

Article

Decentralised Consensus Control of Hybrid Synchronous Condenser and Grid-Forming Inverter Systems in Renewable-Dominated Low-Inertia Grids

Hamid Soleimani ¹, Asma Aziz ^{1,*}, S M Muslem Uddin ², Mehrdad Ghahramani ¹ and Daryoush Habibi ¹

¹ School of Engineering, Edith Cowan University, Joondalup, WA 6027, Australia; h.soleimani@ecu.edu.au (H.S.); m.ghahramani@ecu.edu.au (M.G.); d.habibi@ecu.edu.au (D.H.)

² CSIRO | Energy Systems 2, Newcastle, NSW 2304, Australia; smmuslem.uddin@csiro.au

* Correspondence: asma.aziz@ecu.edu.au

Abstract

The increasing penetration of renewable energy sources (RESs) has significantly altered the operational characteristics of modern power systems, resulting in reduced system inertia and fault current capacity. These developments introduce new challenges for maintaining frequency and voltage stability, particularly in low-inertia grids that are dominated by inverter-based resources (IBRs). This paper presents a hierarchical control framework that integrates synchronous condensers (SCs) and grid-forming (GFM) inverters through a leader–follower consensus control architecture to address these issues. In this approach, selected GFMs act as leaders to restore nominal voltage and frequency, while follower GFMs and SCs collaboratively share active and reactive power. The primary control employs droop-based regulation, and a distributed secondary layer enables proportional power sharing via peer-to-peer communication. A modified IEEE 14-bus test system is implemented in PSCAD to validate the proposed strategy under scenarios including load disturbances, reactive demand variations, and plug-and-play operations. Compared to conventional droop-based control, the proposed framework reduces frequency nadir by up to 0.3 Hz and voltage deviation by 1.1%, achieving optimised sharing indices. Results demonstrate that consensus-based coordination enhances dynamic stability and power-sharing fairness and supports the flexible integration of heterogeneous assets without requiring centralised control.

Keywords: grid-forming inverter; synchronous condenser; consensus control; leader–follower method; BESS; hybrid SC-GFM



Academic Editors: Inga Zicmane and Svetlana Beryozkina

Received: 20 May 2025

Revised: 23 June 2025

Accepted: 4 July 2025

Published: 8 July 2025

Citation: Soleimani, H.; Aziz, A.; Uddin, S.M.M.; Ghahramani, M.; Habibi, D. Decentralised Consensus Control of Hybrid Synchronous Condenser and Grid-Forming Inverter Systems in Renewable-Dominated Low-Inertia Grids. *Energies* **2025**, *18*, 3593. <https://doi.org/10.3390/en18143593>

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1. Introduction

The global drive towards decarbonising energy systems has led to an unprecedented shift in power generation, with renewable energy sources (RESs)—primarily wind and solar—being rapidly deployed to meet ambitious net-zero emissions targets by 2050 [1–4]. This transition has significantly transformed the dynamics of modern power systems. While RESs offer environmental and economic advantages, their inverter-based and intermittent nature introduces major challenges in maintaining system stability, especially in scenarios where traditional synchronous generators (SGs) are being decommissioned or displaced by inverter-based resources (IBRs) [5–7].

The diminishing role of synchronous generation has resulted in a sharp decline in system inertia and short-circuit strength—two critical factors that underpin the abil-

ity of power systems to respond to disturbances and maintain frequency and voltage stability [8–10]. These changes have ushered in the era of low-inertia networks, characterised by rapid frequency deviations [11], undamped oscillations, and increased vulnerability to both small-signal and large-signal instabilities [12,13]. Traditional control methods, largely designed around synchronous machines, are now insufficient to address these fast and complex transients, necessitating new approaches in both control strategies and hardware deployment [14–16].

In most conventional applications [17], IBRs are integrated through grid-following (GFL) inverters, which depend on a strong grid voltage reference to synchronise and inject current. Although widely deployed, GFL inverters cannot form or regulate voltage independently. They are inherently limited in their ability to support critical services such as black start, synthetic inertia, or autonomous fault ride-through [7,18,19]. Their operation becomes increasingly unstable in weak grid conditions, where high impedance and reduced system strength are prevalent [20,21].

To overcome these limitations, GFM inverters have emerged as a pivotal solution [22]. Unlike GFL inverters, GFM units can generate voltage and frequency references internally, thereby enabling them to operate autonomously or in coordination with other power electronic devices and synchronous machines [23,24]. Various control schemes have been developed to emulate the behaviour of SGs—including droop control, virtual synchronous generator (VSG) control, and virtual oscillator control (VOC)—providing synthetic inertia, voltage regulation, and frequency support [3,25]. With their ability to operate in both islanded and grid-connected modes, GFM inverters are increasingly recognised as essential components in high-RES penetration systems [26,27].

Complementing the functionality of GFM inverters, synchronous condensers (SCs) have re-emerged as a strategic asset in modern grids [28,29]. SCs contribute real rotational inertia, fault current injection, and dynamic voltage support without the need for additional control loops [30,31]. Their effectiveness in increasing system short-circuit ratio (SCR), stabilising frequency, and mitigating subsynchronous oscillations (SSOs) has been validated in various studies [32,33]. Moreover, SCs retain the inherent robustness of rotating machinery, providing predictable behaviour during grid disturbances and facilitating protection coordination [18,31,34].

While the benefits of SCs and GFMs are well established, their limitations persist. SCs have slower response times, high mechanical wear, and operational costs, whereas GFM inverters face challenges in current limitations and synchronisation during faults [35,36]. To address this, hybrid synchronous condensers (HSCs)—integrating SCs with GFM inverters or battery energy storage systems (BESSs)—are being explored as a promising solution. These hybrid systems combine the inertia and fault current strength of SCs with the fast, programmable response of power converters, delivering a balanced approach to frequency and voltage regulation in low-inertia grids [37–39].

Additionally, the role of BESSs in hybrid architectures is gaining attention. With their fast-acting power converters, BESSs offer rapid frequency support, virtual inertia, and bidirectional power flow—making them invaluable in mitigating the variability in renewable generation [40,41]. When coupled with SCs, they enable grid operators to not only recover system strength but also provide flexible services tailored to operational needs [42].

However, beyond hardware deployment, the success of these hybrid systems critically depends on control coordination. Traditional centralised control approaches are limited in scalability and resilience, particularly under high-RES penetration and decentralised generation scenarios [43,44]. As such, a shift towards decentralised and distributed secondary control strategies has been observed. Among these, leader–follower consensus

(LFC) control has gained attraction for its ability to coordinate voltage and frequency regulation without relying on a central controller [45]. In this framework, GFM inverters act as leaders, while SCs or GFL inverters serve as followers, collectively stabilising system variables through local interactions [46–49].

Despite advancements in GFM and SC technologies, significant gaps remain in their coordinated control for low-inertia grids. Existing studies, such as [25,43,44], focus primarily on GFM inverters or homogeneous inverter-based systems, often neglecting the integration of SCs, which provide critical inertia and fault current support. Centralized control approaches [43,44] lack scalability and resilience in distributed, renewable-dominated networks, while decentralized methods like virtual synchronous generator (VSG) control [25] or distributed averaging [48] do not account for the distinct dynamics of SCs versus GFMs. Moreover, the plug-and-play integration of hybrid SC–GFM units remains underexplored, limiting flexible asset deployment.

This paper addresses these gaps by proposing for the first time a decentralised consensus framework that enables seamless coordination between synchronous condensers and GFM inverters for joint voltage and frequency regulation, suggesting a robust, scalable foundation for reliable operation in low-inertia, renewable-integrated power systems. A modified IEEE 14-bus test system is developed in PSCAD, integrating multiple SCs, GFM inverters, and inverter-based DERs. Various simulation scenarios—including frequency disturbances, voltage regulation events, and plug-and-play operations—are evaluated to validate the effectiveness of leader–follower consensus control architecture. The results demonstrate that coordinated control of SCs and GFMs significantly enhances power sharing, fault resilience, and dynamic stability in renewable-dominated, low-inertia power systems.

2. Modelling of Grid-Forming and Synchronous Condenser Control

This section presents the detailed modelling and control structure of GFMs and SCs, which form the basis of the proposed hybrid stability-enhancement framework. The objective is to capture the essential dynamic characteristics required for accurate power sharing, voltage regulation, and inertial response—laying the groundwork for the coordinated secondary control strategy introduced in the subsequent section.

2.1. GFM Inverter Model and Control

In low-inertia power systems with high penetration of inverter-based resources, accurate modelling of GFMs is critical for evaluating system performance during steady-state and dynamic conditions. The GFM inverter is typically implemented using a voltage source converter (VSC) interfaced to the grid through a filter composed of series resistance R_f , inductance L_f , and shunt capacitance C_f , as illustrated in Figure 1.

In this configuration, V_{DC} represents the DC-link voltage sourced from a big rack of batteries. The inverter's internal voltage V_i is modulated via pulse-width modulation (PWM) and controlled through a multilayer structure comprising current control, voltage control, and primary control loops that are usually based on droop control. The filter smooths the output voltage V_t before injection into the grid. The measured active and reactive powers P_m and Q_m are used in feedback to track reference setpoints P_{ref} and Q_{ref} .

The inverter dynamics are commonly represented in the rotating dq -reference frame, where three-phase signals are transformed into two orthogonal components to facilitate decoupled control of active and reactive power [50]. The electrical dynamics of the inverter filter can be expressed as

$$i_{dq} = R_f i_{i,dq} + C_f \frac{dv_{dq}}{dt} + jC_f \omega_n v_{dq} \quad (1)$$

$$v_{t,dq} = L_f \frac{di_{i,dq}}{dt} + R_f i_{i,dq} + v_{g,dq} \quad (2)$$

where i_{dq} and v_{dq} represent the dq-components of the inverter current and voltage. The term ω_n denotes the nominal angular frequency of the system [50].

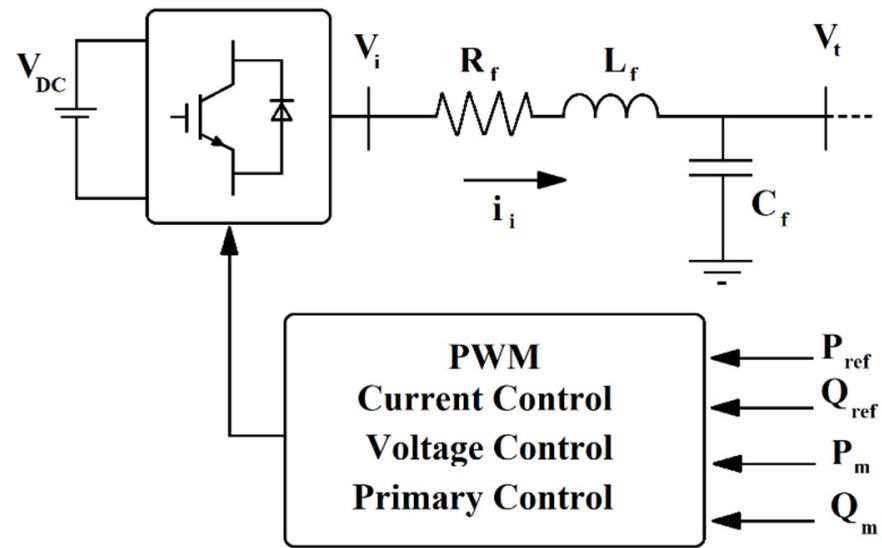


Figure 1. An inverter with an RLC filter and GFM control.

The current injection into the grid is further detailed by separating the equations for the d - and q -axes:

$$i_d = i_{i,d} + \frac{C_f dv_d}{dt} - C_f \omega_n v_q \quad (3)$$

$$i_q = i_{i,q} + \frac{C_f dv_q}{dt} + C_f \omega_n v_d \quad (4)$$

The GFM inverter is conceptually modelled as a voltage source behind an impedance, with internal dynamics governed by [51]

$$\dot{\theta}_i = u_{\theta_i}, \quad E_i = u_{V_i}$$

Here, θ_i is the internal voltage angle of the i^{th} inverter, and E_i is the internal voltage magnitude. The control signals u_{θ_i} and u_{V_i} are derived from droop-based primary control logic, which regulates power exchange with the grid.

The frequency and voltage droop control laws are defined as [3]

$$\omega_{ref,i} = \omega_{n,i} - m_{p_i} (P_i - P_{ref,i}) \quad (5)$$

$$V_{ref,i} = V_{set,i} - m_{q_i} (Q_i - Q_{ref,i}) \quad (6)$$

where m_{p_i} , and m_{q_i} are droop coefficients, and $P_{ref,i}$, $Q_{ref,i}$, and $V_{ref,i}$ represent the desired operating points. A proportional–integral (PI) controller tracks the voltage error $V_{ref,i} - V_i$ and generates u_{V_i} to maintain voltage regulation.

The overall control of the grid-forming inverter is illustrated in Figure 2. This schematic demonstrates how the droop control outputs are processed through voltage and frequency controllers to generate the modulation signals required for inverter operation.

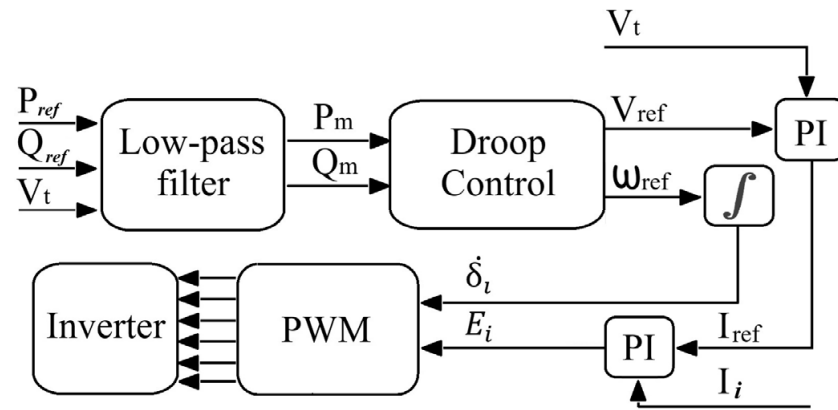


Figure 2. Control structure of a grid-forming inverter.

2.2. Synchronous Condenser Model

The SC shares the same physical structure as a synchronous generator but without mechanical torque input [52]. It is primarily employed to provide dynamic voltage support, reactive power, and real inertia. Figure 3 shows an equivalent circuit of SC.

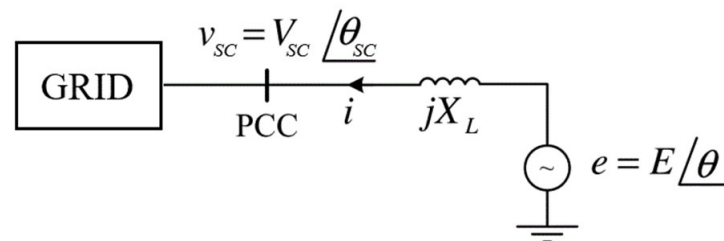


Figure 3. Equivalent circuit of synchronous condenser.

The SC is modelled using standard dq -axis synchronous machine equations [53]:

$$\frac{d\psi_d}{dt} = -R_s i_d + \omega(\omega_q - L_q i_q) + v_d \quad (7)$$

$$\frac{d\psi_q}{dt} = -R_s i_q - \omega(\psi_d - L_d i_d) + v_q \quad (8)$$

where ψ_d and ψ_q are the flux linkages, i_d and i_q are the stator currents, and v_d and v_q are terminal voltages in the dq -frame of the terminal voltage v_{SC} , projected into the rotor's dq -reference frame for dynamic modelling purposes. The rotor dynamics are captured by [53]

$$\frac{d\omega}{dt} = \frac{1}{2H}(T_m - T_e - D(\omega - \omega_n)) \quad (9)$$

Here, ω is rotor speed in per unit (p.u.), H is the inertia constant, D is the damping factor, $T_m = 0$ (no mechanical torque input), and T_e is the electrical torque. The inductances L_d and L_q , and resistance R_s , represent the stator parameters [1].

The excitation system uses a PI-based automatic voltage regulator (AVR) to regulate terminal voltage by adjusting the field voltage. In practical implementations, a limiter may be included to prevent overexcitation [34].

In low-inertia power systems, both GFM and SC units must operate within their technical output limits, particularly when regulating active and reactive power. These constraints are enforced through a saturation function that ensures the controller does not

issue power commands beyond what the device can safely deliver [54]. For GFM inverters and SCs, the active and reactive power references are determined as

$$P_i^{ref} = \mathcal{F}\left[P_i^{ref}, \omega^n, \omega_i, m_{p_i}\right] \Big|_{P_{min}}^{P_{max}}, \quad Q_i^{ref} = \mathcal{F}\left[Q_i^{ref}, V_i^{ref}, V_i, m_{q_i}\right] \Big|_{Q_{min}}^{Q_{max}} \quad (10)$$

The saturation function $\mathcal{F}$ prevents the controller from demanding infeasible output levels, especially during grid disturbances. By bounding the power references, it helps protect the hardware and promote reliable, coordinated behaviour across varying system conditions.

2.3. Equal Power and Var-Sharing Objective

One of the key objectives of primary control is to ensure proportional sharing of active power (PSAP) and proportional sharing of reactive power (PSRP) among GFM inverters, while enabling SCs to contribute to voltage regulation. This is enforced via droop control and quantified by the following indices [45]:

$$PSAP = \sum \frac{m_{p_i} P_i}{S_i} \forall i, \quad PSRP = \sum \frac{m_{q_i} Q_i}{S_i} \forall i \quad (11)$$

where S_i is the rated apparent power of the i^{th} leader and follower units. Deviations in $PSAP$ or $PSRP$ across units indicate imbalance in power sharing or circulating vars, which is a common issue with proportional-only droop control. This motivates the development of a distributed secondary control strategy, as presented in the next section.

3. Leader–Follower Consensus Control with Role-Based GFM–SC Coordination

This section introduces a role-based consensus control strategy [45] designed specifically for hybrid power systems consisting of GFMs and SCs. The framework builds upon the LFC architecture by introducing distinct control roles that reflect the physical and functional characteristics of modern grid-connected devices. Within this structure, selected GFMs are designated as leaders responsible for restoring system frequency and voltage, while other GFMs and SCs participate as followers to facilitate coordinated active and reactive power sharing. This approach enables fully decentralised control and enhances scalability, particularly in low-inertia, renewable-rich grids.

Unlike traditional methods that assign an identical control logic to all GFMs or restrict consensus control to inverter-only systems, the proposed scheme introduces a hierarchical structure that acknowledges the diverse dynamic behaviour of GFMs and SCs. Leadership roles are assigned to GFMs with advantageous locations, robust communication access, or enhanced controller capability—criteria chosen to minimise communication burden and facilitate modular system integration. While the current study adopts predefined leader placement based on these practical criteria, future work may investigate formal optimisation techniques for dynamic leader assignment.

In the proposed consensus framework, leader GFMs actively restore nominal values by injecting correction signals into the consensus loops. Follower GFMs participate in power sharing but do not introduce reference-tracking terms, meaning they contribute to consensus dynamics but rely on leaders to guide the nominal setpoints. SCs, although not involved in active power restoration due to their lack of controllable active power injection, play an important role in voltage regulation and provide rotational inertia, indirectly supporting frequency dynamics. Their excitation systems are used for reactive power modulation, allowing them to integrate seamlessly into the consensus structure.

Let $\mathcal{P} = \{M = \{1, 2, \dots, m\}, N = \{m + 1, m + 2, \dots, n\}\}$ represent the set of participating devices, with $\mathcal{L} \subset \mathcal{P}$ denoting the leader GFMs and $\mathcal{F} \subset \mathcal{P}$ comprising GFM-followers and SCs. Communication among devices is described by a graph with the adjacent matrix $\mathcal{A} = [a_{ij}]$, where $a_{ij} = 1$ if agents i and j share information and $a_{ij} = 0$ otherwise [55]. The consensus dynamics for each device are given by

$$\dot{x}_i = \sum a_{ij}(x_j - x_i), \forall i \in \mathcal{F}, j \in \mathcal{N}_i \quad (12)$$

$$\dot{x}_i = \alpha \sum a_{ij}(x_j - x_i) + \beta \mathcal{D}_i, \forall i \in \mathcal{L}, j \in \mathcal{M}_i \quad (13)$$

The total number of participating units is denoted by n , consisting of $m - n$ follower devices and m leaders, such that $\mathcal{P} = \mathcal{F} \cup \mathcal{L}$ with $\mathcal{F} \cap \mathcal{L} = \emptyset$. This partition allows leaders to inject global reference information, while followers contribute to distributed coordination based solely on local interactions. The communication structure used to build the Laplacian matrix is shown in Figure 4. These dynamics allow reference values—such as nominal frequency and voltage—to be disseminated across the network using only local information, ensuring decentralised coordination [56]. The parameter $\mathcal{D}_i$ is used to give additional control objectives, and α and β are weighting factors for the leader group. The communication and control structure among GFM-leaders, GFM-followers, and SC-followers within the proposed leader–follower consensus framework is illustrated in Figure 5.

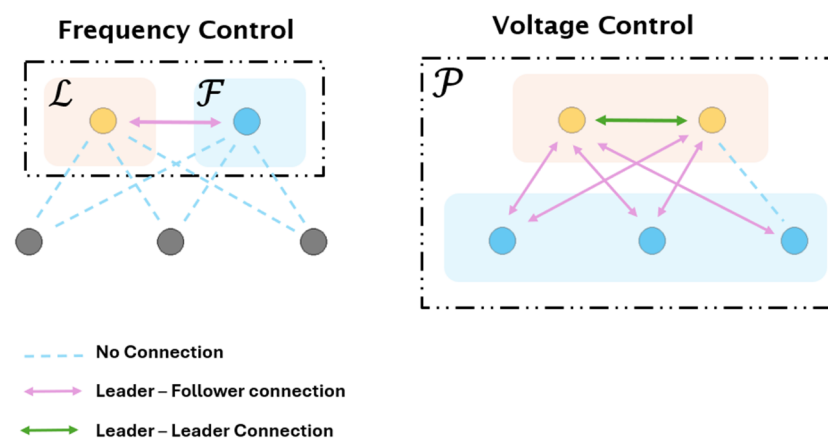


Figure 4. Communication graph for leader–follower consensus control.

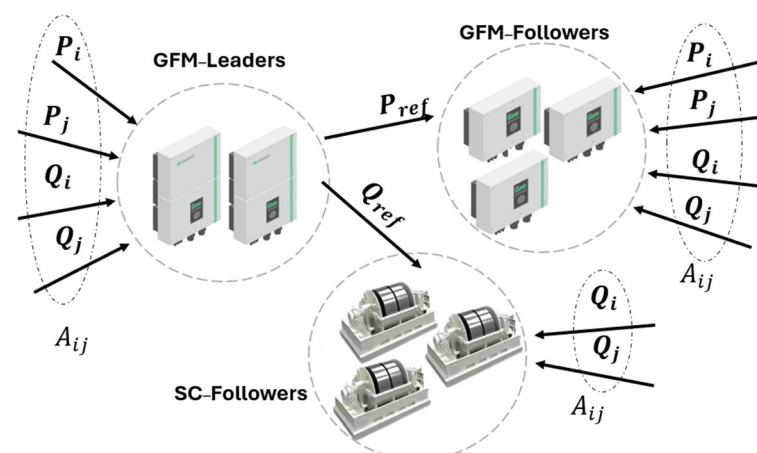


Figure 5. Signal flow and communication topology in the leader–follower consensus framework.

3.1. Frequency Regulation and Active Power Sharing

Frequency regulation is carried out exclusively by leader GFMs through a combination of primary droop control and consensus-based secondary adjustment [45]. GFM-followers participate in active power sharing via consensus but do not contribute to frequency correction. SCs, due to their inability to regulate active power, are excluded from the frequency loop but nonetheless contribute to frequency stability through their inertial response [57].

The consensus-based active power control is defined as follows. For GFM-followers:

$$-k_{p_i} \frac{dP_{ref,i}}{dt} = \sum a_{ij} (m_{p_i} P_{ref,i} - m_{p_j} P_{ref,j}), \quad i \in \mathcal{F}, j \in \mathcal{N}_i \quad (14)$$

For leader GFMs:

$$-k_{p_i} \frac{dP_{ref,i}}{dt} = w_{f_l} (\omega_i - \omega_{nom}) + w_{f_f} \sum a_{ij} (m_{p_i} P_{ref,i} - m_{p_j} P_{ref,j}), \quad i \in \mathcal{L}, j \in \mathcal{M}_i \quad (15)$$

Here, $P_{ref,i}$ is an active power reference, ω_i is the local frequency measurement, m_{p_i} is a droop gain, k_{p_i} is a frequency gain, and $\mathcal{L}$ denotes the set of GFMs. Also, weighting factors w_{f_l} and w_{f_f} govern the dynamics for frequency control. This architecture confines frequency control responsibility to selected leader GFMs, preserving the physical constraints of SCs and simplifying network-wide coordination. If none of the GFMs are designated as followers and all operate in leader mode, Equation (14) becomes redundant. In this case, the control strategy relies solely on Equation (15) to govern GFM behaviour and provide frequency support.

3.2. Voltage Regulation and Reactive Power Sharing

Voltage regulation and reactive power sharing are achieved cooperatively by both GFMs and SCs. All units capable of modulating reactive power—through inverter-based or excitation control—participate in the voltage consensus [48]. Within this structure, leader GFMs restore nominal voltage via droop-based correction, while GFM followers and SCs contribute to var balancing and minimise circulating currents.

For followers (GFM-followers and SCs, or just SCs as followers):

$$-k_{q_i} \frac{dV_{ref,i}}{dt} = \sum a_{ij} (m_{q_i} Q_i - m_{q_j} Q_j), \quad i \in \mathcal{F}, j \in \mathcal{N}_i \quad (16)$$

For leader GFMs:

$$-k_{q_i} \frac{dV_{ref,i}}{dt} = w_{v_f} (V_i - V_{nom}) + w_{v_l} \sum a_{ij} (m_{q_i} Q_i - m_{q_j} Q_j), \quad i \in \mathcal{L}, j \in \mathcal{M}_i \quad (17)$$

where V_i is the terminal voltage, V_{nom} is the nominal setpoint, and Q_i is the reactive power output. The droop gains m_{q_j} , tuning gains k_{q_i} , and weighting factors w_{v_f} and w_{v_l} govern the dynamics in voltage control mode. Importantly, SCs can participate in this consensus loop using their existing AVR structure, without requiring additional communication or structural modifications.

This coordinated scheme enables a seamless combination of fast-response GFM control and the inherent inertia and var capacity of SCs. By distributing control responsibilities based on device capabilities, the system achieves robust voltage regulation without the need for central supervision.

The overall structure of the proposed leader–follower consensus-based control framework, including its interaction with the communication network, is illustrated in Figure 6,

highlighting the distinct roles of GFM-leaders, GFM-followers, and SC-followers in active and reactive power coordination.

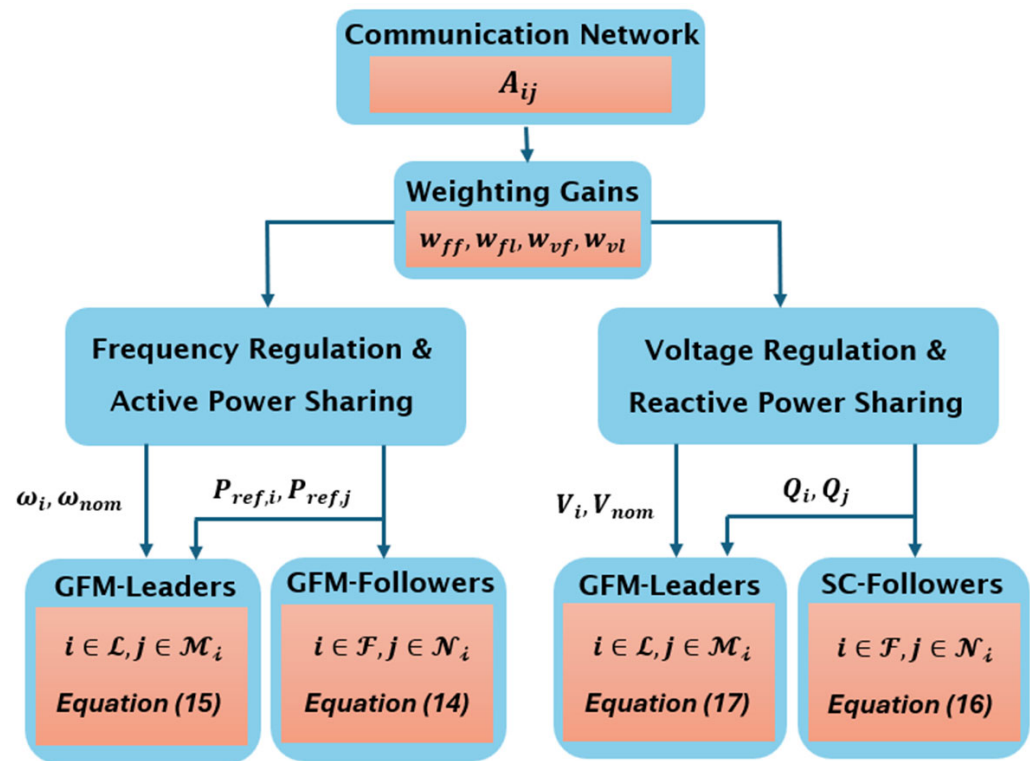


Figure 6. Detailed block diagram of the proposed leader–follower consensus control structure.

3.3. Communication Requirements and Plug-and-Play Capability

The proposed consensus-based control framework is fully decentralised, requiring each device to communicate only with its immediate neighbours. This local-only interaction significantly enhances scalability and resilience, particularly in renewable-dominated, low-inertia grids. For consensus convergence, the communication graph $\mathcal{G} = (\mathcal{P}, \mathcal{E})$ must remain connected, ensuring that information propagates across all devices.

This requirement can be formalised using the Laplacian matrix $\mathcal{L}_C$ derived from the adjacency matrix $\mathcal{A} = [a_{ij}]$. Convergence is guaranteed if $\lambda_i(\mathcal{L}_C) > 0$. The Laplacian is defined as $\mathcal{L}_C = \mathcal{D} - \mathcal{A}$ where $\mathcal{D}$ is the degree matrix with diagonal elements $d_i = \sum_j a_{ij}$. Convergence of the consensus dynamics in Equations (12) and (13) is guaranteed if the second-smallest eigenvalue of $\mathcal{L}_C$, known as the algebraic connectivity $\lambda_i(\mathcal{L}_C)$ is positive. This eigenvalue ensures that information can propagate through the network, even when only local communication is available [58]. Here, λ_i is the second-smallest eigenvalue, known as the algebraic connectivity. A positive λ_i ensures that information can propagate through the network even when only local communication is available.

GFM-leaders can be assigned based on practical criteria such as location, control strength, or communication capability, offering flexibility across diverse grid configurations. Moreover, the structure inherently supports plug-and-play integration: newly added GFMs or SCs can join the network as followers without requiring system-wide updates [59]. As long as a new agent establishes communication with at least one existing node, it automatically participates in the consensus process.

This architecture represents, to the best of the authors' knowledge, the first decentralised consensus strategy to integrate synchronous condensers alongside GFMs for hybrid voltage and frequency control. By preserving the distinct roles of each technology while

maintaining decentralised coordination, the framework offers a scalable and resilient solution for modern grid operation.

In this study, leader GFMs are statically assigned based on known grid topology and communication access; however, future work will explore dynamic leader selection strategies based on real-time system conditions, such as local inertia, grid strength, or communication availability, to further enhance control flexibility and resilience.

3.4. Communication Requirements and Practical Implementation Considerations

The proposed leader–follower consensus control relies on peer-to-peer communication, which can be affected by latency, packet loss, and network attacks [60]. Latency may delay consensus updates, causing slower convergence or oscillations [61]. Packet loss can disrupt information flow and affect power-sharing accuracy, while attacks may compromise signal integrity and stability [62].

To address these, the system could use a fast communication interval suitable for typical power networks, a memory-based update to handle brief data loss, and the future integration of encryption and anomaly detection for security [63]. These features enhance robustness, with further validation planned.

Implementing the proposed leader–follower consensus control in existing networks requires attention to parameter tuning and communication reliability. The decentralised nature of the framework eliminates the need for system-wide reconfiguration, relying solely on local peer-to-peer communication. To support integration in practice, droop and consensus control gains can be tuned using offline optimisation techniques, which reduce manual effort and ensure stable power sharing [45]. The framework is compatible with standard protocols such as IEC 61850, allowing it to utilise existing communication infrastructure [64]. Its plug-and-play design enables incremental deployment, where new units can join by connecting to a single neighbouring device. In the event of communication loss, devices revert to primary droop control, maintaining autonomous operation with reduced coordination. These features support a practical and resilient pathway for adopting the proposed control strategy in low-inertia networks.

4. Simulation Framework and Test Scenarios

This section presents the simulation framework and test scenarios developed to validate the proposed hierarchical consensus control strategy for the hybrid coordination of GFMs and SCs. A modified IEEE 14-bus system is modelled in PSCAD/EMTDC to represent a low-inertia network dominated by inverter-based resources. The simulations aim to assess the dynamic performance of the control scheme in maintaining frequency stability, voltage regulation, and reactive power sharing under a range of operational conditions.

4.1. System Setup

A modified IEEE 14-bus network serves as the testbed for this study, configured to emulate a weak grid by decreasing the size and inertia of synchronous generators and adding GFMs to supply the grid. The system integrates two hybrid nodes, each comprising a GFM operating in parallel with a synchronous condenser, and an additional standalone SC. The general network topology follows the standard IEEE layout, with modifications to accommodate the hybrid configuration. The system architecture and unit placements are depicted in Figure 7.

Specifically, a 30 MW/20 MVar GFM is installed at Bus 3 alongside a 60 MVA SC, while at Bus 8, a 30 MW/30 MVar GFM operates in conjunction with a 55 MVA SC. An additional 60 MVA SC is connected at Bus 6 to provide reactive support and inertia. The GFMs are modelled as voltage source inverters with embedded primary droop control

and secondary consensus-based regulation. Among the two GFMs, the unit at Bus 3 is designated as the leader responsible for frequency and voltage restoration, while the unit at Bus 8 operates as a follower.

All synchronous condensers operate in a pure synchronous condenser mode, supplying dynamic reactive support and rotational inertia. Their excitation systems are controlled using a conventional AVR, enabling integration into the consensus-based reactive power-sharing scheme.

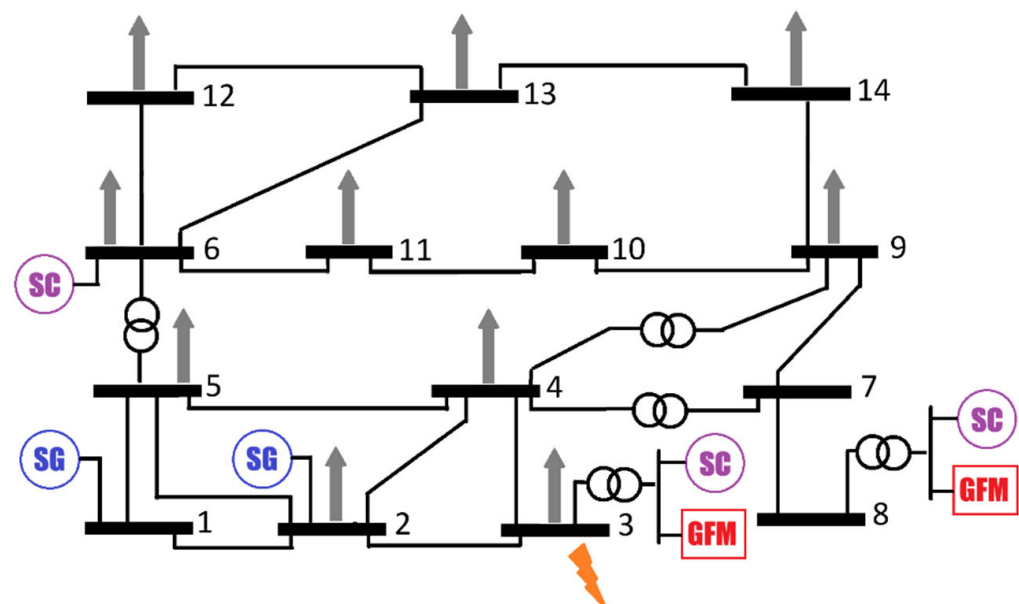


Figure 7. Modified IEEE 14-bus system setup with GFMs and SCs.

The simulation environment is developed in PSCAD/EMTDC with a time step of 50 microseconds to accurately capture fast dynamics. Communication between agents for consensus control is implemented using ideal peer-to-peer signal exchange blocks, with consensus variables updated at a fixed interval of 10 milliseconds to mimic realistic controller response times.

4.2. Control Parameters

The primary droop gains for active and reactive power, m_{p_i} and m_{q_i} , are tuned to achieve proportional power sharing under nominal operating conditions. The secondary consensus control gains, k_{p_i} and k_{q_i} , are selected to ensure sufficient convergence speed while preserving stability margins. GFM-leaders incorporate an additional feedback correction term to restore nominal voltage and frequency, while GFM-followers and SCs contribute to consensus-driven active and reactive power sharing.

Each voltage regulation loop employs a PI controller that adjusts the voltage setpoint based on deviations from nominal conditions. SCs, which lack frequency control capability, participate only in reactive power sharing and voltage support through their excitation systems regulated by AVRs.

Table 1 summarises the key parameters used in simulations, including droop gains, device ratings, and system settings. These values were selected to ensure proportional power sharing, stability, and realistic representation of a low-inertia grid, as detailed in Sections 4.1 and 4.2.

Table 1. Simulation parameters and variables for modified IEEE 14-bus system.

Parameter/Variable	Description	Value/Range	Unit
P_i/Q_i (Bus 3)	Active/Reactive power (GFM)	30/20	MW/MVAr
P_i/Q_i (Bus 8)	Active/Reactive power (GFM)	30/20	MW/MVAr
S_i (Bus 3)	Rated apparent power (SC)	60	MVA
S_i (Bus 6)	Rated apparent power (SC)	60	MVA
S_i (Bus 8)	Rated apparent power (SC)	55	MVA
m_{p_i}	Active power droop gain (GFMs)	0.01–0.05	p.u.
m_{q_i}	Reactive power droop gain (GFMs, SCs)	0.02–0.06	p.u.
H	Inertia constant (SCs–SGs)	3.5–5	s
D	Damping factor (SCs)	0.2	s
T_s	Simulation time step	50	μ s
T_c	Communication interval	10	ms

4.3. Test Scenarios

Three test scenarios are designed to evaluate the effectiveness and robustness of the proposed consensus-based control framework under dynamic conditions.

The first scenario introduces a step change in the active load at Bus 3 where an HSC is connected. At $t = 2.0$ s, an increase of 30 MW in active power demand is applied. This test assesses the capability of the GFM-leaders at Bus 3 to restore system frequency through secondary consensus control, while the active power-sharing behaviour of the GFM-follower at Bus 8 is also monitored. The evolution of system frequency and active power outputs for both GFMs is recorded to verify coordinated response and proportional load sharing.

The second scenario applies to a reactive load disturbance at Bus 3. A step increase of 50 MVAr in reactive power demand is introduced at $t = 2.0$ s. This scenario is used to evaluate the ability of the consensus-based voltage control mechanism to maintain voltage stability and coordinate reactive power sharing between the GFMs and SCs. The performance is assessed in terms of voltage regulation, var-sharing equality, and the suppression of circulating reactive currents.

The third scenario examines the plug-and-play capability of the proposed architecture. At $t = 2.0$ s, the HSC connected at Bus 8 is intentionally disconnected and reconnected at $t = 4.0$ s. The objective is to validate whether the system can autonomously re-establish consensus-driven power and voltage sharing following changes in network composition. Key indicators such as voltage setpoints, power contributions, and frequency stability are analysed to confirm seamless reintegration without requiring global controller reconfiguration.

Together, these scenarios represent typical operational challenges in low-inertia and weak grids, including dynamic load changes, flexible asset integration, and disturbance resilience. Simulation results for each case are presented and discussed in the next section.

The simulation-based evaluation in this study provides a practical and reliable way to assess the dynamic performance of the proposed control scheme. By applying step changes in active and reactive loads, as well as plug-and-play events, the simulations replicate typical disturbances that occur in low-inertia networks. Key system responses—such as frequency stability, voltage regulation, and power sharing—are monitored in real time to evaluate how effectively the control strategy manages these events. Using PSCAD/EMTDC allows for detailed modelling of both inverter-based and synchronous condenser dynamics, with time steps small enough to capture fast transients. While experimental testing will be explored in future work, the current simulation framework offers valuable insights into the behaviour and robustness of the proposed approach under realistic conditions.

5. Results and Discussion

This section presents the simulation results of the proposed hierarchical consensus-based control strategy applied to the modified IEEE 14-bus test system described in Section 4. The test scenarios introduced earlier are evaluated to demonstrate the effectiveness of the hybrid leader–follower coordination framework in achieving system-wide frequency and voltage regulation, as well as fair and dynamic power sharing between GFMs and SCs.

The evaluation is performed across three distinct control configurations: (i) baseline operation without consensus control, in which only primary droop and AVRs are employed; (ii) general decentralised control, relying on droop-based methods without coordination; and (iii) the proposed leader–follower consensus strategy incorporating secondary control dynamics. Comparisons between these cases are used to highlight the impact of the proposed coordination method.

System responses are analysed in terms of both time-domain behaviour and quantitative performance indices. The assessment focuses on four key performance metrics: (1) frequency restoration, (2) active power-sharing accuracy, (3) reactive power coordination, and (4) voltage regulation. For each test scenario, the effectiveness of control is evaluated through the time series plots of system variables and through the sharing quality indices defined below.

To quantitatively assess the accuracy and fairness of power sharing among GFMs and SCs, two performance indices are utilised: optimised sharing of active power (OSAP) and optimised sharing of reactive power (OSRP). These indices measure the deviation from ideal droop-based proportional sharing of active and reactive power, respectively, and are defined as [45]

$$\text{OSAP} = \frac{1}{N_P} \sum_{i \in \mathcal{G}_P} \left(\frac{m_{p_i} P_i}{S_i} - \eta_P \right)^2 \text{ where } \text{PSAP} = \frac{1}{N_P} \sum_{i \in \mathcal{G}_P} \frac{m_{p_i} P_i}{S_i} \quad (18)$$

$$\text{OSRP} = \frac{1}{N_Q} \sum_{i \in \mathcal{G}_Q} \left(\frac{m_{q_i} Q_i}{S_i} - \eta_Q \right)^2 \text{ where } \text{PSRP} = \frac{1}{N_Q} \sum_{i \in \mathcal{G}_Q} \frac{m_{q_i} Q_i}{S_i} \quad (19)$$

In these expressions, P_i and Q_i represent the active and reactive power outputs of unit i , while S_i is the rated apparent power of that unit. The terms m_{p_i} and m_{q_i} denote the active and reactive power droop coefficients, respectively. The set $\mathcal{G}_P$ includes all GFMs responsible for active power control, and N_P is the corresponding number of devices. The set $\mathcal{G}_Q$ includes both GFMs and SCs involved in reactive power sharing, with N_Q representing the total number of participating units.

The average sharing values, PSAP and PSRP , are used as reference baselines for evaluating deviation in power contribution among the units. A lower value of OSAP or OSRP indicates closer adherence to ideal proportional sharing, signifying better load balancing and control coordination across the network.

The results for each test case are presented in the following subsections, where system responses are analysed and compared under the different control strategies. Emphasis is placed on evaluating the responsiveness, accuracy, and robustness of the proposed control architecture in addressing key challenges encountered in low-inertia, inverter-dominated networks.

5.1. Frequency Restoration and Active Power Sharing

To evaluate the effectiveness of the proposed consensus-based secondary control in managing frequency dynamics, a disturbance is applied in the first test scenario by introducing a 30 MW step load at Bus 3, where an HSC is located. The system's frequency

response under three different control configurations—no consensus, general control, and the proposed consensus-based strategy—is presented in Figure 8.

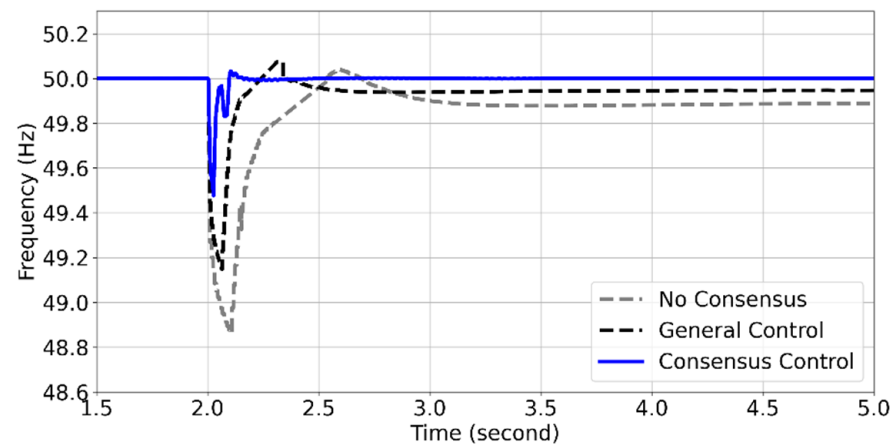


Figure 8. System frequency response following 30 MW load disturbance at Bus 3.

Under the case of no consensus control, the system relies solely on primary droop responses, resulting in significant frequency deviation and sustained oscillations due to the lack of coordination between units. The general control case, which includes droop and AVR regulation but omits secondary coordination, improves the transient behaviour slightly but still exhibits noticeable overshoot and slow damping.

In contrast, the proposed leader–follower consensus control exhibits clear improvements. The GFM-leader, equipped with frequency-tracking secondary control, quickly adjusts its active power output to mitigate the frequency drop. The GFM-follower contributes through proportional droop control, while the SCs inject inertia, assisting in frequency arrest. The combined effect leads to reduced overshoot, improved damping, and rapid restoration to nominal frequency.

These results demonstrate that the consensus-based scheme enhances the system’s dynamic response and stability, enabling decentralised frequency regulation in weak grid conditions with limited synchronous generation.

Figure 9 illustrates the corresponding active power output of the GFM-leader during the same disturbance event. Without secondary consensus control, the leader unit experiences a sharp power surge and prolonged oscillatory behaviour, reflecting the absence of coordinated load redistribution. In the general control case, while droop control contributes to improved response, a steady-state mismatch in power sharing remains evident.

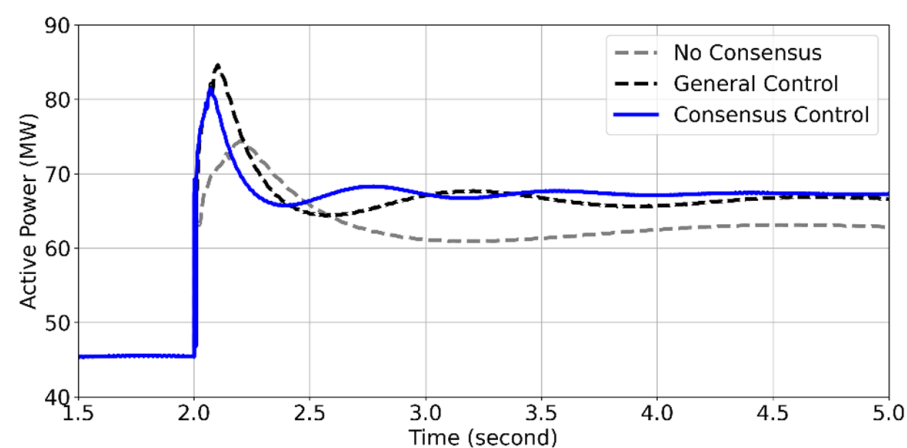


Figure 9. Active power output of the GFM-leader under three control configurations.

The consensus control case significantly improves power delivery. The GFM-leader responds with a smoother and more gradual increase in active power, effectively suppressing oscillations and maintaining proportionality with the system demand. Real-time exchange of power information between GFM-leaders and GFM-followers ensures dynamic balance, while SCs offer inertia without participating in active power control.

These observations confirm that the proposed consensus mechanism enhances both the responsiveness and accuracy of active power sharing. It prevents local overloading, mitigates frequency excursions, and supports system resilience during transient events.

Overall, the results validate that the hierarchical leader–follower control strategy enables robust frequency recovery and balanced active power distribution, even in low-inertia environments with high penetration of inverter-based resources.

5.2. Reactive Power Sharing and Voltage Support

The second test scenario evaluates the performance of the proposed consensus-based voltage control strategy during a reactive disturbance. A 50 MVar reactive load is introduced at Bus 3 at $t = 2.0$ s, and the resulting reactive power and voltage responses are analysed under three control configurations: no consensus control, general droop-based control, and the proposed leader–follower consensus coordination.

Figure 10a shows the reactive power output of the GFM-leader located at Bus 3. In all cases, the unit responds quickly to support the voltage drop. Under no consensus control, the leader is forced to absorb the full reactive load imbalance, resulting in a disproportionate var contribution. While the general control case includes voltage regulation, it lacks coordination among devices, causing limited improvement in sharing and persistent imbalance.

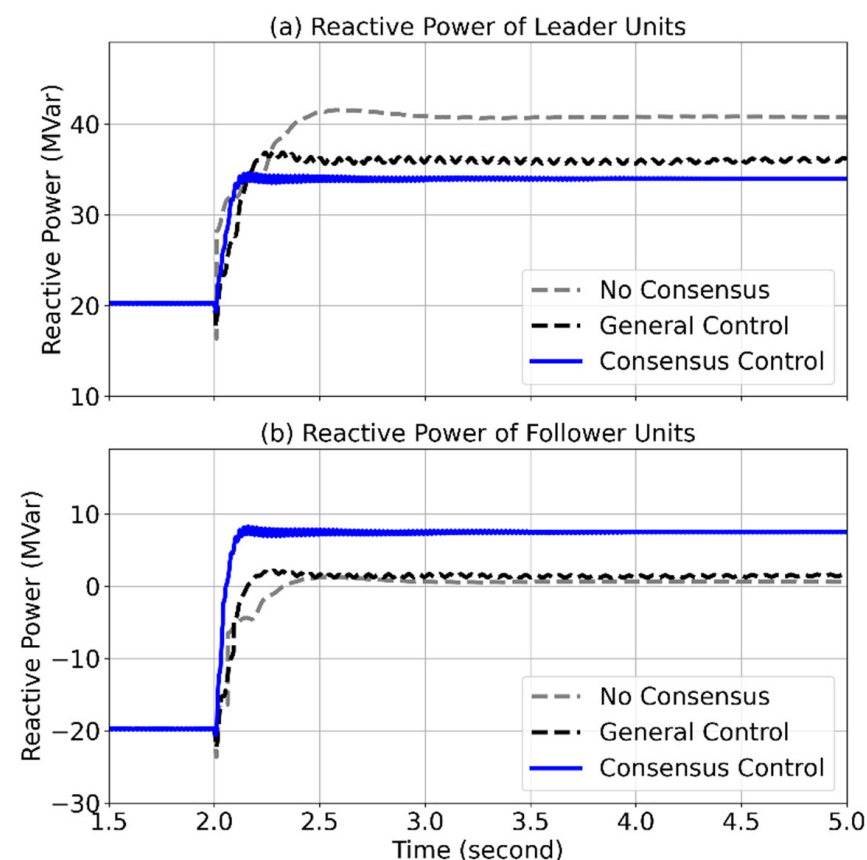


Figure 10. Reactive power output of leader (a) and follower (b) units during a disturbance at Bus 3.

In contrast, under consensus-based control, the leader GFM not only adjusts its voltage reference but also coordinates with other units in real time. This results in more balanced var sharing and reduces stress on the leader. Figure 10b illustrates the response of follower units, including the SCs and the GFM-follower at Bus 8. Without consensus, these units provide minimal support and exhibit noticeable oscillations. General control offers marginal damp improvements but still fails to engage the followers effectively.

With consensus coordination, the follower units dynamically adjust their reactive output in response to the system's need, contributing significantly to voltage support. The sharing is smoother, the overall var burden is distributed more fairly, and circulating reactive currents are suppressed. These results confirm that the proposed scheme enables decentralised var sharing across heterogeneous assets.

To further evaluate voltage regulation under the same reactive disturbance, Figure 11 presents the voltage profiles at critical buses—Buses 3, 6, and 8—where GFMs and SCs are installed. In the no consensus case, voltage recovery is slow and insufficient, with values stabilising well below nominal at approximately 0.95 p.u. Although general control improves damping via local AVR action, full voltage restoration is not achieved.

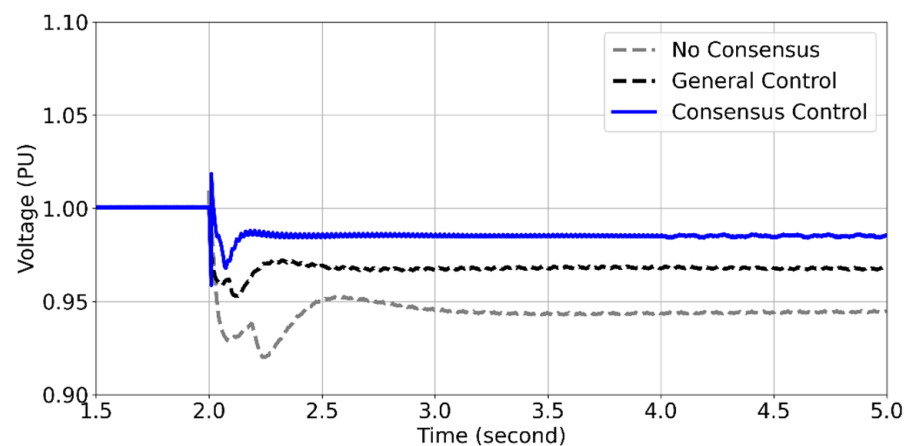


Figure 11. Terminal voltage response at Bus 3 under reactive load disturbance.

The proposed consensus approach significantly enhances voltage stability. Coordinated voltage setpoint updates enable the units to act collaboratively, restoring voltages at all key buses to nearly 1.0 p.u. within a short time. Oscillations are effectively damped, and the system remains stable throughout the response.

These observations clearly demonstrate that the consensus-based control strategy provides more reliable voltage support in low-inertia grids. By leveraging coordinated behaviour among GFMs and SCs, the controller improves both voltage quality and reactive power distribution.

In summary, the results illustrate the capability of the proposed leader–follower consensus control to orchestrate collaborative reactive power support and voltage recovery across hybrid assets. This contributes to improved dynamic stability and operational reliability in weak and inverter-dominated networks.

To further evaluate the proposed leader–follower consensus control, we compare its performance against other modern decentralized approaches, independent general droop control [65] and VSG control (as no consensus control) [66]. These methods were implemented in the same modified IEEE 14-bus system under the test scenarios. Table 2 presents a quantitative comparison of key performance metrics—frequency nadir and voltage deviation—for the proposed consensus control, general droop control, and no consensus control under two scenarios of active and reactive load disturbance.

Table 2. Quantitative comparison of decentralized control strategies.

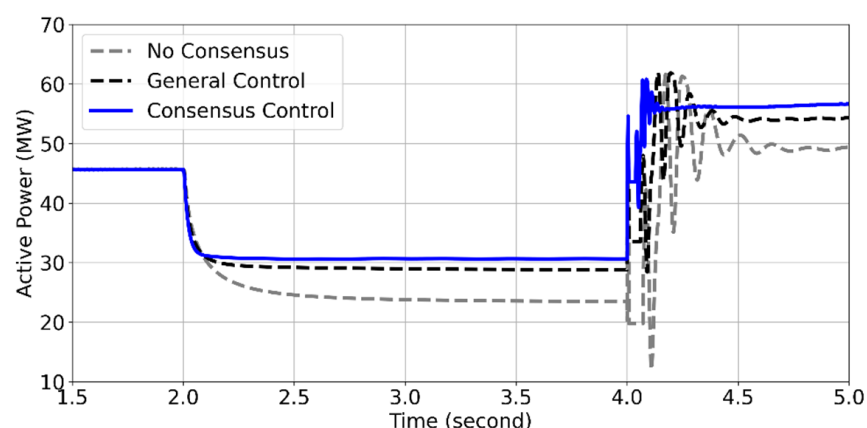
Control Strategy	Freq. Nadir (Hz) In Scenario 1	Voltage Deviation (p.u) In Scenario 2
Proposed Consensus Control	49.50	0.021
General Droop Control	49.20	0.035
Separate Control (No Consensus)	48.85	0.055

The results demonstrate that the proposed consensus control achieves a better frequency nadir and lower voltage deviation compared to the other methods. These improvements stem from the role-based coordination of GFM and SCs, which leverages the strengths of both device types, unlike the uniform control logic in distributed averaging or the inertia-emulation focus of VSG control.

5.3. Plug-and-Play Operation of Leader–Follower Hybrid Unit

To evaluate the plug-and-play capability of the proposed consensus-based control framework, an HSC—comprising a GFM and an SC—located at Bus 8 is disconnected from the system at $t = 2.0$ s and reconnected at $t = 4.0$ s. This test assesses the dynamic flexibility and resilience of the coordination scheme during sudden changes in network configuration. System behaviour is analysed in terms of active power, voltage, frequency, and reactive power, under three different control modes: no consensus control, general control, and the proposed leader–follower consensus strategy.

Figure 12 shows the active power response of the GFM-leader during the plug-and-play event. Upon disconnection of the HSC, the leader inverter increases its output to compensate for the loss of support. Without consensus, this leads to a sharp power surge and noticeable oscillations, while the general control case exhibits slower convergence and residual mismatch. Under consensus control, the leader unit responds smoothly, maintaining balanced power sharing with minimal transient deviation. Upon reconnection of the HSC at $t = 4.0$ s, the hybrid unit is seamlessly re-integrated into the control loop, restoring its active power contribution without disturbing system stability.

**Figure 12.** Active power output of the GFM-leader during HSC disconnection and reconnection.

The frequency response of the system is shown in Figure 13. The disconnection of the HSC introduces a frequency dip that is most pronounced in the no consensus case, where oscillations persist due to a lack of coordination. General control reduces deviation but cannot suppress all transient behaviour. The consensus-based scheme, however, enables GFMs to collaboratively adjust their frequency setpoints through secondary control. This leads to faster damping and more accurate frequency restoration both during the disconnec-

tion and upon the return of the HSC, illustrating the robustness of the distributed leader–follower architecture.

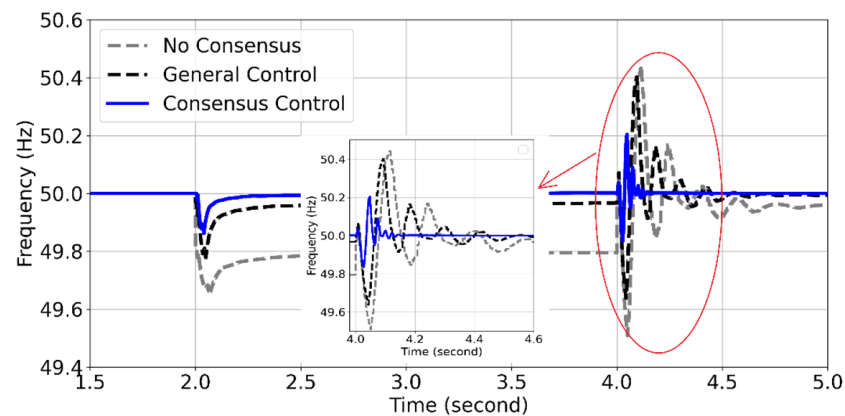


Figure 13. System frequency response under plug-and-play disturbance.

Figure 14 illustrates the reactive power redistribution among the GFM and SCs during the plug-and-play event. Without consensus, the sudden loss of reactive support from the HSC leads to a disproportionate burden on the GFM-leader, with poor sharing and heightened oscillations. General control shows minor improvements but still lacks the coordination needed for a balanced response. With consensus enabled, reactive power demands are shared more equitably among all active units. The reconnected HSC re-enters the var-sharing loop with no visible disruption, contributing immediately to voltage support and reducing circulating vars.

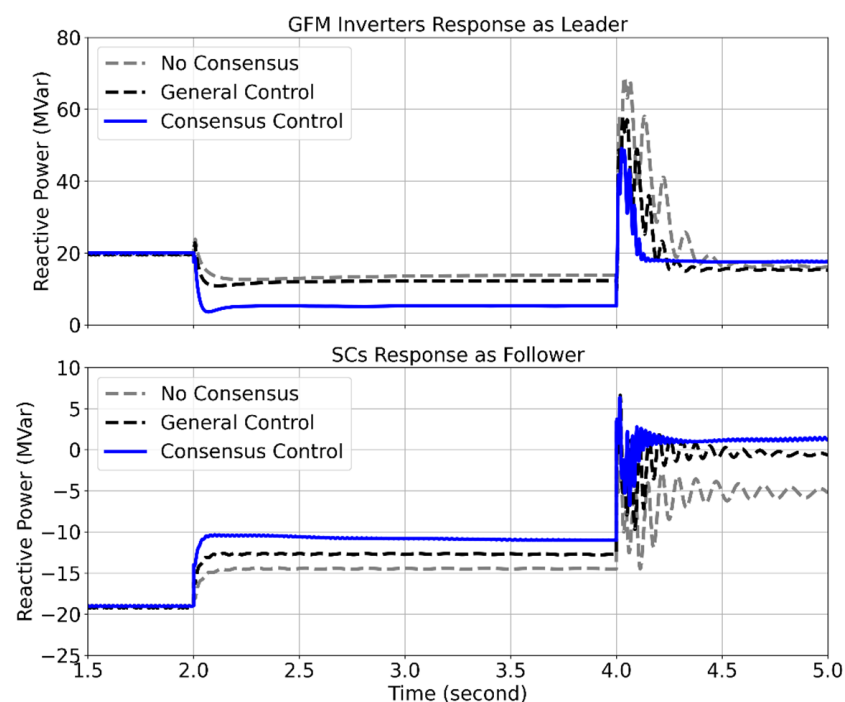


Figure 14. Reactive power output of GFM and SC during the HSC plug-and-play test.

The voltage profile at Bus 3 is shown in Figure 15, representing one of the critical nodes impacted by the reactive disturbance. Following the disconnection of the HSC, the voltage experiences a sharp drop. In the no consensus and general control cases, the voltage remains below nominal for an extended period. The consensus-based strategy provides superior regulation: voltages recover swiftly and remain stable following both disconnection and

reconnection events. This performance is attributed to real-time coordination among GFMs and SCs through voltage setpoint consensus, enhancing system voltage resilience in the presence of structural changes.

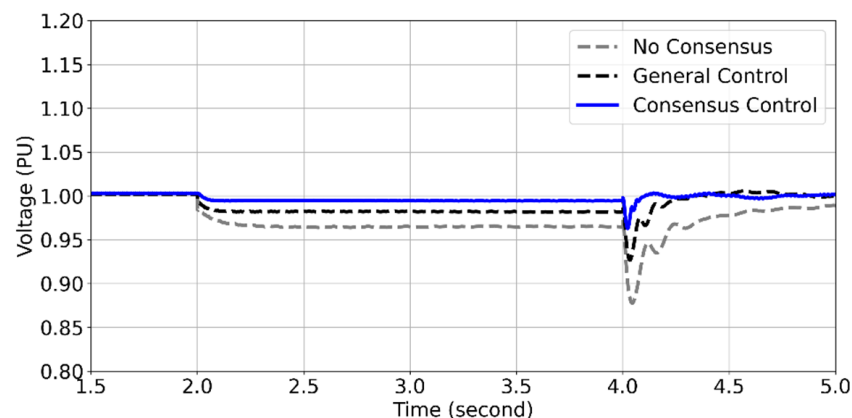


Figure 15. Voltage response at Bus 3 during disconnection and reconnection of HSC at Bus 8.

The simulation results validate the effectiveness of the proposed hierarchical consensus-based control architecture by demonstrating its capability to address three critical operational challenges in low-inertia grids: fast frequency and voltage restoration, fair power sharing, and resilient plug-and-play integration. Using a modified IEEE 14-bus system in PSCAD/EMTDC, dynamic responses were tested under active load disturbances (30 MW), reactive load variations (50 MVar), and plug-and-play events. The results indicate that the proposed leader–follower strategy achieves a frequency nadir of 49.50 Hz—compared to 48.85 Hz without consensus—and reduces voltage deviation by 1% (0.021 p.u. vs. 0.055 p.u.). The plug-and-play scenario further confirms the robustness of the architecture, maintaining system stability during hybrid unit disconnection and reintegration without requiring global control adjustments. These performance improvements highlight the effectiveness of the role-based leader–follower design, which utilises the rapid control capabilities of GFMs and the inherent inertia of SCs to enhance dynamic stability, scalability, and grid resilience.

6. Conclusions and Future Work

This paper has proposed a hierarchical consensus-based control strategy for the coordinated operation of GFMs and SCs in low-inertia power systems with high renewable energy penetration. The framework extends the leader–follower consensus architecture to hybrid configurations, where selected GFMs serve as leaders responsible for global frequency and voltage regulation, while GFM-followers and SCs contribute to proportional power and reactive power sharing.

The proposed control scheme was implemented and tested on a modified IEEE 14-bus system using PSCAD/EMTDC. Simulation results validated the effectiveness of the architecture in addressing key operational challenges. Specifically, the proposed strategy demonstrated rapid frequency recovery, achieving a frequency nadir of 49.50 Hz, compared to 49.20 Hz with general droop control and 48.85 Hz without coordination. It also improved voltage restoration following large disturbances, reducing the voltage deviation from 0.055 p.u. in the uncoordinated case to 0.021 p.u. under the coordinated approach. In addition to these improvements, the method ensured fair distribution of active and reactive power among diverse assets and showed strong plug-and-play capability, maintaining stable operation during the connection and disconnection of hybrid units without requiring global control adjustments. Compared to conventional droop-based and non-coordinated

approaches, the consensus-based method achieved superior transient performance, enhanced damping, and reduced circulating vars, without relying on centralised coordination.

A notable contribution to this work is the seamless integration of synchronous condensers as reactive power and inertia-supporting agents within a network dominated by distributed inverters. The decentralised control design relies solely on local communication among neighbouring units, making it scalable, resilient to topology changes, and suitable for emerging distribution-level grid applications.

Future research will focus on experimental validation using real-time digital simulation (RTDS) or hardware-in-the-loop (HIL) testbeds. Furthermore, the impact of practical constraints, such as communication delays, cybersecurity vulnerabilities, and inverter saturation limits, will be investigated. The proposed architecture is also planned to be extended to include grid-following inverter clusters, battery energy storage systems, and demand-side flexibility, thereby enabling broader applicability in next-generation distributed energy systems.

Author Contributions: Conceptualisation, H.S. and A.A.; methodology, H.S.; software, H.S.; validation, H.S.; formal analysis, H.S., A.A. and S.M.M.U.; investigation, H.S.; resources, A.A. and S.M.M.U.; data curation, H.S.; writing—original draft preparation, H.S.; writing—review and editing, H.S., A.A., S.M.M.U., D.H. and M.G.; visualisation, H.S.; supervision, A.A., S.M.M.U. and D.H.; project administration, A.A. and S.M.M.U.; funding acquisition, S.M.M.U. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Australian Research in Power Systems Transition (AR-PST) program, funded by CSIRO.

Data Availability Statement: No new data were created or analysed in this study.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AVR	Automatic Voltage Regulator
BESS	Battery Energy Storage System
DER	Distributed Energy Resource
GFL	Grid-Following
GFM	Grid-Forming
HIL	Hardware-in-the-Loop
HSC	Hybrid Synchronous Condenser
IBR	Inverter-Based Resource
LFC	Leader-Follower Consensus
OSAP	Optimised Sharing of Active Power
OSRP	Optimised Sharing of Reactive Power
PI	Proportional-Integral
PSAP	Proportional Sharing of Active Power
PSRP	Proportional Sharing of Reactive Power
PU	Per Unit
PWM	Pulse-Width Modulation
RES	Renewable Energy Source
RTDS	Real-Time Digital Simulation
SC	Synchronous Condenser
SG	Synchronous Generator
SSO	Subsynchronous Oscillation
VOC	Virtual Oscillator Control
VSG	Virtual Synchronous Generator

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