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Impact of FACTS Devices on Reactive Power Optimization in Hybrid Renewable-Grid Networks

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Abstract

Renewable energy integration with conventional electric power networks creates power-quality and stability difficulties because of their inherent volatility. The reliability improvement of hybrid renewable-grid systems depends heavily on reactive power optimization for achieving voltage control as well as loss reduction. The research explores the application of Flexible AC Transmission System (FACTS) devices with special emphasis on Distribution Static Compensator (DSTATCOM) devices for distributing reactive power compensation at the distribution level. The optimization process utilizes Particle Swarm Optimization (PSO) because it demonstrates both quick convergence and strong abilities for global search within nonlinear systems. The PSO algorithm functions to determine the perfect settings of the DSTATCOM device that enables voltage regulation within safety bounds and improves power factor performance. The hybrid system connects PV array components with wind turbines for power management together with the main grid while dealing with fluctuating load requirements. Under optimized conditions simulation output shows that DSTATCOM reduces reactive power requirements in substantial amounts. DSTATCOM's implementation enables the system to achieve better voltage security together with diminished power losses and superior load power factor levels. Detailed research shows that DSTATCOM proves efficient while being attached to the main grid for real-time compensation operations. The PSO system enables it to function efficiently throughout changing conditions of power generation and load requirements. Smart grid efficiency along with resilience advances because of the combined operation of FACTS devices and swarm intelligence methods. Through its proposed method the system ensures lasting grid sustainability and manages renewable resources intermittency effectively for process innovation.

Keywords: Hybrid Grid Connected Systems, Flexible AC Transmission System, Power Quality, Genetic Algorithm, Process Innovation

1. Introduction

Modern power grids now accept Renewable Energy Sources (RES) such as solar and wind power because society requires clean energy at an increasing rate [1], [2], [3], [4]. The environmental advantages of these energy sources come with the drawback of creating construction obstacles regarding voltage stability and power quality alongside reactive power management in hybrid systems. A dependable and stable power supply demands effective advanced compensation methods to integrate solar and wind system power. The operation of DSTATCOM offers an effective response to these operational difficulties since this FACTS-based power electronic device specifically controls reactive power in real time [5].

The basic structure of DSTATCOM as an appropriate FACTS device created for low and medium voltage distribution systems to deliver swift reactive power compensation for sustaining voltage stability and enhancing power quality [6]. The superior dynamic capabilities and fast response along with precise control of reactive power occur naturally from DSTATCOM because the device uses voltage source inverters to deliver fast grid disturbance responses and precise voltage regulation. Such systems find extensive use throughout hybrid renewable power systems like solar and wind-based microgrids because generation variations lead to voltage instability issues [7]. The distribution static compensator serves commercial and industrial facilities by addressing both voltage sags and harmonic distortion and improving

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power factor when load systems are unbalanced [8]. Due to their adaptable modular format these devices can successfully operate in every power distribution network and both metropolitan and distant locations thus serving as fundamental components of sustainable power structures.

The source of PQ problems can either be found in the customer facilities or the distribution system (such as harmonic currents) or the customer's own property. Circuit breakers as well as equipment energization operations can produce such faults. These events develop from the relationship between utility systems components along with other customer loads. Power system resonance phenomena form a vital cause of power quality problems because they occur when distribution system equipment interacts with end-user load. This condition occurs mainly because of system frequency response changes coupled with weak network schemes and deficient damping mechanisms [9]. Various adverse impacts stem from power system resonance including higher power losses together with capacitor overheating and equipment overloading of transformers and motors and capacitors. Electricity providers who faced power quality challenges started prioritizing its improvement following sensitive electronic circuit adoption and the shift from state-owned to competitive ownership of electric energy systems [10]. Power quality experts consider these devices real solutions because they respond quickly and work well with various operation procedures. DSTATCOM stands as a confirmed technology that improves power quality conditions thoroughly. The power quality enhancement ability of DSTATCOM represents indisputable power compared to other available devices.

The evaluation of PQ problems benefits from measurements regarding voltage and current. Prolonged continuous monitoring for an extended duration is needed to record unusual or unexpected disruptions. The monitoring system serves two functions: continuous performance tracking as well as condition observation to alert utility staff and customers about required attention [11]. System performance evaluation greatly depends on PQ monitoring techniques. Detection of abnormal features by utilities enables public services to offer consumers relevant information so they can connect actual PQ characteristics to their sensitive equipment while the utility maintains system power quality data [12].

2. Background and Related Works

The analysis conducted optimization of an independent hybrid power system for Zhanjiang Guangdong China's 100 houses through HOMER software. The optimized system design features an 80 kW PV array with 25.55 kW converters and a WT yielding $494,119 NPC which results in $0.043/kWh COE [1]. The WT-PV-grid hybrid system emits the smalles annual amount of carbon dioxide at 174,236 kilograms per year. The HOMER software allows increased levels of solar irradiation and wind velocity to drive down both COE and NPC values leading to system cost efficiency [2024]. WT-PV-Grid configuration represents the most environmentally-friendly and least expensive system among different configurations.

A two-level PV system described in this research enables waveform control and low voltage ride through properties while preserving the power maximizing function. This system distinguee itself from traditional systems because it manages active power and reactive power while continuing to track maximum power point. A genetic algorithm manages the SRF-PLL through settling time reduction and frequency dynamic improvement for LVRT synchronization. The system performance verification platform uses MATLAB/Simulink. The developed control algorithm together with optimized PLL produces superior reactive power management results compared to conventional low-gain PLL techniques [2].

The study presents advanced techniques to compensate grid impedance for Phase-Locked Loop (PLL) in Voltage Source Inverters (VSIs) functioning within very weak AC grids (SCR<1.3). The standard inductive compensation method provides stability for grid connection but shows weakness against grid impedance changes leading to stability issues [3]. This proposed method provides advanced performance during impedance shifts because it prevents sudden overcompensation issues. Small-signal model development allows the design of stability parameters [13]. Simulation results validate those operations of VSI improve when the proposed control method is applied rather than conventional compensation techniques.

The document introduces adaptive model predictive control (AMPC) as a system that reduces resonance effects in LCL filtered grid-interactive inverters under weak grid conditions. LCL filter resonance occurs because of weak power grids and low short-circuit ratio (SCR) and parasitic impedance thereby putting inverter operation stability at risk [4]. AMPC implements a control technique that modifies the control targets and feedback current selection mechanism between using inverter or grid current feeds for weak and stiff grids respectively. The feedback switch implements a system that compares RMS variables of grid current against user-specified current targets in a moving fashion. The research exhibits superior functionality together with efficient transitions while satisfying power quality demands based on IEEE standard 1547 [14].

A power conditioner control system uses unified power quality metrics (UPQC) developed by developers to achieve power quality enhancement within microgrids. Microgrids powered by renewable sources necessitate UPQC units to address problems that result from changing load demand and voltage disturbances and harmonic power variations [5]. The control system predicts fundamental and harmonic frequency levels for both load current and source voltage to generate operational estimates. The simulated system demonstrates PQ maintenance during various disturbances [15]. The procedure underwent evaluation on a single-phase power distribution system for microgrid power station PQ monitoring purposes.

An online system designed by this research solves voltage and reactive power control problems in modern distribution network systems with high distributed generation. The proposed method unites deterministic and stochastic reactive power optimization methods by implementing a Mechanism-Data Hybrid Drive (MDHD) model that deals with source-load uncertainty. Research-based development of a CNN-GRU network model occurs offline to evaluate optimization changes when operating under ambiguous conditions. Fast voltage control through a hybrid-operated control system functions online because its adjustments react to changing source-load dynamical conditions. The proposed method outperforms traditional methods according to real-time observational research during controls of dynamic systems [6].

A new control approach for voltage source converters dealing with weak power grids introduces a solution to address both lowered system inertia and synchronization issues. The VSC side voltage operates based on a rotationally-based reference system which follows the shortest SCR ratio standards defined by AEMO and utility benchmarks. The outer loop configuration integrates VSG control elements to virtually imitate the behavior of synchronous generators. The VSG system extracts its operating parameters through detailed small-signal stability tests as explained in reference [7]. AEMO implemented guidelines for evaluation under the National Electricity Rules to govern the procedure. The testing simulations operate within the PSCAD platform as time domain applications.

This document investigates obstacles in installing bidirectional Voltage Source Converters (VSCs) in rectification mode during DC subgrid connections to Very Weak Grids (VWGs). The VSC-to-weak grid system model is designed in state-space form before small-signal investigation through modal-sensitivity methods. The VSC-VWG impedance connection led to the emergence of two pairs of complex unstable modes according to [16]. The operational stability range of VSCs stands lower in the rectification mode compared to inversion mode operation. The proposed dual-active compensation scheme improves the stability behavior during the integration process. The DAC scheme attains validation by conducting both time-domain simulations and Hardware-in-the-Loop (HIL) experiments according to research documented in [8].

Weak AC grids that include Wind energy systems experience power quality degradation as a result of wind speed variations together with grid resistance along with non-linear load behavior. A DSTATCOM equipped with fuzzy logic-based synchronous reference frame (FLSRF) control technology serves as a solution for these problems. The feedforward block uses wind speed adjustment abilities for faster system reactions [9]. A control system generates effective switching signals by taking into account grid strength combined with DC-link dynamics in addition to load variations. Analysis through the MATLAB platform supports the claim that adding WE resources with DSTATCOM technology results in improved power grid quality in weak power system networks.

The work presents a DSTATCOM design which contains a three-phase five-level voltage source inverter for addressing power quality issues caused by current flow. The PV system functions as a power backup method instead of batteries to drive the DSTATCOM module. The DSTATCOM system needs adaptive P-Q theory to generate reference currents that successfully reduce THD in source current [10]. Less surcharge consumption and quicker response occur with stable voltage profiles when using a Fuzzy Logic-tuned PI controller. The modeling and simulation procedures for the

DSTATCOM system operate on the MATLAB platform. The proposed DSTATCOM system leads to significant enhancement of distribution network Total Harmonic Distortion levels.

Voltage levels increase due to adding many solar and wind generators to low voltage networks. Reactive power control regulates voltage problems using available methods PF(P) and Q(V) that deliver strong voltage regulation but produce increased losses or means minimal losses with poor regulation. A proposed method operates at the intersection of PF(P) and Q(V) through measurements of local voltage and active power to regulate reactive power [12]. The proposed method effectively regulates voltages strongly while simultaneously reducing network losses per 2020. Low voltage system performance measures depend on an existing simulation model. Simulation testing results in superior outcomes than conventional testing methods. This study produces improved operational performance and enhanced voltage system control.

Reactive power compensation must be implemented to decrease power factor in hybrid grid-connected systems operated by inverters. Such power systems which unite PV wind turbines with batteries serve as essential power systems to support reliable remote energy services. The authors conducted research to control reactive power flow while addressing issues related to sags and harmonics and flicker problems [16]. A UPQC system containing optimized PI controllers developed using Genetic Algorithm represents a power quality enhancement method. The grid performance improves significantly when the MATLAB/Simulink models are validated.

The digital economic infrastructure incurs major financial damages as power quality declines further because of rising distributed power generation systems combined with growing power demands. Voltage source converters with electrolytic capacitors (e-caps) show poor reliability since they have a high failure rate during their operational period [17]. The integrations of D-STATCOM without capacitors and MPC control enhance both maintenance lifetime and power quality compensation effect. Excessive control precision leads to higher electric switch operations that diminish converter reliability and increases power losses. The adopted adaptive MPC control technique achieves IEEE 519 THD regulations by maintaining a proper trade-off between system operational integrity and switching timing [18]. Testing the hardware prototype employing 7.5 kVA functionality confirms the methodology which operates at switching frequencies above 30%. The experimental data proves that this conversion system operates with higher efficiency and delivers enhanced reliability factors.

The financial performance of electronic systems suffers significantly when power quality diminishes mainly because of expanding distributed power sources and steadier customer demands. Traditional voltage source converters function through electrolytic capacitors (e-caps) which demonstrate high risk of failure. D-STATCOM system reliability grows through capacitor removal and its power quality compensation becomes accurate because of MPC control technology. Excessive set points drive increased switching procedures which leads to increased power loss together with component aging [19]. The adaptive MPC control system for D-STATCOM achieves balanced performance accuracy and switching frequency distribution which comply with the THD restrictions defined in IEEE 519. Testing of a demonstration unit with 7.5 kVA capacity in the laboratory demonstrated more than 30% switching frequency reduction without compromising power quality performance.

The research uses GWO-PSO hybrid optimization to address problems in electric power network ORPD operations. GWO-PSO produces a hybrid integration between the search capabilities of PSO and GWO allowing better results from global search operations. The research resolves optimal power loss reduction with precise voltage control throughout the designated system boundaries. The research employs standard IEEE test systems based on the reference [20] for its validation tasks. Research findings show that the network system output performance reaches better results using the GWO-PSO approach when compared to other methods. The integrated approach delivers important behavioral developments according to simulation data.

3. Methodology

The figure 1 depicts a combined renewable energy system which integrates wind power with solar power to provide reactive power control through DSTATCOM while managing power quality at both the electrical grid and DSTATCOM. The power generation output from hybrid renewable systems must undergo conversion to become useful for electric grid and consumer systems [18]. The ripple filter functions as a harmonic cleaning device and output smoothing element that ensures power delivery safety to the Point of Common Coupling (POC). The POC incorporates both the electrical grid along with three-phase (3Φ) loads that experience power quality changes because of renewable energy intermittent operation. The system stabilization process needs a DSTATCOM device installation at the POC which proves effective at reducing voltage sags and minimizing harmonic distortion while enhancing power factors under unbalanced load conditions [11]. A Pulse Width Modulation (PWM) generator generates necessary switching signals through its power electronic components to control DSTATCOM operations. Real-time system conditions enable the controller to manage compensation through proper PWM instructions sent to the generator [19].

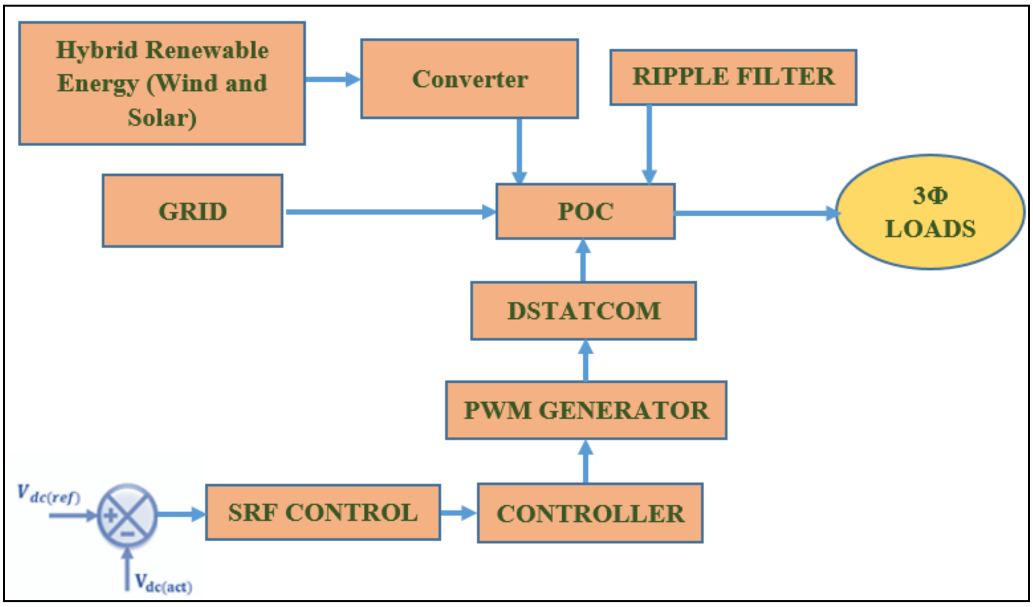

Figure 1. Proposed Methodology for Hybrid Renewable Grid Network System

The power quality stays stable because the control system activates when loads require changes together with fluctuating renewable energy availability. The Synchronous Reference Frame (SRF) control method serves as an implementation process for DSTATCOM systems which enhances power quality performance through distinct active and reactive power control. DSTATCOMs function specifically at distribution-level boundaries using voltage ranges from 400 V up to 33 kV. The SRF performs a transformation of three-phase signals spanning from the abc stationary frame to the dq rotating reference frame. The d-axis indicates real power whereas the q-axis indicates reactive power elements. The dq frame control completes before returning the signals to the abc frame for VSI implementation of the compensation process. System maintenance detects a continuous Vdc(act) and Vdc(ref) comparison to produce bothersome control signals required by DSTATCOM operations. Dynamic voltage disturbance management through the feedback system enables dependable three-phase power delivery that eliminates power quality defects including voltage sags together with harmonic distortions and voltage swells [10]. The complete system delivers advantages for power grid stability combined with better power factor management and allows renewable energy systems to work optimally in connected hybrid networks.

4. Particle Swarm Optimization Technique

PSO functions as a social-inspired metaheuristic that allows birds and fish to gather together effectively for solving complex high-dimensional optimization problems. The PSO algorithm operates differently from traditional gradient-based approaches because it employs population-based exploration through multiple candidate solutions without needing an objective function to be either differentiable or continuous [20]. PSO proves highly effective for solving practical problems specifically in applications of engineering together with artificial intelligence as well as machine learning and power systems. Figure 2 illustrates the structure of PSO that used in this research.

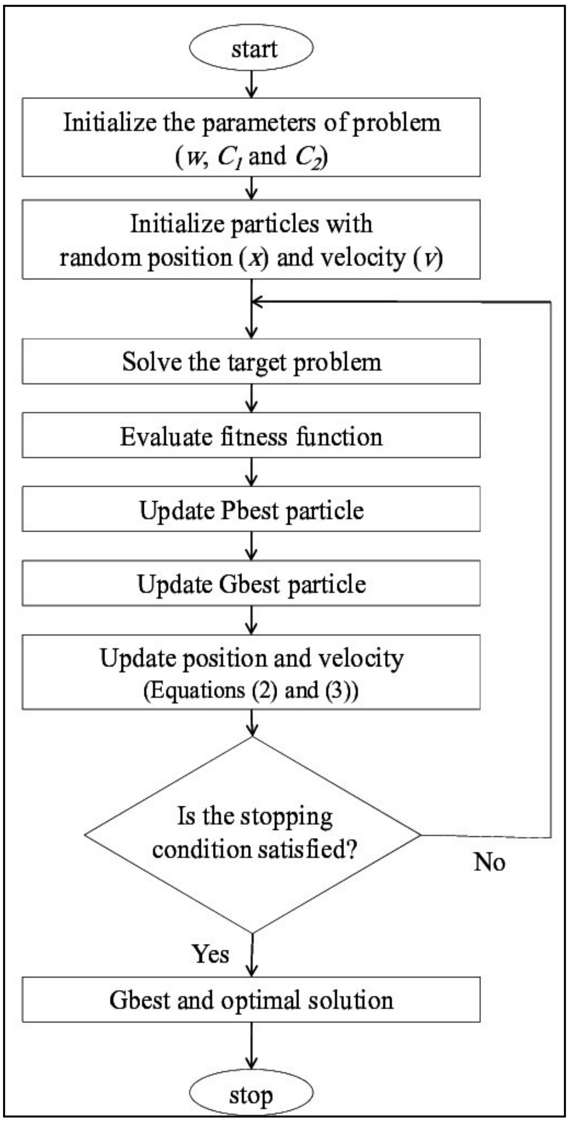

Figure 2. Flowchart of Particle Swarm Optimization Technique

The PSO algorithm bases its basic structure on maintaining both composite candidate solutions named swarms and standalone solutions designated as particles. The search-space particles execute their movement following basic operational rules. Swarm particles move according to information from both their personal best position record and the best global position discovered by all swarm members. All particles in the swarm follow the movement directions established by new superior positions that swarm members identify [2]. The system executes repeated runs while looking for feasible solutions although it cannot confirm complete accomplishment of its target. The start of PSO execution generates multiple particles which work as potential solutions toward the optimization problem. The search procedure of PSO adjusts swarm positions between personal best (P_best) and global best (G_best) positions discovered by the swarm. The movement of particles depends on how they previously measured their velocity as well as their self-best position measurement and their group-best position measurement [4].

The PSO application aims to enhance performance by optimizing selected control parameters in reactive power compensation systems and power quality enhancements. The implementation of PSO enables reduction of harmonic distortion by controlling switching angles or phase shifts in a VSC. Components within the system experience less stress because PSO optimization decreases the switching frequency which results in decreased losses with better stability and reliability along with rapid load response times. The implementation of PSO algorithms guarantees the optimal operation of DSTATCOM systems under varying grid conditions while delivering top-quality stable power along with noteworthy THD reductions which comply with IEEE specifications.

5. Simulation Results and Discussion

This section presents the simulation outcomes of the grid-connected hybrid power system, both with and without the integration of a DSTATCOM. The objective is to evaluate the impact of DSTATCOM on voltage stability, current waveform quality, real and reactive power regulation, power factor correction, and harmonic distortion mitigation.

5.1. System Parameters

The system analyzed in this study is a grid-connected hybrid renewable energy configuration comprising PV and wind power generation units. This setup reflects the growing integration of renewable energy sources into modern power systems and aims to address the associated challenges of power quality and stability. The grid is modeled as a balanced three-phase medium-voltage network operating at 11 kV, representative of typical regional distribution systems. To characterize the strength of the grid and its capacity to absorb disturbances, a short circuit capacity of 1000 MVA is assumed. This high fault-level capacity ensures that the grid behaves as a stiff voltage source during transients, minimizing its sensitivity to fluctuations from the renewable sources or load disturbances.

The renewable energy input consists of a 100 MW solar generation system and a 50 MW wind power system. The solar system employs a detailed PV array model with maximum power point tracking (MPPT) algorithms and variable irradiance profiles to mimic realistic daytime operating conditions. The wind generation system reflects typical utility-scale installations, incorporating stochastic wind profiles to simulate natural intermittency. Together, these two sources provide a substantial 150 MW of combined generation capacity, sufficient to evaluate the behavior of the system under high renewable penetration.

To enhance power quality and dynamic voltage regulation, a DSTATCOM is integrated into the system. Rated at ±100 MVAR, the DSTATCOM operates in both inductive and capacitive modes, offering fast-acting reactive power support. It is implemented using a VSC topology with pulse-width modulation (PWM) and controlled through a high-speed digital loop operating at a sampling frequency of 10 kHz. The controller employs a cascaded PI-based voltage and current regulation strategy, coordinated with a phase-locked loop (PLL) for accurate grid synchronization.

Power interfacing between the DSTATCOM and the grid is achieved using a 250 kVA step-down transformer, which provides galvanic isolation and impedance matching. The transformer rating ensures that the system remains within thermal and voltage limits during steady-state and transient operations. Additionally, the transmission line connecting the distributed generators to the grid is modeled with a per-phase impedance of (0.15 + j0.0012) ohms. This line model introduces realistic voltage drops and impedance characteristics, which are critical for evaluating reactive power flow and voltage regulation under dynamic operating conditions.

Table 1 provides a summary of the key input parameters used in the simulation model. The parameter values were carefully chosen to reflect practical conditions in medium-voltage hybrid distribution systems and to assess the performance of DSTATCOM under realistic load and generation scenarios.

Table 1. Input Parameter description for Grid Connected Hybrid Power System

Input Parameter	Values / Description
Grid Voltage Level	11 KV
Grid Short Circuit Capacity (SCC)	1000 MVA
Solar Power Capacity	100 MW
Wind Power Capacity	50 MW
FACTS Rating	±100 MVAR
Transformer Rating	250 KVA
Sampling Control loop frequency	10 kHz
Line Impedance	(0.15 + j0.0012) Ω

5.2. System Performance Without DSTATCOM

In the absence of a DSTATCOM, the grid-connected hybrid power system exhibits significant degradation in power quality and voltage stability. Figure 3 presents the waveform of the load voltage under this uncompensated condition. The waveform is visibly distorted, deviating markedly from the ideal sinusoidal form. The presence of irregular peaks, notches, and voltage fluctuations indicates poor voltage regulation and a high level of harmonic content. These distortions are indicative of weak voltage support, which is often exacerbated in systems with a high penetration of nonlinear or fluctuating renewable energy sources.

Figure 4 shows the corresponding load current waveform, which further confirms the degradation in power quality. The current signal is highly non-sinusoidal, with clear evidence of harmonic distortion and waveform asymmetry. The variation in amplitude and shape of the waveform points to unbalanced load behavior and the influence of harmonic-producing elements within the system. These current distortions contribute to increased line losses, potential overheating of system components, and reduced efficiency of power delivery.

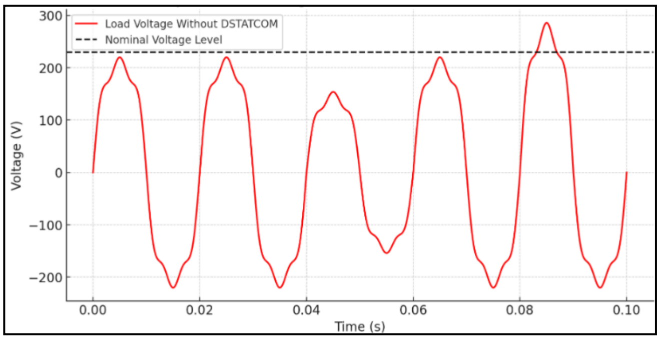

Figure 3. Output Load Voltage waveforms without DSTATCOM Controller

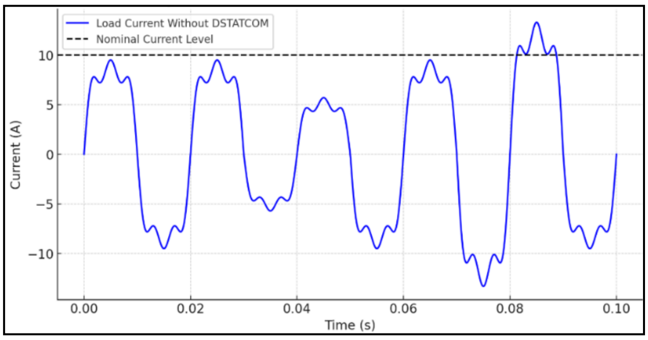

Figure 4. Output Current waveforms without DSTATCOM Controller

The impact of poor compensation is further highlighted in figure 5, which displays the profiles of real and reactive power during the same operating condition. The real power output exhibits frequent oscillations, ranging between 3 kW and 7 kW, while the reactive power fluctuates significantly, peaking close to 5 kVAR. Such variations are symptomatic of unstable power flow, with insufficient reactive power support to maintain voltage levels within acceptable limits. These dynamics not only stress the grid infrastructure but also result in operational inefficiencies and voltage sags.

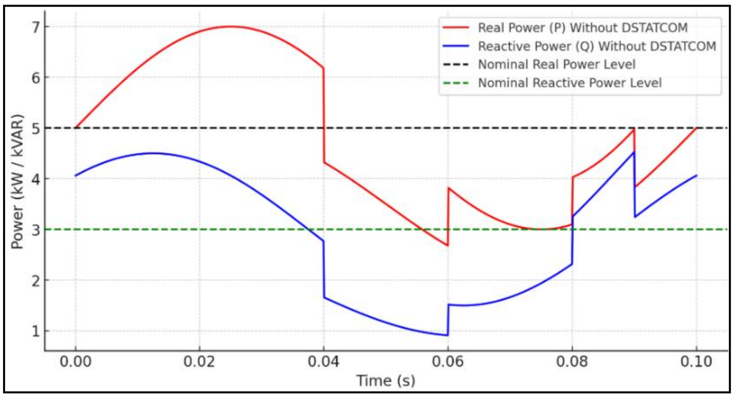

Figure 5. Output waveform of Real and Reactive Power without DSTATCOM Controller

As a consequence of the aforementioned distortions and instability, the overall system exhibits a reduced power factor of approximately 0.86, which reflects poor utilization of active power and elevated reactive power demand. Moreover, the total harmonic distortion (THD) in the system is measured at 8.8%, exceeding the recommended threshold as per IEEE 519 standards. These findings are consistent with previously reported results in the literature [5], and underscore the limitations of operating a hybrid renewable system without appropriate power quality enhancement mechanisms.

In summary, the system without DSTATCOM demonstrates substantial performance limitations, including harmonic distortion, reactive power imbalance, voltage instability, and reduced power factor—all of which degrade the reliability and efficiency of the power system.

5.3. System Performance With DSTATCOM

The integration of a DSTATCOM into the hybrid grid-connected power system yields substantial improvements in both dynamic and steady-state performance. As an active power quality conditioner, the DSTATCOM enhances voltage stability, improves current waveform quality, regulates real and reactive power flow, and minimizes harmonic distortion. Figure 6 presents the load voltage waveform after the implementation of DSTATCOM. The voltage waveform exhibits a smooth and nearly ideal sinusoidal shape, with the magnitude consistently tracking the nominal voltage level. The absence of notches, spikes, or abrupt transitions confirms the effectiveness of the DSTATCOM in maintaining voltage regulation under varying load and generation conditions. This indicates successful dynamic voltage support, especially during transient disturbances or fluctuations caused by intermittent renewable inputs. The corresponding load current waveform, depicted in figure 7, shows significant improvement compared to the uncompensated scenario. The current becomes nearly sinusoidal and phase-balanced, indicating that harmonic content has been greatly reduced. The waveform symmetry and regularity suggest that the DSTATCOM's harmonic filtering and reactive current injection are functioning as intended. This not only improves power quality but also reduces conduction losses, thermal stress on equipment, and interference with sensitive loads.

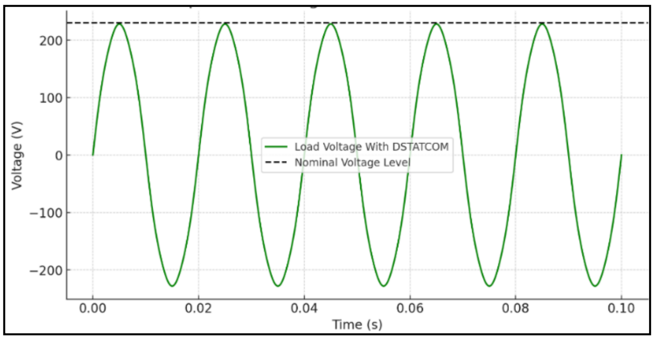

Figure 6. Output Load Voltage with DSTATCOM Controller

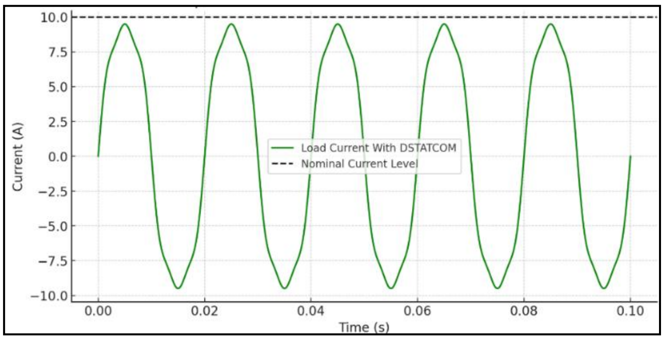

Figure 7. Output Load Current with DSTATCOM Controller

Figure 8 illustrates the profiles of real and reactive power with the DSTATCOM in operation. The real power output stabilizes at approximately 5 kW, closely aligning with the nominal demand, and exhibiting minimal oscillations. More importantly, the reactive power is effectively compensated, maintaining values well below 1.5 kVAR. This reduction in reactive power flow minimizes unnecessary burden on the grid, enhances voltage profile control, and supports a higher power factor. Such behavior underscores the capability of the DSTATCOM to dynamically inject or absorb reactive power based on system requirements.

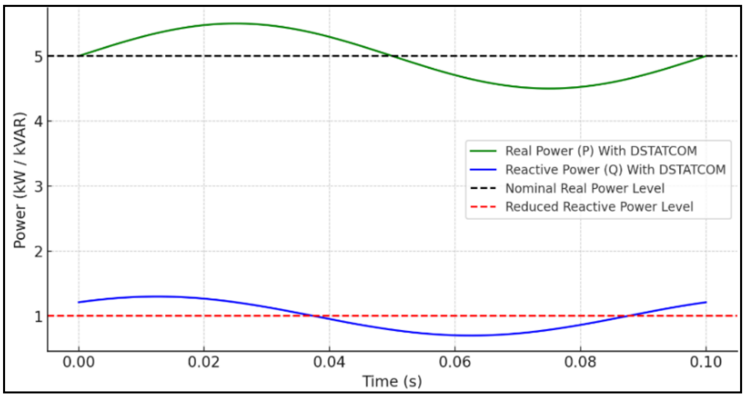

Figure 8. Output waveform of Real and Reactive Power with DSTATCOM Controller

Overall, the deployment of the DSTATCOM leads to a substantial enhancement in the operational performance of the hybrid power system. It mitigates the effects of nonlinear and intermittent sources, ensures better utilization of the

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generation capacity, and brings the system closer to compliance with international power quality standards. These results demonstrate the critical role of DSTATCOM in enabling reliable and efficient integration of renewable energy into modern power grids.

5.4. Power Factor and Harmonic Performance

The effectiveness of the DSTATCOM in improving power quality is further substantiated through a detailed analysis of power factor correction and harmonic mitigation, as illustrated in figure 9. This figure presents a comparative view of system performance with and without the presence of DSTATCOM, specifically focusing on power factor values and THD levels under dynamic loading conditions.

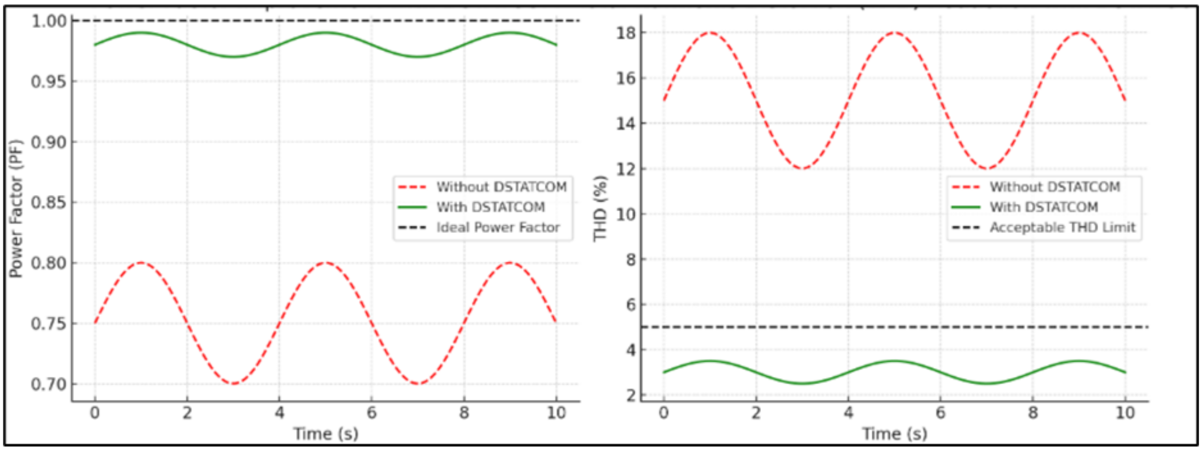

Figure 9. Power Factor Correction and Total Harmonic Distortion waveform with and without DSTATCOM Controller

In the uncompensated scenario, the system exhibits a fluctuating power factor ranging between 0.75 and 0.86. These suboptimal values indicate a significant presence of reactive power and poor alignment between the voltage and current waveforms, which is detrimental to system efficiency and can lead to higher operational costs due to increased apparent power demand. Such performance is particularly problematic in systems with nonlinear or renewable loads, where reactive components and harmonic pollution are typically pronounced.

Upon integration of the DSTATCOM, the power factor improves dramatically, stabilizing at approximately 0.99. This value is very close to the ideal unity power factor, signifying near-perfect synchronization of voltage and current waveforms and a substantial reduction in reactive power flow. The compensation mechanism of the DSTATCOM, which injects or absorbs reactive current as needed, plays a key role in achieving this enhancement. As a result, the system experiences improved energy efficiency and reduced voltage drops across distribution feeders.

In parallel, the THD levels also shown marked improvement. Without DSTATCOM, the system records peak THD values reaching up to 18%, a level that far exceeds the limits recommended by IEEE Standard 519, which stipulates that THD should remain below 5% for acceptable power quality in most low- and medium-voltage networks. Following the implementation of the DSTATCOM, the THD is effectively reduced to below 3%, demonstrating the compensator's capability to suppress high-frequency harmonic components generated by nonlinearities in renewable generation and power electronic interfacing. The observed improvements in both power factor and harmonic distortion collectively underscore the robustness of the DSTATCOM as a power quality enhancement solution. These results confirm its practical relevance for modern hybrid renewable systems, where maintaining high power quality is critical for reliable grid operation and compliance with international standards.

5.5. Summary of Performance Metrics

To quantitatively evaluate the impact of DSTATCOM integration on the performance of the grid-connected hybrid renewable energy system, a comparative assessment of several key performance indicators (KPIs) is presented in table 2. These indicators encompass both power quality metrics and dynamic system response characteristics, providing a comprehensive overview of system behavior under compensated and uncompensated scenarios.

The THD, a critical measure of waveform purity, is significantly reduced from 8.8% in the uncompensated system to 2.65% with the application of DSTATCOM. This reduction is crucial in ensuring compliance with international standards such as IEEE 519, and it minimizes the adverse impacts of harmonics on sensitive equipment and overall system efficiency.

Voltage recovery time, which indicates the duration the system takes to return to steady-state following a disturbance, also shows substantial improvement. In the absence of DSTATCOM, the recovery time is measured at 145 milliseconds, reflecting slower system stabilization. With DSTATCOM, this value is reduced to just 40 milliseconds, demonstrating the compensator's ability to rapidly restore voltage levels after transient events.

Table 2. Output Values with Grid connected Hybrid Power System

Output Parameter	Without DSTATCOM	With DSTATCOM
THD	8. 80%	2.65%
Voltage Recovery Time (ms)	145.00	40.00
Power factor correction	0.86	0.99
Settling Time (ms)	220.00	70.00
Maximum Overshoot	18.00%	6.00%

Power factor correction is another area where the improvement is evident. The baseline system operates with a suboptimal power factor of 0.86, indicating significant reactive power flow. With DSTATCOM compensation, the power factor is improved to 0.99, nearing the ideal unity value. This improvement implies better utilization of electrical power and reduced losses in the distribution network.

The system's dynamic response is further characterized by settling time and maximum overshoot—two parameters that describe the transient performance of the voltage and current signals. Without DSTATCOM, the settling time is relatively high at 220 milliseconds, and the system exhibits a maximum overshoot of 18%, which may result in overvoltage stress on equipment. After compensation, the settling time is significantly reduced to 70 milliseconds, and the maximum overshoot is curtailed to just 6%, indicating improved damping and control stability.

These findings, summarized in table 2, confirm that DSTATCOM integration leads to significant enhancements in both steady-state and transient performance metrics. The improvements span power quality, voltage regulation, system responsiveness, and operational stability—factors that are critical for the reliable and efficient operation of hybrid renewable energy systems in grid-connected environments.

5.6. Discussion

The comprehensive simulation analysis presented in the preceding sections confirms the critical role of DSTATCOM in enhancing the operational performance of a grid-connected hybrid renewable energy system. The introduction of DSTATCOM results in marked improvements across multiple performance dimensions, particularly in power quality, system stability, and dynamic responsiveness. One of the most notable impacts is observed in the significant enhancement of voltage and current waveform quality. The compensated system exhibits nearly ideal sinusoidal waveforms, which reflects the DSTATCOM's ability to mitigate harmonic distortions effectively. This is further supported by the substantial reduction in THD, from 8.8% in the uncompensated case to just 2.65% after compensation—well below the IEEE 519 threshold of 5%. This level of harmonic suppression is essential not only for maintaining the integrity of electrical equipment but also for ensuring the long-term reliability of the distribution network.

In addition to harmonic filtering, DSTATCOM demonstrates excellent capability in regulating reactive power and stabilizing power flows. The reactive power is dynamically compensated, resulting in a dramatic improvement in the system's power factor from 0.86 to 0.99. This enhancement implies more efficient utilization of the apparent power capacity, reduced line losses, and improved voltage regulation—benefits that are critical in systems with high shares of intermittent renewable sources such as solar and wind.

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From a transient performance perspective, the improvements in settling time, voltage recovery, and overshoot further highlight the dynamic capabilities of the DSTATCOM controller. Faster recovery times and lower overshoot translate into enhanced resilience against load fluctuations and generation variability—both of which are inherent characteristics of renewable energy integration.

Moreover, these improvements contribute directly to the system's compliance with modern grid code requirements, which increasingly demand tighter control over voltage, frequency, harmonic levels, and reactive power exchange. The results affirm that DSTATCOM is not merely a supplemental device but a necessary infrastructure component for future-proofing hybrid distributed energy systems within the context of smart grids and evolving regulatory standards.

The DSTATCOM proves to be a highly effective solution for addressing the technical challenges posed by hybrid renewable energy integration. Its implementation ensures not only better power quality and energy efficiency but also facilitates smoother interaction between distributed generation units and the utility grid, making it indispensable in the transition toward more sustainable and intelligent power systems.

6. Conclusion

This study has demonstrated that the integration of DSTATCOM significantly enhances the performance of grid-connected hybrid renewable energy systems. By providing dynamic voltage support, suppressing harmonic distortion, and correcting poor power factor, DSTATCOM plays a crucial role in stabilizing the interface between intermittent renewable sources—such as solar and wind—and the electrical grid. The simulation results confirm that, in the absence of DSTATCOM, the system suffers from voltage instability, elevated total harmonic distortion, and inefficient power delivery, particularly under fluctuating generation conditions. With DSTATCOM in operation, the system achieves marked improvements in power quality metrics, including a reduction in THD from 8.8% to 2.65%, and a power factor increase from 0.86 to 0.99. Additionally, the voltage recovery time and settling time are significantly shortened, indicating improved transient performance. These enhancements support more reliable energy transfer, reduce losses, and ensure compliance with grid codes and international power quality standards. Despite its technical advantages, the deployment of DSTATCOM systems presents practical challenges. High capital investment, maintenance complexity, and the need for advanced control schemes and coordination in large-scale networks remain significant barriers. Furthermore, scalability and real-time operation become increasingly complex in distributed power systems with multiple compensation devices. Nevertheless, ongoing advancements in power electronics, digital control systems, and communication technologies are progressively mitigating these limitations. As such, DSTATCOM is poised to serve as a foundational technology in the development of resilient and sustainable hybrid renewable energy systems, supporting the broader transition toward smart grids and clean energy integration.

7. Declarations

7.1. Author Contributions

Conceptualization: R.R., L.D., M.B.; Methodology: R.R., L.D.; Software: R.R.; Validation: L.D., M.B.; Formal Analysis: R.R.; Investigation: R.R.; Resources: L.D., M.B.; Data Curation: R.R.; Writing – Original Draft Preparation: R.R.; Writing – Review and Editing: L.D., M.B.; Visualization: R.R.; All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

7.4. Institutional Review Board Statement

Not applicable.

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7.5. Informed Consent Statement

Not applicable.

7.6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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