The North African Journal of Scientific Publishing (NAJSP)
مجلة شمال إفريقيا للنشر العلمي (NAJSP)
E-ISSN: 2959-4820
Volume 3, Issue 2, 2025
Page No: 151-162
Website: https://najsp.com/index.php/home/index

SJIFactor 2024: 5.49 | معامل التأثير العربي (AIF) 2024: 0.71 | ISI 2024: 0.696

Impact of Energy Storage in PV-Based Distributed Generation for Mitigating Grid Disturbances

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تأثير تخزين الطاقة في توليد الطاقة الموزعة القائمة على الطاقة الكهروضوئية للتخفيف من اضطرابات الشبكة

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Received: March 16, 2025	Accepted: May 25, 2024	Published: June 12, 2025

Abstract:
Researchers have acknowledged the pivotal role of photovoltaic (PV) systems in enhancing the performance of energy storage systems, particularly in the context of power quality improvement (PQI). PV systems have demonstrated substantial contributions in mitigating common power quality disturbances such as voltage sags, overvoltages, and harmonic distortions. A prominent challenge associated with the integration of PV systems into electrical power systems (EPS) is the optimization of power quality parameters, wherein the application of unified power flow controllers (UPFCs) combined with maximum power point tracking (MPPT) algorithms has garnered considerable attention. The MPPT technique is employed to ensure the extraction of maximum available power from the PV source under varying environmental conditions. This study further explores the modeling and simulation of an EPS integrated with a PV-UPFC configuration, emphasizing its influence on improving PQI. A 400.0 kW PV-UPFC system is modeled, comprising four PV arrays, each capable of delivering 100.0 kW under standard solar irradiance conditions (1 kW/m²). Each PV-UPFC array consists of 64 parallel strings, and within each string, five SunPower SPR-315E photovoltaic modules are connected in series. The system modeling and performance evaluation are conducted using MATLAB/Simulink, offering a robust framework for assessing the efficacy of PV-UPFC technology in enhancing the overall power quality of the electrical power network.

Keywords: Photovoltaic, Power Quality Improvement, Unified Power Flow Controller, Maximum Power Point Tracking, Electrical Power Systems.

الملخص
أقرّ الباحثون بالدور المحوري الذي تؤديه أنظمة الطاقة الشمسية الكهروضوئية في تعزيز أداء أنظمة تخزين الطاقة، لا سيما في سياق تحسين جودة الطاقة **.**وقد أظهرت أنظمة الطاقة الشمسية الكهروضوئية مساهمات كبيرة في التخفيف من اضطرابات جودة الطاقة الشائعة مثل انخفاضات الجهد، وزيادة الجهد، والتشوهات التوافقية. وتُعدّ من أبرز التحديات المرتبطة بدمج أنظمة الطاقة الشمسية الكهروضوئية ضمن نظم الطاقة الكهربائية مسألة تحسين مؤشرات جودة الطاقة، حيث حظي تطبيق وحدات التحكم الموحد في تدفق الطاقة بالتكامل مع خوارزميات تتبع نقطة القدرة العظمى باهتمام متزايد. وتُستخدم تقنية MPPT لضمان استخراج أقصى قدرة ممكنة من المصدر الكهروضوئي تحت ظروف بيئية متغيرة. تُعمق هذه الدراسة في نمذجة ومحاكاة نظام EPS مدمج بتكوين PV-UPFC ، مع التركيز على تأثيره في تحسين جودة الطاقة.

تم تصميم نظام PV-UPFC بقدرة 400.0 كيلوواط، يتكون من أربع مصفوفات شمسية، تبلغ قدرة كل منها 100.0 كيلوواط تحت شروط الإشعاع الشمسي القياسي (1 كيلوواط/م²). وتتكون كل مصفوفة PV-UPFC من 64 سلسلة متصلة على التوازي، وتضم كل سلسلة خمسة ألواح شمسية من نوع SunPower SPR-315E متصلة على التوالي. وقد تم إجراء نمذجة النظام وتقييم أدائه باستخدام برنامجMATLAB/Simulink ، مما يوفر إطارًا تحليليًا قويًا لتقييم فعالية تقنية PV-UPFCفي تعزيز جودة الطاقة الكلية لشبكة الطاقة الكهربائية.

الكلمات المفتاحية: التعلم التعاوني عبر الإنترنت، تعليم الرياضيات، إغلاق كوفيد-19، التربية الرقمية، التعليم العالي.

Introduction

In recent years, there has been a notable surge in the deployment and development of energy storage systems (ESS), driven by the global shift toward sustainable energy solutions and the increasing penetration of intermittent renewable sources, particularly solar photovoltaic (PV) systems [1-3]. Among the evolving technological innovations within the electric power system (EPS), the photovoltaic unified power flow controller (PV-UPFC) has emerged as a highly promising yet complex advancement. Despite its significant potential, PV-UPFC technology presents substantial challenges, particularly in terms of its integration into existing grid infrastructure, dynamic operational control, and the coordination between power flow regulation and renewable energy variability [4-8].

The PV-UPFC system holds considerable promise in enhancing the role of renewable energy within electric utilities (EU). Its ability to combine the functionalities of power flow control and renewable generation makes it a viable candidate for addressing stability, voltage regulation, and overall power quality issues, key concerns in high-penetration renewable scenarios [8-10]. Moreover, the rapid technological race among electric utilities to develop and deploy PV-UPFC systems reflects a growing recognition of its strategic importance. This competition could position the PV-UPFC as a transformative innovation within the energy sector, with the potential to redefine how utilities manage distributed generation and grid resilience [10-12].

Figure 1 presents a schematic diagram of a PV-ESS integrated system, illustrating the structural configuration and interaction between the photovoltaic array, the unified power flow controller, and the energy storage unit. This configuration enables not only enhanced power flow management but also energy balancing and system support during periods of generation intermittency or load fluctuation. As such, PV-ESS technology represents a key enabler for the future of smart, adaptive, and resilient power systems.

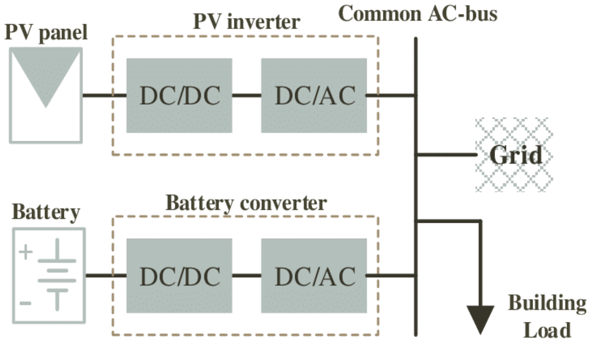

Figure 1. Schematic diagram of PV-ESS technology.

The PV-UPFC (Photovoltaic Unified Power Flow Controller) technology is fundamentally designed to ensure the reliable delivery of electrical energy from renewable sources to meet end-user demand within the electric utility (EU) framework. A core objective of this technology is to minimize power quality issues (PQI), including voltage fluctuations, harmonic distortions, and frequency instability, thereby ensuring smooth and uninterrupted power delivery across the electrical power system (EPS) [13-15].

Figure 2 illustrates the schematic structure of UPFC technology, highlighting the integration of multiple power electronic devices. These components play a crucial role in modulating and controlling power flow, especially under varying load and generation conditions. The implementation of such a configuration enables the establishment of a targeted power quality index, which contributes to maintaining voltage and frequency stability across the EPS. PV-UPFC technology has gained significant traction in recent years, particularly as a key enabler within energy storage systems (ESS). Its ability to support grid reliability and operational flexibility aligns with broader societal goals toward environmental sustainability and decarbonization [16-19]. By integrating power electronics and advanced control strategies, PV-UPFC facilitates the effective management of renewable energy intermittency while enhancing the efficiency and resilience of power networks.

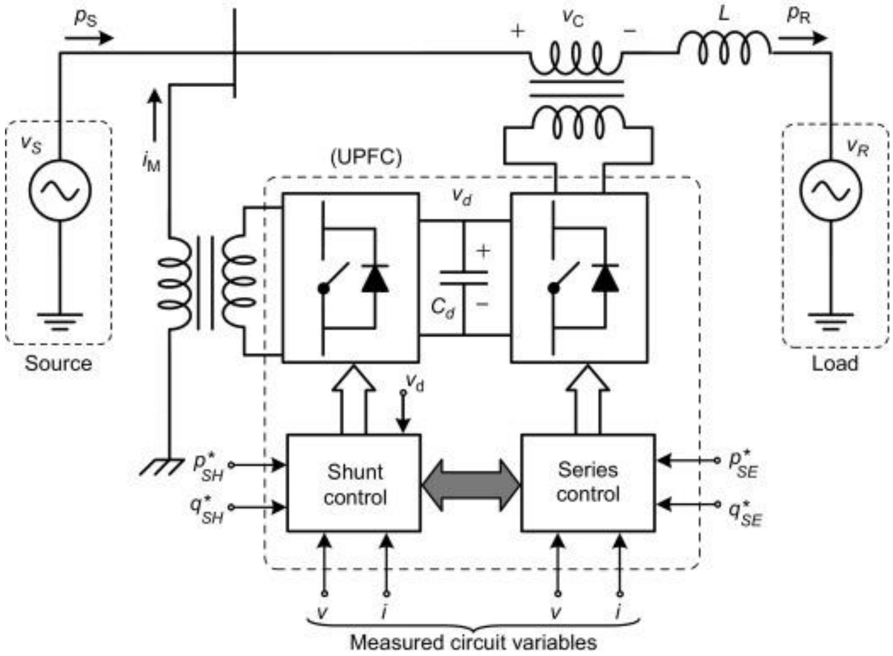

Figure 2. The schematic structure of UPFC technology.

As depicted in Figure 2, various inverter designs employ specialized power electronic topologies to enable rapid and dynamic control of power flow. These configurations are especially advantageous in ESS applications where precise modulation of energy exchange between generation sources and the grid is critical. Such control capabilities extend the utility of PV-UPFCs across a wide range of EU applications, including frequency regulation, voltage profile management, and the mitigation of delays in generation, transmission, and distribution (T&D) systems [20-24].

In this context, at the scale of electric utilities (EU), the customer-side integration, including industrial, commercial, and residential sectors, is becoming increasingly attractive. This interest stems from the potential of PV-UPFC technologies to stabilize power demand, reduce volatility, and enhance self-consumption of solar energy by improving system reliability and flexibility [25-27].

In summary, the existing literature on PV-ESS (Photovoltaic-Energy Storage Systems) and Power Quality Improvement (PQI) strongly emphasizes the importance of embedding PV-ESS within active power filtering devices, such as the Shunt Active Power Filter (SAPF), to mitigate power quality disturbances and promote clean energy generation [28-30]. This article builds upon that foundation by employing a Perturb and Observe (P&O) technique to track the maximum power point (MPPT), while simultaneously regulating current-voltage (I-V) behavior and PQI. Furthermore, the MPPT control algorithm is integrated into a simulation model and validated through real-time interfacing.

Various methodologies have been proposed in the literature for optimizing PV-ESS technologies. This study contributes by examining multiple optimization techniques used in the mathematical modeling of PV-ESS systems, focusing on:

(a) the formulation of objective functions,
(b) the type of system model applied,
(c) parameter extraction algorithms, and
(d) the advanced computational techniques used for performance analysis.

Additionally, the paper provides a comprehensive comparative evaluation of existing optimization strategies. This includes a critical analysis of the integrated models, performance benchmarks under standardized test conditions (STC), and case-specific scenarios involving continuous solar radiation profiles. The study assesses the advantages and limitations of each method, platform compatibility, and applicability to parameter estimation frameworks. Moreover, the article conducts an in-depth evaluation of various algorithmic management strategies, taking into account system size, operational scale, and targeted application domains.

A key contribution of this research is its investigation and validation of several MPPT strategies tailored to PV-UPFC configurations, with a focus on advanced modeling techniques. These methods are especially relevant to researchers working on parameter-specific modeling of PV-UPFC systems. The simulation model developed in this study represents an EPS structure composed of multiple feeders, simulating conditions at 25.0 kV, along with transmission and distribution (T&D) systems rated at 120.0 kV. The system includes a three-phase Voltage Source Converter (VSC) operating at 0.5 kV (DC) and 0.26 kV (AC), designed to maintain a unit power factor (PF). The converter has a nominal rating of 400.0 kVA, interfaced at 260.0 V, and ultimately connected to the grid at 25.0 kV for full integration into the EPS.

PV-UPFC and Its Properties

In this section, a specialized PV-UPFC (Photovoltaic Unified Power Flow Controller) module is proposed, which can be configured either in series or parallel arrangements within PV-UPFC cells. Each module is designed to support high-generation capacity suitable for integration into electric utility (EU) networks. To enhance overall power quality (PQ), the PV-UPFC modules are strategically grouped into multiple interconnected units. This modular structure enables greater scalability, improved load management, and enhanced operational stability within the electrical power system [31-33].

From a technical perspective, the performance of PV-UPFC systems is highly sensitive to environmental conditions, particularly solar irradiance levels. This section evaluates the system behavior under a range of irradiance scenarios: 1000 W/m², 800 W/m², 600 W/m², 400 W/m², and 200 W/m². These variations are essential for analyzing the current-voltage (I-V) and power-voltage (P-V) characteristics of the system, which influence the dynamic response of the PV-UPFC under real-world operating conditions [34-39]. The overall performance specifications of the PV-UPFC system are governed by several critical design and operational parameters, such as internal resistance, capacitance, switching frequency, and temperature coefficients. Accurate representation of these parameters is essential during MATLAB/Simulink-based modeling and simulation, where precise modeling enables realistic evaluation of the system's effectiveness in enhancing power quality and supporting grid stability.

PV-UPFC Cell Materials and Their Impact on System Performance

This section discusses the material composition of PV-ESS (Photovoltaic Energy Storage System) cells, which correspond directly to the functionality and performance of PV-UPFC (Photovoltaic Unified Power Flow Controller) units across multiple technological generations. The evolution of PV-UPFC cell materials spans from first-generation to third-generation devices, and even includes emerging twenty-first-century technologies characterized by the use of organic polymers, crystalline silicon, cadmium telluride (CdTe), and nanocrystalline materials.

Currently, over 90% of commercially deployed PV-UPFC cells are categorized as first-generation, primarily based on monocrystalline or polycrystalline silicon. Approximately 29% to 43% of these systems utilize monocrystalline panels, which typically exhibit energy conversion efficiencies ranging from 14.0% to 17.5%. In contrast, polycrystalline (multicrystalline) silicon cells offer slightly lower efficiencies, between 12.0% and 14.0%, yet remain favorable due to lower production costs and mechanical robustness. Additionally, thin-film solar cells, which employ CIGS (Copper Indium Gallium Selenide) and CdTe (Cadmium Telluride) materials, achieve efficiencies between 9.0% and 12.0%, offering flexible form factors and reduced material usage.

Third-generation PV-ESS cells, which include Dye-Sensitized Solar Cells (DSSCs) and nanocrystalline-based technologies, promise higher efficiency-to-cost ratios, although they often suffer from issues such as limited light absorption capacity (in DSSCs) and complex fabrication processes (in nanocells). Among these, perovskite solar cells have emerged as the most promising, due to their rapidly improving efficiencies and low-cost fabrication techniques. As shown in Table 1, each photovoltaic material exhibits distinct performance characteristics, including conversion efficiency, stability, and suitability for integration into PV-UPFC architectures. Materials covered include perovskite, monocrystalline silicon, polycrystalline silicon, CIGS, nanocrystalline silicon, DSSC, polymers, and CdTe.

The PV-UPFC technique plays a critical role in maintaining power quality indices (PQI), particularly in mitigating harmonic distortion and oscillations within Electrical Power Systems (EPS). By accurately tracking the reference signal, PV-UPFC systems can effectively respond to disturbances that may otherwise degrade power stability. Although potential failure scenarios do exist due to environmental or grid-side variations, the adaptive control and power buffering capabilities of PV-UPFC make it a valuable asset for improving the resilience and quality of power delivery.

Table 1. The Different Solar-PV-Ess Cell Materials

Num.	Name of material	Efficiency (%)
1	Perovskite	31 %
2	Mono-Silicon	14% to 17.5%
3	Poly- Silicon	12% to 14%
4	CIGS	10% to 12%
5	Nano	7% to 8%
6	Amorphous silicon	4% to 8%
7	DSSC	10%
8	Polymer	3% to 10%
9	CdTe	9% to 11%

Table 1 presents a comparative overview of various photovoltaic (PV) materials used in PV-ESS (Photovoltaic Energy Storage System) applications, highlighting their respective efficiency ranges. The choice of PV material is critical to the overall performance, cost-effectiveness, and applicability of PV-UPFC (Photovoltaic Unified Power Flow Controller) systems within Electrical Power Systems (EPS). Each material offers distinct advantages and limitations depending on its generation, composition, and environmental adaptability. Perovskite solar cells stand out with the highest reported efficiency at 31%. They represent a new class of third-generation PV technologies that are gaining substantial attention for their low fabrication costs, tunable bandgaps, and compatibility with flexible substrates. Despite these advantages, perovskites face technical barriers such as long-term stability, moisture sensitivity, and scalability issues, which limit their immediate commercial deployment.

Monocrystalline silicon, a well-established first-generation material, offers high conversion efficiencies ranging from 14% to 17.5%. Its long lifespan, structural stability, and consistent performance make it ideal for grid-connected PV-UPFC applications, especially in space-constrained or performance-critical environments. Polycrystalline (or multicrystalline) silicon, while slightly less efficient at 12% to 14%, provides a cost-effective alternative with reasonable reliability, making it suitable for large-scale utility installations where space is less of a concern. Thin-film technologies such as CIGS (Copper Indium Gallium Selenide) and CdTe (Cadmium Telluride) demonstrate moderate efficiencies (10%–12% and 9%–11% respectively) and are praised for their lightweight and flexible properties. These features make them suitable for portable and building-integrated PV applications. However, concerns about material availability, toxicity (in the case of cadmium), and end-of-life recycling limit their adoption in environmentally sensitive contexts.

Emerging materials such as nanocrystalline silicon, DSSCs (Dye-Sensitized Solar Cells), and polymers provide innovative pathways for developing low-cost and flexible PV technologies. Nanocrystalline and polymer-based cells, though still in developmental stages, offer efficiencies between 3% and 10%, and are mainly explored for consumer electronics and low-power applications. DSSCs achieve about 10% efficiency and are suitable for niche applications like building-integrated or semi-transparent solar modules. However, their limited thermal stability and lower power densities restrict their deployment in high-demand grid scenarios. Amorphous silicon, with efficiency ranging from 4% to 8%, is another low-cost option but suffers from high degradation rates and reduced performance in long-term applications. While suitable for low-power or short-term use, its application in PV-UPFC systems is generally limited.

In the context of power quality improvement (PQI) and energy stabilization in EPS, PV materials with higher efficiency, long-term reliability, and predictable I-V characteristics are preferred. Monocrystalline silicon remains the most practical choice for current deployments due to its proven performance and maturity. Perovskites, while promising, require further development before large-scale grid integration is feasible. Thin-film materials, though advantageous in terms of cost and flexibility, must overcome environmental and durability concerns. Ultimately, the integration of PV materials into PV-UPFC systems must balance efficiency, cost, and environmental sustainability. The performance of the PV-UPFC depends not only on the inherent properties of the PV material but also on its compatibility with energy storage systems and power electronic interfaces. As research continues, the selection of suitable materials will be instrumental in advancing the effectiveness of PV-UPFC systems for power quality enhancement and future energy security.

Within the broader context of Energy Storage Systems (ESS), PV-UPFC technology is increasingly regarded as a strategic solution to future energy security challenges in EPS. Its ability to store energy chemically during the charge phase and release it during discharge ensures energy availability on demand, particularly during load peaks or generation shortfalls. Owing to its versatility, PV-UPFC systems are being widely explored for applications ranging from grid-scale power management to portable electronic devices.

This growing interest from both academic researchers and industry practitioners underscores the importance of PV-UPFC in hybrid and standalone ESS configurations. Furthermore, PV-UPFC systems are gaining significant traction as a renewable energy source (RES) within the European Union (EU), aligning with broader energy transition objectives. To ensure optimal integration, simulation-based methods employing adjustable phase and voltage parameters are applied to model and refine grid-interfacing strategies. Ultimately, this work emphasizes the relevance of PV-UPFC in supporting stable phase production and voltage regulation within modern EPS environments.

Model of PV-UPFC Integration For EPS

The PV-UPFC technology is generally known as a fairly widely recognized green electricity type. Part of the contribution of this manuscript is the modeling of a 400 kW PV-UPFC farm that can be integrated into a 25 kV EPS by using a two-phase voltage source converter. The output of the 400 kW PV-UPFC technology is consistent when the EPS is stabilized to PQI type. The mathematical proof of the single-diode PV-UPFC can be made using Equation (1).

$$I = I_{ph} - I_d - I_p = I_{ph} - 1_0 \left[exp\left(\frac{V + 1_* R_{solar\ cell}}{V_t} \right) - 1 \right] - \frac{V + I_* R_{sc}}{R_{pc}} \tag{1}$$

In this context, the phrase "I_{ph}" refers to the light that is produced, the term "I_0" refers to the amount of diode saturation that is set aside, and R_pc represents the parallel resistance. The formation of a PV-UPFC comes about when a large number of solar cells are connected in series with one another. In accordance with Equation, the formula for the model's outcome current I and outcome voltage V is as follows Equation (2).

$$I = I_{ph} - I_0 = \left[exp\left(\frac{1}{V_t} \left(+I_* R_{solar\ cell)} \right) \right) - 1 \right] - \frac{1}{R_{pc}} \left(\frac{V}{NS} + R_{pc} \right) \left(\frac{V}{NS} + R_{pc} \ * I \right) \tag{2}$$

The assessment of the performance of PV-UPFC technology outlet power, on the other hand, is a highly complicated scenario that can be difficult to accomplish. This is due to the fact that the elements of the evaluation significantly differ across EPS.

Simulation Parameters of PV-UPFC

This section presents the simulation framework and key operational parameters used in modeling the PV-UPFC (Photovoltaic Unified Power Flow Controller) system within the Electrical Power System (EPS). The simulation is designed to evaluate the effectiveness of PV-UPFC integration for power quality enhancement using the Maximum Power Point Tracking (MPPT) control technique. The simulation architecture incorporates critical components such as the Electric Utility (EU), PV-UPFC array, DC-DC converter, inverter, and a three-phase transformer, forming a comprehensive system for dynamic analysis. The parameters used in the simulation were selected based on site-specific measurements and standardized operational conditions, ensuring realistic performance assessments. These include irradiance levels, ambient temperature, voltage regulation limits, and converter switching frequencies. The PV-UPFC arrays are modeled to reflect real-world power generation capabilities, interfacing with both the DC and AC sides of the system through bidirectional converters and voltage source inverters.

Table 2 presents the detailed simulation parameters, including those associated with the Energy Storage System (ESS) integrated with the power grid. These parameters were implemented within the MATLAB/Simulink environment, offering a robust platform for evaluating system behavior under different loading conditions, grid disturbances, and solar irradiance fluctuations. The incorporation of HESS supports enhanced voltage stabilization, load balancing, and improved energy dispatch during PV intermittency.

The comprehensive set of simulation parameters in Table 1 ensures that the PV-UPFC system is modeled with high fidelity, allowing for in-depth performance analysis and validation of the MPPT-based control strategy. Through this simulation, the article aims to demonstrate the viability of PV-UPFC systems as effective tools for power quality improvement and reliable renewable energy integration into modern EPS infrastructures.

Table 2. The detailed simulation parameters.

	Parameters	Unite	Value
Electrical Utility	Special distribution system	“Kv”	“25”
	Special transportation system	“kV”	“120”
PV Array	Maximum energy and power (W)	“kW”	“400”
	Solar energy radiation	“W/m^{2}”	“1000”
	Cells in each unit (Ncell)	-	“96”
	Isc short circuit current	“Amps”	“6.14”
	Special voltage inside the open circuit (Voc)	“Volts”	“64.6”
	Special short circuit current (Isc)	“Amps”	“9.34”
	Maximum within system voltage	“kV”	“1”
	Temperature of operation	“°C”	“25”
DC-DC Converter	Special level of effort	“V”	“500”
Inverter	Maximum voltage nominal	“V”	“260”
	Efficiency	“%”	“95”
	Life span time	“15”	“Years”
3-phase transformer	-	“kVA”	“400”
	-	“V “	“260”
	-	“kV”	“25”

Results and Discussion

This section presents and analyzes the simulation results related to the integration of PV-ESS (Photovoltaic Energy Storage System) technology within an Electrical Power System (EPS) using the PV-UPFC (Photovoltaic Unified Power Flow Controller) framework. The primary objective is to evaluate the behavior and effectiveness of the proposed PV-UPFC system in enhancing power quality and system stability under realistic operating conditions. To accurately model the interaction between the PV-UPFC and the grid, the EPS simulation incorporates two representative types of feeders. The DS-type feeder, operating at 25.0 kV, represents a typical medium-voltage distribution line, while the TS-type feeder, rated at 120.0 kV, acts as a strong equivalent of a high-voltage transmission system. These feeders ensure a realistic simulation environment for assessing the multi-voltage level integration of PV-UPFC systems.

The simulation also models a three-phase Voltage Source Converter (VSC), which transforms DC voltage (0.5 kV) generated from the PV-UPFC into AC voltage (0.26 kV), suitable for grid injection. Post-conversion, the VSC unit is utilized for power factor correction (PFC), ensuring that the reactive power is well-managed within the EPS. This VSC is coupled with a three-phase transformer rated at 400.0 kVA, with a primary voltage of 260.0 V and a secondary voltage of 25.0 kV, enabling proper voltage level matching and grid interconnection. Figure 3 presents the specialized modeling approach used to simulate the behavior of the photovoltaic array, capturing its I-V characteristics under variable irradiance levels.

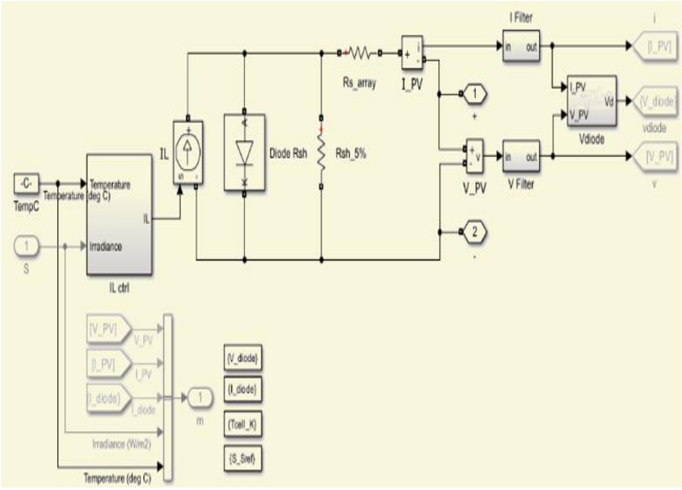

Figure 3. A special flowchart of the simulation process individually for a PV-UPFC array.

Furthermore, Figure 4 illustrates the DC-DC converter control process, governed by the Maximum Power Point Tracking (MPPT) technique. This control ensures maximum power extraction from the PV source under dynamic environmental conditions.

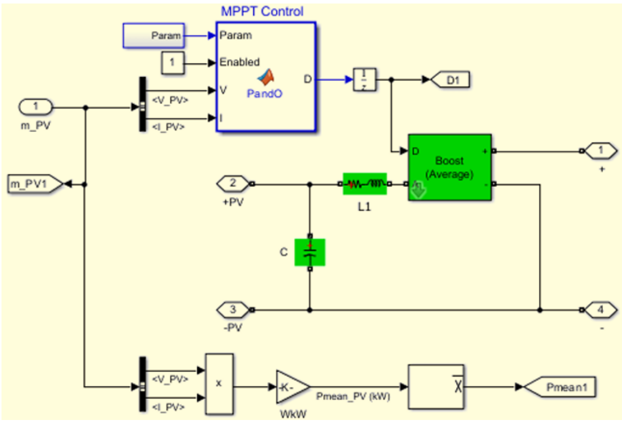

Figure 4. Special DC-DC converter by using MPPT control in PV-UPFC with connection inside EPS.

The figure also shows the interface logic enabling seamless integration of the PV-UPFC into the EPS. Lastly, Figure 5 provides insight into the primary control mechanism embedded within the VSC, which includes voltage regulation, synchronization with grid frequency, and harmonic compensation. This control logic is essential to maintain grid stability, ensure efficient energy transfer, and enhance overall power quality.

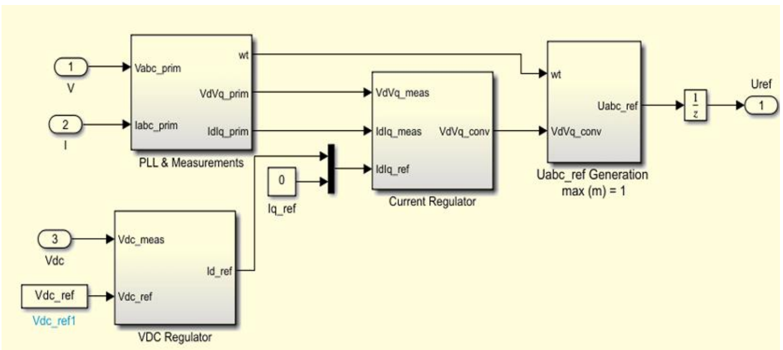

Figure 5. The control application is mainly carried out inside the VSC on the PV-UPFC type with the interconnection carried out inside the EPS.

Continuing the simulation analysis, additional figures are presented to further demonstrate the performance of the PV-UPFC system under varying environmental and electrical conditions within the Electrical Power System (EPS).

Figure 6 illustrates the solar irradiance levels (in W/m²) applied to the PV-UPFC system during operation. These irradiance values, ranging from standard test conditions (1000 W/m²) to lower sunlight intensities, are critical for evaluating the dynamic response of the system under realistic environmental scenarios. The figure highlights how fluctuations in solar radiation influence the PV-UPFC's electrical conduction behavior, directly affecting the output power, voltage stability, and energy yield within the EPS. Such analysis is essential for designing robust MPPT algorithms capable of tracking optimal power points efficiently across diverse irradiance conditions.

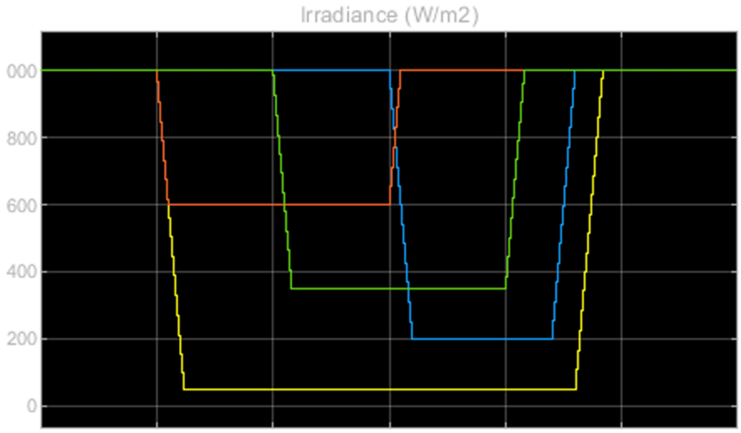

Figure 6. The radiations present in ($W/m2$) which are applied to the PV-UPFC type with electrical conduction process inside the EPS.

Figure 7 presents the main active power output of the PV-UPFC system as it interconnects with the EPS. The results confirm that the system is capable of stable and continuous power delivery, even during varying load and irradiance conditions. The power output curve shows a consistent profile, reflecting the efficacy of the MPPT-controlled DC-DC converter and the VSC (Voltage Source Converter) in ensuring effective power flow regulation and grid compatibility. This reinforces the suitability of PV-UPFC technology for distributed generation applications where reliability and grid compliance are paramount.

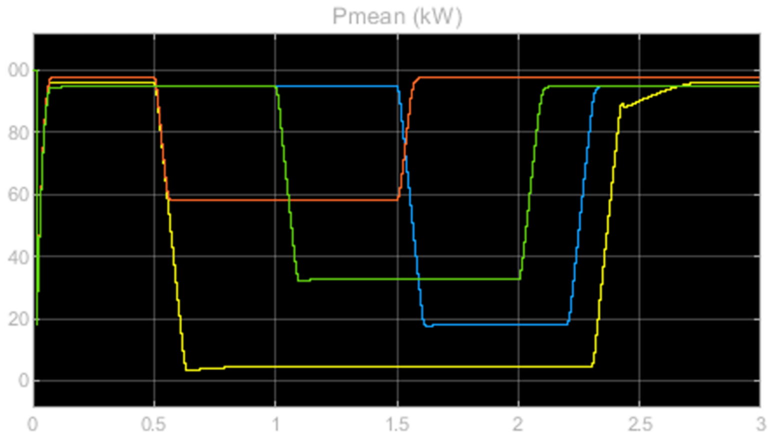

Figure 7. Main power of PV-UPFC type with interconnection inside EPS.

Figure 8 provides a comprehensive overview of the electrical parameters, including voltage, current, apparent power (kVA), and power quality indices, during the operation of the PV-UPFC system. The figure captures the behavior of these parameters during the cross-linking of the PV-UPFC with the EPS. Notably, the results indicate that the system maintains voltage and current within acceptable grid standards, while also improving power quality by mitigating harmonic distortion and supporting power factor correction.

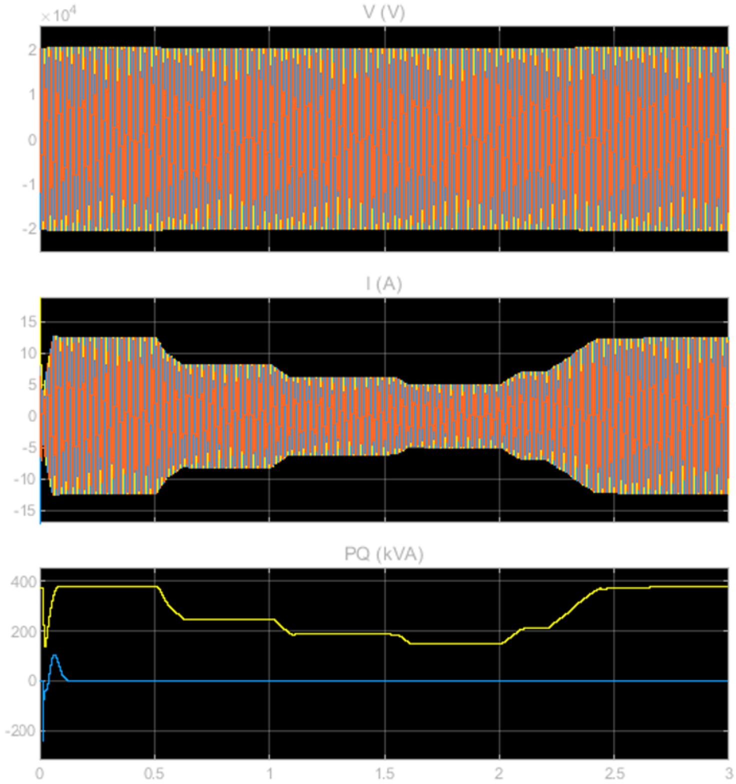

Figure 8. Voltage, current, process and power quality (kVA) for PV-UPFC type with cross-linking inside ESP.

Collectively, Figures 6 to 8 substantiate the robust performance of the PV-UPFC system in real-time simulation, validating its potential as a scalable and adaptable solution for both renewable energy integration and grid power quality enhancement in next-generation electrical networks.

Conclusion

The integration of Photovoltaic Unified Power Flow Controller (PV-UPFC) technology into the Electrical Power System (EPS) has demonstrated a significant impact on enhancing power quality (PQI) and improving overall grid stability. As highlighted throughout this study, PV-UPFC plays a pivotal role in addressing key challenges associated with renewable energy penetration, particularly in terms of voltage regulation, power factor correction, and harmonic mitigation within Electric Utility (EU) networks. Recent interest in PV-UPFC systems has surged due to their dual capability of interfacing photovoltaic energy generation with active power flow control, although this integration introduces new complexity into the EPS that requires careful system design and control coordination. This study has shown that, when effectively implemented, PV-UPFC technology significantly contributes to the stabilization and operational efficiency of power systems. A central feature of the proposed system is the use of the Maximum Power Point Tracking (MPPT) control strategy, which ensures that the PV arrays operate at their optimal power output under varying irradiance conditions. The MPPT algorithm is instrumental in extracting peak power from the PV sources, contributing directly to improved system performance and energy yield.

The modeling and simulation presented in this article successfully demonstrate the operation of a PV-UPFC integrated EPS, consisting of a 400.0 kW PV-UPFC farm. This system comprises four PV-ESS arrays, each rated at 100.0 kW under a standard solar irradiance of 1.0 kW/m². Each array includes 64 parallel strings, and each string is configured with five SunPower SPR-315E photovoltaic modules connected in series. The generated DC voltage (0.5 kV) is converted to AC voltage (0.26 kV) through a three-phase Voltage Source Converter (VSC), which also maintains unity power factor (PF). The VSC is further connected to the EPS via a three-phase transformer rated at 400.0 kVA, 260.0 V/25.0 kV, ensuring compatibility with the grid voltage levels and supporting efficient power transfer. In conclusion, this study confirms that PV-UPFC technology, when integrated with robust control techniques such as MPPT, offers a comprehensive solution for renewable energy integration while simultaneously addressing critical power quality issues. It represents a viable pathway for enhancing the reliability, flexibility, and sustainability of future smart grids.

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