell, flicker, harmonics, voltage imbalance.

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I. INTRODUCTION

Despite considerable efforts to promote renewable energy sources such as solar and wind through policy and technological advancements, both India and the world continue to rely heavily on conventional energy resources. Power quality remains a major concern, as the grid is a dynamic system prone to various issues related to power quality [1]. Fossil fuel-based energy generation is not sustainable in the long run, making renewable energy resources the only viable alternative [2]. Often, electricity generation from renewable sources is conducted on a local scale, with rooftop solar installations being a popular choice [3].

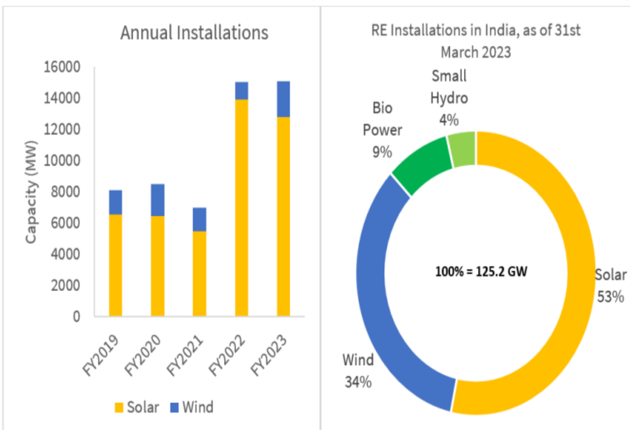

Figure 1. RE installation trends in India(Source: MNRE, JMK Research)

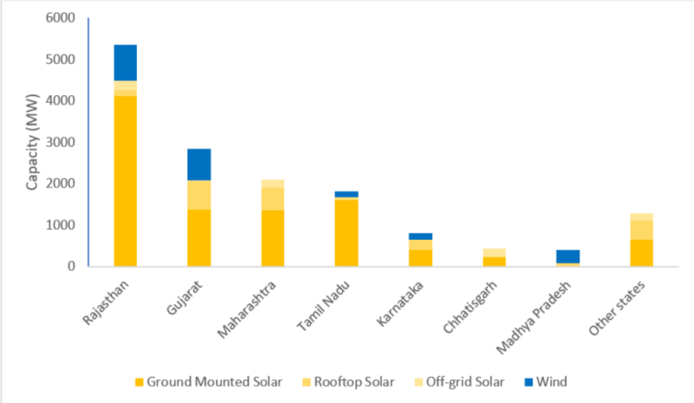

Figure 2. State-wise solar and wind capacity addition in India in FY 2023(Source: MNRE, JMK Research)

The increased integration of renewable energy sources into the grid has shifted the focus of utility engineers and researchers to power quality issues. The most common interface between solar PV systems and the grid is a power electronics converter, which inherently produces harmonics. To address these power quality challenges, researchers are increasingly exploring the use of customized power devices integrated into the distribution system [4].Key power quality problems include voltage control issues, voltage sags and swells, and flicker. Various studies have proposed different mitigation strategies, particularly targeting reactive power issues and their compensation methods [5].A revamped inverter controller has been shown to address under-voltage situations by generating reactive power proportional to the severity of the voltage sag. This enhanced controller is specifically designed to mitigate voltage sags and ensure low-voltage ride-through. Additionally, a dynamic voltage restorer can correct imbalances caused by complex loads or reduced inverter voltage output and can also alleviate voltage flicker. To eliminate harmonics from the grid, various filter designs combining resistors (R), inductors (L), and capacitors (C) can be employed [6]. Due to challenges with resonance in passive filters, modern power electronics strategies now employ advanced current and voltage control techniques [7]. A study conducted in a rural area of Portugal analysed various power quality metrics and found that, at times, the system was operating well beyond its voltage limits [8]. Additionally, some researchers have examined the impact of photovoltaic (PV) generation on the distribution system, focusing on issues such as reverse power flow and harmonic distortion [9].

II. POWER QUALITY AND ITS IMPORTANCE

Power quality refers to the ability of an electrical system to deliver high-quality power to users while maintaining all parameters within acceptable limits. Good power quality means a stable voltage supply where both frequency and voltage remain within the specified tolerance bands [12]. Good power quality alleviates financial strain on both consumers and utilities. Enhancing power quality leads to overall cost-effectiveness in system performance and reduces operational and maintenance expenses. Improved power quality can extend the lifespan and performance of equipment, indirectly boosting production efficiency and quality. Good power quality minimizes system outages, enhances system reliability, and reduces maintenance costs. The condition of appliances and utilities at the load end is significantly influenced by having good quality power [14].

III. POWER QUALITY CHALLENGES IN GRID-CONNECTED SOLAR PV SYSTEMS

This discussion focuses on the most significant and notable advancements in Grid-Connected Solar Photovoltaic (GCSPV) systems. Power electronic converters are utilized to meet load demands when the PV cells receive photon energy as a function of time. The article addresses power quality (PQ) issues and anti-islanding concerns (AII) related to PV systems connected to low and medium voltage networks[21][22]. The goal is to optimize the efficiency of the entire solar PV system, including the PV module, inverter, and filter control mechanisms, to ensure that complex power and voltage variations remain within specified guidelines. Systems are designed for either single-phase or three-phase configurations, and when multiple PV arrays are connected, the harmonics generated often span a broad frequency range, from sub-harmonics to various orders of harmonic frequencies. Custom Power Devices (CPDs) play a crucial role in many GCSPV integration scenarios. These CPDs, connected to non-linear loads, introduce harmonics into the grid. Therefore, when developing controllers for these CPDs, it is essential to ensure that the output remains stable at the Point of Common Coupling (PCC) [23][24]. The uses of these devices are briefly discussed in the referenced literature.

IV. CATEGORICAL OVERVIEW OF POWER QUALITY ISSUES

As illustrated in the figure 3, power quality issues are broadly categorized into transients, voltage variations, voltage imbalance, waveform distortions, and flicker, typically affecting the consumer end. Transients are temporary power quality disturbances frequently caused by the switching of non-linear loads. Voltage variations are usually associated with load changes at the distribution end or fluctuations in solar PV panel insolation levels. Waveform distortions often involve harmonic interference, where additional frequency signals are superimposed on the fundamental frequency. Flicker results from the combined effects of the above issues, leading to observable effects like reduced light intensity in bulbs, flickering, or fluctuating speeds in fans and large motors**.**

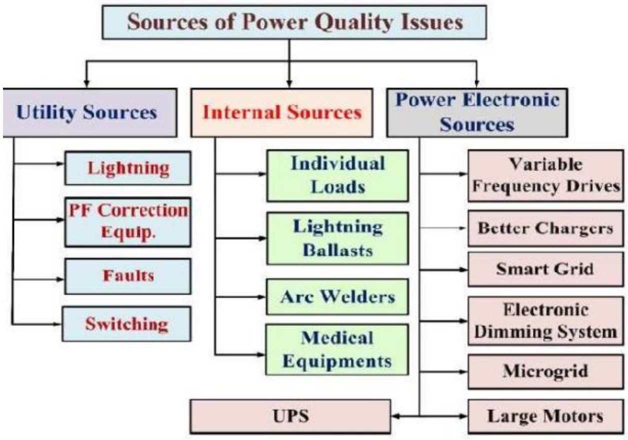

Figure 3: Categorical Overview of Power Quality Issues

As illustrated in the block diagram in Figure 4, there are three primary sources of power quality issues in grid-connected solar PV systems, or in any electrical system in general:
Utility Sources: These include transient events such as lightning strikes, switching operations, and faults, which last for a few milliseconds to seconds. Power factor correction systems, which are often part of the grid, can introduce reactive power, potentially causing voltage surges depending on the system load conditions.
Internal Sources: These involve both linear and non-linear loads within the system. Switching these loads can result in voltage sags or swells, leading to temporary disturbances in the system.
Harmonics: Most harmonics in the system originate from various power electronic devices. While filtering can reduce these harmonics, they still present a significant challenge.
Voltage and frequency disturbances are prevalent in grid-connected solar PV systems due to synchronization problems caused by fluctuating irradiance levels and inverter issues. The main source of harmonic distortion in solar PV systems is the inverter interface that connects the solar PV system to the grid. Short-term and long-term interruptions are often the result of various protection mechanisms, especially anti-islanding protection. Voltage sags and swells are primarily due to protection systems designed to guard against under voltage and overvoltage conditions.

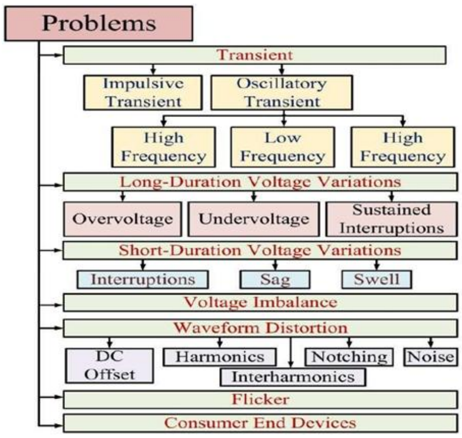

Figure 4. Classification of Power Quality Issues

V. POWER QUALITY ISSUES ON GRID-CONNECTED SOLAR PV SYSTEMS [1][4]

The core components of grid-connected solar PV power systems include:

Solar PV Modules: These are connected in series and parallel, depending on the size of the solar PV array, to generate DC power directly from the captured solar energy.

Maximum Power Point Tracker (MPPT): This ensures that the DC power generated by the solar PV modules is optimized for maximum power output throughout daylight hours.

Grid-Tied DC/AC Inverter: This converts the produced DC power into AC power and ensures that it is safely fed into the utility grid when the system is operational.

Safety Equipment: This includes fuses and DC/AC breakers, which are installed according to local utility standards and regulations to ensure secure grid interconnection.

Solar photovoltaic (PV) systems can help reduce distribution generation overloads and prevent load shedding. However, improper integration, installation, and placement can negatively impact power quality. Inverters, which are a major source of harmonics, are the main contributors to power quality issues in the distribution grid. Common power quality problems include:

Flicker: Sudden changes in power, typically due to nonlinear load conditions. Harmonics: Voltage harmonics are generated primarily through the switching of power electronic devices, which can also create current harmonics depending on line impedance. Voltage Sags and Swells: These are mainly caused by variations in solar insolation levels and voltage imbalances at the grid due to load switching and fault conditions.

Different Mitigation Techniques for Enhancing Power Quality [11]

Mitigation technique	Problems that are mitigated	Performance level
UPQC	voltage sags/swells, flicker, voltage unbalance, harmonics, power factor, load harmonic currents, and load unbalance	***
D-STATCOM	power factor, current harmonics, filtering, voltage regulation, and load balancing	**
UPS	emergency power shortage	*
TVSS	voltage transients	*
Isolation transformer	isolation of sensitive loads	*
STATCOM	transient conditions, voltage fluctuations, voltage flickers, and power oscillatory damping	***
DVR	voltage sag and swells	*
Surge Protector, Varistor and Capacitor	overvoltages	*
STS	interruptions and voltage dips	*
SVC	flicker, unsymmetrical loads	**
Spinning Reserve	harmonics, THD, Power oscillatory damping	***

***** = Excellent, ** = Satisfactory, * = Acceptable**

Table 1: Techniques for Mitigating Power Quality Issues

Table 1 outlines various mitigation strategies for addressing power quality issues and their corresponding effectiveness. The Unified Power Quality Conditioner (UPQC) addresses voltage sags/surges, flicker, voltage imbalance, and harmonics through its series circuit, while its shunt circuit manages power factor, load harmonics, and load imbalance. The Distribution Static Synchronous Compensator (D-STATCOM) not only compensates for low power factor and current harmonics but also acts as a load balancer and voltage regulator on the distribution bus. Uninterruptible Power Supplies (UPS) are typically used to manage power shortages and provide backup power for system equipment during outages. Voltage Transient Suppression Systems (TVSS) correct voltage transients using isolation transformers. For handling voltage droop/surge issues, a Dynamic Voltage Restorer (DVR) is a highly effective solution. The Static Synchronous Compensator (STATCOM) offers benefits such as superior operational characteristics, faster response, compact size, cost-effectiveness, and the ability to provide both active and reactive power.

HarmonicVoltageDistortionin%atPCC			
	2.3-69 kV	***69-161 kV***	***>161KV***
Maximum for Individual Harmonic	3.0	1.5	1.0
TotalHarmonicDistortion	5.0	2.5	1.5

Table 2: Harmonic Voltage Distortion Limits for Nonlinear Loads at the Point of Common Coupling (PCC) (IEEE Standard 519-1992) [26]

Issues	**IEC61727**		**IEEE1547**	
NominalPower	**10kW**		**30kW**	
HarmonicCurrentLimits	**Harmonics(n^{th})**	**THD(%)**	**Harmonics(n^{th})**	**THD(%)**
	3-9	4	3-9	4
	11-15	2	11-15	2
	17-21	1.5	17-21	1.5
	23-33	0.6	23-33	0.6
			>35	0.3
Max.CurrentTHD	5 %		5 %	

Table 3: Standards for Grid Interconnection of PV Systems [25]

CONCLUSION

Power quality issues in renewable energy systems, particularly solar photovoltaic (PV) systems, pose significant challenges for both system designers and utility operators. When a solar PV system is connected to the grid, synchronization requires aligning the inverter's voltage and frequency levels with those of the distribution network. Once synchronized, various power quality problems can arise, including voltage imbalance, low voltage ride-through, sags, swells, flicker, harmonics, and interruptions. This paper outlines different power quality standards, their potential causes, and proposed mitigation strategies. While India is still working to enhance its installed capacity for solar PV projects, the qualitative aspects of solar PV power are currently underdeveloped but are expected to improve with increased public, private, and individual support in the near future

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