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Improving Power System Reliability Using Hydrogen Fuel Cell–Integrated D-FACTS for Power Quality Enhancement

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تحسين موثوقية نظام الطاقة باستخدام خلايا وقود الهيدروجين المدمجة مع أنظمة نقل التيار المتردد المرنة (D-FACTS) لتعزيز جودة الطاقة

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Abstract:
The increasing penetration of renewable energy sources, proliferation of power electronic converters, and growth of dynamic loads are intensifying power quality challenges and reliability constraints in modern power systems. Conventional compensation and control solutions are often insufficient to address both fast-electrical disturbances and long-duration energy support requirements. This paper investigates the integration of hydrogen fuel cells with Distributed Flexible AC Transmission System (D-FACTS) devices as an advanced and sustainable approach to enhancing power system reliability and mitigating power quality issues. A comprehensive conceptual framework is developed to describe the system architecture, operational principles, and energy flow coordination of hydrogen fuel cell–integrated D-FACTS in contemporary power networks. Critical power quality problems, including voltage sags and swells, harmonic distortion, flicker, unbalance, and transient disturbances, are analyzed in the context of high renewable energy penetration and dynamic load behavior. The study further examines detailed modeling and control strategies, emphasizing real-time, adaptive, and intelligent controllers for coordinated voltage regulation, power flow control, and harmonic mitigation under steady-state and dynamic operating conditions. Performance evaluation based on simulation-based and experimental case studies demonstrates significant improvements in voltage profiles, harmonic reduction, loss minimization, dynamic response, reliability indices, and system resilience during contingencies. Finally, techno-economic and environmental assessments highlight the potential of hydrogen fuel cell–integrated D-FACTS solutions to deliver cost-effective, low-carbon, and scalable grid support, while identifying key deployment challenges and future research directions. The results confirm that the proposed integrated approach offers a promising pathway toward reliable, resilient, and sustainable next-generation power systems.

Keywords: Hydrogen fuel cells; D-FACTS; Power quality; Power system reliability; Renewable energy integration.

الملخص:
إن التوسع المتزايد في دمج مصادر الطاقة المتجددة، والانتشار الواسع لمحوّلات القدرة الإلكترونية، والنمو المتسارع للأحمال الديناميكية، يؤدي إلى تفاقم تحديات جودة القدرة والقيود المرتبطة بموثوقية أنظمة القدرة الحديثة. وغالبًا ما تكون

حلول التعويض والتحكم التقليدية غير كافية لمعالجة كلٍّ من الاضطرابات الكهربائية السريعة ومتطلبات الدعم الطاقي طويل الأمد. تتناول هذه الدراسة تكامل خلايا الوقود الهيدروجينية مع أنظمة نقل التيار المتناوب المرنة الموزعة (D-FACTS) بوصفه نهجًا متقدمًا ومستدامًا لتعزيز موثوقية أنظمة القدرة ومعالجة مشكلات جودة القدرة. يتم تطوير إطار مفاهيمي شامل يوضح بنية النظام، ومبادئ التشغيل، وآليات تنسيق تدفق الطاقة لأنظمة D-FACTS المدمجة مع خلايا الوقود الهيدروجينية في شبكات القدرة المعاصرة. كما يتم تحليل مشكلات جودة القدرة الحرجة، بما في ذلك هبوطات وارتفاعات الجهد، والتشوه التوافقي، والوميض، وعدم اتزان الجهد، والاضطرابات العابرة، في ظل الارتفاع الكبير لاختراق الطاقات المتجددة وطبيعة الأحمال الديناميكية. علاوة على ذلك، تستعرض الدراسة نمذجة واستراتيجيات التحكم بالتفصيل، مع التركيز على التحكم الآني والتكيفي والذكي لتحقيق تنظيم منسق للجهد، والتحكم في تدفق القدرة، والتخفيف من التوافقيات تحت ظروف التشغيل المستقرة والديناميكية. وتُظهر نتائج تقييم الأداء، المعتمدة على دراسات محاكاة وتجارب عملية، تحسنًا ملحوظًا في ملفات الجهد، وتقليل التشوه التوافقي، وخفض الفواقد، وتحسين الاستجابة الديناميكية، ومؤشرات الموثوقية، وتعزيز مرونة النظام أثناء حالات الطوارئ والاضطرابات. وأخيرًا، يبيّن التقييم التقني–الاقتصادي والبيئي أن حلول D-FACTS المدمجة مع خلايا الوقود الهيدروجينية تمتلك إمكانات واعدة لتوفير دعم شبكي منخفض الكربون، وقابل للتوسع، وذو جدوى اقتصادية، مع تحديد أبرز تحديات النشر واتجاهات البحث المستقبلية. وتؤكد النتائج أن النهج المتكامل المقترح يمثل مسارًا واعدًا نحو أنظمة قدرة مستقبلية أكثر موثوقية ومرونة واستدامة.

الكلمات المفتاحية: خلايا وقود الهيدروجين؛ أنظمة نقل التيار المتردد المرنة (D-FACTS)؛ جودة الطاقة؛ موثوقية نظام الطاقة؛ تكامل الطاقة المتجددة.

1. Introduction

Global hydrogen demand rose to nearly 100 million tonnes (Mt) in 2024, representing an increase of about 2% compared with 2023 and broadly tracking overall growth in energy demand. This expansion was driven mainly by higher consumption in traditional hydrogen-use sectors, notably oil refining and industrial processes, while uptake in emerging applications remained marginal [1,2]. In fact, demand from new uses contributed less than 1% of total hydrogen consumption and was concentrated almost entirely in biofuels production. On the supply side, hydrogen production in 2024 continued to rely predominantly on fossil fuels, requiring approximately 290 billion cubic metres (bcm) of natural gas and about 90 million tonnes of coal equivalent (Mtce). Although low-emissions hydrogen output increased by around 10% in 2024 and is projected to reach roughly 1 Mt in 2025, it still represents less than 1% of global hydrogen production, underscoring that the transition away from unabated fossil-based hydrogen remains in its early stages [3,4].

Improving power system reliability has become a critical objective in modern electric grids due to the increasing penetration of renewable energy sources, the widespread use of power electronic converters, and the growing sensitivity of industrial and commercial loads to power quality disturbances [5,6]. Conventional grid infrastructures and compensation techniques are often inadequate to address the combined challenges of fast voltage fluctuations, harmonic distortion, reduced system inertia, and limited fault current contribution [7,8]. In this context, the integration of hydrogen fuel cells with Distributed Flexible AC Transmission System (D-FACTS) devices emerges as a promising solution capable of simultaneously addressing reliability and power quality concerns.

Hydrogen fuel cell–integrated D-FACTS systems leverage the complementary strengths of both technologies. D-FACTS devices provide rapid and localized control of voltage, reactive power, and power flow, enabling effective mitigation of disturbances such as voltage sags, swells, flicker, and unbalance [9,10]. Meanwhile, hydrogen fuel cells supply clean, dispatchable, and sustained active power support, which is particularly valuable during prolonged disturbances, contingencies, and islanded operation [11,12]. Through coordinated control strategies, the integrated system enhances voltage stability, reduces harmonic distortion, minimizes losses, and improves dynamic response under both steady-state and transient operating conditions [13, 14].

The combined impact of hydrogen fuel cell–integrated D-FACTS on power system reliability extends beyond immediate power quality improvements [15,16]. By supporting critical loads during outages, reducing stress on network components, and enabling faster recovery following disturbances, the integrated approach contributes to improved reliability indices and enhanced system resilience [17,18]. Furthermore, when coupled with green hydrogen production pathways, this solution aligns reliability enhancement with decarbonization objectives, offering a scalable and future-ready framework for the development of resilient, low-carbon, and intelligent power systems [19-21]. Several studies have investigated improving power system reliability using hydrogen fuel cell–integrated D-FACTS for power quality enhancement, as outlined below.

Kılıç et al., [22] proposed a hydrogen fuel cell–integrated D-STATCOM architecture specifically targeted at mitigating voltage sags, which are among the most common triggers of nuisance trips and process interruptions in distribution systems. The study emphasizes that combining fuel-cell-based active power support with fast D-STATCOM reactive compensation enables deeper and faster sag recovery than conventional compensators operating without a dispatchable energy source. The reported contribution is not limited to steady-state voltage support; rather, it frames the integrated HFC–D-STATCOM as a reliability-oriented custom power solution validated through MATLAB-based simulations and advanced fuzzy control, demonstrating improved voltage sag reduction and operational stability under disturbance conditions.

Khaleel et al., [23] develop and simulate an integrated distribution-network scheme in which a hydrogen fuel cell (HFC) is used to strengthen the D-STATCOM's capability to mitigate voltage sag events and support sensitive loads. A key technical insight is that fuel-cell integration can improve the responsiveness and sustainability of voltage injection and compensation actions by providing a controllable energy source behind the converter, thereby enhancing PQ performance under changing operating conditions. The paper positions the approach as both a technical and environmental opportunity, highlighting the suitability of HFC-supported compensation for modern grids experiencing variability from distributed generation and load dynamics.

In [24], the article investigates power quality enhancement achieved by integrating a fuel cell (FC) into the grid through a DC–DC chopper and a grid-tied inverter controlled using a conventional PI-based scheme. Two PI controllers are designed and subsequently tuned using three recent evolutionary computing approaches—Harmony Search (HS), the Modified Flower Pollination Algorithm (MFPA), and Electromagnetic Field Optimization (EFO). These optimized PI controllers regulate the operation of the inverter interfacing the on-grid FC, with the primary objective of maintaining the point of common coupling (PCC) voltage within acceptable limits under disturbed network conditions. In particular, the controllers are applied to the inverter's power and current regulation loops to ensure robust performance during various voltage sag and swell events. The effectiveness of HS, MFPA, and EFO is then benchmarked against Particle Swarm Optimization (PSO) in terms of voltage profile improvement, overall power quality performance, and computational execution time.

This study contributes a unified and implementation-oriented framework for enhancing power system reliability by integrating hydrogen fuel cells with D-FACTS devices, explicitly linking system architecture, operational principles, and coordinated energy flow management to measurable power quality and reliability outcomes. It advances the state of the art by systematically characterizing contemporary power quality disturbances and reliability constraints under high renewable penetration and dynamic loads, and by consolidating multi-time-scale modeling and control strategies that enable real-time, adaptive, and intelligent coordination of voltage regulation, power flow control, and harmonic mitigation. The work further strengthens the evidence base through performance evaluation pathways and KPIs that capture steady-state and transient benefits, including voltage profile improvement, harmonic reduction, loss minimization, and enhanced resilience during contingencies, while also extending the discussion to techno-economic and environmental feasibility, scalability, and deployment enablers, thereby providing a comprehensive roadmap for research translation toward low-carbon, reliable, and intelligent power systems.

2. Conceptual Framework

The increasing penetration of renewable energy sources, electrification of critical loads, and the growing sensitivity of modern electrical equipment have imposed stringent requirements on power system reliability and power quality. Conventional grid infrastructures, originally designed for centralized generation and unidirectional power flow, are increasingly challenged by voltage instability, harmonic distortion, power flow congestion, and reduced system resilience under dynamic operating conditions. In this context, advanced power-electronic-based solutions and alternative energy carriers are emerging as key enablers for maintaining reliable, flexible, and sustainable power system operation [25,26].

Distributed Flexible AC Transmission System (D-FACTS) devices have gained considerable attention due to their modularity, fast dynamic response, and ability to provide localized voltage regulation, reactive power compensation, and power flow control [27,28]. However, D-FACTS devices are inherently limited by their reliance on grid-supplied energy, particularly during severe disturbances, islanding events, or prolonged contingencies [29,30]. To overcome these limitations, the integration of dispatchable and low-carbon energy sources has become a strategic research direction. Figure 1 demonstrates Ideal shunt compensator connected in the middle of a transmission line. Figure 2 illustrates Ideal series compensator connected in the middle of a transmission line. Figure 2 outlines Ideal generic series compensator.

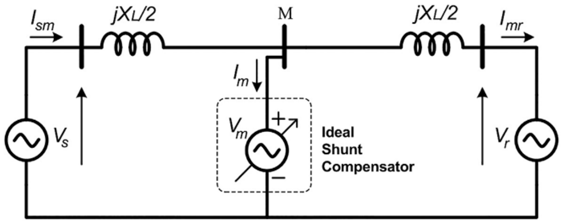

Figure 1. Ideal shunt compensator connected in the middle of a transmission line [25].

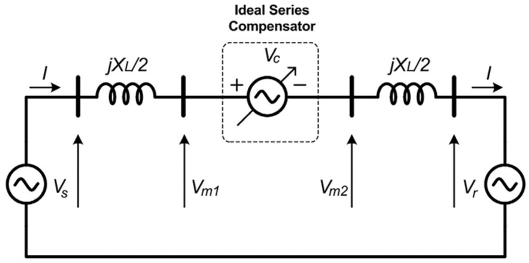

Figure 2. Ideal series compensator connected in the middle of a transmission line [25].

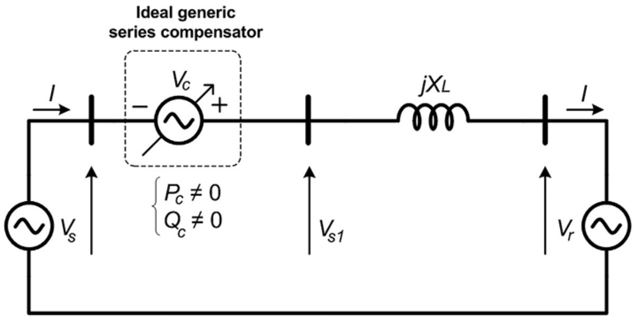

Figure 3. Ideal generic series compensator [25].

Hydrogen fuel cells represent a promising complementary technology, offering clean, controllable, and long-duration energy support [31,32]. When integrated with D-FACTS devices, hydrogen fuel cells can provide both active and reactive power support, thereby extending the functional capabilities of conventional D-FACTS solutions as highlighted in Figure 4. This integration enables a hybrid electro–energy framework that enhances grid flexibility, resilience, and sustainability while simultaneously addressing power quality challenges [33,34]. The conceptual framework presented in Table 1 formalizes this integration by outlining the system architecture, operational principles, coordination mechanisms, and reliability contributions of hydrogen fuel cell–integrated D-FACTS in modern power systems.

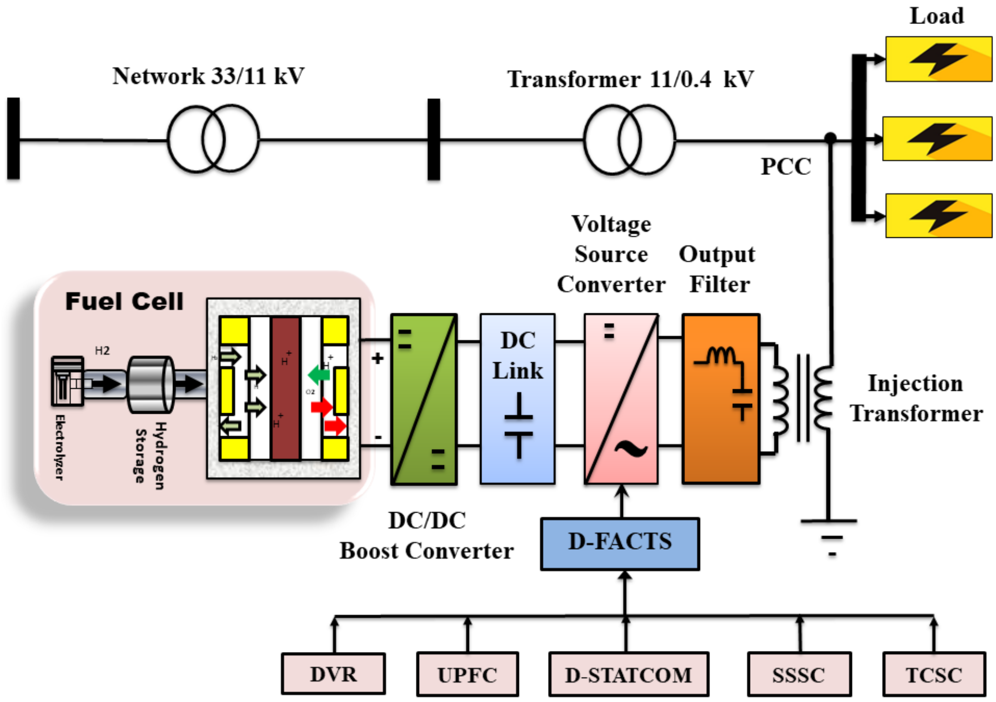

Figure 4. Power systems with fuel cell interfacing to D-FACTS [26].

Table 1. Conceptual Framework of Hydrogen Fuel Cell–Integrated D-FACTS in Modern Power Systems [35-48]

Framework Element	Core Definition	Key Components / Variables	Functional Role in the Grid	Power Quality / Reliability Contribution	Design and Implementation Considerations
System Architecture	Integrated platform combining hydrogen fuel cell generation with D-FACTS devices.	Fuel cell stack, DC/DC converter, inverter, D-FACTS modules, sensors, communication layer.	Provides distributed active and reactive power support.	Voltage regulation, congestion relief, contingency support.	Modular deployment, grid-code compliance, protection coordination.
Operational Principle	Coordinated control of fuel cell output and D-FACTS compensation.	P–Q control, droop control, PLL, current controllers.	Ensures fast electrical response with sustained energy support.	Mitigation of voltage sags, swells, and flicker.	Multi-time-scale control design to avoid instability.
Energy Flow Coordination	Supervisory management of power and energy flows.	Energy management system, forecasts, optimization algorithms.	Optimizes dispatch and compensation under constraints.	Loss minimization and improved reliability indices.	Consider ramp limits, hydrogen storage state, and network constraints.
D-FACTS Functional Layer	Distributed power electronic compensation devices.	D-STATCOM, SSSC, DVR modules.	Local voltage and power-flow control.	Harmonic reduction and voltage stability enhancement.	Optimal placement and sizing are critical.
Sustainability and Resilience Role	Use of hydrogen as a clean, dispatchable energy carrier.	Green hydrogen supply, storage systems, fuel cell efficiency metrics.	Enhances grid flexibility and resilience.	Reduced outage impacts and carbon emissions.	Lifecycle assessment and safety standards required.

Table 1 presents a structured conceptual framework that captures the key functional layers and interactions involved in integrating hydrogen fuel cells with D-FACTS devices. Each framework element plays a distinct yet interconnected role in enhancing power system reliability and power quality.

The system architecture defines the physical and functional integration of hydrogen fuel cell units with D-FACTS devices through power electronic interfaces. By combining fuel cell stacks, DC/DC converters, voltage source inverters, and distributed compensation modules, the architecture enables decentralized active and reactive power support at strategically selected network locations. This modular deployment approach improves voltage profiles and reduces congestion, particularly in weak buses and heavily loaded feeders.

The operational principle is based on coordinated control between the fuel cell power conversion system and D-FACTS compensation mechanisms. While D-FACTS devices provide rapid, high-bandwidth voltage and current regulation, the hydrogen fuel cell supplies sustained real power and supplementary reactive support. This multi-time-scale operation allows the system to respond effectively to fast transients, such as voltage sags and flicker, while maintaining long-term stability during extended disturbances.

The energy flow coordination layer introduces a supervisory energy management system responsible for optimal dispatch and control. By incorporating load forecasts, network constraints, hydrogen storage state, and fuel cell ramp-rate limits, the coordination layer ensures that active power injection and reactive compensation are delivered efficiently. This optimization-driven coordination minimizes system losses, avoids over-compensation, and improves overall reliability indices under both normal and stressed operating conditions.

The D-FACTS functional layer focuses on localized power quality enhancement through devices such as D-STATCOMs, SSSCs, and dynamic voltage restorers. These devices provide precise control of voltage magnitude, phase angle, and impedance, enabling effective mitigation of harmonics, voltage unbalance, and power flow deviations. When supported by fuel cell energy, D-FACTS devices maintain their effectiveness even during weak-grid or fault conditions. Finally, the sustainability and resilience role highlight the broader contribution of the integrated framework to low-carbon and resilient power systems. Hydrogen fuel cells, particularly when supplied by green hydrogen, significantly reduce greenhouse gas emissions while offering dispatchable energy for critical loads. This capability enhances grid resilience by supporting islanded operation, accelerating service restoration, and reducing the severity and duration of outages.

3. Power Quality Challenges and Reliability Constraints in Contemporary Power Networks

Modern power networks are undergoing a profound structural transformation driven by the large-scale integration of renewable energy sources, widespread deployment of power electronic converters, electrification of transportation, and increasing demand for high-quality and uninterrupted electricity supply. While these developments support decarbonization and energy efficiency objectives, they also introduce new operational challenges that directly affect power quality and system reliability. The shift from synchronous, inertia-dominated generation to inverter-based resources has altered fault characteristics, voltage regulation behavior, and frequency dynamics, thereby increasing the vulnerability of power systems to disturbances as illustrated in Figure 5 [49,50].

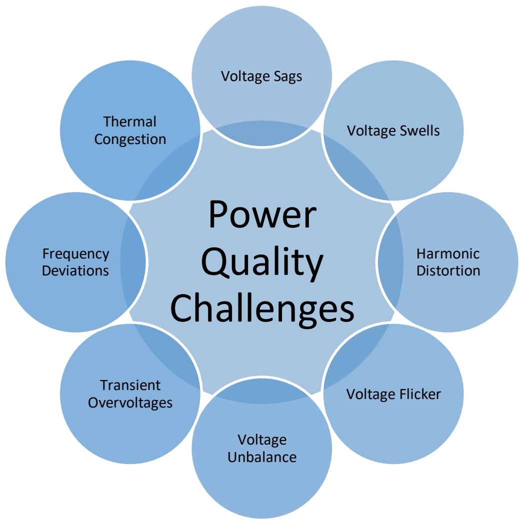

Figure 5. Power Quality Challenges.

Power quality disturbances, such as voltage sags and swells, harmonic distortion, flicker, voltage unbalance, and transient overvoltages, have become more frequent and severe in contemporary grids. These phenomena are particularly critical for sensitive industrial processes, digital infrastructure, medical equipment, and data centers, where even short-duration deviations can lead to significant economic losses and operational disruptions. At the same time, reliability constraints related to weak grid conditions, congestion, reduced fault current contribution, and thermal overloading further exacerbate system performance, especially under high renewable energy penetration and rapidly varying loads such as electric vehicle charging stations [51,52].

Against this background, a systematic understanding of power quality challenges and their reliability implications is essential for the design and deployment of advanced mitigation technologies. Table 2 provides a technical overview of the dominant power quality issues and reliability constraints in contemporary power networks, highlighting their causes, impacts, monitoring indices, and typical mitigation measures. This structured assessment forms a critical basis for evaluating advanced solutions such as hydrogen fuel cell–integrated D-FACTS devices.

Table 2 categorizes the most significant power quality disturbances and reliability constraints affecting modern power systems and links them to their technical origins and operational consequences. Voltage sags are identified as one of the most frequent disturbances, typically arising from short-circuit faults, large motor starting, and switching operations. In networks with high renewable penetration, reduced fault current levels and weak short-circuit strength intensify sag severity and duration. These events commonly trigger equipment trips and control system resets, leading to increased outage frequency and degraded reliability performance.

Voltage swells, although less frequent, pose serious risks due to overvoltage stress on insulation and power electronic components. They are often associated with sudden load rejection or capacitor switching and are amplified in distribution networks with high photovoltaic penetration and reverse power flow. Persistent exposure to swells accelerates equipment aging and can result in protection maloperations, ultimately compromising system availability.

Table 2. Power Quality Challenges and Reliability Constraints in Contemporary Power Networks [50,57].

PQ / Reliability Issue	Technical Definition / Metric	Primary Causes	Impact under High RES & Dynamic Loads	Monitoring Indices / Standards	Typical Mitigation Measures
Voltage Sags	RMS voltage drop (0.1–0.9 pu, 0.5 cycle–1 min)	Faults, motor starting, switching events	Reduced fault current, weak grid conditions	ITIC/CBEMA, IEC 61000-4-30	DVR, STATCOM, fast reactive power support
Voltage Swells	RMS voltage rise (1.1–1.8 pu, 0.5 cycle–1 min)	Load rejection, capacitor switching	Reverse power flow, PV overgeneration	IEC 61000-4-30, IEEE 1159	Volt/VAR optimization, controlled switching
Harmonic Distortion	Non-sinusoidal waveform (THD, TDD)	Power electronic converters, nonlinear loads	High inverter penetration, resonance effects	IEEE 519, IEC 61000 series	Active filters, harmonic control
Voltage Flicker	Rapid voltage fluctuation (Pst, Plt)	Arc furnaces, wind/PV intermittency	Fast irradiance variation	IEC 61000-4-15	STATCOM, ramp-rate control
Voltage Unbalance	Phase voltage asymmetry (VUF %)	Single-phase loads, uneven DER allocation	Single-phase PV/EV dominance	EN 50160	Phase balancing, three-phase DER
Transient Overvoltages	Short-duration high-voltage spikes (µs–ms)	Lightning, switching surges	Frequent DER switching	IEC 61000-4-5	Surge arresters, insulation coordination
Frequency Deviations	Deviation from nominal frequency, ROCOF	Generation/load imbalance	Low inertia systems	PMU frequency, grid codes	Virtual inertia, fast frequency response
Thermal Congestion	Persistent loading above ratings	EV charging, DER backfeed	High coincidence factors	Asset loading indices	D-FACTS flow control, demand response

Moreover, Harmonic distortion has emerged as a dominant challenge in converter-dominated grids. Nonlinear loads, renewable inverters, and fast EV chargers inject harmonic currents that interact with network impedances, leading to elevated voltage distortion levels. Excessive harmonics cause overheating of transformers and cables, misoperation of protective relays, and reduced asset lifetime. As indicated in the table, compliance with harmonic standards such as IEEE 519 is increasingly difficult in weak grids without dedicated mitigation measures.

Voltage flicker reflects rapid voltage fluctuations caused by intermittent renewable generation and dynamic industrial loads. In high-RES systems, fast irradiance variations and fluctuating wind output significantly increase flicker severity. Although flicker may not immediately damage equipment, it results in customer complaints, visual discomfort, and accelerated wear of voltage regulation devices, creating both technical and regulatory challenges. In addition, Voltage unbalance is primarily linked to uneven phase loading and the proliferation of single-phase distributed energy resources and EV chargers. Unbalance introduces negative-sequence components that increase motor losses and thermal stress, leading to reduced efficiency and premature failure of rotating machines. At the system level, unbalance limits feeder capacity and reduces overall power delivery capability.

Transient overvoltages and switching transients represent high-impact, low-duration events resulting from lightning strikes, switching operations, and converter interactions. Despite their short duration, these transients impose severe electrical stress on insulation systems and sensitive electronics, often causing immediate failures or latent damage that reduces long-term reliability. However, Frequency deviations and high rates of change of frequency (ROCOF) have become increasingly relevant in low-inertia power systems. High renewable penetration and sudden load variations can lead to rapid frequency excursions, triggering inverter disconnections and under-frequency load shedding schemes. Such events threaten system stability and increase the risk of widespread outages. Finally, thermal congestion is highlighted as a critical reliability constraint driven by EV charging clusters, DER backfeed, and changing load patterns. Persistent overloading accelerates asset aging and increases forced outage rates, directly impacting reliability indices such as SAIDI and SAIFI.

4. Modeling and Control Strategies

The integration of hydrogen fuel cells (HFCs) with Distributed Flexible AC Transmission System (D-FACTS) devices represents a paradigm shift in the control and operation of modern power networks. As power systems transition toward high shares of inverter-based renewable generation, traditional control approaches, largely designed for synchronous machines, are increasingly inadequate to address fast dynamics, reduced inertia, and complex power quality challenges. In this context, advanced modeling and control strategies are essential to fully exploit the complementary characteristics of hydrogen fuel cells and D-FACTS devices [58,59].

Hydrogen fuel cells provide dispatchable, low-carbon, and long-duration energy support, making them well suited for sustained active power injection and resilience enhancement. In contrast, D-FACTS devices offer fast-acting, high-bandwidth control of voltage, reactive power, and power flow through power electronic interfaces. The effective integration of these technologies requires accurate mathematical models, robust real-time control algorithms, and coordinated multi-layer control architectures capable of operating under both steady-state and highly dynamic conditions. Table 3 summarizes the key modeling approaches and control strategies for hydrogen fuel cell–integrated D-FACTS systems, highlighting their objectives, coordination mechanisms, constraints, and performance indicators.

Table 3. Modeling and Control Strategies for Hydrogen Fuel Cell–Integrated D-FACTS Devices [60-67]

Layer / Component	Mathematical Model	Control Objective	Control Algorithms	HFC–D-FACTS Coordination	Key Constraints	Key Performance Indicators
Hydrogen Fuel Cell Stack	Polarization and dynamic electrochemical model	Regulate active power and efficiency	PI / adaptive control, MPC	HFC supplies sustained active power	Current, thermal, ramp limits	Power tracking error, efficiency
DC/DC Converter Interface	Averaged state-space model	Stabilize DC-link and regulate HFC current	Current-mode, sliding-mode, MPC	Buffers fast AC-side dynamics	Duty-cycle and ripple limits	DC voltage stability, settling time
DC-Link	Capacitor dynamic model	Maintain DC voltage stability	PI with feedforward control	Absorbs short-term power mismatch	Voltage and thermal limits	DC voltage deviation
Grid-Side Inverter (VSC)	dq-frame model with L/LCL filter	Active/reactive power control	Vector control, PR control	Provides fast Q and harmonic control	Current and switching limits	THD, dynamic response
D-FACTS Shunt Device	VSC-based shunt compensator model	Voltage regulation and flicker mitigation	Droop control, MPC	Primary voltage stabilization	Reactive power rating	Voltage deviation, Pst/Plt
D-FACTS Series Device	Series voltage injection model	Power flow control	Phase-angle and damping control	Manages congestion with HFC support	Injection and thermal limits	Power flow deviation
Supervisory EMS	Optimization-based dispatch model	Coordinated energy and PQ management	Rule-based, MPC, AI-assisted	Allocates P and Q setpoints	Hydrogen SOC and network constraints	Cost, voltage violations

Table 3 organizes the modeling and control framework into functional layers, reflecting the hierarchical and multi-time-scale nature of hydrogen fuel cell–integrated D-FACTS systems. At the core of the framework is the hydrogen fuel cell stack model, which captures the electrochemical behavior and dynamic characteristics of the fuel cell. Polarization-based and dynamic models are commonly employed to represent voltage losses and transient response. Control strategies at this level focus on regulating active power output while maximizing efficiency and respecting thermal and ramp-rate constraints. Adaptive and model predictive controllers are particularly effective in handling nonlinearities and ensuring smooth power delivery.

The DC/DC converter interface plays a critical role in decoupling the fuel cell dynamics from grid-side disturbances. Averaged state-space models are typically used for controller design, enabling precise regulation of fuel cell current and stabilization of the DC-link voltage. Advanced control techniques such as sliding-mode and predictive control enhance robustness against parameter variations and load transients, ensuring reliable power transfer under rapidly changing conditions.

The DC-link subsystem serves as an energy buffer between the fuel cell and the grid-connected inverter. Its dynamic behavior is governed by capacitor charge balance equations, and its primary control objective is to maintain a stable DC voltage. Feedforward-assisted PI control is widely adopted to suppress voltage fluctuations arising from power mismatches. By absorbing short-term transients, the DC-link enables seamless coordination between slow fuel cell dynamics and fast D-FACTS control actions.

The grid-side voltage source converter (VSC) is responsible for injecting controlled active and reactive power into the network. dq-frame and proportional–resonant (PR) models are used to design vector and resonant controllers capable of tracking current and voltage references with high accuracy. Through these controllers, the VSC delivers fast reactive power support, harmonic compensation, and voltage regulation, forming the primary interface between the integrated system and the power grid.

Within the D-FACTS domain, shunt-connected devices such as D-STATCOMs focus on voltage regulation and flicker mitigation at the point of common coupling. Their control strategies typically employ droop-based or model predictive approaches to ensure rapid voltage recovery and stable operation. In parallel, series-connected D-FACTS devices manage power flow and congestion by injecting controllable series voltages. Phase-angle control and power oscillation damping techniques enable these devices to enhance system stability, particularly under heavily loaded or disturbed conditions.

At the system level, the supervisory energy management system (EMS) coordinates the operation of hydrogen fuel cells and D-FACTS devices across different time scales. Optimization-based dispatch models allocate active power setpoints to the fuel cell while assigning reactive power and series compensation references to D-FACTS devices. This coordination ensures that power quality requirements are met at minimal operational cost and hydrogen consumption, even under network constraints and uncertainty. Overall, the modeling and control strategies summarized in Table 3 demonstrate that hydrogen fuel cell–integrated D-FACTS systems require a tightly coordinated, hierarchical control framework. By combining accurate component-level models with advanced real-time and supervisory control algorithms, the integrated system can effectively mitigate voltage, power flow, and harmonic issues while enhancing reliability, resilience, and sustainability in modern power networks.

5. Performance Evaluation and Reliability Enhancement Analysis

The effectiveness of hydrogen fuel cell–integrated D-FACTS systems must be rigorously validated through comprehensive performance evaluation and reliability analysis before large-scale deployment in modern power networks. While the conceptual framework and control strategies establish the theoretical feasibility of such integration, quantitative assessment under realistic operating conditions is essential to demonstrate tangible benefits. Simulation-based studies and experimental or hardware-in-the-loop (HIL) validations provide critical insight into system behavior under steady-state operation, dynamic disturbances, and extreme contingency scenarios.

In contemporary power systems characterized by high renewable energy penetration and dynamic load profiles, performance evaluation extends beyond conventional voltage regulation metrics. It encompasses power quality improvement, loss minimization, transient response, and the enhancement of reliability and resilience indices. Accordingly, Table 4 presents a structured evaluation framework that links representative case study scenarios to key performance indicators (KPIs), comparative benchmarks, and recommended evidence. This framework enables a holistic assessment of how hydrogen fuel cell–integrated D-FACTS devices contribute to improved grid performance and reliability.

Table 4. Performance Evaluation and Reliability Enhancement Analysis for HFC–Integrated D-FACTS Systems

Evaluation Category	Case Study Scenario	Test Setup / Disturbance	Baseline vs. Proposed Comparison	Expected Technical Outcome	Recommended Evidence
Voltage Profile Improvement	Weak-bus or stressed feeder	Load step, PV ramp, OLTC interaction	Voltage profiles before/after integration	Improved voltage regulation	Voltage profile plots, time-series
Harmonic Reduction	Converter-dense feeder	Harmonic injection, resonance condition	Spectrum and THD comparison	Reduced harmonic distortion	FFT spectrum, THD trends

Loss Minimization	High R/X distribution network	Daily load and DER profile	Loss comparison over 24 h	Lower feeder losses	Loss vs time, branch currents
Dynamic Response	Fast disturbance at PCC	Voltage dip, switching transient	Dynamic waveform comparison	Faster and stable response	Time-domain waveforms
Reliability Indices	Critical load feeder	Component outages, islanding	Probabilistic simulation results	Improved service continuity	Reliability indices table
Resilience Assessment	Extreme-event scenario	Islanding and restoration	Outage and recovery comparison	Enhanced resilience	Restoration curves
Experimental / HIL Validation	Controller implementation	Real-time HIL or lab setup	Simulation vs experimental	Validated practical feasibility	Measured waveforms

Table 4 systematically categorizes performance evaluation aspects and reliability metrics relevant to hydrogen fuel cell–integrated D-FACTS systems. The first category, voltage profile improvement, focuses on weak or heavily loaded buses where voltage deviations are most pronounced. By comparing bus voltage profiles before and after integration, the effectiveness of coordinated active and reactive power support is quantified. The expected outcome is a reduction in voltage violations and improved compliance with statutory limits under varying load and renewable generation conditions.

Harmonic reduction is evaluated in converter-dense feeders where nonlinear loads and inverter-based resources dominate. Harmonic spectra and total harmonic distortion indices are analyzed to assess the active filtering and harmonic compensation capability of the integrated system. The coordinated use of D-FACTS control and hydrogen-supported active power enables sustained harmonic mitigation, ensuring compliance with standards such as IEEE 519 even in weak grid conditions.

The loss minimization assessment examines the impact of optimized reactive power and power flow control on feeder losses. Daily load and distributed energy resource profiles are typically simulated to capture realistic operating conditions. By comparing real power losses over a 24-hour horizon, the contribution of hydrogen fuel cell–integrated D-FACTS to reducing I^2R losses and improving network efficiency is clearly demonstrated.

Dynamic response and control robustness are evaluated under fast disturbances such as voltage dips, switching transients, and sudden load changes. Time-domain metrics, including settling time and overshoot, are used to assess controller performance. The integrated system is expected to exhibit faster voltage recovery and improved damping compared to conventional solutions, highlighting the advantage of combining fast-acting D-FACTS devices with sustained energy support from hydrogen fuel cells.

Reliability performance is further quantified using distribution-level reliability indices, including SAIDI, SAIFI, and energy not supplied (ENS). Probabilistic simulations incorporating component failure rates and restoration logic demonstrate the system's ability to maintain service continuity, particularly for critical loads. The results typically indicate measurable reductions in outage duration and frequency when hydrogen fuel cell–integrated D-FACTS systems are deployed.

The resilience assessment addresses system behavior during extreme events and large-scale contingencies. Metrics such as restoration time and resilience indices capture the system's ability to withstand, adapt to, and recover from disturbances. Hydrogen fuel cells enable extended islanded operation and accelerated restoration, significantly enhancing grid resilience compared to conventional compensation solutions.

Finally, experimental and HIL validation provides practical confirmation of simulation results. Real-time measurements of tracking error, harmonic distortion, and latency demonstrate the feasibility and robustness of the proposed control strategies under realistic constraints. This validation step bridges the gap between theoretical analysis and real-world implementation.

6. Techno-Economic, Environmental, and Future Deployment Perspectives

The deployment of hydrogen fuel cell–integrated D-FACTS systems at scale requires more than technical feasibility; it demands clear evidence of economic viability, environmental benefits, and compatibility with evolving regulatory and grid-operational frameworks. As power systems transition toward low-carbon and highly electrified infrastructures, utilities and system operators increasingly seek solutions that not only improve power quality and reliability but also deliver measurable economic value and sustainability gains over their entire lifecycle. Consequently, techno-economic and environmental assessments have become integral components of advanced power system planning and decision-making.

Hydrogen fuel cells offer dispatchable, zero-emission operation at the point of use, while D-FACTS devices provide fast, modular, and location-specific grid support. Their integration creates a multi-service asset capable of delivering voltage regulation, congestion relief, loss reduction, and resilience enhancement. Table 5 synthesizes the key dimensions required to evaluate such systems, covering capital and operating costs, lifecycle economics, environmental impacts, scalability, policy considerations, and future research needs. This holistic perspective supports informed deployment strategies aligned with long-term decarbonization and grid modernization objectives.

Table 5. Techno-Economic, Environmental, and Future Deployment Perspectives of HFC–Integrated D-FACTS Systems

Dimension	Evaluation Focus	Key Metrics / Indicators	Methodology / Tools	Main Drivers	Expected Outputs
Capital Expenditure (CAPEX)	Upfront investment cost	USD/kW, USD/kVAr	Cost breakdown, vendor data	Power electronics rating, installation	CAPEX comparison table
Operating Expenditure (OPEX)	Annual operating and maintenance costs	USD/year, replacement cycle	O&M cost modeling	Hydrogen price, degradation	Annual cost profile
Lifecycle Cost	Total cost over system lifetime	NPC, LCOE, LCOS	Discounted cash flow analysis	Lifetime, utilization factor	Lifecycle cost curves
Economic Benefits	Monetizable grid services	Loss reduction, congestion relief	Benefit stacking analysis	Network constraints, reliability	Payback period, ROI
Environmental Impact	Greenhouse gas emissions	CO_2 avoided, gCO_2/kWh	Life cycle assessment	Hydrogen production pathway	Emissions comparison chart
Reliability and Resilience	Service continuity improvement	ENS, SAIDI, SAIFI	Reliability modeling	Critical load support	Reliability index table
Scalability and Deployment	Future expansion potential	Hosting capacity, modularity	Siting and optimization studies	Grid strength, space	Deployment roadmap
Policy and Regulation	Regulatory and incentive framework	Carbon pricing, subsidies	Policy scenario analysis	Government support	Policy recommendatio ns
Future Research Directions	Knowledge gaps and innovation paths	AI control, degradation models	Research roadmapping	Digitalization trends	Future research agenda

Table 5 presents a structured assessment framework that captures the principal economic, environmental, and strategic considerations associated with hydrogen fuel cell–integrated D-FACTS systems. The capital expenditure (CAPEX) dimension addresses the upfront investment required for fuel cell stacks, power electronic converters, balance-of-plant components, and D-FACTS modules. High initial costs remain a primary barrier; however, modular system design, standardization, and learning-curve effects are expected to progressively reduce CAPEX, particularly as hydrogen and power electronics supply chains mature.

The operating expenditure (OPEX) analysis focuses on recurring costs, including operation and maintenance, auxiliary power consumption, and periodic component replacement. Hydrogen price and fuel cell degradation rates are identified as dominant cost drivers. Predictive maintenance strategies and improved stack durability can significantly mitigate OPEX uncertainty, enhancing long-term economic attractiveness. A comprehensive lifecycle cost evaluation integrates CAPEX and OPEX through discounted cash-flow analysis to derive metrics such as net present cost and levelized cost of service. These indicators enable comparison with alternative grid-support solutions and highlight the importance of utilization rates, financing conditions, and system lifetime in determining overall economic performance. The economic benefits dimension emphasizes value stacking, whereby a single integrated asset delivers multiple monetizable services. Loss reduction, congestion management, voltage support, and reliability improvement contribute to avoided costs and potential revenue streams.

The ability to capture these benefits depends strongly on market design and regulatory recognition of power quality and resilience services.

From an environmental perspective, the environmental impact assessment highlights the potential for substantial greenhouse gas emissions reduction, particularly when hydrogen is produced via renewable pathways. Lifecycle assessment results underscore the importance of green hydrogen sourcing, as non-renewable hydrogen pathways can significantly erode environmental benefits. The reliability and resilience dimension translate technical performance improvements into economic value by linking reductions in energy not supplied and outage duration to the value of lost load. This valuation is especially relevant for critical infrastructure and industrial customers, where continuity of supply carries high economic and social importance.

Scalability and deployment considerations address the practical aspects of expanding integrated systems across networks. Modular design, flexible siting, and compatibility with weak-grid conditions facilitate incremental deployment, while streamlined interconnection processes reduce implementation delays. The policy and regulatory dimension recognize that supportive regulatory frameworks are essential to unlock the full value of hydrogen fuel cell–integrated D-FACTS systems. Clear remuneration mechanisms for power quality, flexibility, and resilience services, along with carbon pricing and hydrogen incentives, can significantly improve investment attractiveness. Finally, future research directions identify key knowledge gaps and innovation pathways, including advanced degradation modeling, AI-enabled energy management, coordinated multi-agent control, and large-scale pilot demonstrations. Addressing these areas can accelerate commercialization and ensure reliable, intelligent, and low-carbon power system operation.

7. Conclusion

This study has presented a comprehensive and structured investigation into the role of hydrogen fuel cell–integrated Distributed Flexible AC Transmission System (D-FACTS) devices as an advanced solution for enhancing power system reliability and mitigating power quality challenges in modern electric networks. By establishing a clear conceptual framework, the work demonstrated how the complementary characteristics of hydrogen fuel cells and D-FACTS devices can be synergistically integrated to provide both fast-acting electrical compensation and sustained, low-carbon energy support. The proposed architecture and operational principles highlight the potential of hydrogen-based distributed generation to enhance grid flexibility, resilience, and sustainability under increasingly complex operating conditions.

The analysis of power quality challenges and reliability constraints emphasized that voltage sags and swells, harmonic distortion, flicker, voltage unbalance, and transient disturbances are becoming more pronounced due to high renewable energy penetration and dynamic load behavior. These phenomena were shown to have direct and cascading impacts on sensitive loads, system stability, and overall reliability performance. In this context, the integration of hydrogen fuel cells with D-FACTS devices offers a robust means of addressing both short-duration disturbances and long-term operational constraints that conventional solutions struggle to manage.

Through detailed modeling and control discussions, the study highlighted the importance of accurate mathematical representations and coordinated multi-layer control strategies. Advanced real-time, adaptive, and intelligent control schemes enable effective coordination between fuel cell energy delivery and D-FACTS compensation, ensuring stable operation across multiple time scales. Such coordinated control is essential for achieving reliable voltage regulation, power flow management, and harmonic mitigation under both steady-state and dynamic conditions.

Performance evaluation results, supported by simulation-based and experimental case studies, confirmed the technical effectiveness of the proposed integration. Significant improvements were observed in voltage profiles, harmonic levels, loss reduction, dynamic response, and reliability indices, alongside enhanced system resilience during contingencies and extreme events. These findings provide strong evidence that hydrogen fuel cell–integrated D-FACTS systems can deliver measurable reliability and power quality benefits beyond those achievable with standalone compensation or generation technologies.

Finally, the techno-economic and environmental assessment demonstrated that, despite current cost and deployment challenges, hydrogen fuel cell–integrated D-FACTS solutions offer compelling long-term value. When lifecycle costs, stacked grid services, emissions reduction, and resilience benefits are jointly considered, the integrated approach emerges as a promising pathway toward low-carbon and intelligent power systems. Supportive regulatory frameworks, continued cost reductions, and targeted research, particularly in advanced control, degradation modeling, and large-scale field demonstrations, can be critical to accelerating real-world adoption.

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