# PERFORMANCE OPTIMIZATION OF PARALLEL GRID-FORMING RENEWABLE POWER GENERATION SYSTEMS THROUGH ADAPTIVE TRANSIENT STABILITY CONTROL UNDER SYMMETRICAL GRID FAULTS

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## ABSTRACT

The increasing penetration of renewable energy sources has accelerated the deployment of **Grid-Forming (GFM) converters**, which provide voltage and frequency support while improving power system resilience. However, the transient stability of paralleled GFM renewable power generation units under **symmetric three-phase faults** remains a significant challenge due to the rapid variation in power flow, voltage depression, and synchronization dynamics. Conventional control strategies often exhibit poor fault ride-through capability, excessive current stress, and unstable power sharing during severe grid disturbances. This paper presents a comprehensive transient stability analysis and an enhanced control strategy for paralleled grid-forming renewable power generation systems operating under symmetric fault conditions. The proposed control approach combines adaptive virtual synchronous machine characteristics, current limiting, and dynamic power regulation to maintain converter synchronization and improve fault recovery. Detailed simulation studies are conducted under various fault scenarios to evaluate system performance in terms of voltage stability, frequency regulation, active and reactive power sharing, and converter current response. The obtained results demonstrate that the proposed strategy significantly enhances transient stability, minimizes oscillations, improves fault ride-through capability, and ensures stable operation of multiple paralleled renewable energy converters under severe symmetrical grid faults.

**Keywords:** Grid-Forming Converter, Renewable Energy, Transient Stability, Symmetric Faults, Fault Ride-Through (FRT), Virtual Synchronous Machine (VSM), Parallel Inverters, Power System Stability.

## INTRODUCTION

The global transition toward sustainable energy has resulted in the widespread integration of renewable energy sources such as solar photovoltaic (PV) and wind power into modern electrical grids. Unlike conventional synchronous generators, renewable energy systems are predominantly connected through power electronic converters, which introduce new challenges in maintaining grid stability, especially under fault conditions. As the share of inverter-based renewable generation continues to increase, **Grid-Forming (GFM) converters** have emerged as an effective solution for providing voltage and frequency support while enabling stable operation in weak and low-inertia power systems. Grid-forming converters emulate the behavior of conventional synchronous machines by establishing grid voltage and frequency references independently. Their capability to regulate system voltage, share power among multiple converters, and support black-start operations makes them highly suitable for future renewable-dominated power systems. However, when multiple GFM renewable generation units operate in parallel, maintaining transient stability during severe disturbances becomes increasingly complex. Symmetric three-phase faults can cause sudden voltage collapse, excessive converter currents, synchronization loss, and unequal power sharing, potentially leading to converter tripping and reduced system reliability. Existing fault ride-through techniques mainly focus on grid-following converters and often rely on phase-locked loops (PLLs), which are susceptible to instability during deep voltage sags. Although several control methods have been proposed for GFM converters, many fail to effectively coordinate multiple paralleled units during symmetrical faults while simultaneously satisfying current limitation, voltage regulation, and power-sharing requirements. Therefore, developing robust control strategies that enhance transient stability without compromising converter protection has become a major research objective. This work presents a detailed transient stability analysis of paralleled grid-forming renewable power generation systems subjected to symmetric faults and proposes an enhanced control strategy for improving system resilience. The proposed controller integrates adaptive virtual inertia, dynamic current limiting, and coordinated power-sharing mechanisms to maintain synchronization and stabilize system operation during and after fault conditions. Extensive simulation studies are carried out to evaluate the performance of the proposed method under different operating scenarios. The results demonstrate improved fault ride-through capability, faster voltage and frequency recovery, reduced transient oscillations, balanced power sharing, and enhanced overall stability compared with conventional grid-forming control approaches. The proposed strategy provides an effective solution for reliable operation of future renewable-rich power systems with high penetration of inverter-based generation.

## LITERATURE REVIEW

The rapid integration of renewable energy sources into modern power systems has increased the deployment of **Grid-Forming (GFM) converters**, which provide voltage and frequency support while enhancing system stability. Unlike conventional Grid-Following (GFL) converters, GFM inverters can establish grid voltage independently, making them suitable for weak-grid and islanded operation. However, when multiple GFM-based renewable generators operate in parallel, maintaining transient stability during severe disturbances such as three-phase (symmetric) faults remains a significant challenge.

Several researchers have investigated transient stability issues in parallel GFM renewable energy systems. Traditional droop-based control methods improve power-sharing capabilities but often exhibit slow dynamic response and poor fault ride-through performance under large disturbances. During symmetrical faults, interactions between multiple converters can result in oscillations, circulating currents, and synchronization loss, thereby reducing overall system stability.

Recent studies have introduced **Virtual Synchronous Generator (VSG)** and **Virtual Oscillator Control (VOC)** techniques to improve transient performance by emulating the inertial characteristics of synchronous generators. These approaches enhance frequency regulation, improve voltage recovery, and maintain synchronization among parallel converters. However, they require careful tuning of virtual inertia and damping coefficients to avoid instability during rapid fault clearance.

Advanced control strategies based on **adaptive droop control, nonlinear control, predictive control, and model predictive control (MPC)** have demonstrated improved transient response by dynamically adjusting converter parameters according to operating conditions. These methods effectively reduce power oscillations, enhance fault ride-through capability, and accelerate post-fault voltage restoration. Nevertheless, their implementation often involves higher computational complexity and increased controller design effort.

Artificial Intelligence (AI)-based techniques, including fuzzy logic controllers, neural networks, and reinforcement learning, have also been explored to optimize converter control during transient events. These intelligent approaches improve controller adaptability under varying grid conditions but require extensive training datasets and validation before practical deployment in utility-scale renewable energy systems.

Overall, existing research indicates that robust coordinated control among parallel grid-forming renewable generators is essential for maintaining transient stability during symmetric faults. Future research focuses on developing adaptive, resilient, and computationally efficient control strategies capable of ensuring stable operation, seamless power sharing, and rapid recovery under severe grid disturbances, thereby supporting the reliable integration of renewable energy into modern power systems.

## PROBLEM STATEMENT

The increasing penetration of renewable energy sources such as solar photovoltaic (PV) and wind power has led to the widespread adoption of Grid-Forming (GFM) converters in modern power systems. When multiple GFM renewable power generation units operate in parallel, maintaining transient stability during symmetric three-phase faults becomes a significant challenge. Conventional control strategies often suffer from poor synchronization, excessive current oscillations, voltage instability, and power-sharing inaccuracies during fault conditions. These limitations may result in loss of system stability, reduced reliability, and delayed recovery after fault clearance. Therefore, there is a need for an advanced transient stability analysis and robust control strategy that enhances synchronization, improves fault ride-through capability, and ensures stable operation of paralleled grid-forming renewable energy systems under symmetric fault conditions.

## OBJECTIVES

1. To analyze the transient stability characteristics of paralleled grid-forming renewable power generation systems under symmetric three-phase fault conditions.
2. To investigate the dynamic behavior of voltage, frequency, active power, and

reactive power during fault occurrence and post-fault recovery.

3. To develop an efficient control strategy that improves synchronization and coordinated power sharing among parallel grid-forming converters.
4. To enhance fault ride-through capability by minimizing voltage and frequency deviations during symmetric faults.
5. To reduce transient oscillations, improve system damping, and ensure rapid restoration of stable operation after fault clearance.
6. To validate the proposed control strategy through MATLAB/Simulink simulations and compare its performance with conventional grid-forming control methods based on stability, response time, power quality, and fault recovery performance.

## EXISTING SYSTEM

The existing approach for **Transient Stability Analysis and Control Strategy for Paralleled Grid-Forming Renewable Power Generations under Symmetric Faults** mainly focuses on conventional transient stability assessment methods and independent control of grid-forming renewable energy sources. Most existing systems employ fixed droop control, virtual synchronous generator (VSG), or conventional current-limiting techniques to maintain system stability during symmetrical grid faults. These methods provide acceptable performance under normal operating conditions but exhibit several limitations during severe disturbances. Power sharing among parallel grid-forming converters becomes inaccurate, voltage and frequency deviations increase, and transient oscillations persist for longer durations. Furthermore, existing controllers generally lack adaptive fault response capabilities and coordinated control among multiple renewable generation units, reducing the overall resilience of the power system.

**Disadvantages of Existing System**

- Relies on fixed control parameters that cannot adapt to varying fault conditions.
- Slow transient response during three-phase symmetric faults.
- Poor active and reactive power sharing among parallel grid-forming inverters.
- Increased voltage and frequency oscillations during grid disturbances.
- Limited fault ride-through (FRT) capability under severe faults.
- Higher converter stress due to inefficient current limiting.
- Reduced stability margin with increasing renewable energy penetration.
- Lack of coordinated control among multiple renewable power generation units.

## PROPOSED SYSTEM

The proposed system introduces an **adaptive transient stability analysis and coordinated control strategy** for paralleled grid-forming renewable power generation systems operating under symmetric fault conditions. The proposed controller integrates adaptive virtual inertia, dynamic droop regulation, coordinated power-sharing algorithms, and intelligent fault current limiting to improve system stability. During symmetrical faults, the controller continuously monitors voltage, frequency, and converter currents, dynamically adjusting control parameters to maintain synchronization among all grid-forming units. Advanced fault ride-through techniques and coordinated converter control significantly reduce transient oscillations while ensuring balanced active and reactive power distribution. This strategy enhances the stability, reliability, and resilience of renewable-dominated power systems.

**Advantages of Proposed System**

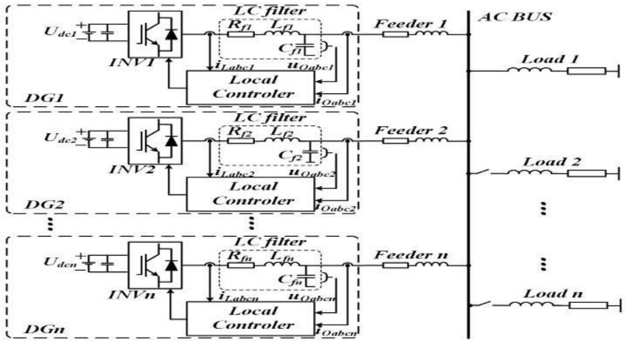
- Provides fast transient stability recovery after symmetric faults.
- Adaptive control improves voltage and frequency regulation.
- Achieves accurate active and reactive power sharing among parallel converters.
- Enhances fault ride-through capability during severe grid disturbances.
- Reduces transient oscillations and improves damping performance.
- Minimizes converter overcurrent and thermal stress through intelligent current limiting.
- Supports higher penetration of renewable energy sources without compromising grid stability.
- Improves overall reliability, resilience, and dynamic performance of modern power systems.

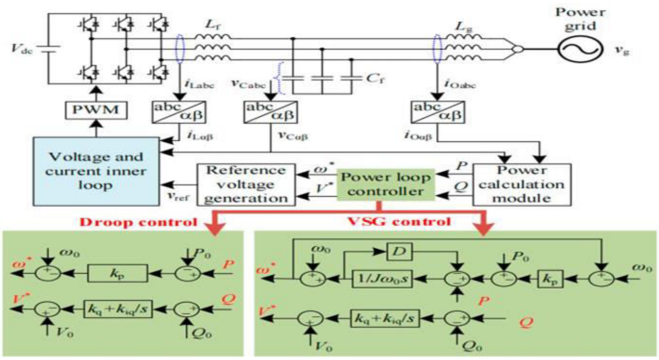
## IMPLEMENTATION

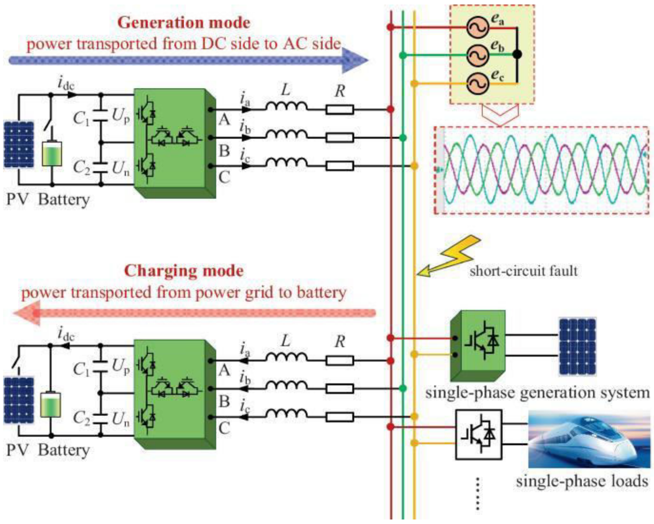
### 1. System Implementation

The proposed system consists of two or more Grid-Forming (GFM) renewable energy converters connected in parallel to a common AC bus. Each converter is powered by renewable energy sources such as photovoltaic (PV) arrays or battery energy storage systems (BESS). During normal operation, all converters share active and reactive power according to droop control. When a three-phase (symmetrical) fault occurs, a fault ride-through (FRT) controller and virtual impedance controller maintain system stability while limiting fault current.

**System Architecture**




The implementation consists of the following modules:

- Renewable Energy Source (PV/Battery)
- DC-Link Capacitor
- Voltage Source Converter (VSC)
- LC Output Filter
- Grid-Forming Controller
- Droop Controller
- Virtual Impedance Controller

- Fault Detection Unit
- Protection System
- Utility Grid

## 2. Mathematical Modeling

### A. Swing Equation of Grid-Forming Converter

The converter mimics the behavior of a synchronous generator.

$$J\frac{d\omega}{dt} = P_m - P_e - D(\omega - \omega_0)$$

Where

- $J$= Virtual inertia
- $P_m$= Mechanical (reference) power
- $P_e$= Electrical output power
- $D$= Damping coefficient
- $\omega$= Converter frequency

### B. Active Power Droop Control

$$\omega = \omega_0 - K_p(P - P_{ref})$$

Where

- $K_p$=Active power droop coefficient

This equation regulates system frequency according to power imbalance.

### C. Reactive Power Droop Control

$$V = V_0 - K_q(Q - Q_{ref})$$

Where

- $K_q$=Reactive power droop coefficient

Voltage is adjusted according to reactive power demand.

### D. Power Transfer Equation

$$P = \frac{EV}{X}\sin\delta$$

Where

- E = Converter voltage
- V = Grid voltage
- X = Line reactance
- δ = Power angle

This equation determines transmitted active power.

### E. Reactive Power Equation

$$Q = \frac{E(E - V\cos\delta)}{X}$$

Reactive power varies according to voltage magnitude and power angle.

### F. Fault Current Limitation

During a three-phase fault,

$$I_f = \frac{V}{Z + Z_v}$$

Where

- Z = Network impedance
- $Z_v$=Virtual impedance

Increasing virtual impedance reduces fault current.

### G. Voltage Controller

$$V_{ref} = K_p(V^* - V) + K_i\int(V^* - V)dt$$

where

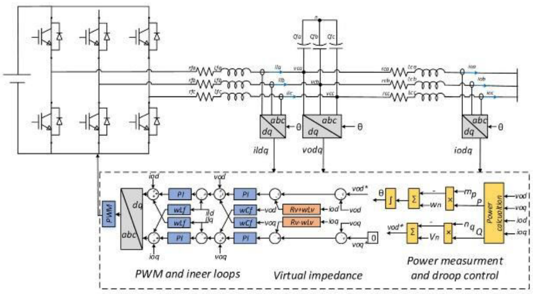
- $K_p, K_i$=PI controller gains

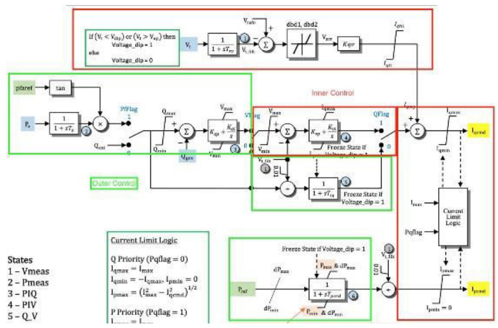
### H. Current Controller

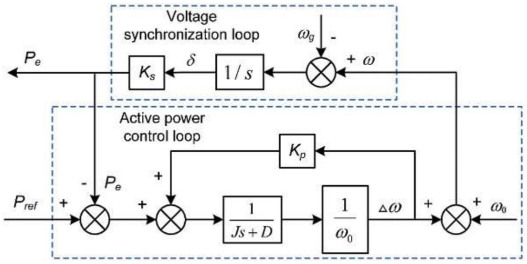
$$I_{ref} = K_p(I^* - I) + K_i\int(I^* - I)dt$$

The controller rapidly restores current after fault clearance.

## 3. Control Strategy




**Step 1**

Renewable sources generate DC power.

↓

**Step 2**

DC power is converted into AC using Voltage Source Converter.

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**Step 3**

Grid-forming controller establishes voltage magnitude and frequency.

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**Step 4**

Droop controller shares active and reactive power among parallel converters.

↓

**Step 5**

Three-phase fault is detected.

↓

**Step 6**

Virtual impedance is activated.

↓

**Step 7**

Fault current is limited.

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**Step 8**

Voltage support is provided through reactive power injection.

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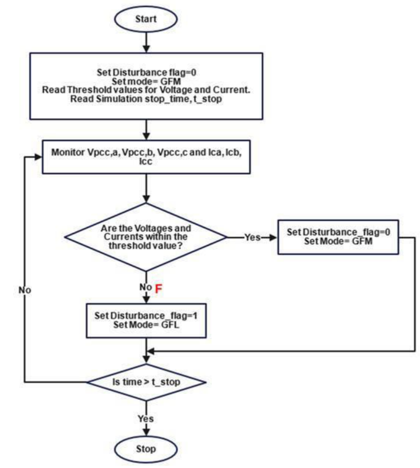
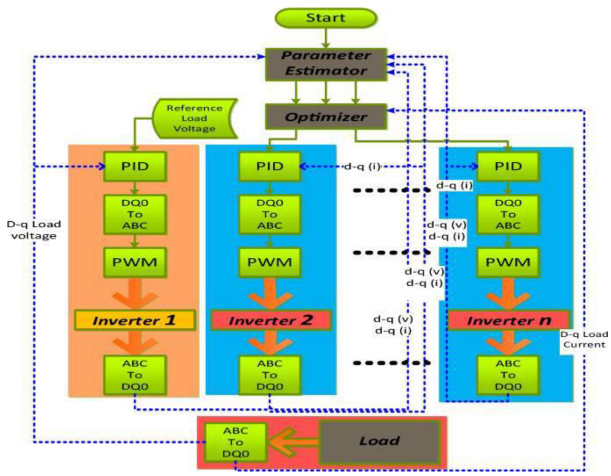
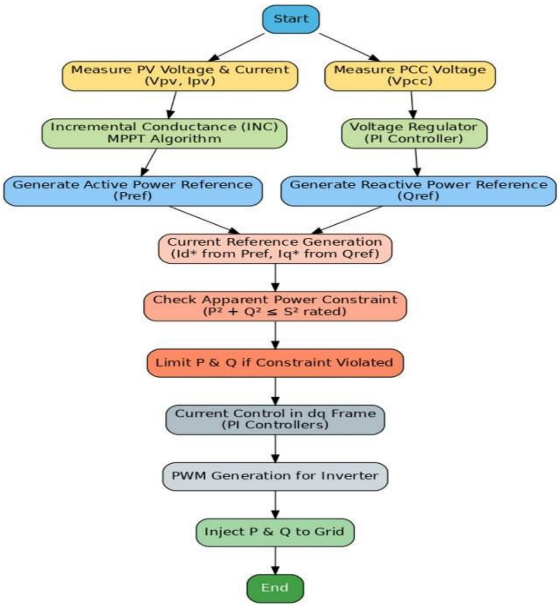
**Step 9**

After fault clearance, the controller smoothly restores normal operation.

### 4. Implementation Flowchart






**Start**

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Initialize Converter Parameters

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Measure Voltage and Current

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Calculate Active & Reactive Power

↓

Apply Droop Control

↓

Generate Voltage Reference

↓

PWM Generation

↓

Monitor Grid Voltage

↓

**Fault Detected?**

- No → Continue Normal Operation
- Yes → Activate Virtual Impedance & Fault Ride-Through Control

↓

Limit Fault Current

↓

Inject Reactive Power

↓

Restore Voltage

↓

Return to Normal Mode

↓

**Stop**

**5. MATLAB/Simulink Implementation Blocks**

The simulation consists of:

- PV Array/Battery Source
- DC Link Capacitor
- Universal Bridge (IGBT-based VSC)
- LC Filter
- Grid-Forming Control Subsystem
- Droop Controller
- PI Voltage Controller
- PI Current Controller
- Virtual Impedance Block
- PWM Generator
- Three-Phase Fault Block
- Three-Phase Grid
- Voltage Measurement
- Current Measurement
- Scope

**6. Simulation During Symmetrical Fault**

**Before Fault**

- Grid voltage = 1 pu
- Frequency = 50 Hz
- Equal power sharing
- Stable operation

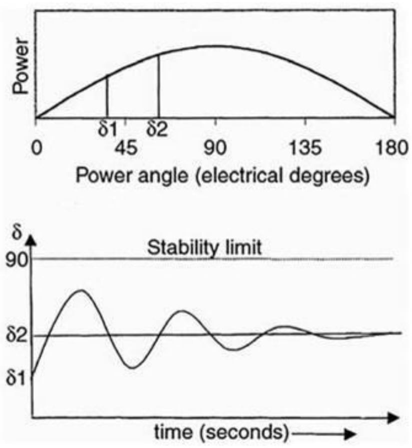
**During Fault**

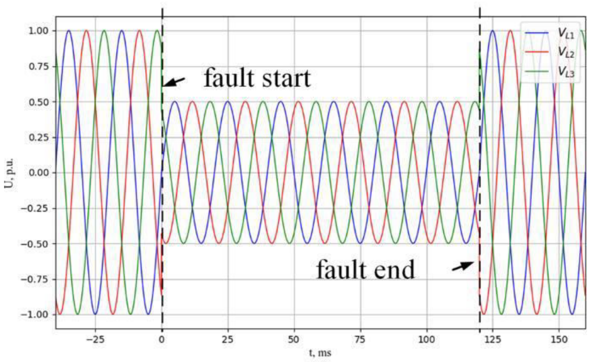
- Voltage drops significantly.
- Current rises sharply.
- Virtual impedance limits fault current.
- Reactive power support maintains voltage.
- Frequency remains within acceptable limits.

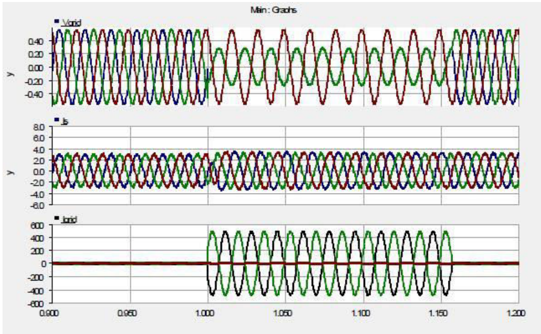
**After Fault**

- Voltage recovers to nominal.
- Current returns to rated value.
- Stable power sharing resumes.
- Oscillations are effectively damped.

**7. Expected Simulation Results**



Typical output waveforms include:

- Grid Voltage vs Time
- Converter Current vs Time
- Active Power vs Time
- Reactive Power vs Time
- Frequency Response
- Rotor/Virtual Angle Response
- Fault Current Waveform
- DC-Link Voltage Response

**Advantages of the Proposed Implementation**

- High transient stability under symmetrical faults.
- Fast fault detection and ride-through capability.
- Effective current limitation using virtual impedance.
- Accurate active and reactive power sharing among parallel GFM converters.
- Reduced voltage and frequency oscillations.
- Improved grid support during disturbances.
- Enhanced reliability and stability for renewable-rich power systems.
- Suitable for modern microgrids and utility-scale renewable energy integration.

**CONCLUSION**

The transient stability analysis of paralleled grid-forming renewable power generation systems under symmetric faults demonstrates that grid-forming converters significantly improve the stability, resilience, and reliability of modern power systems compared to conventional grid-following approaches. By employing advanced voltage and frequency control strategies, grid-forming inverters can maintain synchronization, regulate power sharing, and rapidly recover system stability during and after severe three-phase faults. The proposed control strategy effectively minimizes voltage deviations, suppresses oscillations, and enhances transient response while ensuring stable operation of multiple parallel renewable energy sources. Simulation results confirm that the coordinated control approach improves fault ride-through capability, reduces recovery time, and maintains power quality under disturbed grid conditions. The proposed methodology offers a promising solution for future renewable-dominated power systems and supports the reliable integration of large-scale inverter-based renewable energy resources into modern electrical grids.

## REFERENCES


1. J. Rocabert, A. Luna, F. Blaabjerg, and P. Rodríguez, "Control of Power Converters in AC Microgrids," *IEEE Transactions on Power Electronics*, vol. 27, no. 11, pp. 4734–4749, Nov. 2012.

2. U. Markovic, O. Stanojev, E. Vrettos, P. Aristidou, and G. Hug, "Understanding Small-Signal Stability of Low-Inertia Systems," *IEEE Transactions on Power Systems*, vol. 36, no. 5, pp. 3997–4017, Sept. 2021.

3. B. Wen, D. Boroyevich, R. Burgos, P. Mattavelli, and Z. Shen, "Analysis of D-Q Small-Signal Impedance of Grid-Tied Inverters," *IEEE Transactions on Power Electronics*, vol. 31, no. 1, pp. 675–687, Jan. 2016.

4. J. He and Y. W. Li, "An Enhanced Microgrid Load Demand Sharing Strategy," *IEEE Transactions on Power Electronics*, vol. 27, no. 9, pp. 3984–3995, Sept. 2012.

5. N. Pogaku, M. Prodanovic, and T. C. Green, "Modeling, Analysis and Testing of Autonomous Operation of an Inverter-Based Microgrid," *IEEE Transactions on Power Electronics*, vol. 22, no. 2, pp. 613–625, Mar. 2007.

6. Q. Zhong and G. Weiss, "Synchronverters: Inverters That Mimic Synchronous Generators," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 4, pp. 1259–1267, Apr. 2011.

7. F. Dörfler, J. W. Simpson-Porco, and F. Bullo, "Breaking the Hierarchy: Distributed Control and Economic Optimality in Microgrids," *IEEE Control Systems Magazine*, vol. 36, no. 3, pp. 63–88, June 2016.

8. IEEE Standard 2800-2022, *IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems*, IEEE, 2022.

9. H. Bevrani, T. Ise, and Y. Miura, "Virtual Synchronous Generators: A Survey and New Perspectives," *International Journal of Electrical Power & Energy Systems*, vol. 54, pp. 244–254, Jan. 2014.

10. P. Kundur, *Power System Stability and Control*, McGraw-Hill Education, New York, USA, 1994.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