

Power Quality in Grid-Connected Solar PV Systems

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INTRODUCTION

1.1 Introduction to Power Quality in Grid-Connected Solar PV Systems

Grid-connected solar photovoltaic (PV) systems have become an attractive choice to fulfil the world's growing energy demands while lowering greenhouse gas emissions in the pursuit of sustainable and clean energy sources. These devices capture the sun's plentiful energy and transform it into electricity that can be connected to the grids that are already in place. The increasing prevalence of solar photovoltaic systems has the potential to completely transform the way humankind produces and uses energy. Nevertheless, there are particular power quality difficulties associated with their integration into the electrical grid [1].

In electrical engineering, the word "power quality" refers to the properties of the electrical power supply, including waveform fidelity, harmonic distortion, frequency control, and voltage stability. Reliability and conformity to established standards are attributes of high-quality power, guaranteeing a steady and uninterrupted supply of electricity [2]. Power quality is a crucial factor to take into account when considering grid-connected solar PV systems because these systems bring variability by nature because of variations in solar irradiation.

If [solar power](#) output variability is not properly controlled, it can result in voltage dips, swells, and frequency deviations due to variables such as cloud cover and the daily availability of sunshine. Such problems with power quality can impair the stability of the electrical grid and interfere with the functioning of delicate electrical equipment [3].

Power quality enhancement is a critical area of focus for grid-connected solar PV systems to maximize benefits and overcome obstacles. To guarantee that the electricity produced by solar PV installations is smoothly integrated with the current grid infrastructure while maintaining high levels of power quality, this entails the development and implementation of technologies, strategies, and standards [4].

This chapter delves into the vital aspects of power quality in grid-connected solar photovoltaic (PV) mechanisms. And introduce the importance of renewable energy integration and discover obstacles such as voltage fluctuations and distortion in harmonics. Also offers an overview of grid-connected

solar PV systems, including their historical growth. highlight the requirement for the reliability of power improvement, scrutinize particular difficulties confronted by grid operators, and emphasize the function of power electronics, especially inverters, in improving power quality. The following section presents an extensive basis for recognizing and dealing with power quality issues in grid-connected solar PV systems.

By dealing with these difficulties and utilizing innovative solutions, can guarantee that grid-connected solar PV systems not only influence an environmentally friendly energy future but also function seamlessly within the electrical grid, maintaining the most stringent requirements of power quality.

1.2 Power Quality

Within the field of electrical engineering, power quality is recognized as a critical component that ensures the flawless and effective functioning of electrical power supply systems. It includes an evaluation of all kinds of electrical properties, including voltage, current, frequency, and waveform. Power quality is essentially the criterion by which an electrical power supply's integrity is assessed [5]. The characteristics of high-quality electricity are its consistency, dependability, and lack of disruptions or variations that could otherwise prevent electrical devices and equipment from operating without any issues.

In this setting, the importance of quality of power takes priority when contemplating the incorporation of grid-connected solar photovoltaic (PV) systems into the larger electrical grid structures. The energy sector is changing as a result of the widespread use of solar PV technology as a clean, sustainable source of electricity. Through the photovoltaic effect, these systems effectively convert sunlight into clean, renewable electrical power, utilizing the sun's limitless energy [6]. Power quality management is crucial because the integration of solar PV systems with the current electrical grid presents a distinct set of opportunities and constraints.

Because grid-connected solar PV systems preserve a significant amount of energy costs and contribute to the reduction of greenhouse gas emissions, they represent a potential step toward a greener future. However, because of its integration with the electrical grid, power quality problems must be carefully considered [7].

1.2.1 Relevance of Power Quality in Renewable Energy Systems

Since renewable energy sources like solar, wind, and hydropower are essential to move toward a more ecologically friendly and sustainable energy landscape, the importance of power quality in these systems cannot be emphasized. The term "power quality" describes the properties of electrical power, such as waveform fidelity, harmonic distortion, frequency control, and voltage stability.

Maintaining excellent power quality is crucial in renewable energy systems for various reasons [8].

1.2.1.1 Grid Integration Challenges

- Renewable energy sources

Renewable energy sources are naturally inconsistent and their results rely on expected factors such as sunlight, wind speed, and water flow. This variability may result in variations in the power output, which may cause problems with power quality if they are not well controlled. Power quality must be carefully taken into account when integrating intermittent renewable energy sources because grids are built for a steady, constant supply of electricity [9].

- Voltage Stability

Sags and swells in voltage can be caused by irregular [power generation](#) from renewable sources. Appliances and other electrical devices may have trouble operating as a result of these voltage fluctuations. To make sure that the provided power is within allowable bounds and doesn't harm delicate equipment, voltage stability must be maintained.

- Frequency Control

Typically, grids run at a particular frequency, such as 50 Hz or 60 Hz. Electrical device operation can be interfered with by variations in the frequency of the power provided. To avoid instability problems, renewable energy systems need to synchronize their output with the grid frequency.

- Harmonic Distortion

The existence of harmonics in the electrical waveform is another aspect of power quality. Harmonics can enter the grid from renewable energy systems, especially those that include power electronics. Overly high harmonics can cause equipment to overheat and cause electromagnetic interference, which lowers the power's overall quality.

- Protection of Grid Infrastructure

Inadequate power quality can cause harm and raise maintenance costs by wearing down grid infrastructure. To maintain the integrity of the electrical system, renewable energy sources must generate high-quality power.

- Consumer Reliability

Consumers are directly impacted by power quality. Variations in voltage or frequency have the potential to cause disturbances in important applications, data centers, and industrial processes. Sustaining such systems' dependability and functionality requires high-quality power [10].

1.2.1.2 Addressing Power Quality in Renewable Energy Systems

This section addresses the power quality of renewable energy systems

- Advanced Inverters

Inverters are essential for transforming DC electricity provided by renewable [energy systems like solar and wind](#) into AC power. Modern inverters are built with features that enhance power quality by regulating voltage and frequency.

- Energy Storage Integration

Batteries and other energy storage devices can mitigate power variations resulting from intermittent renewable energy sources. They improve grid stability and power quality by storing excess energy during times of high generation and releasing it when needed [11].

- Grid-Interactive Controls

Real-time communication and control between renewable energy systems and the grid are made possible by smart grid technologies. Power quality is improved by this bidirectional connection, which enables modifications in renewable energy output to match grid demand.

- Monitoring and Control Systems

Continuous monitoring systems equipped with sensors and analytics can detect deviations in power quality. These systems can automatically adjust the operation of renewable energy sources to maintain power quality within specified limits.

1.3 Significance of Power Quality in Renewable Energy Integration

This section discusses the impact of Solar PV Integration on Grid Quality and Environmental and Economic Benefits of Renewable Energy

1.3.1 Impact of Solar PV Integration on Grid Quality

The term “Impact of Solar PV Integration on Grid Quality” describes how the quality, stability, and dependability of the electrical supply within the electrical grid may be impacted by the integration of solar photovoltaic (PV) systems [12].

- Increased Renewable Generation

The increasing output of renewable energy is facilitated by the integration of solar photovoltaics into the grid. To lessen dependency on [fossil fuels](#) and mitigate climate change, this is essential.

- Intermittent Nature of Solar PV

Solar photovoltaic systems produce power in response to the amount of available sunshine. Because

they only generate power during the day and their production varies depending on the weather, they are by nature intermittent.

The unpredictable and variable nature of this intermittency can affect the quality of the grid.

- Voltage and Frequency Control

To guarantee grid stability and ensure compatibility with electrical equipment, grids are designed to operate within particular voltage and frequency ranges.

Variations in solar PV generation have the potential to impact both the voltage levels and frequency of the grid. Voltage sags can result from sudden drops in solar power (such as those caused by passing clouds), while voltage swells can be caused by quick increases in solar output.

- Voltage Regulation Challenges

When solar PV generation is distributed over a large geographic area, it becomes difficult to keep the voltage within reasonable bounds. When there is a lot of cloud cover, voltage levels in places with high solar PV penetration may drop, which could lead to equipment failures [13].

- Grid Congestion

Grid congestion can happen in areas with significant solar PV systems, particularly during times of high solar generation. Increased line losses and wasteful utilization of the transmission and [distribution systems](#) may arise from this.

- Power Quality Issues

Variability in solar PV generating can result in power quality problems like harmonics and voltage flicker. Fast generation changes can result in voltage flicker, which can flicker lights or other equipment. The sinusoidal waveform of the grid can be distorted by harmonics, which can affect sensitive equipment's ability to operate.

- Grid Resilience

A grid with a high solar PV penetration rate ought to be able to withstand variations in generation. To properly balance supply and demand, this calls for sophisticated grid management systems, energy storage options, and demand-side control.

- Frequency Control

It takes frequency stability for the grid to function. Grid frequency may be impacted by sudden variations in solar PV power. Frequency deviations must be managed by grid operators using techniques like energy storage or load shedding.

- Advanced Grid Control

To facilitate solar PV integration, grid operators are increasingly utilizing sophisticated control systems, such as smart grids. To guarantee power quality and grid stability, these systems allow for real-time grid operation monitoring, control, and optimization.

- Energy Storage Integration

Batteries and other energy storage technologies are being used to store extra solar energy during high solar generating periods and release it when needed. This improves grid quality and evens out fluctuations.

1.3.2 Environmental and Economic Benefits of Renewable Energy

Renewable energy has major positive effects on the environment and the economy, and it is essential for tackling issues like energy security, [climate change](#), and sustainable economic growth.

1.3.2.1 Environmental Benefits

In this section, the Environmental Benefits of Renewable Energy is listed below,

Reduced Greenhouse Gas Emissions

Reducing greenhouse gas emissions is one of renewable energy's most important environmental advantages. Renewable energy sources, such as solar, wind, and hydropower, don't release carbon dioxide (CO₂) or other dangerous pollutants when they generate electricity, in contrast to fossil fuels. By lowering [air pollution](#) and mitigating climate change, this promotes cleaner, healthier habitats [14].

Improved Air Quality

The discharge of air pollutants such as sulfur dioxide (SO₂), nitrogen oxides (NO_x), and particulate matter is reduced when renewable energy sources are used. These pollutants have been associated with acid rain, smog formation, and respiratory ailments. Renewable energy sources enhance public health and air quality by lowering their emissions.

Water Conservation

In contrast to fossil fuel power plants, which need large amounts of water for steam production and cooling, many renewable energy systems use little to no water, such as solar and wind turbines. In areas where there is a water shortage or drought, this water conservation is crucial.

Protection of Ecosystems

renewable energy projects have less of an adverse effect on ecosystems than large-scale mining or fossil fuel extraction. When planned and executed properly, biodiversity and wildlife habitats are protected through careful siting and environmental assessments.

Reduced Land Use

Compared to traditional power facilities, renewable energy solutions often have a smaller land footprint. To reduce the demand for new land, wind turbines and solar panels can coexist alongside farming activities on rooftops or in non-agricultural locations.

Energy Independence

A country's energy security can be improved by investing in renewable energy sources since they lessen dependency on imported fossil fuels, which are prone to price swings and geopolitical unrest. An energy supply that is more reliable and secure comes from locally derived renewables.

1.3.2.2 Economic Benefits

In this section, the Economic Benefits of Renewable Energy is listed below,

Job Creation

The industry of renewable energy has been an important source of job development. It offers possibilities for employment in production, installation, maintenance, research, and advancement. The industry supports a wide range of skill sets and boosts local economies as it expands [15].

Economic Growth

Both urban and rural communities can see economic growth when investments are made in renewable energy projects. Significant capital investments are frequently needed for these initiatives, which boosts the local economy in the areas where they are implemented.

Stable Energy Prices

Renewable sources of energy provide stability in prices as they possibly rely on free and numerous assets like sunlight and wind. Customers and companies may be shielded from the erratic prices of fossil fuels by this steadiness.

Energy Cost Savings

Renewable energy solutions, including rooftop solar panels, can result in long-term energy cost savings for homes and businesses. They lessen or do away with their reliance on the grid and the corresponding utility costs by producing their electricity.

Innovation and Technological Advancement

Innovation and technical breakthroughs in energy storage, grid management, and energy efficiency have been sparked by the rise of renewable energy. These advancements may have wider uses outside the field of renewable energy.

Reduced Health Care Costs

Renewable energy can result in large savings in healthcare costs, which will benefit both individuals and governments, by lowering [air pollution and related health](#) problems like respiratory ailments and early deaths.

1.4 Challenges in Power Quality for Grid-Connected Solar PV Systems

This section offers the Challenges in Power Quality for Grid-Connected Solar PV Systems

1.4.1 Variability and Intermittency of Solar Generation

Nature of Solar Energy

The amount of sunlight available, which fluctuates during the day, season, and location, is a major factor in the production of solar energy. Due to their variability, solar PV systems can only generate power when they are in direct sunlight, which causes generation to fluctuate on a daily and seasonal basis [16].

Intermittency

Cloud cover, shading, and weather conditions may trigger sudden changes in solar generation, even over short periods. The power supply to the grid is made unclear by these sudden variations in output.

Impact on Grid

Grid operators' capacity to successfully balance supply and demand is challenged by variability and intermittency. In the absence of proper forecasting and grid management, abrupt declines in solar generation may result in unstable power systems and the requirement for backup power sources.

Power Quality Degradation

Poor power quality can be caused by voltage fluctuations and harmonic distortion, which can ruin equipment, lower industrial process efficiency, and interfere with operations in vital facilities like data centers and hospitals.

1.4.2 Grid Stability and Resilience Issues

Frequency Deviations

Frequency fluctuations in the grid may result from sudden variations in solar power. These aberrations have the potential to cause blackouts or damage equipment if they are not managed, as they can impact the stability of the entire grid [17].

Voltage Regulation

For grid stability, voltage must be kept within allowable bounds. Voltage-related problems could arise from solar PV systems' inability to provide the required voltage regulation capabilities.

Resilience to Grid Disturbances

Solar PV systems that are connected to the grid need to be built to resist disruptions from the grid, such as voltage spikes, sags, and outages. In the event of grid events, these systems could become unstable if they are not properly protected and controlled.

Synchronization Challenges

Grid-connected inverters have to adjust to the voltage and frequency of the grid. The overall stability of the grid may be impacted by synchronization difficulties caused by variability in solar power.

1.5 Overview of Grid-Connected Solar PV Systems

A typical kind of solar energy generation is grid-connected solar PV systems, sometimes referred to as grid-tied or grid-interconnected systems. Photovoltaic solar panels are the main component of these systems, while there are other important ones as well. These panels, which are usually positioned on rooftops or in ground-mounted arrays, are made to use the photovoltaic effect to collect sunlight and turn it into power. Solar inverters are used to convert this electricity into a form that may be used by homes, businesses, or the grid [18]. The process of converting the direct current (DC) electricity produced by the solar panels into alternating current (AC), the common type of electricity utilized in most buildings and delivered via the electrical grid, is largely dependent on inverters.

The purpose of grid-connected solar PV systems is to link them to the local or regional power grid. Two-way electrical flow is made possible by this connection, which also allows the system to interact dynamically with the grid. The excess power produced by the solar panels is injected into the grid during times of high solar output and plenty of sun. Through methods like net metering, this excess electricity helps the grid and frequently results in credits or compensation for the system operator. On the other hand, power is taken from the grid to supply the urgent power demand when solar generation is insufficient [19]. The seamless connection with the grid guarantees a consistent and

dependable power supply, especially in situations where solar output fluctuates because of external variables like the season or weather.

Grid-connected solar PV systems are essentially integrated parts of the electrical grid rather than independent power sources. They promote grid stability and reliability while also aiding in the production of clean, renewable energy. Additionally, by feeding excess electricity into the grid, companies lessen their reliance on fossil fuels and contribute to the fight against climate change by lowering greenhouse gas emissions linked to the production of electricity. The installation, interconnection, and compensation of grid-connected solar photovoltaic systems can be influenced by regional variations in regulations, policies, and incentives. The grid-connected solar PV system is depicted in Figure 1.1.

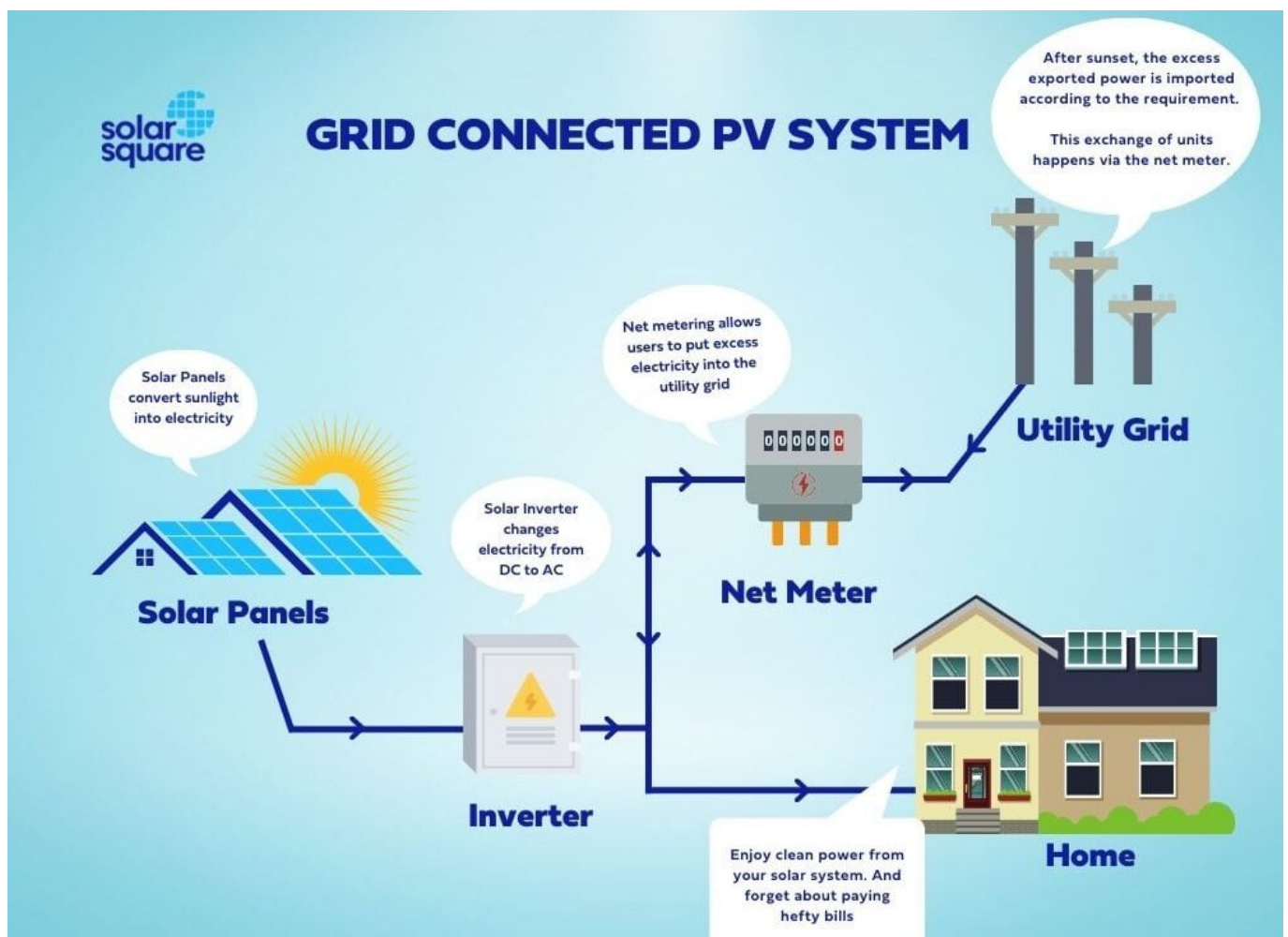


Figure 1.1: Grid-connected Solar PV systems

1.5.1 Advantages

- It does not have expensive upkeep costs.
- Solar energy reduces electricity usage by harnessing sunlight, making installation easy.
- The GCPV structure has a short development time.

- It operates without emitting carbon dioxide.

1.5.2 Disadvantages

- The system relies on a grid for its operation. If the grid malfunctions, the system will cease functioning.
- The cost of installing initially is expensive.
- Models without battery backup cannot supply electricity when there is a power outage [20].

1.6 History and Growth of Solar PV Installations

Over time, the development and history of solar photovoltaic (PV) systems have changed dramatically,

Early Beginnings (19th Century to Mid-20th Century)

The initial identification of the photovoltaic effect by scientists in the 19th century set the groundwork for modern solar PV technology. French physicist Alexandre-Edmond Becquerel noticed in 1839 that some materials generated an electric current when they came into contact with light. However, useful uses for solar PV didn't start to appear until the middle of the 20th century [21].

Emergence of Solar Cells (1950s-1960s)

The first useful solar cells were created in the 1950s and 60s by American researchers at Bell Laboratories using silicon, which went on to become the primary material used in PV technology. The main uses for these early solar cells were in specialized fields, such as satellite and remote communication equipment powering.

Grid-Connected PV (2000s)

The 2000s witnessed a major change toward grid-connected solar PV installations. The solar sector has experienced significant growth due to advancements in technology, improved manufacturing capacity, and favourable legislation and incentives. Installing solar PV systems became financially advantageous for utilities, businesses, and homes thanks to feed-in tariffs and net metering programs.

Rapid Expansion (2010s-2020s)

The solar PV industry had tremendous expansion in the 2010s. Globally, there has been an increase in solar installations due to factors such as declining solar panel prices, increased efficiency, and raised environmental awareness. Distributed solar systems and utility-scale solar farms on residential and commercial rooftops have grown in popularity [22].

Global Impact

Installing solar photovoltaic systems has greatly aided in the shift to cleaner energy sources. Among the renewable energy sources with the greatest rate of growth in the globe is solar energy. Ambitious goals for the adoption of solar energy and the reduction of carbon emissions have resulted from governments, corporations, and individuals realizing the economic and environmental advantages of solar electricity.

Future Prospects

Perovskite solar cells and bifacial panels are two examples of cutting-edge materials and technologies that are being researched as the solar PV industry develops. Batteries and other energy storage technologies are being incorporated with solar power systems to improve dependability and adaptability. Solar PV is anticipated to become more and more important in supplying energy needs and building a sustainable energy future as efforts are made around the globe to mitigate climate change and reduce greenhouse gas emissions.

1.7 Need for Power Quality Improvement in Solar PV Integration

Several important considerations highlight how important it is to address power quality issues in grid-connected solar photovoltaic (PV) systems, which in turn drives the need for power quality enhancement in solar PV integration [23].

Grid Stability and Reliability

The stability and dependability of the electrical system depend on high-quality power. Because solar PV installations are intermittent, the grid may experience voltage variations and frequency aberrations. If these disruptions are not adequately controlled, they may cause system instability and even power outages. To guarantee a consistent and dependable supply of electricity, power quality needs to be enhanced.

Impact on Sensitive Equipment

A lot of contemporary electronics and industrial operations are sensitive to changes in frequency and voltage. Such equipment can be harmed or have its operation disrupted by poor power quality, which is typified by voltage sags, swells, and harmonics. This can result in expensive downtime and repairs. Enhanced power quality protects against these hazards.

Grid Integration Challenges

Combining fluctuating electricity production with variable demand is a challenge when integrating solar PV into the grid. Problems with power quality make these difficulties worse by making it more difficult to efficiently balance supply and demand. To guarantee the seamless and effective

integration of renewable energy sources, power quality issues must be addressed [24].

Environmental Advantages

An essential part of the switch to clean, renewable energy sources is solar photovoltaic systems. Improving the quality of power in these systems boosts the dependability and effectiveness of producing renewable energy. Consequently, this quickens the decrease in greenhouse gas emissions and contributes to the fight against climate change.

Regulatory Compliance

Grid rules and laws that specify acceptable power quality criteria for systems connected to the grid have been established in many nations. Developers and operators of solar PV systems must abide by these standards to guarantee compliance, prevent fines, and limit the amount of energy produced.

Economic Considerations

Businesses and utilities may experience cost savings as a result of improved electricity quality. Solar PV integration becomes more commercially feasible as a result of decreased equipment damage, downtime, and operational disruptions brought on by power quality problems, which eventually benefits investors and customers.

Energy Resilience

Improved power quality plays a role in energy resilience. When fitted with the proper power quality safeguards, solar photovoltaic systems can function in the event of grid disruptions, offering a dependable supply of electricity under difficult circumstances.

Support for Energy Transition

Ensuring sure solar PV systems deliver high-quality power is crucial to gaining the public's trust and support as the world moves toward renewable energy sources. Increased use of sustainable energy is promoted by solar PV installations' dependable and steady power.

1.8 Power Quality Issues Faced by GCPV Systems

While supervising grid-connected equipment, grid operators deal with several power quality problems, such as reactive power imbalance, harmonic distortion, and voltage fluctuations:

1.8.1 Voltage fluctuations and harmonics

Generation of distribution in terms of Solar PV installations can prevent load shedding by reducing distribution system overload. However, incorrect planning, installation, and placement could affect the efficiency of power systems. The inverter's functioning, which is thought to be the biggest source of harmonics, is the key cause of PQ problems in the distribution grid.

Voltage fluctuations

One of the causes of power oscillations in GCPV schemes is the recurrent nature of solar PV. Voltage fluctuations are mostly caused by irregular solar irradiance brought on by passing vapours, the position of the PV connection, and the chosen angle of occurrences/reflections. In the distribution network, these erratic oscillations generate voltage flicker and flicker noise, overcapacity problems, line fatalities, and network fatalities [25].

Harmonics

One of the key effects that must be taken into interpretation while functioning GCPV schemes is harmonic alteration. When utilized to change DC to AC, inverters introduce power and energy harmonics into the scheme, which leads to energy harmonics. Due to the warmness of convertors and condenser groups, the scheme develops more unbalanced and undependable as the number of inverters rises [26].

1.8.2 Voltage imbalances and flicker

Voltage imbalances

PV (photovoltaic) systems experience power imbalances when the solar electricity generated either exceeds or falls short of demand or grid needs. This imbalance can result in problems like excessive power output, which could be too much for the local grid's capacity or demand, or insufficient generation, which would call for backup sources. Furthermore, the unforeseen imbalances caused by solar power's intrinsic fluctuation and intermittency, which are impacted by weather, affect the stability of the grid. A comprehensive strategy including good system design, the integration of energy storage like batteries, and smart grid techniques is essential to reducing these imbalances. To provide a steady and consistent energy supply, it is essential to strike a balance between solar energy generation and consumption [27].

Flicker

Fast and obvious changes in the power supply called flickers are primarily produced by nonlinear loads in the electrical scheme. The power waveform's smoothness is interfered with by nonlinear loads, which are frequently connected to electronics and other nonlinear loads. These fast power shifts can impair the functionality of delicate electronic gadgets and cause noticeable changes in lighting. To provide a constant and steady power supply, flicker reduction entails regulating nonlinear loads and utilizing power conditioning devices [28].

1. Intermittency and variability of solar power generation

Solar power generation in PV (photovoltaic) systems is hampered by intermittency and fluctuation. Due to varying weather, cloud cover, and day-night cycles, solar energy generation is irregular and

unexpected, which is referred to be intermittent. Variability includes the daytime variations in solar power output caused by shifting clouds and other environmental conditions. To maintain a steady and consistent power supply from solar PV systems, especially when demand and grid requirements are constant, both intermittency and variability call for appropriate energy storage technologies and grid integration strategies. For effective use and integration into the larger energy environment, solar power's intermittent and fluctuating characteristics must be balanced [29].

These problems with power quality are especially important when more renewable energy sources, such as solar PV, are integrated. Grid operators must control voltage fluctuations, harmonics, flicker, and imbalance to preserve grid stability, safeguard equipment, and guarantee a dependable and superior power supply to customers. As grid operators strive to create a more sustainable and resilient electrical system, technological advancements and improved grid management strategies are assisting them in addressing these issues [30].

1.9 Role of Power Electronics in Enhancing Power Quality

By addressing several facets of the electrical supply, such as voltage regulation, reactive power compensation, and inverter control, power electronics significantly improve power quality. Their functions in improving the quality of power are explained as follows:

1.9.1 Inverters and Their Control

An essential part of solar PV systems are inverters, which transform the direct current (DC) generated by solar panels into alternating current (AC) that is compatible with the electrical grid. Improving power quality is largely dependent on their control [31].

Frequency and Voltage Control

Inverters have advanced control techniques that allow them to coordinate with the grid's frequency and voltage as well. This contributes to grid stability and quality by guaranteeing that the AC power produced by solar PV systems is in phase and at the appropriate voltage level.

Anti-Islanding Protection

Anti-islanding protection measures built into inverters allow them to recognize and separate from the grid in the event of a disturbance. With the help of this safety feature, solar PV systems won't accidentally operate as independent islands during grid disruptions, which could endanger utility workers' safety and compromise the stability of the grid.

Dynamic Voltage Support

Dynamic voltage support is a feature of certain sophisticated inverters. When voltage variations happen, they can help maintain voltage stability by adding reactive power to the grid or absorbing it.

1.9.2 Reactive Power Compensation

Improving power quality requires reactive power compensation, particularly when reactive power imbalances can be caused by grid-connected renewable energy sources such as solar photovoltaics [32].

Capacitors and Reactors

Capacitors and reactors in power factor correction systems are controlled by power electronics. By guaranteeing that the grid maintains a near-unity power factor, these devices lower line losses and improve overall efficiency. They also supply or absorb reactive power as needed.

Synchronous Condensers

Power electronics are used by synchronous condensers to simulate the actions of synchronous generators. They assist the grid with reactive power and aid in maintaining voltage stability when there are disruptions in the grid.

1.9.3 Voltage Regulation Techniques

Power quality requires constant voltage levels to be maintained. Numerous methods of voltage regulation include power electronics [33].

Voltage Regulators

Voltage regulators that use power electronics can change voltage levels instantly. When a voltage deviation is detected, these devices automatically alter reactor impedance or control transformer taps to maintain the desired voltage.

Voltage Sag and Swell Mitigation

By injecting or absorbing actual and reactive power as needed, inverters with superior control capabilities can help alleviate voltage sags (reductions) and swells (increases). This feature is especially beneficial in places where solar PV is widely used.

To improve power quality, power electronics such as inverters and reactive power correction devices are crucial. They guarantee the smooth integration of solar PV systems and other renewable energy sources with the grid, preserving consistent voltage and frequency, supporting reactive power, and enhancing the general quality and dependability of the grid. To maintain a strong and reliable electrical infrastructure while utilizing clean energy sources to their maximum potential, these technologies are essential.

1.10 Advanced Technologies for Power Quality Improvement

Customers are responsible for the excellence of the power energy they receive from the utility, and the energy circulation supplier is accountable for the PQ. Transients, short-duration differences, long-duration differences, and waveform alterations are the four categories used to classify electromagnetic phenomena that influence the power PQ of systems. [34].

1.10.1 Maximum Power Point Tracking (MPPT) Techniques

To maximize the energy from SPV cells, the MPPT method is employed. Researchers have proposed several different MPPT scheme types, including exposed trip, short trip, perturb and observe (P&O)/hill climbing, incremental conductance, and others [35]. While the P&O and incremental conductance approaches iteratively perturb the functioning point to track the MPP, the exposed trip and short trip methods identify the MPP by studying the extremes of the I-V curve. These MPPT methods are essential for increasing the effectiveness and energy output of solar PV systems and promoting the wider utilization of RES. To further enhance the competence and cost-effectiveness of solar power generation, researchers are constantly modifying and innovating MPPT systems [36].

1.10.2 Grid synchronization methods

Figure 1.2 shows the Synchronization Techniques of the Grid

Synchronization Techniques

Single phase

Three phases

Open loop

Closed loop

Open loop

Closed loop

- ZCD
- ANF
- KAMAN
- WLSE
- DFT
- Classical single phase PLL

- FLL
- ANF
- SRF-PLL
- FLL
- ANF
- DFT
- LPF Based
- KALMAN
- WLSE
- SVF

Figure 1.2: Synchronization Techniques

According to control research, the most important characteristics that must be measured and managed for grid-tied applications are voltage's frequency, phase, and amplitude [37].

Synchronization is a major issue in the operation of grid-tied inverters. Both open-loop and closed-loop approaches are used. Input signal characteristics can be immediately detected using open-loop approaches, whereas phase errors are said to be reduced using closed-loop techniques. A feedback loop mechanism in a closed loop system updates the projected charge of the stage as needed. This loop fixes the sign's estimated value to its real charge. Likened to open-loop methods, closed-loop methods are preferable. The phase-locked loop (PLL) technique is a well-liked technique for producing orientation power in closed-loop systems. A PLL is a device that produces output signals whose phases are related to their input signals. In noisy communications channels, it is frequently used to modulate, demodulate, filter, or recover a signal. A PLL is a non-linear feedback switch system that upholds a constant minimum phase error(s) while freezing its yield sign to the input sign. Phase-detector (PD), loop-filter (LF), and voltage-controlled oscillator (VCO) make up the PLL block diagram. Even though certain new approaches have been studied in the literature and proven to achieve improvements to outmoded PLL, PLL is still well-liked for its dependability and simplicity [38].

1.10.3 Selective harmonic elimination (SHE)

The output power from two or more inverters is successfully blended utilizing transformer connections in the selective harmonic reduction approach. When these inverters' switching patterns and phases are precisely coordinated, the total output shows a markedly lower harmonic content than the voltages from the separate inverters. Each inverter's harmonics tend to cancel one another out or add together in a way that dramatically reduces the undesired harmonics, producing a cleaner and smoother output waveform. This method helps to improve power quality by ensuring that the total output voltage is more sinusoidal and in compliance with grid specifications, hence reducing the possibility of system interruptions or interference [39].

1.10.4 FACTS (Flexible AC Transmission Systems)

The term "Flexible AC Transmission Systems" refers to a collection of tools utilized to get around

some restrictions on the capacity of electrical networks for static and dynamic transmission. According to the IEEE, FACTS are irregular power communication schemes that incorporate static controllers based on energy semiconductor technology and other technologies to enhance the switch and energy allocation capabilities. These systems' major objective is to deliver the system with inductive or capacitive sensitive energy that is personalized to its exact requirements as rapidly as possible, while also enhancing spread superiority and the effectiveness of the energy transmission system. energy businesses will be able to more effectively use their current communication systems thanks to FACTS, which will also significantly grow the obtainability and dependability of their line systems and enhance both lively and fleeting system constancy while confirming a higher standard of stream [40]. The common features of FACT are as follows,

- Dissolute power rule,
- Improved energy transmission over long AC lines,
- Checking of vigorous energy fluctuations, and
- Load movement regulator in meshed schemes,

1.10.5 SVC (Static Var Compensators)

An SVC is a similar assembly of the immovable shunt capacitor and controlled reactor depicted in the image below. The device is managed by the thyristor switch gathering in the SVC. The power across the inductor, and consequently the power elegant via the inductor, are measured by the thyristor's firing angle. The inductor's sensitive energy draw can be managed in this method. The SVC may steplessly adjust reactive power over an infinite range without experiencing any delay. It raises the system's power factor and stability. The following SVC schemes are the most popular ones. TCR: Thyristor-controlled reactor Capacitor with a thyristor switch (TSC) SR: Self Reactor, Fixed capacitor thyristor-controlled reactor (TCR-FC), TSC-TCR stands for thyristor-switched capacitor - thyristor controlled reactor. The advantages of SVS are,

- It improved the transmission lines' ability to transmit power.
- It increased the system's transient stability.
- Both the steady state and transient overvoltage were within its control.
- As a result, line losses were decreased and system capability was increased. It also enhanced the load power factor. The Static Var Compensators shown in Figure 1.3.

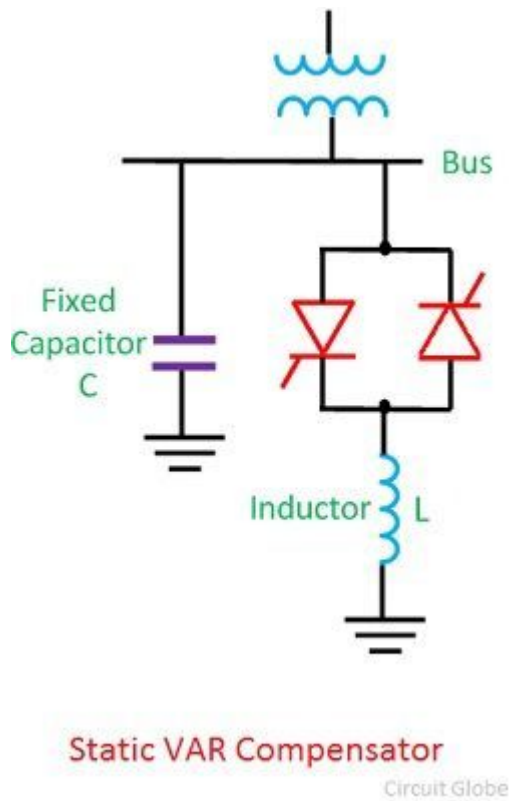


Figure 1.3: SVC

1.10.6 Static Synchronous Series Compensator (SSSC)

A power basis missioner is utilized in the SSSC, a contemporary PQ, FACTS device, which is coupled in sequence to a communication stripe via a modifier. The SSSC functions as a sequence condenser and inductance with variable capacitance. The main distinction is that its vaccinated power can be controlled independently and is not reliant on the line intensity. This characteristic enables the SSSC to function successfully under both heavy and light loads. Three fundamental parts make up the SSSC: The primary component, is the voltage source converter (VSC). The modifier connects the SSSC to the communication link. The power source supplies power crosswise to the DC condenser and makes up for trick sufferers. The Static Synchronous Series Compensator is shown in Figure 1.4.

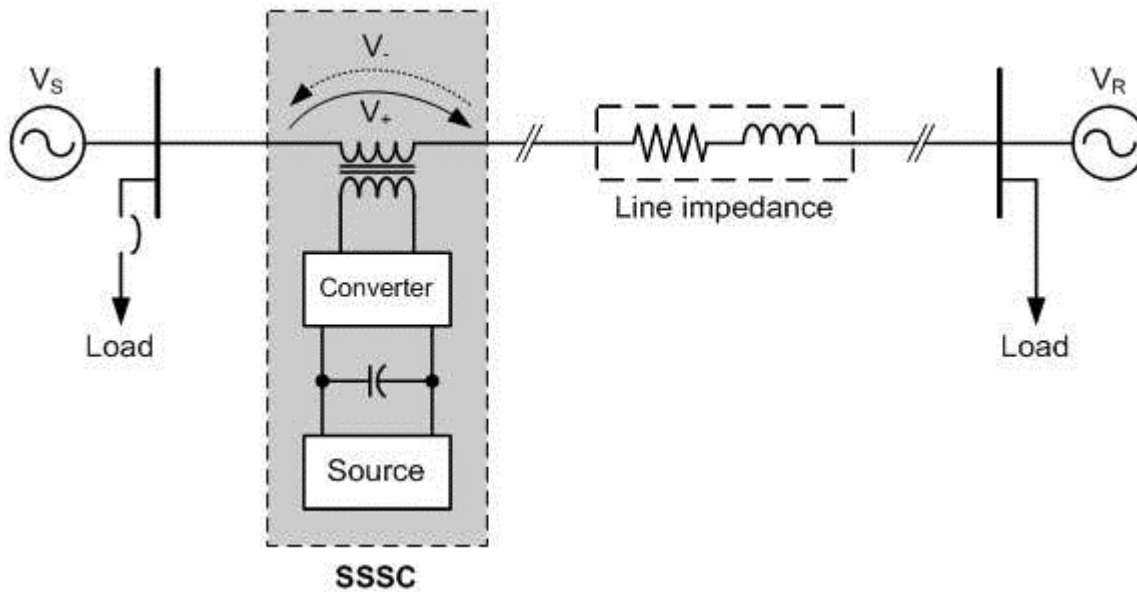


Figure 1.4: SSSC

Typically, the SSSC is used to restore voltage when there is a power system fault. However, it also offers several benefits in typical circumstances:

- Power factor adjustment using a correctly designed controller in conjunction with continuous voltage injection.
- Distribution networks with connections that balance load.
- use active filtering to reduce harmonic distortion.
- power flow management.

1.11 Problem statement

[28] covers the incorporation of RES into the grid, PQ difficulties connected to these issues, the part of energy electrical strategies, and FACTS. Due to its high production and installation costs, PV technology confronts difficulties that prevent its mainstream adoption. Additionally, despite progress, PV system efficiency is still insufficient to fully convert solar energy. For solar energy solutions to become more sustainable and affordable, these obstacles must be removed. [39] The unexpected and variable nature of renewable energy sources makes it difficult to maintain power quality and stability when they are integrated into the utility grid. The type of control algorithms utilized affects how well DFACTS devices work, including DSTATCOM and DVR, which are used to reduce power quality issues. [40] The proposed research project has been simulated in MATLAB and modelled and managed using ANFIS intelligence. Voltage fluctuations and protection issues may result from the distributed AC power grid's integration of renewable energy sources, which may provide difficulties for the utility grid's dependability and power quality.

1.12 Motivation of the study

The research on Power Quality Enhancement for Grid-Connected Solar PV Systems is driven by the increasing need to mitigate climate change and shift to cleaner energy sources worldwide. One of these sources is solar photovoltaic (PV) systems. The increasing number of solar PV systems poses substantial issues for power quality when integrating this variable energy source into the electrical grid. Variability, voltage swings, harmonic distortion, and grid instability can impair sensitive equipment, affect grid reliability, and make it more difficult to effectively use renewable energy sources. The project is motivated by the pressing need to create novel approaches and plans of action to improve grid-connected solar PV systems' power quality. This will enable the systems to be seamlessly integrated into the grid, support energy transition objectives, and promote a resilient and sustainable energy future.

1.13 Objective of the study

To employ a FOPID controller to enhance the active response of GCSS that are voltage and current harmonic regulated. Further discussed the issue of harmonics in power systems brought on by nonlinear loads and suggested using active filters to reduce current and voltage harmonics. To suggest the RNN as a control technique for the PV-integrated distribution grid. The study's main goals were to minimize THD and provide the most energy possible to the grid side VSC, to create a composite controller capable of synchronizing PV systems with the grid while allowing for bidirectional power flow, and to trial the efficiency of this supervisor using a MATLAB Simulink model. Additionally, evaluate how well RL and LCL filters with the DQ controller perform in reducing PQ difficulties in GCPV systems.

1.14 Contribution of this study

Active filters are a tool designed to address the harmonic issue in power systems brought on by the nonlinear load. The FOPID controller generates and controls inverter switching pulses using a voltage source. Harmonics in current and voltage are reduced using active filters. To determine the properties of energetic sifters utilizing PI and FOPID, simulation results are presented. This research suggests a procedure called RNN for the switch of the PV combined circulation grid scheme to increase the efficiency of the PV integrated distribution grid. The VSC is controlled by this algorithm, which aims to solve power quality issues like load balancing and harmonic abatement. This method aims to provide the grid-side VSC with the most power possible. It is necessary to stabilize the PV scheme integration with the electrical grid. To resolve this issue, this study introduces a composite controller that can synchronize PV systems with the grid and allow for bidirectional power flow in the grid. Both RL and LCL filters are used to investigate the suggested method. A control loop for power quality disturbance reduction is modelled with grid harmonization of PV energy origination. On the grid-connected converter, PQ disruptions are condensed utilizing the multicarrier SVPWM with a DQ controller. The PV Grid configuration is demonstrated utilizing MATLAB Simulink, and the reliability of the composite controller is assessed. The PI controllers are used in the grid-integrated, DQ-controlled PV. criteria for power quality. Both RL and LCL filters are found to have intact THD.

1.15 Thesis Organisation

This thesis's first chapter introduces power quality in grid-connected solar PV systems and discusses its importance for integrating renewable energy sources. and discusses the need for improving power quality in solar PV integration, outlines the problems with power quality that grid operators face, examines the challenges it presents, gives an overview of grid-connected solar PV systems, looks at the history and growth of solar PV installations, and emphasizes the role of power electronics in improving power quality and its consideration of the problem statement of the existing works. Furthermore, the study's motivation, objectives, and contribution are discussed.

Chapter 2 discusses the literature review of existing works and their advantages, disadvantages.

Chapter 3, examines the proposed methodology and presents the results of "Improved dynamic response of voltage and current Harmonic controlled photovoltaic with grid-connected system using FOPID"

Chapter 4, discusses the proposed methodology and represents the results of "Adaptive Control of Grid-Integrated Photovoltaic Using a Recurrent Neural Network"

Chapter 5, discusses the proposed methodology and shows the results of "Power Quality Improvement [Grid Integrated Photovoltaic](#) with LCL Filter Using DQ Controller"

Finally, the thesis concludes in chapter 6 and discusses the future scopes of the study.

1.16 Summary

The usage of GCPV schemes in a variety of situations, including residences, businesses, factories, and educational institutions, is covered in this article. Along with a review of the literature, the report also covered the study's inspiration, goals, and contributions. It explained the details of the results and suggested techniques for each chapter of the study. Future horizons are discussed as the thesis comes to a close. The key aspects of power quality in grid-connected solar PV systems were covered in detail in that chapter. The concept's importance in integrating renewable energy sources was discussed, along with difficulties like harmonic distortion and voltage swings. An introduction to grid-connected photovoltaic systems was given, along with a history of their expansion. The necessity of improving power quality was underlined, along with the particular difficulties grid operators have and the contribution of power electronics, particularly inverters, to improving power quality. A thorough basis for comprehending and resolving power quality problems in grid-connected solar PV systems

was provided in this chapter.

By tackling these obstacles and utilizing creative approaches, the purpose was to guarantee that grid-connected solar PV systems not only influenced environmentally conscious energy in the future but also functioned seamlessly within the electrical grid, maintaining the highest possible standards of power quality.

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