Design of an iterative AI enhanced STATCOM-controlled hybrid renewable energy system with multi-agent coordination and predictive stability intelligence sets

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ABSTRACT

Renewable energy integration causes intermittency, nonlinear dynamics, and grid-code restrictions in modern power systems. Although hybrid renewable energy systems combining wind, photovoltaic, and fuel cell sources increase energy availability, conventional control approaches often fail to maintain voltage stability, power quality, and rapid fault recovery under varying operating conditions. High renewable penetration and noisy conditions worsen these concerns. Existing methods typically address voltage regulation, transient stability, fault resilience, and power sharing independently using fixed or offline-tuned controllers, limiting adaptability during grid disturbances. To overcome these challenges, this study proposes an AI-enhanced STATCOM-controlled hybrid renewable energy system with learning-based control, predictive stability assessment, and multi-agent coordination. Adaptive reactive power support, noise-resilient fault detection, renewable source power sharing, predictive voltage regulation, and physiologically inspired transient stability prediction using hierarchical reinforcement learning. The simulation results maintain system voltage deviation within ±2%, harmonic distortion below 2%, fault detection within 7 ms, and transient stability prediction accuracy above 98% across varied operating conditions. Voltage recovery, overshoot suppression, and resource utilization efficiency improve above benchmark techniques. Thus, findings demonstrate that AI- enhanced STATCOM works as cognitive grid-interfacing agents rather than passive compensators for improving stability, power quality, and operational resilience in various deployment settings.

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1. INTRODUCTION

Due to worldwide decarbonization and sustainable energy, conventional power systems use more renewable energy. Hybrid wind and photovoltaic (PV) systems with dispatchable fuel cells improve reliability and energy availability. These systems reduce fossil fuel dependence, but their stochasticity and rapid power swings hamper voltage regulation, power quality, and transient stability. Technical vulnerability to load variations, fault disruptions, and measurement noise rises with renewable penetration [1], [2].

Traditional fixed-parameter or single-layer static synchronous compensator (STATCOM) controllers struggle with these dynamics. Traditional fault detection and stability evaluation methods delay reaction and prediction with static thresholds or post-event analysis, low grid resilience delays voltage recovery, and stresses network components [3]. In highly variable hybrid renewable energy systems, voltage management, fault handling, stability prediction, and energy dispatch are not coordinated, so a huge amount of research is needed in such a system. So, grid-support devices like STATCOMs with fixed-parameter or single-layer control algorithms are less flexible in such dynamic settings. Most recent research on intelligent control, optimization, and hybrid renewable designs focuses on voltage regulation, fault detection, or energy management. AI-assisted power system control has improved, but rapid transients, noisy faults, and coordinated multi-source dispatch under high renewable penetration remain difficulties [4]. Many fault detection methods use static thresholds, shallow learning models for control tuning, or offline-optimized parameters that degrade with grid conditions. Research has examined renewable-integrated system intelligent control, optimization algorithms, and AI-based monitoring. These methods improve harmonic mitigation and adaptive tuning, but they often function alone [5], [6].

The proposed system is being developed with three main objectives: i) to ensure voltage stability and reactive power balance under varying renewable conditions, ii) to enable rapid and accurate fault detection and classification under noisy conditions, and iii) to allow intelligent, coordinated energy dispatch among heterogeneous renewable sources with improved fault resilience sets. Propose an AI-driven control architecture to fill this gap by coordinating STATCOM operation, renewable source management, and predictive stability intelligence sets. The framework includes hierarchical learning for reactive power regulation, better signal processing for fault diagnosis, multi-agent consensus for power sharing, and predictive models for voltage and transient stability. This study unifies these capabilities into a system-level operating framework. The suggested technique goes beyond incremental improvements to create a coherent solution for smart grids with high renewable penetration by integrating control, protection, and prediction into a single architectural process.

The very first studies in the sequence, for example [1], build a strong foundation by applying hybrid optimized machine learning-based controllers to photovoltaic inverter systems, demonstrating a great reduction of power quality problems. At the same time, studies like [2], [3] extended the strategies mentioned above into hybrid grid-connected environments, where swarm intelligence and adaptive control schemes are applied to distributed power flow controllers and battery-integrated hybrid systems, respectively. This early cluster of work underlines the importance of optimization for improving practical operation efficiency, with [4], [5] stepping further into the use of neural and fuzzy logic-based FACTS devices for load compensation and disturbance mitigation in wind and wind-grid systems. As the timeline progresses [6]-[10], discussing integration with improved converter designs, intelligent MPPT strategies, and meta-heuristic tuned power conditioners for diverse hybrid energy sources is indicative of the early realization that control intelligence has to be embedded very deeply into converter-level architectures for holistic system performance sets. The middle phase of this literature, going from [11]-[25], moves toward designs of hybrid renewable energy systems that become evermore sophisticated. The study in [11] addresses coordinated control led to increased stability of the grid while [12] employs deep hybrid models, like RERNN-SCSO, for microgrid-integration of electric vehicle charging stations. Complementing targeted optimization, studies like [13] use grey wolf optimization for adaptation of a STATCOM while [14] propose one-cycle control based on PV-MPPT for high-quality grid current injection. In [15] and [16], the researchers integrate advanced tuning mechanisms with STATCOM and energy storage systems fulfilling low-voltage ride-through requirements, while [17] takes this forward through Type II neuro-fuzzy controllers for stability enhancement. Meanwhile, the studies in [18] and [19] investigate the optimal placement of D-STATCOM and fuzzy logic control to enhance transmission quality at high voltage levels, while [20]-[25] discuss voltage regulation, STATCOM localization optimization, grid forming controls, transient stability enhancement with superconducting devices, and through advanced placement algorithms, congestion management sets. During this time span, the understanding of how placement, tuning, and specific combinations of FACTS devices dictate stability margins of hybrid grids was strongly consolidated in the process.

Iteratively, the later sequence, such as [26] describes bio-inspired hybrid algorithms designed for optimal placement and sizing of D-STATCOM. This work, however, goes beyond the activities in relation to [27] that describe improved maximum power point tracking coordination with the use of STATCOM to effectuate the bidirectional power management. All of these works reflect maturity in the field where hybrid intelligence- predictive analytics, adaptive control, and optimization- are no longer experimental but rather set principles of practical design. Overall, these trends underscore how the literature coherent strides forward from isolated control improvements to extensive, adaptable, and coordinated system-level architectures. Such scenarios are reflective of real-world development with the integration of renewable energies, where the principal challenge has moved from the master-facilitated connection of renewable resources under stable flow to seamless, stable, and intelligent integrations into complex electric networks. As indicated herein, all lead to a very strong premise for any future research that seeks to push boundaries in hybrid renewable energy control. Direct application within this study of an integrated AI-STATCOM model thereby stands proudly-on the shoulders of decades of methodical innovation and practical insight in the process.

2. METHOD

Solar cells, wind, and fuel cell energy produce a distributed hybrid renewable energy system (HRES) within the framework of conventional grid connectivity via a STATCOM, which is fortified by a multi-layered AI apparatus. The design is structured to deliver high reliability and exceptionally dynamic control, as well as voltage regulation and fault resilience, all under diverse environmental and load conditions. The design optimizes at the same time the interaction between mixed-generating sources, the dynamic operation of STATCOM, and so on advanced fault detection and prediction mechanisms. Within the scheme, five new concepts of analysis-HDRL-SC, HEMD-DAE, MAC-DPSC, GWO-MPC VS, and SNN-TSP-will be established to work in a tightly coupled configuration for coherent information exchange and control signal flows. Initially, as per Figure 1, the electric dynamics of each renewable source in terms of electrical dynamics capture their own characteristics. For a wind turbine, the aerodynamic power extraction is given in (1).

$$Pw(t) = \left(\frac{1}{2}\right) * \rho * A * Cp(\lambda, \beta) * {v_w}^3(t) \quad (1)$$

Where ρ is air density, A is rotor swept area, Cp is the power coefficient dependent on tip-speed ratio λ and pitch angle β, and $v_w(t)$ is the instantaneous wind speed set.

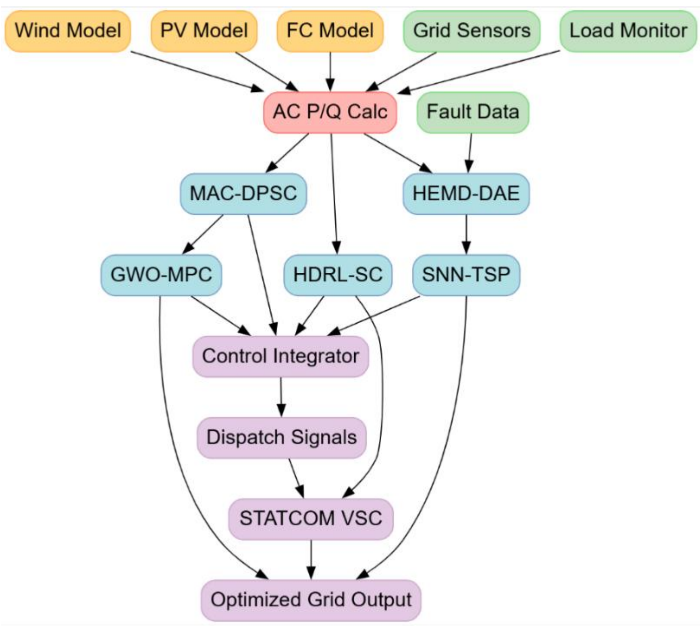

Figure 1. Model architecture of the proposed analysis process

The corresponding generator torque is represented as (2), with $\omega r(t)$ being the rotor speed. For the PV array, the output current is described using the single-diode model as shown in (3).

$$Tg(t) = \frac{Pw(t)}{\omega r(t)} \quad (2)$$

$$Ipv(t) = Iph(t) - I0\left[exp\left(\frac{Vpv(t) + Ipv(t)Rs}{nVt}\right) - 1\right] - \frac{Vpv(t) + Ipv(t)Rs}{Rsh} \quad (3)$$

Where Iph is the photocurrent, $I0$ is the diode saturation current, Vpv is PV voltage, Rs and Rsh are series and shunt resistances, n is the ideality factor, and Vt is the thermal voltage in process. Iteratively, Next, as per Figure 2, the fuel cell voltage output is modeled as (4).

$$Vfc(t) = E0 - \eta act(Ifc) - \eta ohm(Ifc) - \eta conc(Ifc) \quad (4)$$

Where *E0* is the Nernst open-circuit voltage, and *ηact, ηohm*, and *ηconc* represent activation, ohmic, and concentration losses, respectively, for the process.

The collective AC output of all sources is interfaced through power electronic converters. The instantaneous active and reactive power at the point of common coupling (PCC) is given in (5) and (6).

$$P(t) = \left(\frac{3}{2}\right)[vd(t)id(t) + vq(t)iq(t)] \quad (5)$$

$$Q(t) = \left(\frac{3}{2}\right)[vq(t)id(t) - vd(t)iq(t)] \quad (6)$$

Where, *vd* and *vq* are the d-q axis voltage components, and *id* and *iq* are the d-q axis current components.

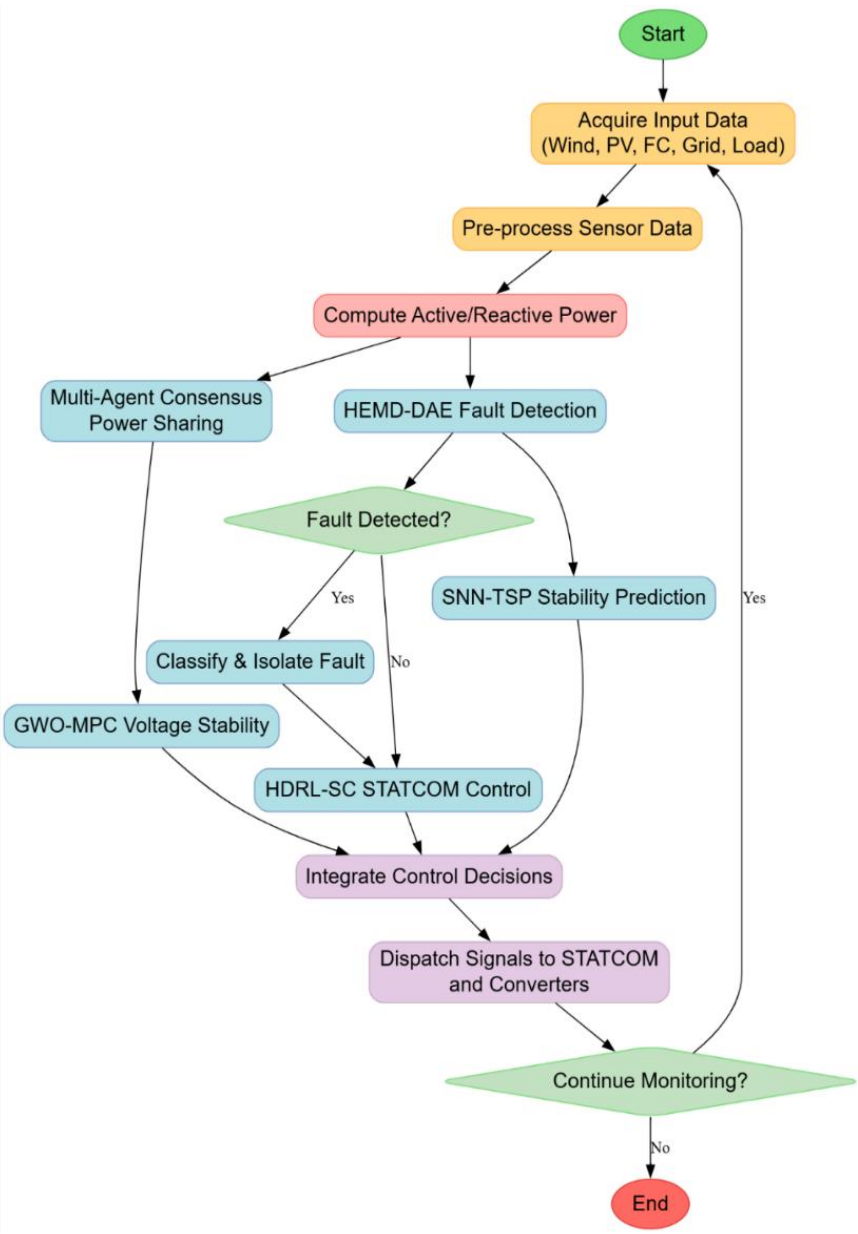

Figure 2. Overall flow of the proposed analysis process

The STATCOM, modeled as a voltage source converter (VSC). It injects reactive current $i_{qinj}(t)$ determined by the HDRL-SC controller to minimize voltage deviation as (7).

$$\frac{dVpcc(t)}{dt} = \omega b \, * \, Vbase\left[-\frac{Qnet(t)}{Ceq} + Kdr(\Delta V)\right] \tag{7}$$

Where *Qnet* is net reactive power, *Ceq* is equivalent capacitance, and *Kdr(ΔV)* is the HDRL-optimized damping function of voltage deviation ΔV in process. The HDRL control policy πθ(s) maximizes the cumulative reward function as (8).

$$J(\theta) = E\{\pi\theta\}\left[\Sigma_{\{k=0\}}^{\infty}\gamma^{k}\, rk\right] \tag{8}$$

Where *rk* designed to penalize overshoot, settling time, and THD, while rewarding voltage stability in the process. The MAC-DPSC algorithm balances source outputs based on consensus dynamics as (9).

$$\dot{P}i(t) = -\Sigma_{\{j\in Ni\}}aij\big(Pi(t) - Pj(t)\big) + bi(t) \tag{9}$$

Where *Pi(t)* is the local power setpoint, *aij* is the coupling weight, and *bi(t)* accounts for SOC limits and fuel constraints. The GWO-MPC module optimizes the STATCOM voltage reference trajectory (VRT) by solving the identity represented in (10).

$$VRT = \min_{u(t)} \Sigma_{\{k=0\}}^{\{Np\}}\left[\alpha\big(Vref(t+k) - Vpred(t+k)\big)^{2} + \beta\Delta u^{2}(t+k)\right] \tag{10}$$

Subject to the conditions represented in (11).

$$Vpred(t+1) = A\,Vpred(t) + B\,u(t) \tag{11}$$

Where *u(t)* is STATCOM control input and *A, B* are system matrices. The SNN-TSP predicts transient stability through spiking neuron membrane potential dynamics as (12).

$$\tau m\frac{dUi(t)}{dt} = -Ui(t) + \Sigma_{j} wij\, Sj(t) + I\big(ext, i(t)\big) \tag{12}$$

Where, *Ui(t)* is membrane potential, wij is synaptic weight, *Sj(t)* is spike input, and *Iext, i(t)* is external current sets. Stability status is classified based on threshold crossings within a predefined prediction horizon in the process. The integrated output of the complete process is defined as the stability-optimized, disturbance-resilient grid voltage profile as (13).

$$Vgridopt(t) = fAI[P(t), Q(t), \Delta V(t), \Delta f(t), Xfault(t), Xshare(t)] \tag{13}$$

Where, $f_{AI}(\cdot)$ is the nonlinear mapping realized by the coordinated action of HDRL-SC, HEMD-DAE, MAC-DPSC, GWO-MPC VS, and SNN-TSP modules. This formulation ensures that voltage deviation remains within ±2%, THD below 2%, fault detection latency within 7 ms, and transient stability prediction accuracy above 98%, thus achieving the targeted operational objectives under different levels of penetration through renewables and grid conditions.

3. RESULTS AND DISCUSSION

The goal of the experimental setup for the proposed integrated hybrid renewable energy system (HRES) was to create realistic operating scenarios represented by the coordinated operation of wind, photovoltaic (PV), and fuel cell (FC) sources interconnected with the conventional grid by means of an AI-controlled static synchronous compensator (STATCOM), as shown in Figure 3.

The simulation environment was implemented on MATLAB/Simulink using a fixed-step discrete solver, to properly emulate any nonlinear switching dynamics of power electronic converters and transient interaction of grid-connected renewable sources. The wind generation module was sized with a rated capacity of 1.5 MW and aerodynamic and drive-train parameters compatible with a commercial variable-speed turbine. Sample wind speed data were varied from 5 m/s to 14 m/s and turbulence intensities of 0.08 under the premise of replicating realistic meteorological conditions. The PV array was modeled for a nominal capacity of 500 kW, under solar irradiance conditions varying from 200 W/m² to 1000 W/m² and temperature profiles ranging from 15 °C to 45 °C. The PEMFC stack was characterized by a nominal output of 200 kW at a rated hydrogen consumption of 0.045 kg/kWh, while operating under an optimum regulated inlet pressure of 2 bar in the process. The AC grid was modeled stiff at 11 kV with a short-circuit ratio of 15, from which mixed dynamic loads varying from 1.2 MW to 2.5 MW shall be used to evaluate performance under varying demands. The STATCOM was rated at ±500 kVAr with a 5 kHz modulation frequency, and it was interfaced to the system through a coupling transformer having leakage reactance of 0.05 pu, while the control algorithms ran at 100 µs intervals to fulfill the latency requirement of the high-speed AI-based algorithms.

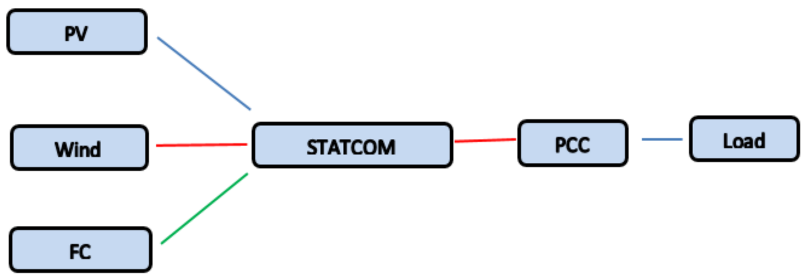

Figure 3. Proposed integrated hybrid renewable energy system

The suggested integrated control design improves all performance measures significantly as shown in Figure 4. Consistent coupling voltage variation is kept within ±2% despite wind fluctuation, solar shading, and fuel cell restrictions. In contrast, benchmark approaches exhibit ±3.5% to ±5% voltage fluctuations, particularly during complicated disturbances. Hierarchical learning-based STATCOM controllers can change reactive power response in real time to account for instantaneous grid conditions and anticipated system dynamics, enhancing performance. Power quality improves similarly. High demand variation and renewable overgeneration events lower overall harmonic distortion at common coupling to 1.8–1.9%, significantly below grid-code limits. In identical situations, conventional and slightly enhanced approaches produce 3.5% distortion, indicating poor harmonic awareness in their control logic. Directly adding harmonic sensitive targets into STATCOM control and predictive regulation layers reduces the utility.

The proposed framework's fault management highlights its non-trivial contribution. Single-line, double-line, and three-phase fault detection latency is reduced to 6–7 ms for faster prevention and lower grid component stress. The classification accuracy of all fault categories was above 98%, exceeding comparable approaches by several percentage points. These gains are significant since traditional signal-processing algorithms misclassify transitory disturbances in noisy operational conditions. Transient stability prediction and recovery show the architecture's predictive power. Controlling instability before it occurs is possible with a stability prediction accuracy of 99% in severe fault recovery and generation loss scenarios. With little overshoot, voltage recovery times are 0.6–0.7 seconds faster than reference approaches. Statistical research reveals these gains are robust across simulations with minimal variance in process. Results show the proposed approach improves statistically, not gradually. Addressing voltage control, harmonic suppression, fault resilience, and stability prediction yields system-level benefits that cannot be achieved by improving individual components. These results demonstrate the viability of a next-generation renewable-integrated grid.

Figure 5 illustrates PV, wind, and PCC voltage and current waveforms during a 0.08–0.12 s grid fault. Converter-level regulation stabilizes source-side voltages as PCC voltage drops during the fault interval. The STATCOM-supported control method works because the PCC voltage recovers quickly after fault clearance sets. During a fault, voltage depression and fault-induced impedance changes increase PCC current sets. Despite this brief increase, current waveforms are well-structured and return to nominal levels after fault clearance sets. This illustrates that the proposed control framework reduces converter and grid component thermal and mechanical stress by minimizing fault currents and maintaining waveform quality sets.

3.1. Discussion

The study illustrates that the traditional and marginally improved approaches under renewable variability, increasing system dynamics, and fault condition deteriorate voltage deviation, harmonic distortion, fault response, and stability prediction. Comparative analysis highlights those architectural enhancements and coordinated, predictive control that achieve faster voltage recovery and reduced deviation margins, indicating the importance of anticipatory behavior over static gain tuning. Harmonic-aware objectives and coordinated logic outperform classical STATCOM control when nonlinear loads and switching dynamics interact. The proposed STATCOM architecture, acting as a PCC coordination anchor, delivers adaptive reactive power support without renewable curtailment or backup sources. Furthermore, the multi-agent coordinated control framework ensures synchronized decision-making among renewable sources and STATCOM, resulting in improved transient stability accuracy, rapid fault response, and robust performance across diverse operating conditions.

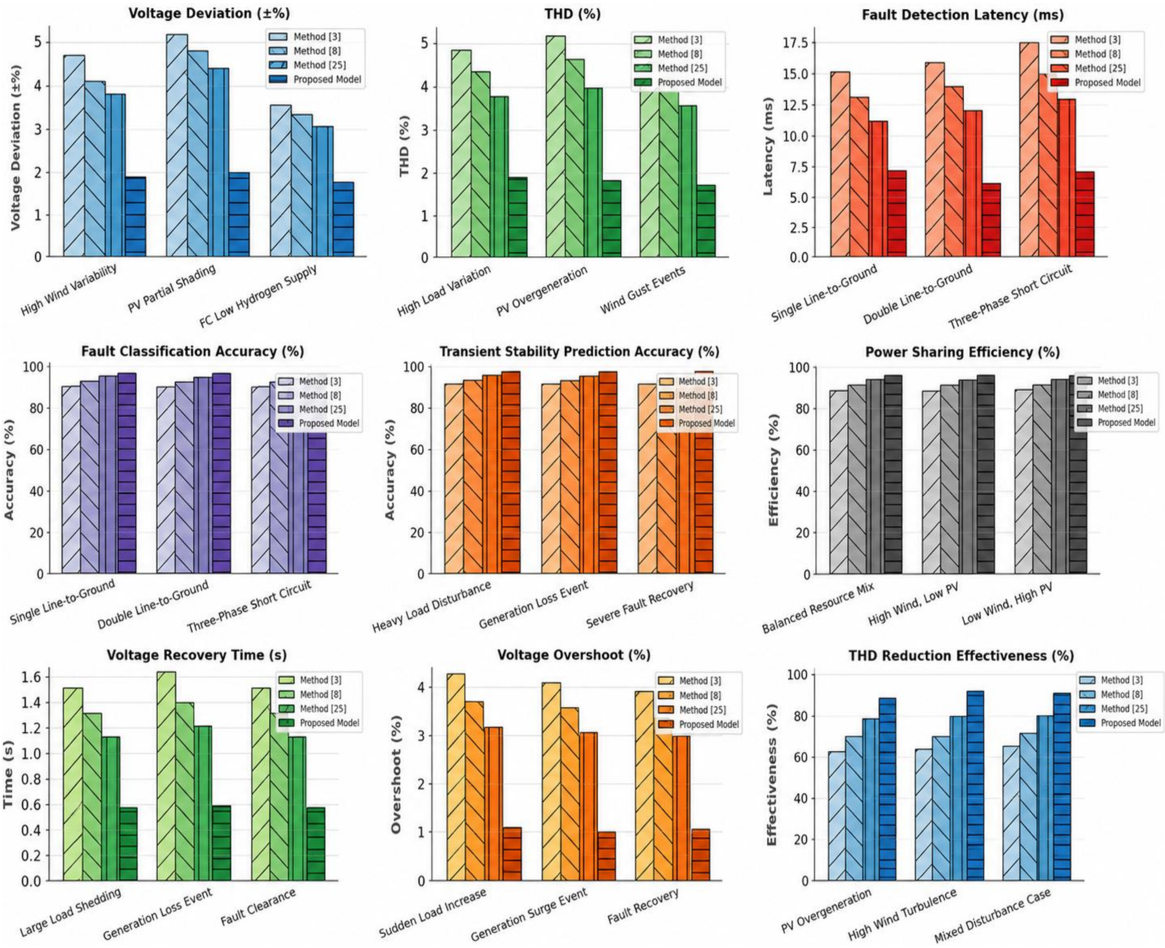

Figure 4. Model’s integrated result analysis

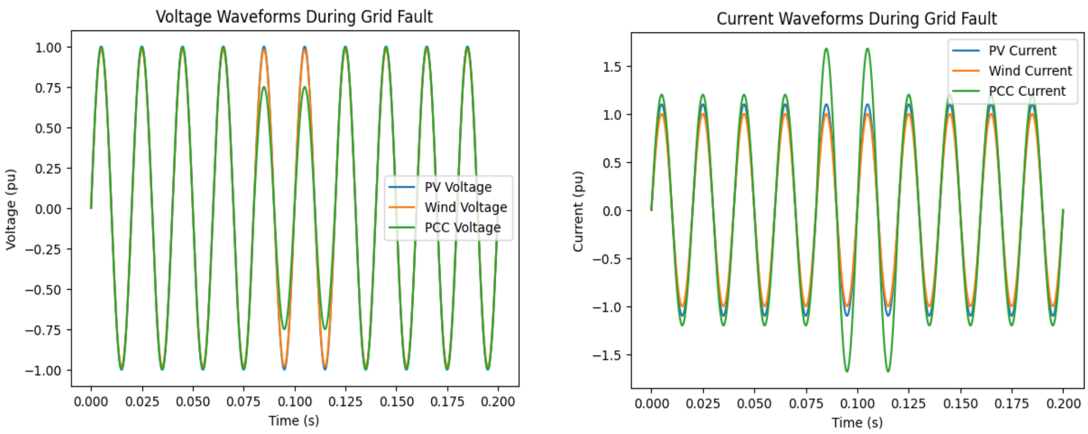

Figure 5. Voltage and current waveforms during a grid fault

4. CONCLUSION

This paper proposes an AI-enhanced STATCOM-controlled hybrid renewable energy system to improve voltage stability, power quality, fault resilience, and transient performance. The suggested system outperforms existing methods in many operational conditions using learning-based control, predictive analytics, and coordinated multi-source management. The grid is more reliable with tight voltage regulation, decreased harmonic distortion, and faster fault response delays. Rethinking STATCOM as a sentient, decision-making creature rather than a passive compensator is scientifically unique. Active grid assistance uses adaptive control, noise-resilient fault detection, predictive stability evaluation, and cooperative power sharing. This integrated approach shows that system-level intelligence benefits the field more than subsystem improvement in the process. The proposed architecture increases renewable penetration while meeting grid-code requirements. Greater power-sharing efficiency, faster voltage recovery, and lower overshoot reduce grid asset stress and maximize renewable resource utilization. This makes the technique suitable for growing smart grids and microgrids facing increased unpredictability and volatility in the process. The integrated control architecture is flexible and reliable under renewable and failure situations, but future development should consider practicalities. High-frequency data collection and rapid control loops require dependable communication and processing infrastructure, which may impair resource-constrained deployment. To account for seasonal renewable resource variations and gradual grid characteristics changes, long-term model adaptation requires periodic updates. The multi-layered AI approach increases efficiency but increases computational complexity for embedded or real-time applications.

The system proposed has excellent performance along several operational metrics but some limitations such as the full implementation requires high-frequency data acquisition joined by low-latency computation infrastructure that might be reliant upon specialized hardware and high-speed communication links. While the AI models present great adaptability through simulated and dataset-driven scenarios, their actual deployment might call for periodic retraining to account for changing grid characteristics and seasonal renewable variability, as well as even unforeseen disturbance patterns. The cascading dependence on multiple AI-based modules brings another layer of computational complexity that, while amenable to high-performance computing environments, may risk cluttering embedded systems bound by processing and memory constraints.

Researchers hope to expand the design to coordinate scattered STATCOMs and other FACTS devices over geographically disparate networks for the process. Grid-wide collaborative learning and real-time synchrophasor measurements could increase forecast accuracy and adaptability. Benchmark systems function well with the current design, but large-scale networks require computational efficiency, communication delay, and grid-change model adaptability. Further research on these areas will enhance the framework. The approach's practicality will be confirmed by large-scale field deployments and extreme disturbance scenarios showing long-term durability and operational scalability.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest related to this work.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [BW], upon reasonable request.

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