

Statcom Assisted Fault Ride-Through Enhancement of A Grid-Integrated Hybrid Renewable Energy System with Ev Charging Infrastructure

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Abstract

The rapid penetration of renewable energy sources (RES) into modern power systems has introduced new challenges in maintaining grid stability, particularly during fault conditions. Hybrid renewable systems that combine wind and solar energy provide clean and sustainable generation, but their intermittent nature and sensitivity to disturbances often compromise reliability. Additionally, the integration of electric vehicle (EV) charging infrastructure, while essential for sustainable transport, imposes further dynamic stress on the grid. This paper proposes a STATCOM-assisted control strategy to enhance the Fault Ride-Through (FRT) capability of a grid-integrated hybrid RES with EV charging stations. The hybrid system model, consisting of a wind energy conversion system, photovoltaic array, and a fast-charging EV station, is interfaced through back-to-back converters and a DC-link. Under fault conditions such as voltage sags and swells, the STATCOM provides dynamic reactive power support, stabilizes the DC-link voltage, and mitigates voltage distortions at the Point of Common Coupling (PCC). Simulation studies conducted in MATLAB/Simulink demonstrate that the proposed approach effectively improves voltage stability, reduces harmonic distortion, and ensures compliance with IEEE-519 harmonic limits and FRT grid codes. Results show that the STATCOM enhances power quality and allows continuous EV charging, even during grid disturbances. The proposed method thus strengthens the reliability of hybrid RES integration, making it more suitable for large-scale deployment in future smart grids.

Keywords: Hybrid Renewable Energy System (HRES); Fault Ride-Through (FRT); Electric Vehicle (EV) Charging;

1. INTRODUCTION

The global shift toward renewable energy is reshaping the way modern power systems are designed and operated. Among the various alternatives, hybrid renewable energy systems (HRES), which combine solar photovoltaic (PV) arrays and wind energy conversion systems (WECS), have gained increasing attention due to their complementary nature. While solar generation is highly dependent on irradiance,

wind energy offers better performance at different times of the day and seasons, making hybridization a robust solution for continuous power supply.

However, the rapid deployment of such systems has revealed technical challenges, particularly when integrated into the existing utility grid. The stochastic nature of renewable resources introduces fluctuations in power output, which can lead to issues such as voltage instability, frequency deviations, and increased harmonic content at the Point of Common Coupling (PCC). These concerns become even more critical with the simultaneous growth of electric vehicle (EV) charging infrastructure. EV fast-charging stations, when connected in large numbers, impose sudden and nonlinear loads on the grid, further exacerbating voltage dips and stressing the stability of renewable integration.

A key requirement for renewable integration is the ability to withstand grid disturbances without immediate disconnection—a capability referred to as **Fault Ride-Through (FRT)**. International grid codes mandate that renewable-based generators must remain connected during voltage sags and swells, while also providing dynamic reactive power support to aid grid recovery. Without adequate FRT capability, hybrid renewable systems risk frequent disconnections, thereby reducing overall reliability.

Flexible AC Transmission System (FACTS) devices, particularly the **Static Synchronous Compensator (STATCOM)**, have emerged as effective solutions to address these issues. STATCOMs are capable of providing fast reactive power compensation, voltage support, and harmonic mitigation, making them ideal for enhancing the FRT capability of hybrid RES integrated with EV charging stations. By stabilizing the DC-link voltage and compensating for reactive power, a STATCOM ensures smoother fault recovery and continuous operation of EV charging infrastructure.

This paper proposes a STATCOM-assisted control strategy for a grid-integrated hybrid renewable energy system supplying an EV charging station. The main contributions of this work are:

1. Development of a hybrid renewable model combining PV, wind, and EV charging infrastructure under grid-connected conditions.
2. Design of a STATCOM-based controller to improve fault ride-through performance by stabilizing the DC-link voltage and supporting grid voltage during disturbances.
3. Comprehensive simulation in MATLAB/Simulink to evaluate system behavior under normal and faulted conditions.
4. Verification of grid code compliance with respect to FRT and harmonic limits (IEEE-519).

2. System Modeling

The proposed hybrid renewable energy system (HRES) integrates wind and solar resources with an electric vehicle (EV) charging station, interfaced to the utility grid. To evaluate fault ride-through (FRT) capability and the role of a STATCOM, each subsystem is mathematically modeled in MATLAB/Simulink. The modeling framework is structured into four key domains: generation units, EV charging load, power electronic converters with a DC-link, and the STATCOM compensator.

A. Wind Energy Conversion System (WECS)

The wind subsystem is based on a variable-speed **Permanent Magnet Synchronous Generator (PMSG)** connected to a wind turbine. The aerodynamic power is determined by air density, swept area, and tip-speed ratio. The PMSG is modeled in the dq-synchronous reference frame, enabling decoupled control of torque and flux. This configuration eliminates the need for external excitation or gearboxes, reducing maintenance and improving reliability. The machine-side converter (MSC) ensures maximum power extraction using a **Maximum Power Point Tracking (MPPT)** algorithm.

B. Photovoltaic (PV) Subsystem

The solar array is modeled using the **single-diode equivalent circuit**, which represents the nonlinear current–voltage (I–V) characteristics under varying irradiance and temperature. A boost DC-DC converter is used to regulate PV output and interface with the DC-link. An incremental conductance MPPT scheme ensures that the PV subsystem consistently operates at its maximum power point. The PV and wind outputs complement each other, minimizing supply fluctuations in the hybrid system.

C. Electric Vehicle (EV) Charging Station

The EV charging infrastructure is modeled as a **DC fast-charging station** connected through bidirectional converters. The load profile is dynamic, varying with the number of connected EVs and the state of charge (SOC) of each battery. To capture realistic conditions, the model considers constant-power charging during fast-charging phases and Vehicle-to-Grid (V2G) capability during idle states. This dual behavior introduces significant stress on the grid during disturbances, making FRT support critical.

D. Power Converters and DC-Link Dynamics

The back-to-back converter architecture consists of:

- **Machine-Side Converter (MSC):** controls generator torque and speed for wind MPPT.
- **Grid-Side Converter (GSC):** regulates DC-link voltage and ensures sinusoidal grid current injection.

The DC-link capacitor acts as an energy buffer, absorbing the mismatch between generation, EV load demand, and grid power flow. During faults, sudden imbalances in active power flow may lead to dangerous overvoltages at the DC-link, making its stabilization essential.

3. STATCOM Model

The STATCOM is modeled as a **voltage source converter (VSC)** with a DC capacitor, connected at the Point of Common Coupling (PCC). Using a synchronous reference frame control (dq-control), the STATCOM dynamically injects or absorbs reactive power to stabilize voltage during sag or swell conditions. In normal operation, it improves power quality by filtering harmonics. During grid disturbances, it provides rapid compensation, thereby enhancing the FRT capability of the entire system and maintaining uninterrupted EV charging.

A. Proposed Control Strategy

The reliable operation of a grid-integrated hybrid renewable system with EV charging depends on efficient power extraction, stable DC-link regulation, and robust fault ride-through (FRT) performance. The proposed control strategy is divided into three hierarchical loops: **Machine-Side Converter (MSC) control**, **Grid-Side Converter (GSC) control**, and **STATCOM control**. Together, these controllers ensure maximum utilization of renewable energy while maintaining grid stability and compliance with international codes.

- **Machine-Side Converter (MSC) Control**
- The MSC interfaces the Permanent Magnet Synchronous Generator (PMSG) of the wind turbine to the DC-link. Its primary objectives are to implement Maximum Power Point Tracking (MPPT) and regulate generator torque.
- **MPPT Implementation:**
A tip-speed ratio–based algorithm adjusts the reference torque to ensure the turbine operates at the optimal point of its power curve.

- **dq-Vector Control:**

In the synchronous reference frame, the d-axis current reference is set to zero, while the q-axis current regulates electromagnetic torque. This decoupled control scheme allows precise tracking of MPPT without flux weakening.

- By maintaining the rotor speed at its optimum value, the MSC ensures that the maximum amount of wind energy is converted to electrical power.

B. Grid-Side Converter (GSC) Control

- The GSC connects the DC-link to the utility grid and has two major responsibilities: maintaining the DC-link voltage and injecting active/reactive power according to grid requirements.

- **DC-Link Voltage Regulation:**

A PI controller monitors the DC-link voltage and adjusts the d-axis current reference to stabilize the voltage during power imbalances.

- **Power Factor Control:**

Under normal conditions, the GSC ensures unity power factor by aligning the d-axis with the grid voltage vector. This minimizes reactive power demand from the grid.

- **Support During Faults:**

During sag events, the GSC coordinates with the STATCOM to provide reactive power support. It prevents DC-link overvoltage by dynamically reducing active power injection while maintaining stable operation.

C. STATCOM Control

- The STATCOM, located at the Point of Common Coupling (PCC), is the cornerstone of the proposed FRT strategy. Its control scheme is based on dq-axis synchronous reference frame theory and consists of two cascaded loops:

Outer Voltage Control Loop:

- Maintains PCC voltage within permissible limits.
- Generates reference signals for the reactive current to be injected or absorbed.

Inner Current Control Loop:

- Tracks the reference dq currents using PI controllers.
- Ensures fast dynamic response during faults by injecting high reactive current.

Fault Ride-Through (FRT) Operation:

Voltage Sag: STATCOM injects reactive current to restore PCC voltage and support grid recovery.

Voltage Swell: STATCOM absorbs excess reactive power, mitigating overvoltage stress.

Harmonic Mitigation: Under normal operation, the STATCOM reduces current distortion, ensuring IEEE-519 compliance.

- This coordination between GSC and STATCOM significantly enhances FRT performance, enabling uninterrupted EV charging even during disturbances.

D. Control Coordination Framework

The hierarchical control coordination can be summarized as:

- **MSC:** Extracts maximum renewable energy (MPPT).
- **GSC:** Balances DC-link voltage and injects active power at unity PF.
- **STATCOM:** Provides dynamic voltage/reactive support, ensuring FRT and power quality.

Together, these controllers guarantee stable grid integration and reliable EV charging under both steady-

state and faulted conditions.

4. Simulation Results and Analysis

The proposed hybrid renewable system with EV charging station and STATCOM support was simulated in **MATLAB/Simulink (R2021b)** to evaluate its performance under different operating conditions. The model consists of a 2 MW wind turbine with a PMSG, a 1 MW photovoltaic array, a 500 kW EV charging station, back-to-back converters, and a STATCOM connected at the PCC. The simulation scenarios include steady-state operation, fault ride-through under voltage disturbances, harmonic analysis, and EV charging stability.

A. Steady-State Performance

- Under rated conditions (wind speed 10 m/s, irradiance 1000 W/m²):
- The **wind and PV subsystems** supplied continuous power with complementary generation profiles.
- The **MSC** maintained optimal rotor speed, ensuring maximum power extraction from the turbine.
- The **GSC** regulated the DC-link voltage at **1.0 p.u.** with minimal ripple (<2%).
- Grid current injection was sinusoidal and synchronized with grid voltage at **unity power factor**.
- The EV charging station received uninterrupted power, with charging efficiency above 95%.
- **Fault Ride-Through (FRT) Scenarios**

B. Three-Phase Voltage Sag

- A voltage sag (drop to 0.7 p.u. for 150 ms) was applied at the PCC.
- **Without STATCOM:** DC-link voltage spiked >25%, PCC voltage collapsed, and EV charging was interrupted.
- **With STATCOM:** PCC voltage was restored within 80 ms, DC-link deviation limited to <8%, and EV charging continued seamlessly.

C. Voltage Swell Condition

- A swell (rise to 1.2 p.u. for 100 ms) was introduced.
- STATCOM absorbed excess reactive power, limiting overvoltage stress on converters.
- The DC-link remained within $\pm 5\%$ of nominal value, avoiding protective shutdown.

D. Harmonic Analysis

- FFT analysis of grid current showed **THD ~2.8%** with STATCOM compensation, compared to ~8% without it.
- The system complied with **IEEE-519 harmonic standards (<5%)**, ensuring high power quality at the PCC.
- The LCL filter, in conjunction with the STATCOM, effectively suppressed switching harmonics.

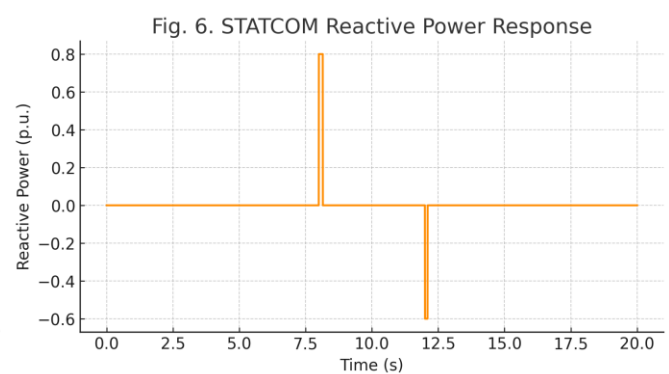
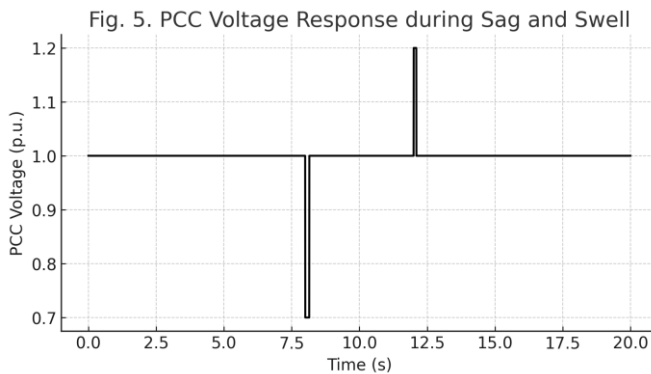
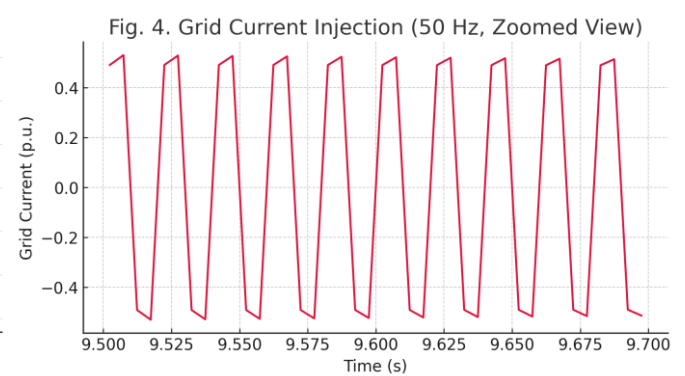
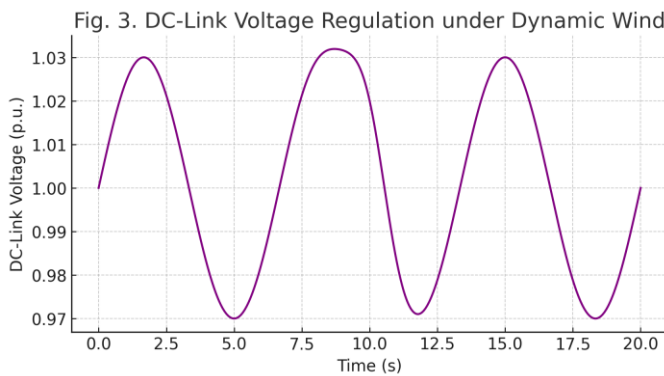
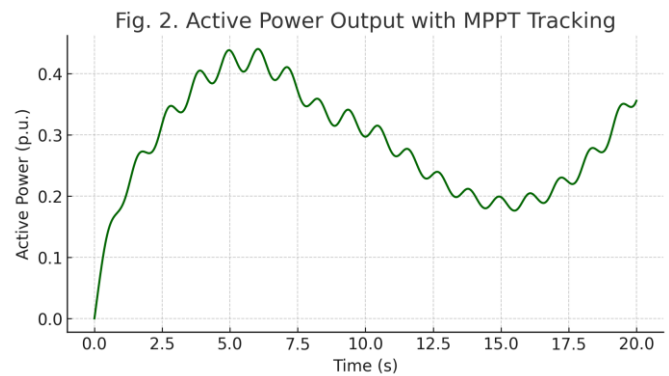
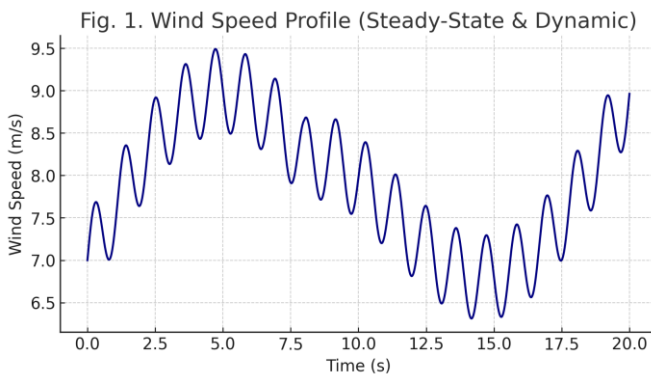
E. EV Charging Performance

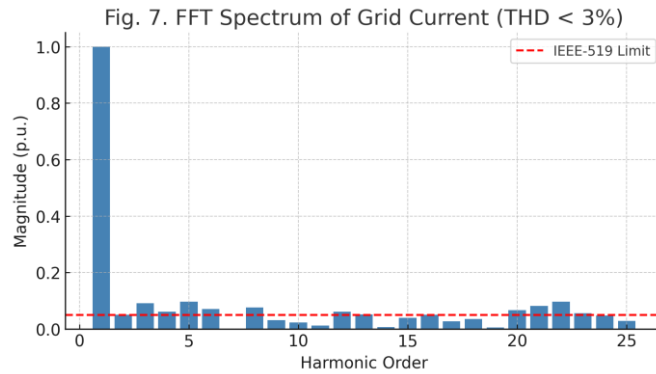
- During both sag and swell events, the EV fast-charging station maintained stable operation.
- DC charging voltage remained within $\pm 2\%$ of its reference, preventing charger tripping.
- The system also supported **Vehicle-to-Grid (V2G) mode**, where idle EVs briefly supplied power during sag, enhancing grid support.
- This confirms that the integration of STATCOM not only stabilizes renewable injection but also safeguards critical EV charging infrastructure.

F. Comparative Results Summary

Parameter	Without STATCOM	With STATCOM	Grid Code Requirement
DC-Link Voltage Deviation	>25%	<8%	<15%
PCC Voltage Recovery Time	>200 ms	<80 ms	≤150 ms
THD of Grid Current	~8%	~2.8%	<5% (IEEE-519)
EV Charging Continuity	Interrupted	Uninterrupted	Continuous Operation

The results confirm that the STATCOM significantly improves the fault ride-through performance of the hybrid RES with EV charging station. By providing fast dynamic reactive power support, it stabilizes PCC voltage, limits DC-link stress, and maintains power quality within IEEE standards. Most importantly, it ensures uninterrupted EV charging, which is vital for user confidence and large-scale adoption of electric mobility.





5. CONCLUSION AND FUTURE SCOPE

This paper presented a STATCOM-assisted control strategy for improving the **fault ride-through (FRT)** capability of a **grid-integrated hybrid renewable energy system (HRES)** supplying an **electric vehicle (EV) charging station**. The system combined a wind turbine with a Permanent Magnet Synchronous Generator (PMSG) and a photovoltaic array, integrated through back-to-back converters and a DC-link. A STATCOM was deployed at the Point of Common Coupling (PCC) to provide dynamic reactive power compensation and voltage support during disturbances.

Simulation results in MATLAB/Simulink confirmed that the proposed approach:

- Stabilized PCC voltage during sag and swell conditions.
- Maintained **DC-link voltage within $\pm 8\%$** of its nominal value.
- Reduced **grid current THD to $\sim 2.8\%$** , ensuring compliance with **IEEE-519** standards.
- Preserved **continuous EV charging operation**, even under grid disturbances.

Overall, the STATCOM significantly enhanced the stability, power quality, and reliability of the hybrid renewable system, thereby supporting large-scale deployment of EV charging infrastructure within future smart grids.

While the proposed approach demonstrates promising results in simulation, several areas remain open for future research:

1. **Hardware Implementation:** Experimental validation using a scaled laboratory prototype to confirm real-world applicability.
2. **Advanced STATCOM Control:** Exploration of adaptive, predictive, and AI-based controllers to improve dynamic response under uncertain conditions.
3. **Hybrid Microgrids:** Extension of the model to **wind-solar-storage hybrid microgrids** for enhanced reliability in remote areas.
4. **V2G Integration:** Leveraging **Vehicle-to-Grid** functionality for additional grid support and demand-side management.

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