

# Enhanced Power Quality Solar PV Energy Generation System Integrated with a Three-Phase Grid

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**Abstract:** Advances in power electronics and the demand for renewable energy globally have paved the way for the integration of solar photovoltaic systems into three-phase grids. Enhancing power quality (PQ) strategies for solar PV systems integrated into three-phase grids is a significant concern, focusing on overcoming technical issues such as voltage unbalance, harmonic distortion, and reactive power management. Solutions such as smart control algorithms and Distributed Flexible AC Transmission Systems/DFACTS combined with energy storage technologies are critically discussed in addressing power quality mitigation and ensuring grid reliabilities. Of course, combining solar PV generation with wind would be beneficial mainly because of these complementary generation activities and stability conditions. This study is an overview of improvement techniques for PQ, underlining the importance of custom power devices, advanced control strategies, and innovative technologies, such as the solid-state transformer, for building sustainable and efficient energy systems.

**Keywords:** Solar PV integration, three-phase grid, power quality improvement, custom power devices, hybrid renewable systems, solid-state transformers.

## I. INTRODUCTION

The use of alternative energy supplies is being promoted by rising energy demand, global environmental concerns, and ongoing advancements in renewable energy technologies. Of all the long-term natural resources available today, solar energy is the most plentiful and reasonably priced. By converting sunlight into direct current in solar cells, or PV cells, solar PV technology is one of the best ways to use solar power to create electricity. Devices based on electronic semiconductors, namely but not only crystalline silicon (c-Si) or thin-film semiconductor materials, are used in PV energy conversion. Monocrystalline and multicrystalline solar modules are the two primary forms of crystalline materials that are often used to build a (c-Si) based solar system. Crystal semiconductors are comparable to polycrystalline materials in terms of their higher electrical properties (20% efficiency). However, because crystalline

wafer-based technology is too costly, monocrystalline PV modules are not cost-effective [1].

When compared to electricity generated from traditional energy sources, solar energy systems-including solar thermal and photovoltaic (PV) technologies-offer notable environmental benefits. Environmental and socioeconomic benefits are the two basic categories into which the advantages of installing and running solar energy systems may be generally divided. There are many benefits to solar energy systems from an environmental standpoint. These include lowering emissions of harmful gases like sulfur dioxide (SO<sub>2</sub>) and particulates, as well as greenhouse gases (GHGs), mainly carbon dioxide (CO<sub>2</sub>) and nitrogen oxides (NO<sub>x</sub>). Furthermore, solar systems help restore degraded land, reduce the need for lengthy transmission lines in the electrical grid, and enhance the quality of water supplies. Socioeconomically speaking, solar technologies promote self-sufficiency by increasing regional and national energy independence. Additionally, they support the establishment of new production activities, push the reorganization of energy markets through the adoption of new technologies, and provide job possibilities. Additional benefits include the stabilization and diversity of energy sources, the quicker electrification of remote and rural areas, and the preservation of foreign exchange by lowering dependency on imported fuels. Collectively, these economical and environmental advantages demonstrate how solar energy technologies might revolutionize sustainable development [2].

As a result, the energy industry, which has historically developed slowly, has experienced significant changes in recent years. DGs and microgrids significantly alter conventional power networks, albeit still making up a comparatively modest percentage of the world's energy mix. Energy systems, in general, are changing significantly in a number of ways. These include a shift in grid infrastructure, with microgrids emerging as new alternatives to traditional distribution systems to improve integration; a change in consumption patterns with new 17 loads, such as energy-saving lighting systems; and a shift from centralized to decentralized generation, which is primarily leaning towards renewables. Microgrids have various drawbacks, despite recent developments showing their promise. Their

low rotational inertia is a major disadvantage. Furthermore, power systems may experience fluctuations in voltage and current due to the growing integration of DGs into utility grids. Maintaining sufficient power levels, also known as power quality, is one of the primary technical obstacles to DG integration into utility networks [3]. Microprocessors and power electronics components are essential to the development of smart gadgets and systems in both home and business settings, as well as nonlinear loads. These devices cause power quality (PQ) issues in the electric power distribution system because of their nonlinear V-I characteristics, but they are also sensitive to the PQ level. Even revenue meters that measure electrical quantities could not be sufficiently resistant to the damage caused by disruptive devices when it comes to electrical energy billing. PQ monitoring is crucial for enhancing the performance of end-user loads and power system equipment due to the increased integration of nonlinear components. Therefore, in addition to utilities, end users, manufacturers, researchers, and engineers are also accountable for PQ disturbances [4].

## II. SOLAR PV ENERGY

Solar PV (SPV) systems or concentrating solar-thermal power (CSP) systems that power traditional turbines are two ways to generate electricity from the sun, as illustrated in Fig. 1. PV power generation systems are commended for their low maintenance costs, low operating costs, and environmental friendliness.

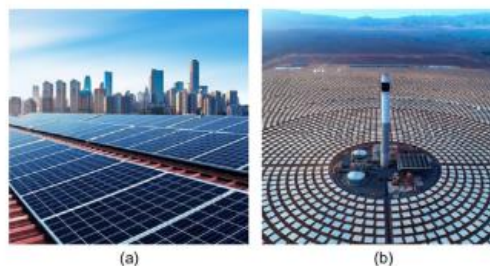


Fig.1 the two primary categories of solar energy systems are (a) SPV and (b) CSP [5]

PV systems, particularly grid-connected ones, have been promoted in many nations because to their potential medium- and long-term economic benefits, despite the high cost of solar panels. The PV business has grown

quickly as a result of certain nations' implementation of alluring financial schemes, including as feed-in tariffs and subsidized policies.

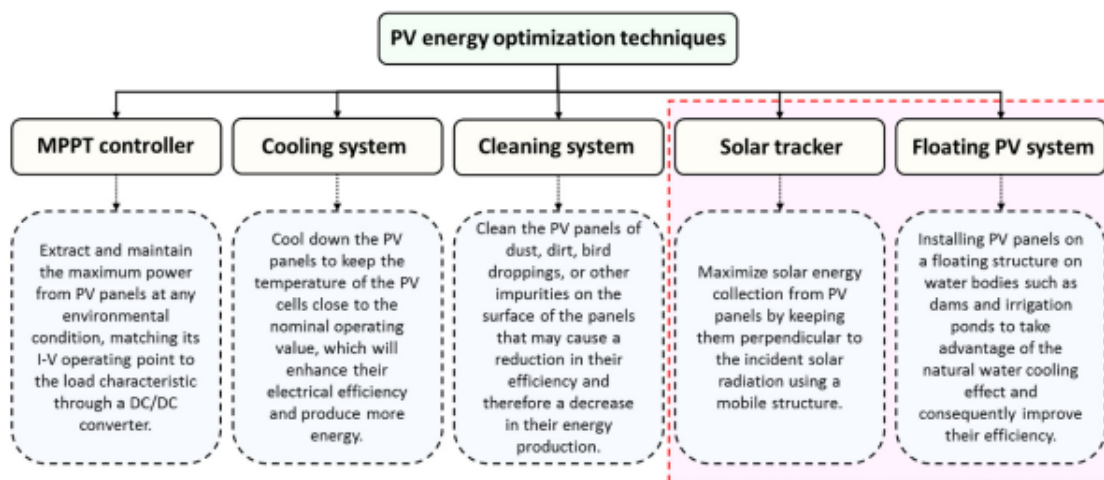


Fig.2 the most popular methods for maximizing PV systems' power output.

This fig.2 highlights key PV energy optimization techniques aimed at enhancing the efficiency of solar photovoltaic systems. These include MPPT controllers that maximize power extraction at different conditions; cooling systems reduce panel temperature and, therefore, enhance efficiency; cleaning systems ensure the removal of dirt and impurities to avoid energy loss; solar trackers position panels to allow the absorption of as much solar radiation as possible; and floating PV systems exploit water bodies to achieve natural cooling and enhance performance. All these methods guarantee higher energy output and reliable systems.

Three basic types of Solar PV and storage systems exist depending on the type of operational configurations they take. The Grid-Tied or Grid-Direct PV System connects directly to the electrical grid; it feeds the excess energy into the grid, but when there is insufficient production by the solar PV, it draws power from the grid. The Off-Grid PV System is one that is independent of the grid, using only solar energy and battery storage to fulfil energy needs, which makes it perfect for remote or isolated areas. Lastly, the Grid/Hybrid or Grid-Interaction System with Energy Storage combines features of both grid-tied and off-grid

systems, allowing energy storage for backup during outages while still interacting with the grid for energy supply or surplus management. Grid-tied solar PV systems with a conventional inverter are relatively cheap, easy, and maintenance-free for generating electricity during the day without storage. Excess electricity can be sold back to the grid to offset energy expenses; however, it cannot be stored for future use or outages. Off-grid systems contain batteries for electricity storage during emergencies, at night, or adverse weather conditions. These systems are good for remote locations but are costlier and require backup generators for extended low-sunlight periods. Hybrid systems combine features of both, offering grid connectivity with battery storage for backup during outages and peak demand, lowering utility bills while ensuring energy reliability [6].

### III. FUNDAMENTALS OF POWER QUALITY

Because it can handle load and grid difficulties at the same time, the unified power quality conditioner (UPQC) has become a popular active compensating solution for PQ-related problems. In a back-to-back arrangement, a series and a shunt converter coupled to the same DC bus create the UPQC. Both converters serve as the conventional shunt and series active power filters (APFs) in its conventional control scheme. As a result, power factor correction and the reduction of non-linear load harmonic current circulation in distribution grids are two applications for the shunt APF (shAPF). The series APF (srAPF), on the other hand, can be used to correct for voltage sags and swells in the voltage source and to remove harmonic voltage components. It is often connected to the grid via coupling transformers. As an alternative, the UPQC has a dual-control architecture called the iUPQC. There are two primary distinctions between the two setups from the perspective of implementation. Initially, the variables that the APFs regulate are inverted: the shAPF is voltage-controlled and directly applies a sinusoidal voltage to the load bus, while the srAPF is current-controlled and necessitates that the source current be the only active component of the fundamental frequency load current. By forcing sinusoidal balanced load voltages through the shAPF control, the srAPF indirectly compensates for the source voltages' harmonic distortion, imbalance, and sags or swells. In addition, the srAPF forces the shAPF to supply the load's reactive power requirement and current harmonic components by blocking them. The second difference is how the APF is used to establish its position.

The shAPF needs to be at the load side of the iUPQC, and the srAPF needs to be attached to the grid side [7]. The aggregate impact on feeder power quality has become a major problem for utilities when a big number of these gadgets are operating in power distribution systems. Over the past few decades, a number of theoretical models and simulations of nonlinear loads have been carried out in order to forecast the injection of harmonic current into the electrical grid and to adopt compensatory techniques. The quantity of injected harmonic pollutions from a group of

nonlinear loads of the same type running simultaneously can be predicted by scaling the typical harmonic current spectrum of one load proportionately to the overall load power [8]. The growth of nonlinear loads and their combined effect on power quality are posing an increasing threat to contemporary power distribution systems. Nonlinear loads inject harmonic currents into the utility grid, which degrades power quality, and leads to problems such as voltage distortion, equipment inefficiencies, and interference with sensitive systems. Predictive models for harmonic pollution have been designed to calculate the total harmonic current injection of several nonlinear loads in terms of the scaling of individual harmonic spectra to the total power of loads. These models assist in the designing of an efficient compensation strategy against harmonic pollution. Although conventional methods of harmonic suppression, such as passive filters, are well adopted, the weaknesses of passive filters, like grid impedance dependency and resonance, create a necessity for advanced solutions. APFs and UPQCs, therefore, deal with these challenges by dynamically suppressing harmonics, compensating reactive power, and mitigating voltage sags and swells. In addition, new developments in APF configurations, such as dual-control strategies like iUPQC, have provided flexible and efficient options for improving power quality. These systems not only improve the reliability of the grid but also reduce the collective impact of nonlinear load harmonics on the distribution network [9].

Improving power quality is necessary because poor PQ has adverse effects, such as device malfunction, power losses, reduced efficiency, and communication interference. Nonlinear loads, including adjustable-speed drives and SMPS, inject harmonics into power systems, which cause voltage distortion, overheating, reduced equipment lifespan, and operational losses. Traditional solutions, such as passive filters, are limited by fixed compensation and resonance risks, while APFs offer dynamic harmonic suppression but are costly. Hybrid Active Power Filters (HAPFs) provide a more economical alternative for mitigating nonlinear load distortions. Advanced solutions such as UPQCs and iUPQC systems further enhance PQ management by addressing harmonic pollution, voltage disturbances, and reactive power imbalances, ensuring reliable and efficient power systems [10].

### IV. THREE-PHASE POWER SYSTEMS

Three-phase power systems face a number of difficult issues, such as load-side imbalanced voltages. The electrical system's power quality is typically deteriorated by voltage imbalance. As a result, power quality issues cost the US economy anywhere from \$15 to \$24 billion annually. The extensive usage of photovoltaic (PV) systems, battery storage units, and electric vehicle (EV) charging stations in contemporary structures exacerbates the issue of voltage imbalance. Additionally, uneven voltages are typically the result of electrical equipment breakdowns in power distribution systems. Generally speaking, either imbalanced loads or network topology asymmetries cause voltage

imbalance in electrical power systems. The primary source of imbalanced voltages in the majority of real-world situations is the uncontrolled distribution of loads. Unbalanced voltages are then produced at the load side as a result of the three lines between the generator and the load having varying volt-amperes. It is not always feasible to maintain balanced voltages at the load side. This is because the loads are often connected and disconnected, and the distribution of loads among the three phases is not uniform [11].

When the efficiency and smooth functioning of three-phase power systems outweigh the cost, they are frequently used in commercial and industrial settings, especially for powering huge motors in heavy machinery or commercial equipment like ventilation and refrigeration systems. In order to manage phase imbalances, these motors link to three-phase terminals and a neutral via three windings that form balanced circuits. On the other hand, as seen in Fig. 3, single-phase service with conventional 120-V outlets is usually used by residential and small commercial clients. These outlets are made up of a safety ground, a neutral terminal, and a phase (hot) terminal. In relation to the neutral, which is grounded for safety and to reduce voltage fluctuations, the phase provides an alternating voltage of 120 V rms. By connecting to the earth, typically via building

water pipes, the ground terminal is an essential safety component intended to reduce the risk of shock and fire during electrical faults. Avoiding or altering proper grounding might make things more dangerous. In contrast to three-phase systems, utility services provide wiring for 240 V or 208 V appliances by supplying one neutral and two phase conductors. While upholding safety and efficiency standards, these configurations guarantee compatibility with a range of residential and commercial electrical requirements.

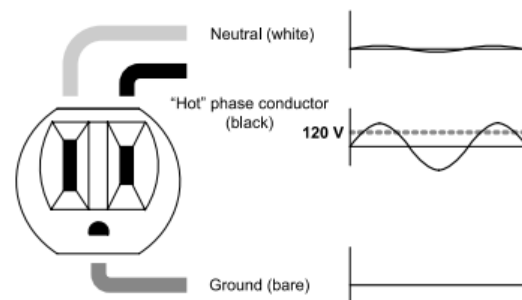


Fig.3 Standard electrical outlet [12]

Addressing the problem of voltage unbalance in three-phase power systems is essential to maintaining optimal power quality and system performance. Advanced solutions include voltage regulation equipment, dynamic balancing devices, and smart grid technologies. These will be implemented in mitigating the adverse effects of unbalanced loads and network asymmetries. Integration of renewable energy sources like photovoltaic (PVs) and battery storage systems adds complexity to modern power systems but presents an opportunity to improve voltage stability. There is an increasing need for load forecasting, adaptive load management, and phase rebalancing in an effort to reduce the difficulties presented by frequent changes in load and uneven distribution. The balanced voltage is ensured through real-time monitoring and control of the intelligent distribution system while reducing losses and equipment malfunctioning. These developments contribute toward a more efficient and reliable three-phase power system that can answer the needs of modern energy consumption [13].

## V. INTEGRATION OF SOLAR PV WITH THE GRID

The rapid expansion of PV power generation is made possible by rigorous research into improving PV cell efficiency, lowering the cost of PV panels, and maximizing power extraction from PV systems. Furthermore, by reducing the usage of fossil fuels without sacrificing the necessary load demand, these clean and environmentally friendly power production options significantly contribute to the reduction of GHG emissions. However, the efficiency, dependability, and safety of the PV integration

into the grid are hampered by the variable generation property as well as other technical and protection-related problems. Integrating solar PV sources into the AC grid enhances reliability but poses significant power quality (PQ) challenges due to the intermittent nature of solar energy and the low strength of rural grids. Common PQ issues include voltage sag, voltage swell, transients, flickers, harmonics, power factor variations, and reactive power imbalances. To address these challenges, Distributed Flexible AC Transmission System (DFACTS) devices are deployed at the point of common coupling (PCC) with advanced control algorithms. These devices, classified into shunt (e.g., DSTATCOM, DSVC), series (e.g., DSSC, DVR), shunt-series (e.g., UPQC, DTCSC), and series-series (e.g., IPFC) configurations, improve grid stability by dynamically adjusting parameters such as voltage, impedance, and active/reactive power.

The control algorithms that are employed have a significant impact on the performance of DFACTS devices. The limitations of conventional algorithms, which are based on theories such as Instantaneous Reactive Power Theory (IRPT) and Synchronous Reference Frame Theory (SRFT), include diminished stability, slower dynamic response, and computational complexity. Although they need sophisticated hardware and software, AI-based methods get around these problems by using machine learning and deep learning approaches to deliver precise PQ mitigation. Solar PV systems benefit greatly from adaptive control algorithms, such as those that use least mean square (LMS) and its variants, which provide enhanced dynamic response, stability, and adaptivity to environmental changes [14] [15].

Faults in the solar PV plant, especially on large-scale systems, can either be on the AC or DC side. However, AC faults are more often associated with issues related to the grid, like phase-to-ground, phase-to-phase, double phase-to-ground, or three-phase-to-ground faults. Grid faults lead to power quality problems, such as voltage fluctuations, power factor reduction, and harmonic distortion, thereby limiting the integration and performance of solar PV plants in grid networks. In addition, islanding conditions are another factor affecting the efficiency and reliability of the grid-connected PV system. Although smart inverters are able to sense AC side faults and shut down, which helps operators take remedial actions, DC side faults are usually missed by the protection systems. Therefore, there are unnoticed energy losses and prolonged periods of inefficiency in operation. Some common faults on the DC side are faulty PV modules, which result in short circuits, faulty PV strings that may be open circuit, and partial shading or soiling on the strings. Partial shading occurs when some irradiance affects specific strings, reducing power output, and the effect is similar to soiling. Detecting and mitigating such faults is critical to the reliability and efficiency of solar PV plants [16].

Hybrid power generation systems, combining solar PV and wind energy, have gained significant attention due to their economic and eco-friendly benefits. These systems offer enhanced grid stability by leveraging the complementary nature of solar and wind energy production. Solar power generation peaks during the day and in summer, while wind energy production is typically higher at night and during winter. This complementarity addresses seasonal and daily variations in renewable energy availability, making hybrid systems a promising solution for reliable power generation. However, integrating these systems into the grid introduces challenges related to power quality, reliability, and stability. Electrical Energy Storage Systems (EESSs) play a critical role in mitigating these issues by balancing fluctuations in power generation and ensuring a stable energy supply. EESSs, such as supercapacitor, batteries, flywheels, and superconducting magnetic energy storage (SMES), can store energy during periods of excess generation and release it when demand is high or other sources are unavailable. These systems provide an effective approach to addressing the intermittency and variability of renewable energy sources, ensuring grid reliability and stability in hybrid systems [17].

Table 1 Single-Phase vs. Three-Phase vs. Enhanced Solar PV with Three-Phase Grid

Features and Characteristics	Single-Phase System	Three-Phase System	Enhanced Solar PV with Three-Phase Grid
<b>System Configuration</b>	Limited to residential and small loads	Suitable for industrial and heavy loads	Combines three-phase stability with solar PV integration
<b>Voltage Stability</b>	Prone to imbalances and drops	More stable with balanced loads	Improved with devices like DSTATCOM and DVR
<b>Harmonics</b>	Higher harmonic distortion	Lower harmonics in balanced configurations	Actively mitigated with custom power devices
<b>Reactive Power</b>	Minimal management	Better reactive power handling	Enhanced with UPQC and AI-based algorithms
<b>Integration Challenges</b>	Limited capacity for renewable integration	Supports moderate renewable penetration	Optimized for high solar PV penetration and ESS use
<b>Mitigation Devices</b>	Basic (filters, UPS)	Advanced (custom power devices)	Includes SSTs, DFACTS, and hybrid control systems
<b>Renewable Intermittency</b>	Difficult to manage	Moderate flexibility	Mitigated with hybrid systems and ESS
<b>Control Algorithms</b>	Conventional (slow response)	Basic AI-based controls	Advanced adaptive and AI-based control algorithms
<b>Fault Management</b>	Limited detection and isolation capabilities	Moderate fault response	Enhanced with fast-acting SSTs and dynamic reconfiguration

## VI. POWER QUALITY IMPROVEMENT TECHNIQUES

Power quality problems can be defined as the difference between the quality of power supplied and the quality of power required for reliable operation of the load equipment. Several types of power enhancement devices have been developed over the years to protect equipment from power disturbances. Some of the effective and economic measures can be identified as following: i) Power conditioning devices ii) Custom power devices. Power conditioning

devices are essential for protecting electrical systems and sensitive equipment from power disturbances. Lightning and surge arrestors safeguard transformers from surges but are insufficient for protecting sensitive electronics. Transient Voltage Surge Capacitors (TVSC) clamp voltage spikes to safe levels, providing comprehensive transient protection. Filters are designed to block high-frequency noise, such as electromagnetic and radio frequency interference, and harmonics filters prevent harmonic distortion from reaching power sources. Isolation transformers offer noise reduction and isolation through

magnetic separation but do not address power outages or voltage fluctuations.

Despite changes in the input, voltage regulators keep the output voltage constant. Among these are tap-changing transformers, which automatically modify voltage but have disadvantages such as delayed reaction, noise, and maintenance needs. Buck-boost regulators have low noise isolation but can manage high in-rush currents. Although they are big, noisy, and inefficient, constant voltage transformers (CVT) provide excellent noise isolation, precise voltage regulation, and low maintenance. With off-line, line-interactive, and online UPS solutions catered to particular load requirements, uninterruptible power supply (UPS) systems guard against power outages. Despite their effectiveness, UPS systems need regular maintenance, such as battery replacement every five years. All of these gadgets work together to give delicate systems steady, dependable power.

Custom Power Devices, or CPDs, are important for solving power quality problems and making sure that high-quality power reaches those sensitive devices in a reliable manner. This procedure uses power electronic controllers in the distribution system to improve the quality of power. There are two kinds of CPDs: network reconfiguring devices and compensating devices. Reconfiguration network devices, in particular Static Current Limiters, Static Circuit Breakers, and Static Transfer Switches, focus more on fault management and system reconfiguration. For instance, an SCL instantaneously introduces series inductance into the fault path to limit fault currents; an SCB interrupts faulted circuits faster than mechanical breakers by using GTO thyristors. The STS is intelligent to switch between sources and provide an uninterruptible supply when there is a voltage sag or feeder fault; hence, connected loads suffer less disruption. Devices used for compensation are used in

voltage regulation, power factor correction, load balancing, and active filtering. They include DVRs, DSTATCOMs, and UPQCs. The DVR injects compensating voltage into the distribution system with the help of a Voltage Source Inverter (VSI) and an energy storage device, thereby countering voltage sags. The DSTATCOM compensates small voltage variations through reactive power injection, thereby helping to maintain a stable voltage supply despite variations in load and supply conditions [18] [19].

A multi-stage power electronics converter with an isolated HFT is one of the solid-state components that make up SST. The SST concept was actually an old technology that was patented in 1968, but it proved challenging to implement. Using suitable semiconductor devices with a novel topology arrangement has been relevant after a long period of time (about 50 years). In 2008, the FREEDM center projected the introduction of SST, which the MIT study deemed to be one of the ten breakthrough technologies. Figure 4 depicts the basic block diagram of SST. The input and output stages represent the conversions of AC-DC and DC-AC, respectively, while the middle stage denotes the isolation stage (DC-DC), which comprises HFT and dual active bridge.

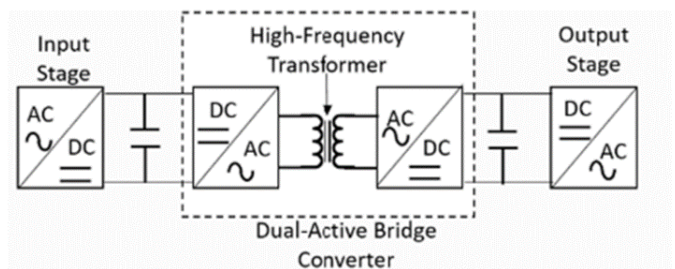


Fig. 4. Block diagram of a solid-state transformer [20]

SSTs are categorized into various types based on their design integrate different sources like storage and renewable ones and operational requirements. The three main types of SSTs and the grid properly [21].

are AC-AC SSTs, AC-DC SSTs, and Hybrid SSTs, each with unique functionalities suited to specific applications. AC-AC SSTs directly convert alternating current (AC) input to alternating current output through power electronic converters, eliminating the need for intermediate DC stages. These transformers are very effective for applications in the case of direct AC transformation. These include railway systems or industrial power distribution. AC to DC SSTs, however, transform AC input to a direct current output. The main uses are for DC microgrids, renewable energy systems, such as solar farms, and electric vehicle charging infrastructure. The design concentrates on energy storage with renewable sources and, thus, is useful in DC-DC connected applications. Hybrid SSTs have AC-AC coupled along with the characteristics of the AC-DC converters and also bidirectional flow and can connect with AC systems and DC. Such type finds good applications for the smart grids that

## VII. CONCLUSION

The integration of solar PV systems with three-phase grids presents some opportunities and challenges in achieving reliable and efficient renewable energy solutions. While enhancing the stability of grids and reducing the emission of greenhouse gases, the solar PV system faces significant problems in PQ: voltage fluctuations, harmonic distortions, and intermittency of renewable generation. Advanced technologies that address these concerns are DFACTS devices, custom power devices, and adaptive control algorithms for improving the effectiveness and reliability of such systems. In addition to stability, further augmentation is facilitated through hybrid energy systems that are capable of inter-tie, integration of wind power with solar PV. PQ

management is highly improved through efficient innovation solutions for applications like smart transformers and intelligent energy storage. This study underlines the need to constantly innovate and implement advanced solutions in order to overcome the hurdles that stand before renewable energy integration in the quest towards a sustainable future energy system.

**Conflict of Interest:** The corresponding author, on behalf of all authors, confirms that there are no conflicts of interest to disclose.

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