

Article

Hybrid SC-BESS-STATCOM for Improved Fault Ride-Through and Load Disturbance Performance in Power Systems

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Abstract

This study investigates the coordinated impact of a synchronous condenser (SC), battery energy storage system (BESS), and static synchronous compensator (STATCOM) on enhancing voltage and frequency stability in a modified IEEE 9-bus power system under severe disturbances. The aim is to quantify the individual and combined contributions of these technologies during both fault ride-through (FRT) and load-increment events. The methodology includes dynamic modelling of all three devices in DIgSILENT PowerFactory. The SC is represented as a synchronous machine with inertia and AVR-based voltage control; the BESS employs converter-based active power and frequency-droop control; and the STATCOM provides fast reactive power injection through a dual-loop voltage regulator. Key indicators include nadir (minimum frequency), Rate of Change of Frequency (RoCoF), steady-state deviation, voltage sag depth, and recovery characteristics. Results indicate distinct roles for each device. The SC increases inertia and improves damping, but it also introduces small, well-damped oscillations. The BESS significantly enhances frequency stability by mitigating nadir, reducing RoCoF, and accelerating recovery, with negligible effect on voltage regulation. The STATCOM substantially reduces voltage sag and speeds up voltage recovery, but it does not influence frequency behaviour. When combined, the hybrid SC–BESS–STATCOM system demonstrates strong complementarity: the SC supports inertia, the BESS stabilizes active-power imbalance, and the STATCOM ensures fast reactive-power compensation.

Keywords: SC; BESS; STATCOM; frequency stability; voltage stability; DIgSILENT PowerFactory



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1. Introduction

The IEEE 9-bus test system utilized in this study is a modified adaptation of the standard IEEE 9-bus benchmark network. The system comprises three generating units (G1, G2, and G3), six transmission lines, three power transformers, and three loads. The modified 9-bus test system is shown in Figure 1. This test system provides an effective framework for examining the coordinated operation of various dynamic devices, such as synchronous condensers (SC), battery energy storage systems (BESS), and STATCOMs, under both fault and load-disturbance conditions.

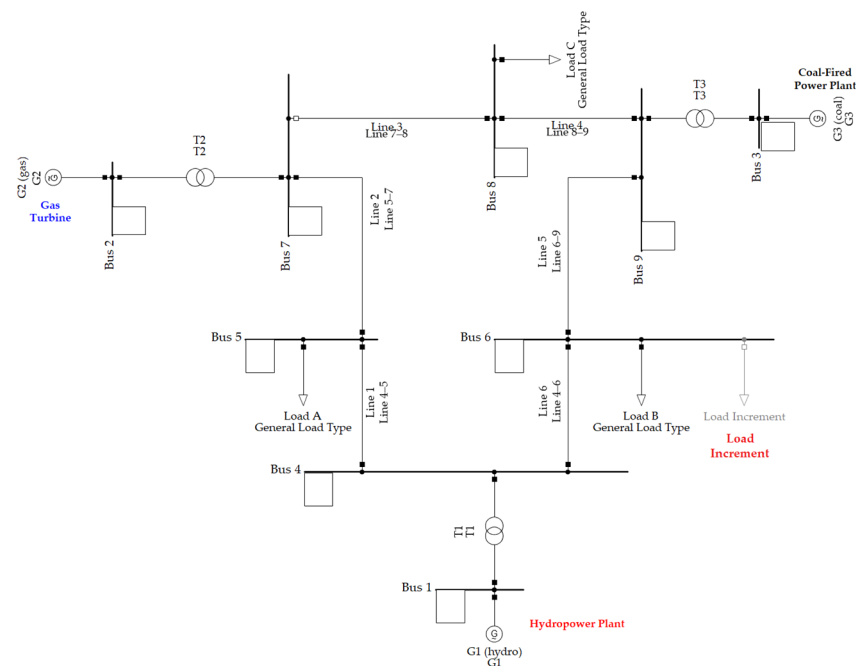


Figure 1. Modified 9-bus test system.

The overall structure of the control system for the synchronous generators is as shown in Figure 2, which is the control frame of all synchronous machines [1–4]. Each generator represents a distinct type of power plant, modelled according to realistic dynamic characteristics and control configurations, and is explained in the following subsections:

1. G1: Hydropower Plant unit models a synchronous generator driven by a hydraulic turbine.
2. G2: Gas Turbine Power Plant represents a medium-size gas turbine operating in simple-cycle mode.
3. G3: Coal-Fired Thermal Power Plant simulates a conventional steam-turbine generator.

The functions of each block in the closed-loop control system shown in Figure 2 are as follows:

1. Power System Stabiliser (pss slot): Improves small-signal stability by adjusting excitation to damp speed oscillations;
2. AVR/Excitation System (avr slot): Provides the excitation field voltage to the synchronous machine, based on the terminal and reference voltages, excitation limiter signals and stabilising signal from the Power System Stabiliser;
3. Governor Control (gov slot): Regulates the mechanical torque of the synchronous machine, based on the rotor speed and reference power input signals;
4. Synchronous Machine (sym slot): Core synchronous machine model integrating the AVR, Governor and Power System Stabiliser slot and providing feedback loops in the control system.

This 9-bus network serves as a compact yet comprehensive benchmark for studying the interaction between active and reactive power control, frequency dynamics, and voltage stability. Its moderate size allows for detailed modelling of control interactions while ensuring computational tractability within the DIgSILENT PowerFactory simulation environment.

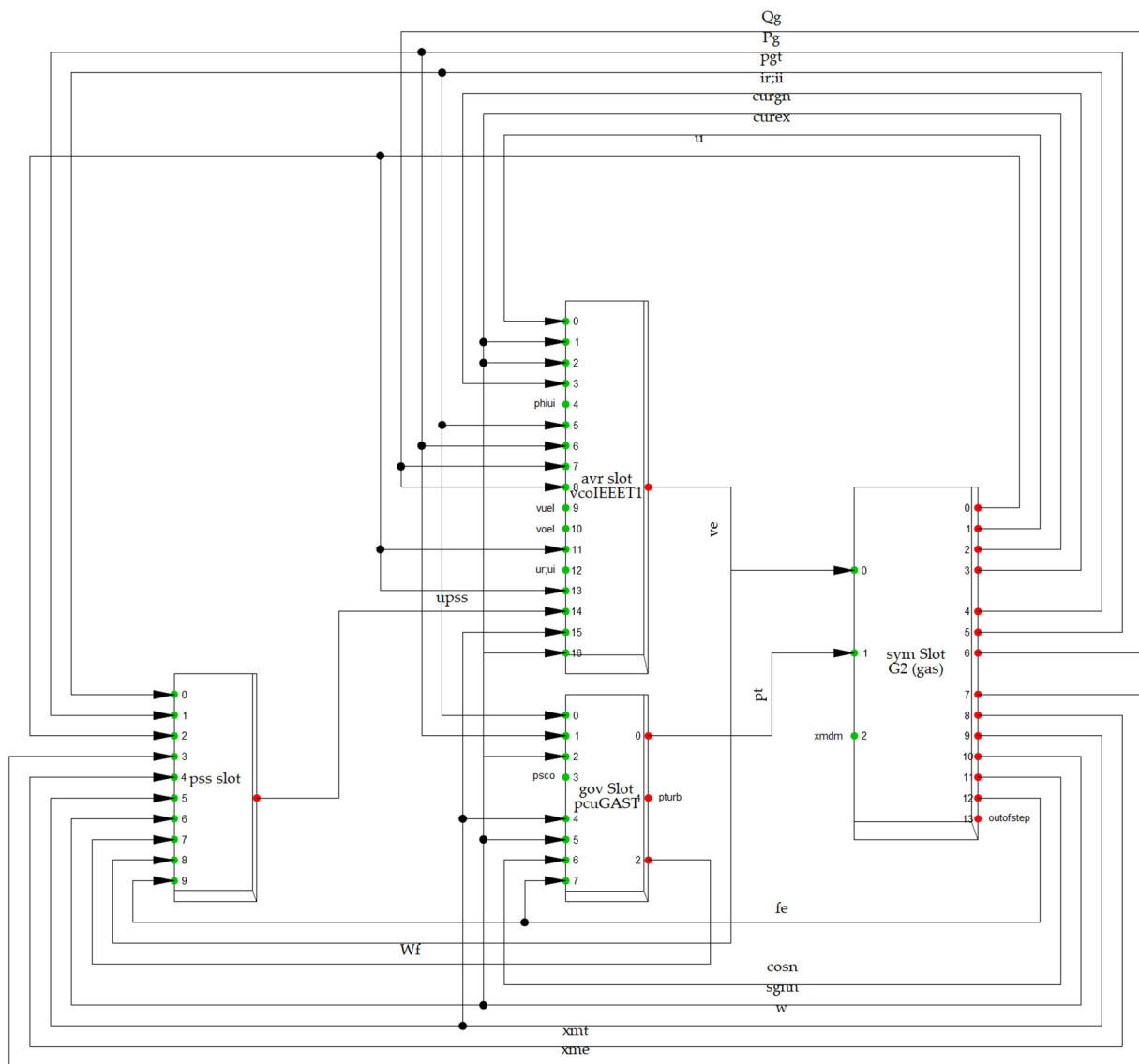


Figure 2. Control system of synchronous machines.

2. Literature Review

Unlike conventional synchronous generators, electronic power generation units typically lack inherent rotational inertia and reactive power reserve, exposing grids to increased vulnerability in terms of frequency deviations, voltage sags, and degraded transient stability. To address these challenges, the power systems community has explored a range of compensating technologies, individually and in various hybrid configurations.

Synchronous condensers (SC) have re-emerged as a critical solution for restoring synthetic inertia and dynamic reactive power support in low-inertia grids. Wu et al. [2] provided a broad overview of SC applications in power systems, highlighting their capacity to reduce the Rate of Change of Frequency (RoCoF) and improve voltage profiles at the point of common coupling (PCC). Nair et al. [5] proposed a parametrically optimised SC coordinated control framework for bulk grid stability in renewable-heavy networks, demonstrating that well-tuned AVR-based excitation can significantly enhance post-fault voltage recovery. While SCs offer strong inertial support, their reactive power response alone is insufficient to address fast transient frequency events, particularly in the sub-second timeframe.

Battery energy storage systems (BESS) are widely recognised for their ability to provide fast, converter-based active power injection, making them highly effective in primary

frequency control. Ahmed et al. [6] conducted a comparative study of BESS and STATCOM effects on post-fault voltage recovery in microgrids, noting that BESS primarily stabilises active power balance while contributing minimally to reactive voltage support. Morovati et al. [4] developed a transient stability analysis framework for microgrids incorporating BESS alongside SCs, observing that the combination of stored energy response and inertial support yields superior frequency damping compared to either device operating alone. Varma et al. [3] explored novel control of BESS configured as a STATCOM (BESS-STATCOM), achieving both reactive compensation and active power regulation in a unified platform—though with increased control complexity.

STATCOMs are voltage-source converter-based devices capable of ultra-fast reactive power injection, making them particularly effective in mitigating voltage sags during fault events. Velukutty et al. [7] demonstrated that STATCOM integration in grid-connected photovoltaic systems significantly enhances power quality and voltage stability, especially during sudden generation–load imbalances. Banda et al. [8] developed a reactive power boosting strategy for BESS-STATCOMs, extending the reactive power capability envelope during grid disturbances. These studies confirm that while STATCOMs excel in the voltage domain, they have negligible direct impact on frequency dynamics due to their inherent active–reactive power decoupling.

Hybrid configurations combining two or more of these technologies have been studied with growing interest. Chen et al. [1] provided a foundational overview of hybrid systems consisting of synchronous condensers and BESS for grid support, identifying strong complementarity between inertial and converter-based responses. However, their work was primarily conceptual and did not extend to three-device coordinated operation under simultaneous voltage and frequency disturbances. Similarly, most prior studies evaluate devices either in isolation or in two-device pairings, leaving a gap in the systematic, quantitative assessment of a three-device hybrid under both fault and load disturbance conditions on a well-established benchmark network.

Recent research has increasingly focused on the challenges associated with low-inertia power systems and the growing penetration of inverter-based resources. Foundational works have highlighted that the reduction in synchronous generation leads to higher RoCoF, frequency instability, and reduced damping capability, necessitating new control strategies and support technologies [9–11]. In this context, concepts such as virtual synchronous machines (VSM) and grid-forming control strategies have been extensively explored to emulate synchronous machine behaviour and provide synthetic inertia [10–12]. Moreover, the interaction between inverter-based generation and conventional synchronous machines has been shown to introduce complex electromechanical dynamics, particularly under transient conditions [13]. To address these challenges, hybrid solutions combining synchronous condensers and battery energy storage systems have been proposed, demonstrating enhanced frequency support and improved system resilience in weak grids [14]. From a theoretical perspective, classical stability frameworks and swing equation-based analyses remain essential for understanding system dynamics and voltage stability phenomena [15]. More recent studies have further emphasized the importance of coordinated control strategies in low-inertia systems, particularly for maintaining frequency security under high renewable penetration [16,17]. In addition, advanced control techniques for voltage regulation, including droop-based and intelligent control approaches, have been investigated to improve fault ride-through capability and voltage stability in modern grids [18]. The role of synchronous condensers in providing both voltage and frequency support in distributed and microgrid environments has also been reinforced in recent literature [19]. Furthermore, operational planning approaches considering frequency stability constraints, such as RoCoF and nadir limits, have been introduced to enhance system security in future power systems [20].

3. Modelling of Dynamic Devices and Control Systems in DIgSILENT PowerFactory

In this study, the IEEE 9-bus benchmark was modified and implemented in DIgSILENT PowerFactory. The original network topology, loads, transformers and six transmission lines were retained, while selected system, generator and dynamic device modifications were introduced. The full set of parameters used in the DIgSILENT PowerFactory model is provided in Appendix A. The modifications introduced are summarised as follows:

1. System frequency: Changed from 60 Hz benchmark to 50 Hz.
2. Generator dynamic models: The three synchronous generators were assigned plant-specific models (Table A4);
3. Synchronous Condenser: An 80 MVA condenser was added at Bus 6 (Table A5);
4. BESS: A 40 MW system was added at Bus 9 (Table A5);
5. STATCOM: A 50 MVA compensator was added at Bus 6 (Table A5).
6. Disturbance events: A three-phase fault and step load-increment event were implemented as separate RMS simulation scenarios (Table A8).

Each device had a distinct control objective and dynamic model, implemented within the DIgSILENT PowerFactory environment.

Figure 3 below illustrates the IEEE 9-Bus test system after the integration of the synchronous condenser (SC), battery energy storage system (BESS), and STATCOM, highlighting their respective locations within the network.

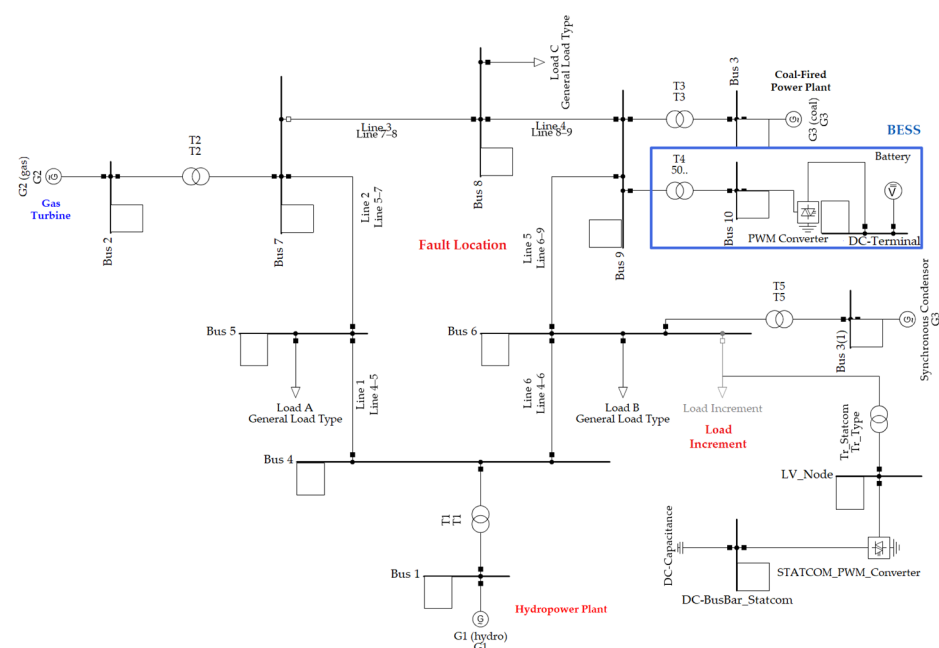


Figure 3. Modified 9-bus test system with SC, BESS, and STATCOM.

The following subsections describe the operational principles, control system structures, and implementation procedures for each component, along with their placement in the network and control schematics.

3.1. Synchronous Condenser (SC)

A synchronous condenser is essentially a synchronous machine operating without a mechanical load. It provides dynamic reactive power compensation and contributes rotational inertia to the grid. By injecting or absorbing reactive power, it regulates the system voltage, while its rotating mass increases the inertia constant (H) of the network,

thereby reducing the Rate of Change of Frequency (RoCoF) and improving transient frequency response after disturbances [7]. The synchronous condenser (SC) has a rated capacity of 80 MVA, providing inertia and reactive power support to the system.

The dynamic model of the SC is analogous to that of a synchronous generator but with zero mechanical torque input. The main subsystems include

- The standard synchronous machine model;
- An Automatic Voltage Regulator (AVR), based on the IEEE Type AC1A, which controls the terminal voltage;
- No governor subsystem, as there is no mechanical prime mover.

The AVR parameters (gain K_A , time constants T_A , etc.) are tuned to maintain voltage stability while avoiding oscillatory modes. In this research, an equivalent inertia constant of $H \approx 4$ s was assigned to emulate the contribution of a medium-size synchronous condenser. Within PowerFactory, the synchronous condenser is connected to Bus 6, indicated by the label SC.

3.2. Battery Energy Storage System (BESS)

The battery energy storage system provides rapid active-power support, enabling primary frequency control within sub-second time frames. During a frequency drop, the BESS injects active power to mitigate the frequency nadir and reduce RoCoF. Conversely, it absorbs power during frequency rises, maintaining balance between generation and demand. Figure 4 presents the internal control framework of the battery energy storage system (BESS) implemented in DIgSILENT PowerFactory. The BESS is rated at 40 MW and is equipped with a converter capable of short-term overload operation up to 200–250% for 2 s to provide fast transient support.

It should be noted that the energy capacity (MWh) of the BESS is not a governing parameter in this study, as all simulations are conducted over a maximum duration of 40 s. During this window, the active power dispatch of the 40 MW BESS remains well within any practical energy capacity for a unit of this rating. The BESS is therefore assumed to maintain a sufficient state-of-charge throughout all simulation scenarios, and energy depletion constraints are not modelled. The scope of this study is limited to short-term frequency and voltage stability, where the dynamic power response (MW) and control bandwidth are the determining factors. Energy capacity sizing and state-of-charge management are considered outside the scope of this work and are left for future study.

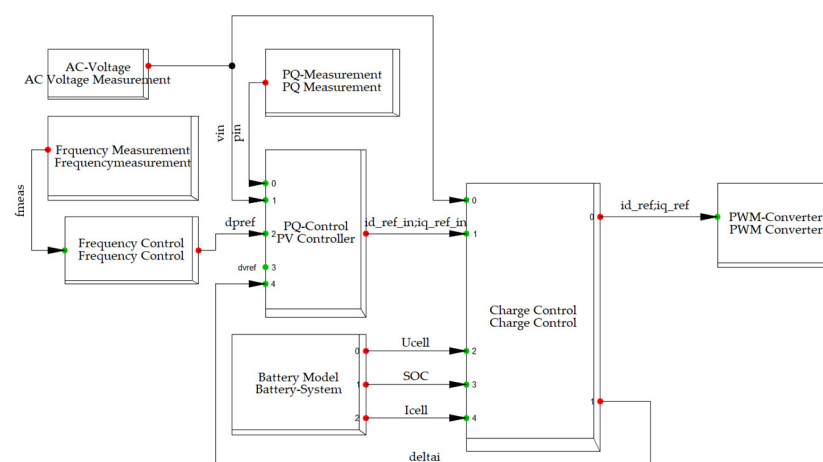


Figure 4. Block diagram of the BESS control system implemented in DIgSILENT PowerFactory.

The structure reflects a modular hierarchy where each block performs a specific control or measurement function to ensure coordinated regulation of active power, reactive power,

and state of charge (SOC) during both steady-state and transient conditions. The framework consists of the following components:

1. **AC-Voltage Measurement:** This unit continuously monitors the three-phase AC voltage at the connection bus. The measured voltage magnitude V_{in} is used as an input for both the PQ controller and the charge-control block;
2. **PQ Measurement:** This block computes the instantaneous active (P) and reactive (Q) power injected by the converter. These signals are essential feedback variables for closed-loop control;
3. **Frequency Measurement:** This component extracts the instantaneous system frequency (f_{meas}) from the grid voltage waveform using a phase-locked loop, implemented as a standard DIgSILENT PowerFactory ElmPhi_Pll element connected at the BESS terminal bus, with default PLL parameters retained. The output f_{meas} is passed exclusively to the control loop to generate the active-power reference (dP_{ref}). It is important to note that the frequency waveforms presented in the simulation results are measured using the internal bus frequency variable (m:fehz) at Bus 6, computed directly by the PowerFactory RMS solver from the rate of change of the voltage angle at each integration time step. This solver-internal variable carries no PLL filtering lag and is independent of the BESS controller's PLL, ensuring that the reported RoCoF and frequency nadir values are not affected by PLL bandwidth.
4. **Frequency Control:** The frequency signal is processed by a droop-based control algorithm that determines the active-power reference (dP_{ref}) according to the deviation from nominal frequency:

$$P_{ref} = P_0 - K_f(f_{meas} - f_{nom}) \quad (1)$$

Here, K_f is the frequency-droop gain, tuning the BESS response intensity to frequency changes. This loop enables the BESS to inject or absorb power proportionally to system frequency deviations.

5. **The PQ-Control or P-V Controller:** This block serves as the central control unit of the BESS. It receives several input signals:
 - V_{in} : measured grid voltage;
 - P_{in} : measured active power;
 - dP_{ref} : active-power reference from the frequency control loop;
 - Q_{ref} : optional reactive-power reference (set-point or droop-based).

The block generates current references (i_d^{ref}, i_q^{ref}) for the converter according to standard dq-frame control laws:

$$i_d^{ref} \propto P_{ref}, \quad i_q^{ref} \propto Q_{ref} \quad (2)$$

ensuring decoupled regulation of active and reactive power.

6. **Battery Model (Battery-System):** This block models the electrochemical and electrical dynamics of the battery system. It includes
 - U_{cell} : cell voltage (DC-link voltage);
 - SOC: state of charge;
 - I_{cell} : battery current;
 - Δi : incremental current change fed to the charge-control subsystem.

The model tracks energy balance, SOC variation, and terminal voltage behaviour during charge/discharge cycles.

7. **Charge Control:** The charge control subsystem ensures stable DC-link voltage regulation and manages battery charging and discharging. Inputs include $i_d^{ref}, i_q^{ref}, U_{cell}$,

SOC, and I_{cell} . It calculates the adjusted current reference vector $(i_d^{\text{ref}}, i_q^{\text{ref}})$ sent to the PWM converter. This control also enforces SOC limits and prevents overcharging or deep discharging.

8. The PWM-Converter: This converter implements the switching mechanism to control real and reactive power exchange with the grid. It receives the current references $(i_d^{\text{ref}}, i_q^{\text{ref}})$ and generates the corresponding gate signals for the voltage-source converter (VSC).

3.3. Static Synchronous Compensator (STATCOM)

STATCOM is a voltage-source converter that provides fast reactive-power support to stabilize the voltage profile. It responds rapidly to voltage sags caused by faults or load increments by injecting reactive current, restoring the bus voltage to its nominal value. While its effect on frequency is minimal due to P-Q decoupling, it plays a major role in voltage stability and transient recovery. The STATCOM employs a dual-loop control structure:

- Inner current control loop (in d-q reference frame) to regulate converter currents;
- Outer voltage control loop to maintain the bus voltage near its reference using a proportional-integral (PI) or droop-based controller.

The voltage-droop control law can be expressed as

$$Q_{\text{ref}} = Q_0 - K_v (V - V_{\text{ref}}) \quad (3)$$

where K_v is the voltage-droop gain. A 5% voltage droop was selected in this project to ensure stable dynamic response and adequate reactive-power sharing. The STATCOM is also connected to Bus 6, identified as the critical voltage bus in the network [5,8]. This connection is shown in Figure 5. The STATCOM is modelled with a 50 MVA continuous rating, and the RMS dynamic controller is implemented with a current reference limiter of $i_{\text{min}} = -2.67$ p.u. and $i_{\text{max}} = 2.67$ p.u. (see Table A5).

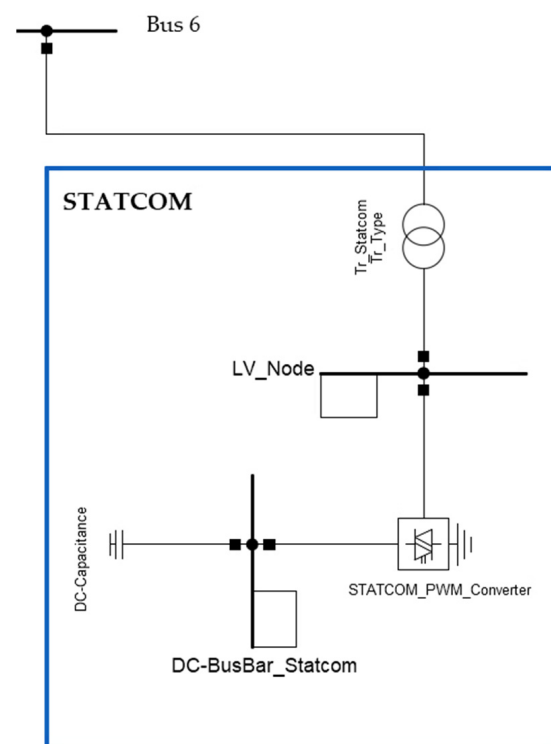


Figure 5. Network topology showing the STATCOM connected at Bus 6, identified as the critical voltage bus.

4. Simulation Results

4.1. Original 9-Bus Grid

4.1.1. Three-Phase Fault Ride-Through (FRT) Response of Original 9-Bus Grid

The baseline performance of the modified IEEE 9-bus network is evaluated under a solid three-phase fault applied at the midpoint of Line 5. In this configuration, no dynamic support devices are present, and the generators operate solely under their native excitation and governor control systems.

As illustrated in Figure 6a, the voltage waveforms across all uncontrolled busbars exhibit a pronounced sag immediately after the fault initiation, with the deepest depression occurring near the PCC (Bus 6). The absence of rapid reactive-power support results in a relatively slow post-fault voltage recovery, governed primarily by the generator excitation systems.

The corresponding transient frequency response, shown in Figure 6b, reveals a moderate frequency overshoot following fault clearance. These oscillations are attributed to the instantaneous imbalance between mechanical and electrical powers. The system subsequently stabilizes around the nominal value, but the oscillatory envelope indicates limited damping capability and low inherent inertia. These results establish the reference dynamic behaviour against which all subsequent compensated configurations are compared [2].

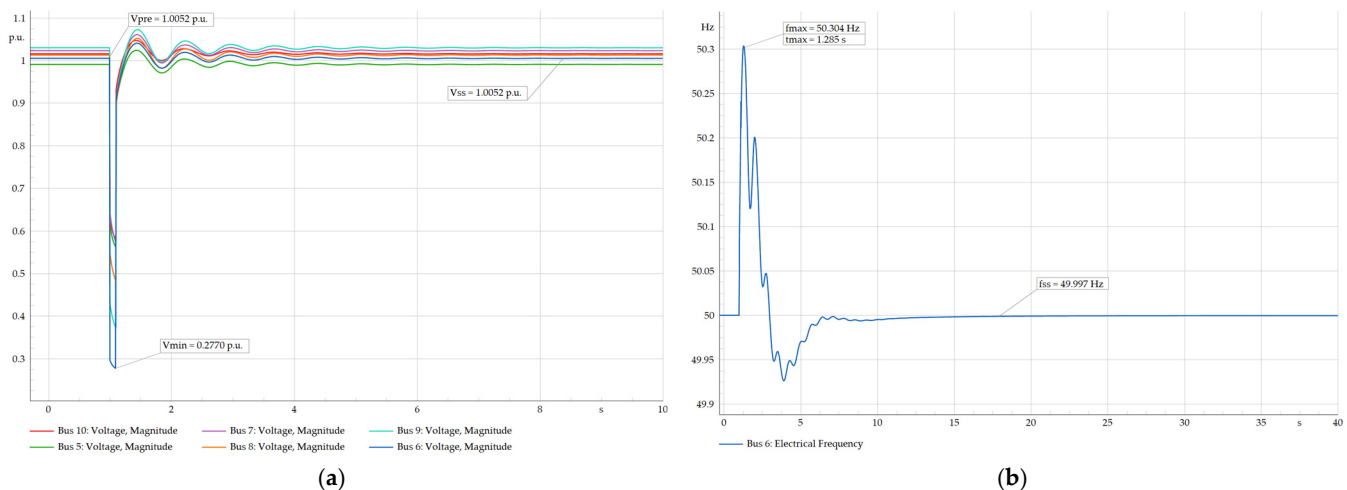


Figure 6. Simulation results for the modified IEEE 9-bus grid under a three-phase fault at the midpoint of Line 5 in the modified IEEE 9-bus network. (a) Voltage of all busbars; (b) frequency of Bus 6 (near the PCC).

4.1.2. Load Increment Response of Original 9-Bus Grid

In the uncompensated configuration of the modified IEEE 9-bus system, a step load increase of 30 MW is applied to evaluate the intrinsic dynamic characteristics of the grid under active-power imbalance. The response of the network provides the baseline behaviour for assessing subsequent compensation scenarios.

As depicted in Figure 7, the system frequency measured at Bus 6 exhibits an immediate drop below the nominal 50 Hz value, followed by a gradual recovery toward a slightly lower steady-state level. The minimum frequency (nadir) and the relatively high Rate of Change of Frequency (RoCoF) highlight the limited inertial and primary control capability of the generators when operating without additional support devices.

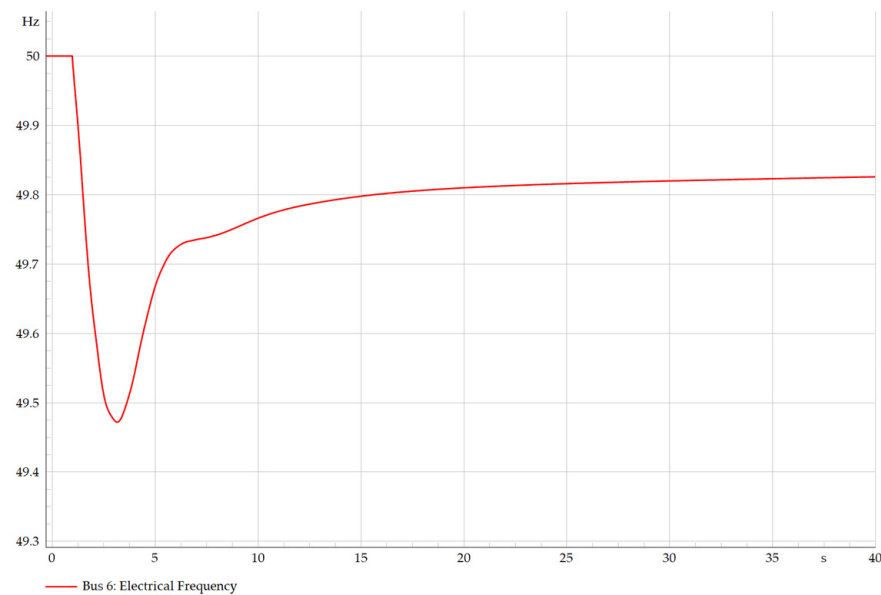


Figure 7. Frequency deviation at Bus 6 following a 30 MW load step in the original network.

4.2. Original Grid + Synchronous Condenser

4.2.1. Three-Phase Fault Ride-Through (FRT) Response of Original Grid + SC

In this scenario, a synchronous condenser (SC) is integrated into the modified IEEE 9-bus system to enhance both voltage and frequency stability during grid disturbances. The condenser, modelled with an equivalent inertia constant of $H = 4$ s, operates without a mechanical load and employs an AVR-based excitation system (IEEE-T1) for automatic terminal voltage regulation.

The voltage performance, illustrated in Figure 8a, demonstrates a clear enhancement when the synchronous condenser is in service. The condenser delivers rapid reactive-power support during the fault period, which substantially mitigates the depth of the voltage sag and accelerates post-fault recovery. The AVR efficiently regulates the terminal voltage, enabling a smooth restoration toward nominal conditions with minimal overshoot.

As depicted in Figure 8b, the addition of the synchronous condenser alters the frequency dynamics of the system following the fault. Instead of reducing oscillations, the condenser's interaction with the network is associated with slightly increased oscillatory behaviour in frequency, consistent with electromechanical coupling effects, leading to the appearance of small, high-frequency damped oscillations in the frequency waveform after fault clearance. This behaviour arises because the condenser acts as an extra rotating mass, such that its mechanical inertia couples dynamically with the synchronous generators. The additional inertia reduces the Rate of Change of Frequency (RoCoF) by increasing the total stored kinetic energy of the system. However, the synchronous condenser adds to the number of interaction pathways for energy exchange and redistribution between the rotating machines, thereby introducing oscillations to the system. These oscillations are well-damped and decay rapidly, indicating stable system behaviour.

Overall, while the synchronous condenser introduces minor transient oscillations in frequency due to electromechanical coupling, it delivers marked improvements in voltage stability and reactive support during and after the fault.

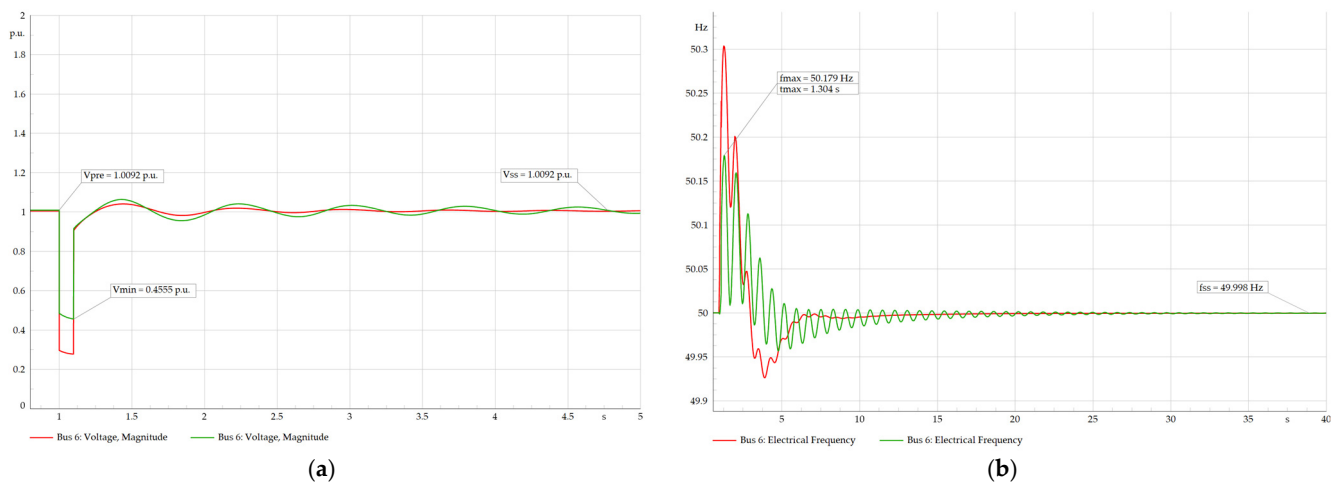


Figure 8. Simulation results for the comparison between the original 9-bus grid (red curve) and the original grid + SC (green curve), both under a three-phase fault at the midpoint of Line 5 in the modified IEEE 9-bus network. (a) Voltage of Bus 6; (b) frequency of Bus 6.

4.2.2. Load Increment Response of Original Grid + SC

In this case, the system's dynamic response to a 30 MW sudden load increase is evaluated in the presence of a synchronous condenser. The purpose of this test is to assess the condenser's contribution to frequency and voltage regulation during active power disturbances.

Figure 9a illustrates the voltage response at Bus 6 during a 30 MW load increase. The red curve, representing the uncompensated network, exhibits a noticeable voltage dip followed by slow, weakly damped oscillations before settling slightly below the nominal value. In contrast, the green curve, corresponding to the system with the synchronous condenser, shows a significantly reduced voltage sag and a faster restoration toward steady-state. The rapid reactive power injection from the condenser improves voltage support; however, small high-frequency electromechanical oscillations appear due to the reactive power exchange between the synchronous condenser and the rest of the grid. The AVR component of the synchronous condenser dynamically adjusts excitation in response to bus voltage deviations, causing the condenser to absorb or inject reactive power. This fast corrective action can lead to temporary overshoot, and in combination with load dynamics and the excitation response of other generators, results in an oscillatory voltage response. These oscillations decay within a few seconds, confirming that the condenser enhances overall voltage stability and transient recovery despite the brief oscillatory behaviour.

As depicted in Figure 9b, the inclusion of the synchronous condenser introduces a modest improvement in frequency stability, primarily by reducing the Rate of Change of Frequency (RoCoF) immediately after the load step. However, due to the electromechanical coupling between the condenser and the generators, small oscillatory modes appear in the frequency response. These oscillations are short-lived and well-damped, confirming that the condenser's inertial interaction transiently redistributes system energy before settling to a new equilibrium.

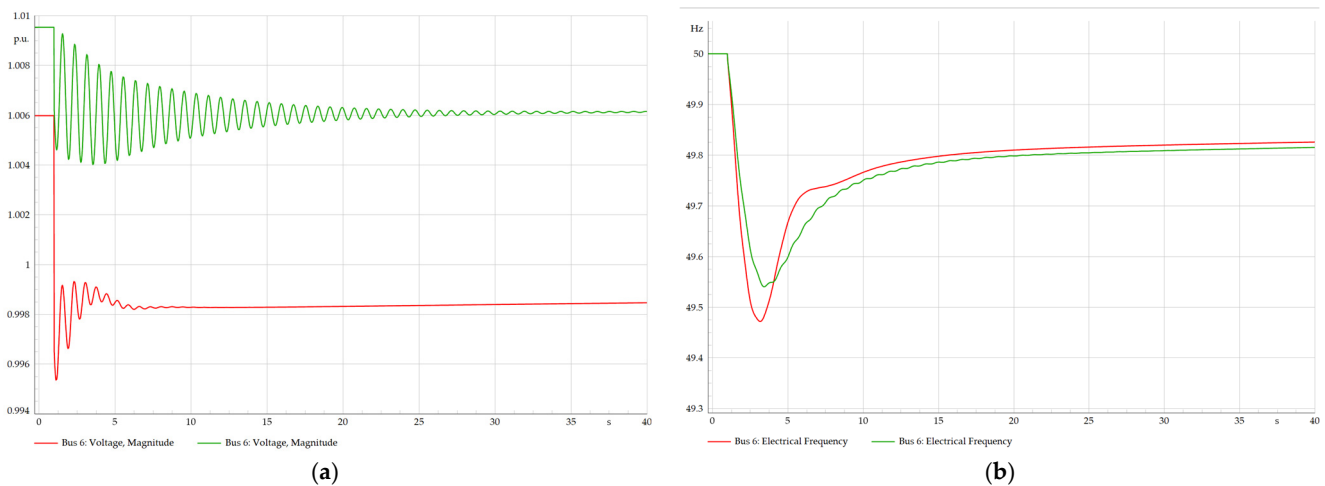


Figure 9. Simulation results for the comparison between the original 9-Bus Grid (red curve) and the Original Grid + SC (green curve), both during a 30 MW load increase at Bus 6. (a) Voltage of Bus 6; (b) Frequency of Bus 6.

4.3. Original Grid + BESS

4.3.1. Three-Phase Fault Ride-Through (FRT) Response of Original Grid + BESS

In Figure 10a, the voltage at the point of common coupling (PCC) exhibits only a marginal improvement compared to the uncompensated network, as the BESS primarily injects active power and does not contribute reactive support during the fault. Consequently, the voltage sag profile remains similar to that of the original system, with a very limited enhancement in transient recovery.

Figure 10b illustrates the grid frequency variation at Bus 6 during the three-phase fault with and without BESS active power support. The red curve (without BESS) exhibits a deeper frequency nadir and a slower recovery following fault clearance, indicating reduced system inertia and weaker frequency stability. In contrast, the blue curve, representing the case with BESS integration, shows a clear improvement in dynamic response: the frequency dip is significantly mitigated, and the system stabilizes more rapidly with minimal oscillations.

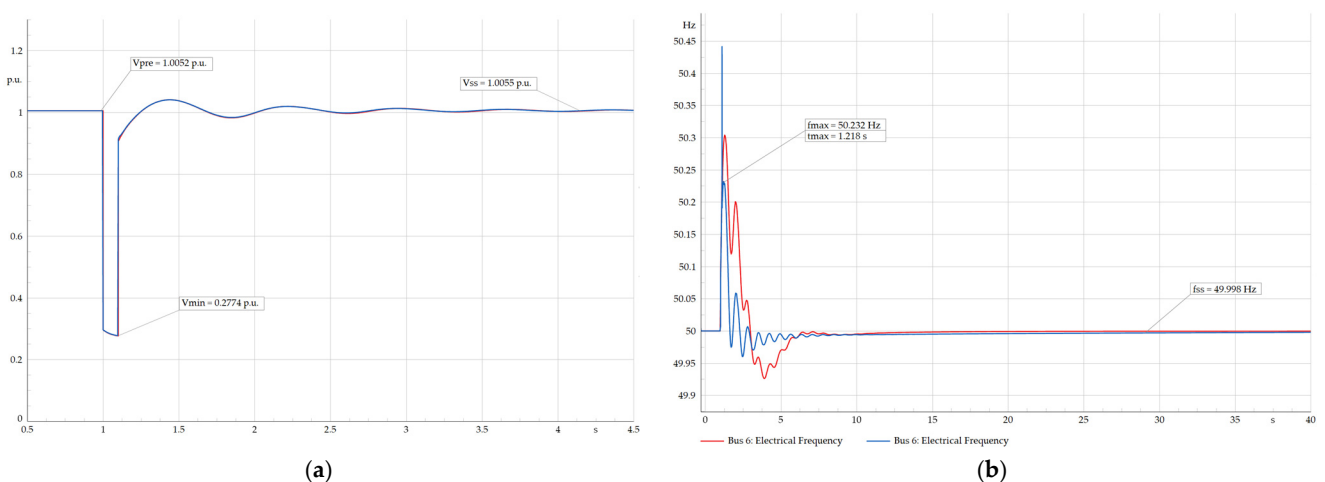


Figure 10. Simulation results for the original 9-Bus Grid (red curve) and the Original Grid + BESS (blue curve), both under a three-phase fault at the midpoint of Line 5 in the modified IEEE 9-bus network. (a) Voltage of Bus 6; (b) Frequency of Bus 6.

The observed improvement in frequency nadir and post-fault recovery is consistent with the expected behaviour of a converter-based BESS, which is capable of responding within sub-second timeframes to reduce the active power imbalance following the fault. The resulting reduction in frequency deviation and faster stabilization are indicative of effective primary frequency support. The BESS contribution to oscillation damping and frequency restoration observed in Figure 10b aligns with the established role of fast converter-based storage in frequency regulation, as reported in the literature.

4.3.2. Load Increment Response of Original Grid + BESS

In Figure 11a, the voltage performance at Bus 6 under load increment exhibits only a minor improvement with the presence of the BESS, as its operation primarily targets active power balance rather than reactive voltage support. The voltage drop following the load increase remains relatively similar to that of the base case, though a slightly faster recovery is observed due to the improved power balance. Overall, the BESS effectively mitigates frequency instability, while its influence on voltage dynamics remains limited.

As illustrated in Figure 11b, the integration of the BESS substantially enhances the system's frequency stability during the 30 MW load increase. The red curve, representing the uncompensated network, shows a deeper frequency nadir, slower recovery, and larger steady-state deviation. In contrast, the blue curve demonstrates a higher minimum frequency and faster return to nominal, indicating the effectiveness of fast active power injection by the BESS. This rapid compensation reduces the rate of change of frequency (RoCoF) and minimizes long-term deviation (Δf_{ss}), leading to a smoother and more resilient dynamic response.

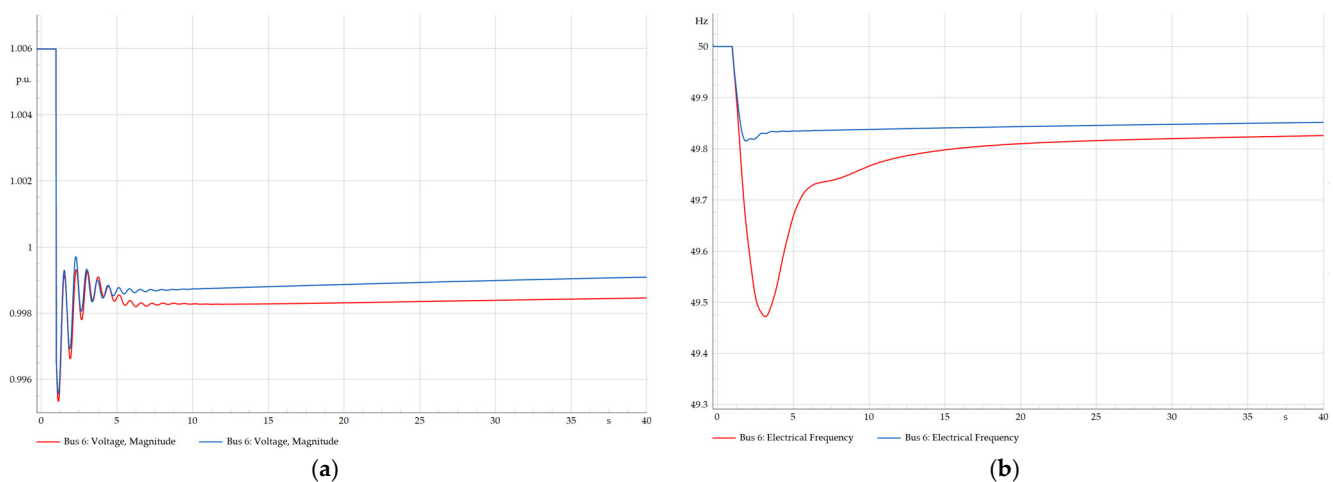


Figure 11. Simulation results for the comparison between the original 9-Bus Grid (red curve) and the Original Grid + BESS (blue curve), both during a 30 MW load increase at Bus 6. (a) Voltage of Bus 6; (b) Frequency of Bus 6.

4.4. Original Grid + STATCOM

4.4.1. Three-Phase Fault Ride-Through (FRT) Response of Original Grid + STATCOM

As shown in Figure 12, the STATCOM rapidly injects reactive power immediately after the voltage drop, reaching approximately 100 Mvar at its transient peak. This value is above the 50 MVA continuous rating, but it is permitted by the RMS dynamic current reference limiter, which is set to ± 2.67 p.u. in the STATCOM controller. The 100 Mvar peak corresponds to approximately 2.0 p.u. on the 50 MVA base and is therefore within the implemented transient current limit. This fast reactive support minimizes the voltage depression and enhances post-fault voltage recovery.

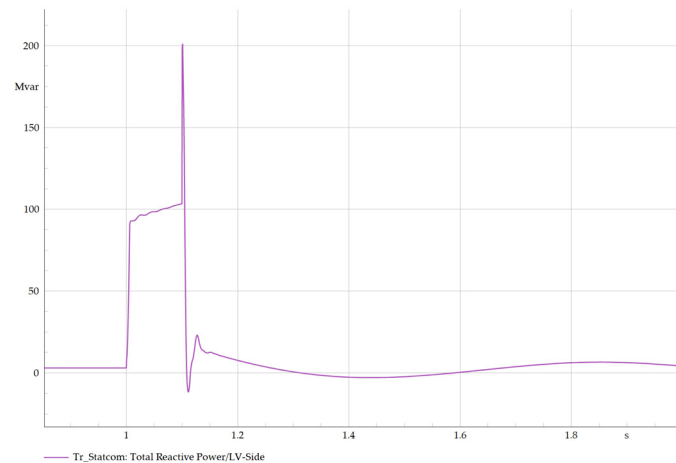


Figure 12. Reactive power injected by the STATCOM during a three-phase fault.

In Figure 13a, the voltage response at Bus 6 highlights the STATCOM's effectiveness in voltage sag mitigation. The minimum voltage improves significantly—from below 0.3 p.u. in the uncompensated case to above 0.35 p.u. with the STATCOM. The STATCOM maintains the voltage around its nominal value with minimal overshoot.

The frequency behaviour shown in Figure 13b, however, remains nearly unchanged compared to the base case, since the STATCOM primarily regulates reactive power and has minimal influence on active power or system inertia. The minor frequency spikes following the fault are a result of the fast reactive power injection by the STATCOM during the fault clearance. After the fault is cleared, the effective network impedance changes abruptly, causing the same current injection to produce a rapid voltage rise and thus the slight overshoot seen in Figure 13a. In the absence of additional inertia, the sudden imbalance between mechanical torque and electrical load is not absorbed, which causes a sharp increase in rotor acceleration of the grid generators and the corresponding short-lived frequency deviations.

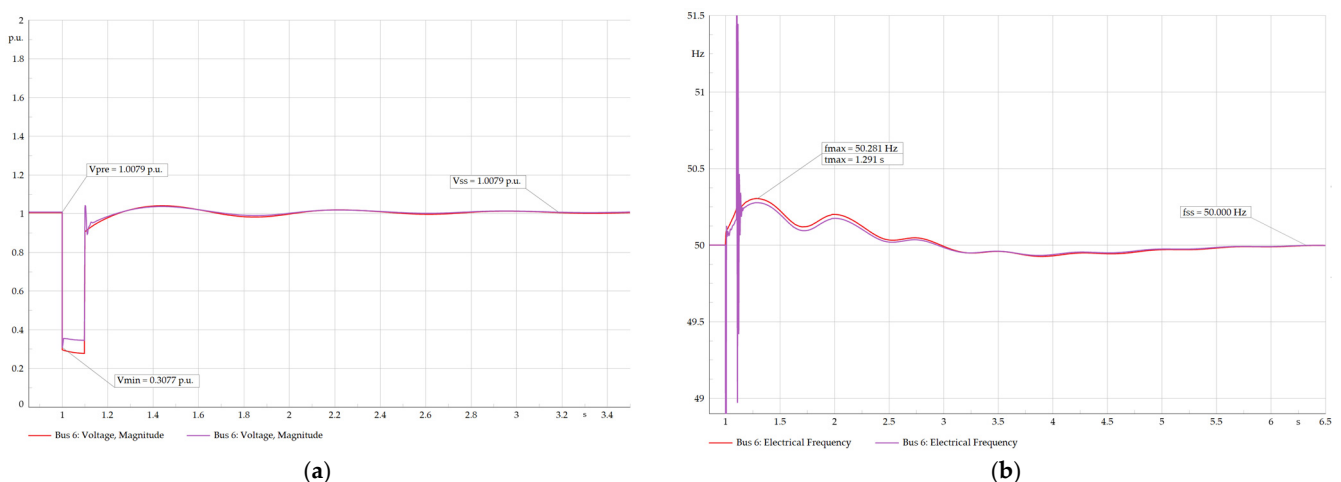


Figure 13. Simulation results for the comparison between the original 9-bus grid (red curve) and the original grid + STATCOM (purple curve), both under a three-phase fault at the midpoint of Line 5 in the modified IEEE 9-bus network. (a) Voltage of Bus 6; (b) frequency of Bus 6.

Overall, the STATCOM enhances transient voltage stability and fault ride-through capability without significantly altering the system's frequency dynamics.

4.4.2. Load Increment Response of Original Grid + STATCOM

The simulation results in this section highlight the STATCOM's contribution to voltage regulation and reactive power compensation during a 30 MW load increase. As seen in Figure 14, the STATCOM injects approximately 4.5 Mvar of reactive power immediately after the load step, which supports the PCC voltage and reduces the transient voltage dip.

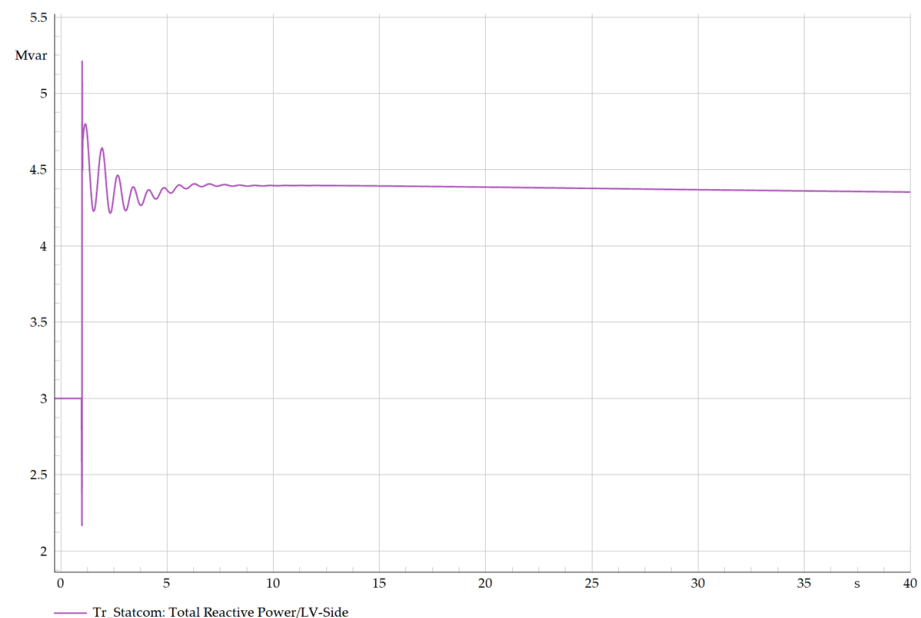


Figure 14. Reactive power injected by the STATCOM during a load increment.

In Figure 15a, the Bus 6 voltage shows a noticeable improvement in both transient and steady-state responses when the STATCOM is active (purple curve). The voltage dip observed in the uncompensated case (red) is mitigated, and oscillations are more effectively damped. The STATCOM restores the voltage more rapidly toward the nominal value by providing dynamic reactive power support, stabilizing the PCC voltage profile. The system frequency response, shown in Figure 15b, remains nearly identical to that of the uncompensated case, confirming that the STATCOM's impact is limited to the reactive domain and does not directly affect active power balance or frequency recovery.

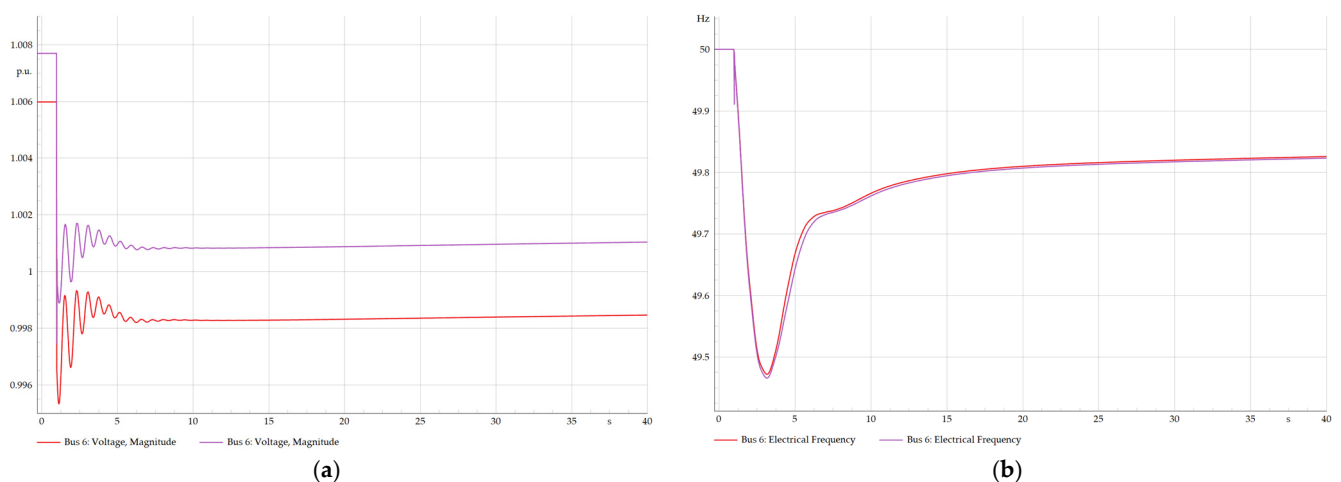


Figure 15. Simulation results for the comparison between the original 9-bus grid (red curve) and the original grid + STATCOM (purple curve), both during a 30 MW load increase at Bus 6. (a) Voltage of Bus 6; (b) frequency of Bus 6.

4.5. Combined SC-BESS-STATCOM

4.5.1. Three-Phase Fault Ride-Through (FRT) Response of Combined SC-BESS-STATCOM

The combined operation of the synchronous condenser (SC), battery energy storage system (BESS), and STATCOM demonstrates a highly coordinated improvement in both frequency and voltage stability.

In Figure 16a, the PCC voltage profile clearly benefits from the STATCOM's reactive power injection and the SC's voltage support capability. The voltage sag depth during the fault is considerably reduced, and the post-fault recovery exhibits a smooth trajectory without overshoot. This cooperative action between reactive and active compensation sources significantly enhances voltage resilience during transient events.

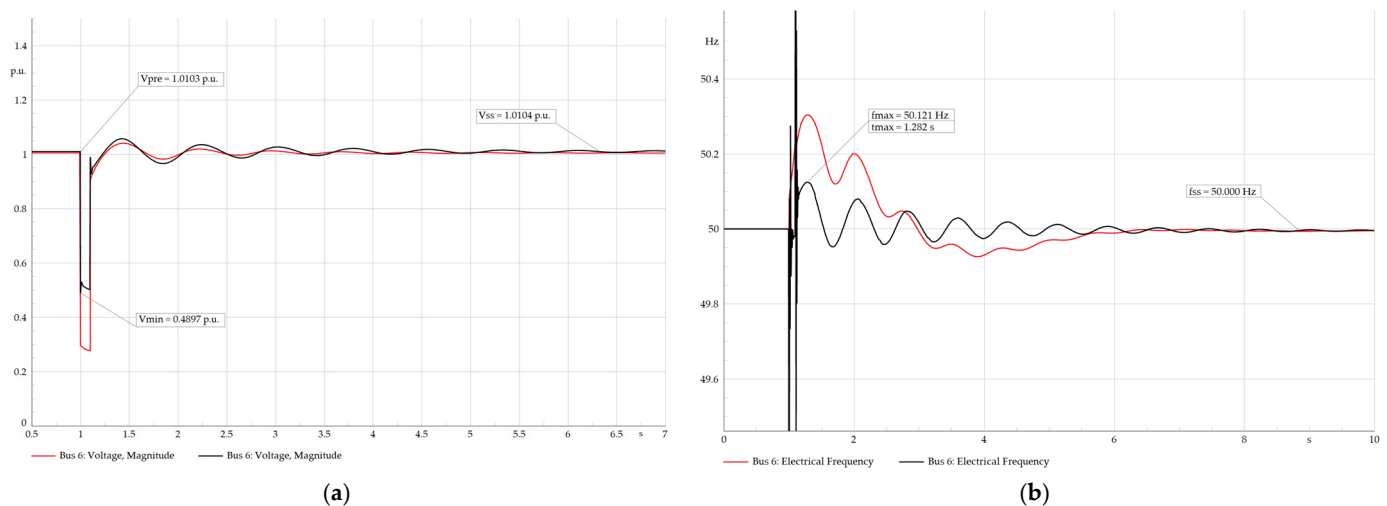


Figure 16. Simulation results for the original system (red curve) with the grid in the presence of SC-BESS-STATCOM (black curve) under a three-phase fault at the midpoint of Line 5. (a) Voltage response; (b) frequency response.

In Figure 16b, the hybrid configuration shows a faster frequency recovery and improved damping compared to the single-device and base grid cases. The SC is associated with reduced frequency oscillations, consistent with an inertial contribution, while the improved frequency nadir is consistent with fast active power support from the BESS and reduced oscillations. Consequently, the overall dynamic frequency deviation is minimized, and the system quickly settles near its nominal value.

Figure 17 compares the voltage waveforms across all uncontrolled busbars, showing a marked improvement in uniformity and damping under the hybrid compensation scheme. The voltage magnitudes across the network stabilize rapidly after fault clearance, and the difference between buses is minimised. Overall, the integration of SC-BESS-STATCOM results in a synergistic enhancement of both transient stability and dynamic voltage performance, combining the strengths of inertia, reactive support, and fast active power regulation.

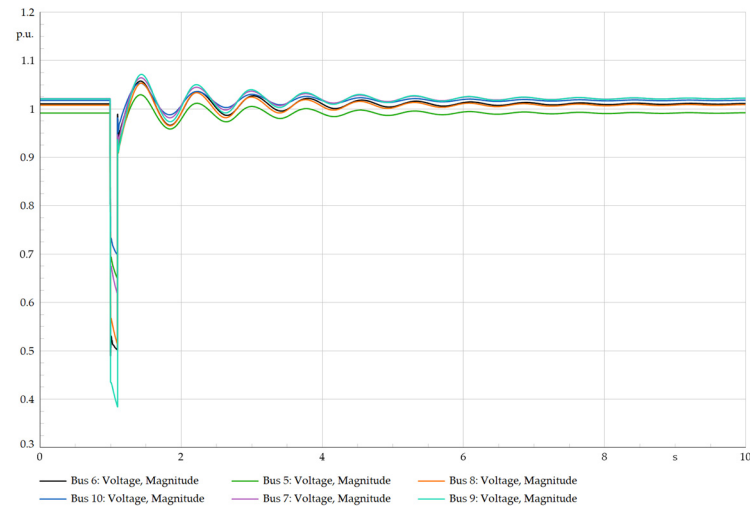


Figure 17. Voltage waveforms of uncontrolled busbars under a three-phase fault at the midpoint of Line 5 in the hybrid SC-BESS-STATCOM configuration.

4.5.2. Load Increment Response of Combined SC-BESS-STATCOM

The integrated operation of the synchronous condenser (SC), BESS, and STATCOM under a 30 MW load increment yields a highly coordinated enhancement in both frequency and voltage stability, as depicted in the following figures.

As shown in Figure 18a, the Bus 6 voltage achieves better dynamic performance and faster restoration compared with the uncompensated network. The hybrid configuration maintains the voltage above 0.998 p.u. during the disturbance and restores it to near 1.01 p.u. in steady state, demonstrating the complementary effects of reactive and active power control.

In Figure 18b, the hybrid system exhibits a substantially improved frequency nadir and a faster return to nominal frequency. The black curve, representing the compensated system, maintains frequency above 49.8 Hz throughout the transient, whereas the red curve (base case) drops below 49.5 Hz. The combined effects of inertial support from the SC, fast active power injection from the BESS, and voltage regulation from the STATCOM lead to a notable reduction in Rate of Change of Frequency (RoCoF) and improved overall damping.

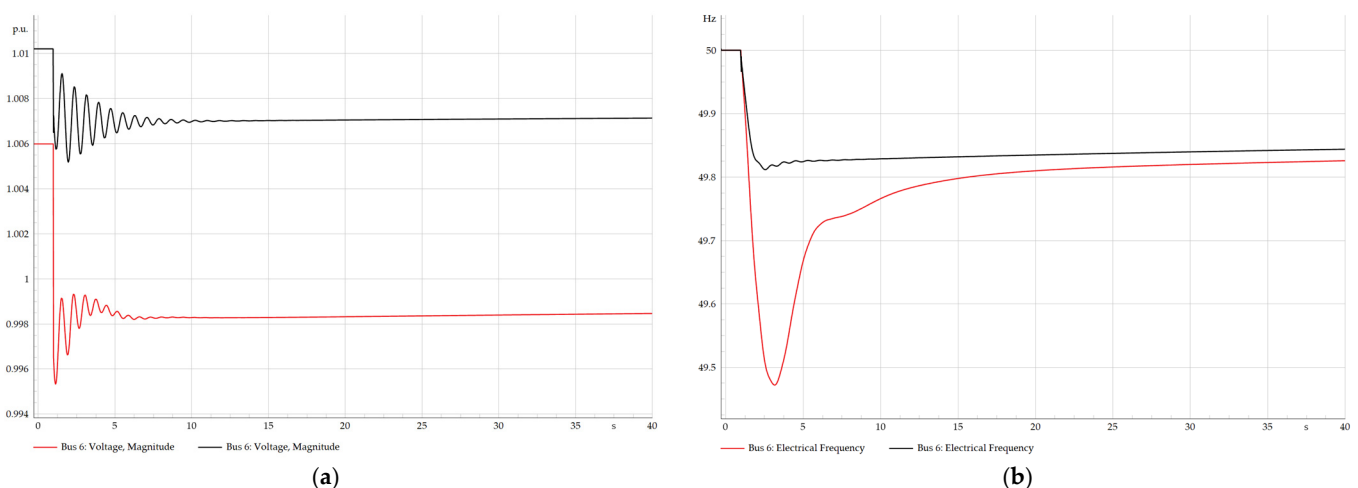


Figure 18. Simulation results for the comparison between the original 9-bus grid (red curve) and the original grid + SC-BESS-STATCOM (black curve), both during a 30 MW load increase at Bus 6. (a) Voltage of Bus 6; (b) Frequency of Bus 6.

4.6. Comparative Study and Discussion

This section presents a quantitative comparison of the 10 simulation cases to evaluate the overall frequency and voltage stability of the system. Building on the previous analyses, the results from both fault ride-through and load increment scenarios are numerically compared across five configurations: the original grid, and those with synchronous condenser, BESS, STATCOM, and their hybrid combination. Key indicators such as frequency deviation, RoCoF, voltage dip, and recovery time are summarized to highlight the distinct and complementary roles of each device. The comparative results demonstrate how the integration of inertial, active, and reactive control mechanisms jointly improves the system's dynamic and steady-state stability [2].

The numerical results in Table 1 confirm that the hybrid system delivers the most stable and well-damped frequency trajectory, combining the benefits of inertial, active, and reactive control mechanisms. This integrated structure ensures superior transient stability and minimal frequency deviation during severe grid faults, outperforming all individual configurations.

Table 1. Comparative Frequency Response Parameters under FRT Scenarios.

Scenario	$f_{\max}$ (Hz)	f_{nadir} (Hz)	f_{ss} (Hz)	Δf_{ss} (Hz)	RoCoF (Hz/s)
Original Grid	50.304	49.47	49.997	−0.003	−0.18
+Synchronous Condenser	50.179	49.55	49.998	−0.002	−0.15
+BESS	50.232	49.80	49.998	−0.002	−0.13
+STATCOM	50.281	49.47	50.000	−0.000	−0.18
+SC + BESS + STATCOM	50.121	49.82	49.998	−0.002	−0.09

The dynamic voltage response of the point of common coupling (Bus 6) during the fault ride-through (FRT) event was analysed across five configurations. The corresponding results are summarized in Table 2.

When the synchronous condenser is integrated, the minimum voltage improves owing to its rotational inertia and excitation control (AVR). The AVR provides immediate reactive-power injection, effectively mitigating the voltage collapse and producing a smooth recovery with a small overshoot and fast damping response. This confirms that the condenser contributes strong short-term voltage support and enhances post-fault voltage recovery [6].

In the BESS configuration, the voltage trajectory remains close to that of the base case. Since the BESS primarily regulates active power, its influence on voltage during the fault is minimal. However, the final steady-state voltage slightly increases, showing that the improved active power and frequency regulation indirectly contribute to smoother voltage recovery.

Table 2. Comparative Voltage Stability Indicators at PCC during FRT.

Scenario	V_{pre} (p.u.)	V_{min} (p.u.)	V_{dip} (%)	V_{ss} (p.u.)	$V_{\text{overshoot}}$ (p.u.)
Original Grid	1.0052	0.2770	72.45	1.0052	0.0657
+Synchronous Condenser	1.0092	0.4555	54.86	1.0092	0.0544
+BESS	1.0052	0.2774	72.41	1.0055	0.0356
+STATCOM	1.0079	0.3077	69.47	1.0079	0.0340
+SC + BESS + STATCOM	1.0103	0.4897	51.53	1.0104	0.0332

The hybrid SC + BESS + STATCOM configuration delivers the most stable and resilient voltage performance among all cases. This superior stability is achieved through synergistic coordination: the synchronous condenser provides inertia and reactive reserve, the STATCOM injects ultrafast reactive power during the first fault cycles, and the BESS balances active power and frequency to prevent secondary voltage dips [7].

The synchronous condenser contributes through inertia and electromagnetic coupling. At its core, a synchronous condenser is a spinning mass of steel and copper electromagnetically coupled to the grid. This rotating mass stores kinetic energy proportional to the square of its rotational speed. When a disturbance causes an imbalance between electrical demand and generation, the laws of rotational mechanics dictate that the machine's speed and, by extension, the grid frequency cannot change instantaneously. This is the physical origin of inertial support, and it explains why the SC reduces the Rate of Change of Frequency (RoCoF).

Unlike the SC, the BESS contains no rotating mass and therefore contributes no natural inertia. However, what it lacks in physical inertia it more than compensates for in response speed and controllability. The BESS interfaces with the grid through a voltage-source converter (VSC), which can alter its active power output within milliseconds, far faster than any mechanical governor or turbine system. It arrests the frequency drop, but this is achieved through programmed logic rather than physics. The result is a higher-frequency nadir (the minimum frequency reached before recovery begins) and a lower RoCoF, because the power imbalance that would otherwise be entirely reflected in frequency deviation is partially absorbed by the BESS's rapid injection.

The STATCOM contributes through instantaneous reactive power injection rooted in power electronics. Voltage sags during faults occur because fault currents draw large reactive power from the network, collapsing the voltage at the PCC. The STATCOM addresses this at the most fundamental level: it is a voltage-source converter that can synthesise reactive current from its DC capacitor without needing to draw it from the grid. Because reactive power is the primary determinant of voltage magnitude in a transmission network, injecting reactive current directly at the PCC acts to prop up the voltage almost immediately.

The hybrid system is effective precisely because these three physical mechanisms are orthogonal and complementary. The SC stabilises the system's inertial foundation and provides sustained reactive support through its AVR. The BESS intercepts active power imbalances at converter speed, limiting frequency excursions that the SC's inertia alone cannot fully suppress. The STATCOM handles the reactive power domain with sub-cycle precision, compensating for voltage sags that neither the SC's AVR nor the BESS's active power control can fully resolve. Because none of these mechanisms competes with or undermines the others, they act on different physical quantities (kinetic energy, active power, reactive power) through different timescales (seconds, milliseconds, sub-cycle) and their combination is not merely additive but synergistic. The hybrid SC-BESS-STATCOM system therefore achieves the highest voltage stability margin and fastest recovery among all configurations.

In summary, the numerical results in Table 2 and the transient waveforms in Figures 16–18 clearly show that the hybrid system achieves the highest voltage stability margin and fastest recovery, combining the inertial and AVR response of the SC, the fast Q–V control of the STATCOM, and the active power balancing of the BESS. This coordinated operation minimizes sag depth, prevents overshoot, and ensures smooth voltage restoration—providing the most robust voltage regulation among all configurations during FRT conditions [1,2].

5. Conclusions

The results of this study clearly demonstrate that coordinated operation between the synchronous condenser, BESS, and STATCOM offers significant advantages for both voltage and frequency stability compared to using each device individually. The synchronous condenser enhances system inertia and damping, providing smoother transitions during disturbances. The BESS contributes rapid active-power support, effectively reducing frequency dips and accelerating recovery. The STATCOM ensures fast and reliable voltage control, minimizing voltage sags and maintaining steady operation during faults and load variations.

When these three technologies operate together, their complementary characteristics create a strong synergy that results in superior transient and steady-state performance. The hybrid configuration achieves faster stabilization, minimal oscillations, and balanced control of both active and reactive power flows across the grid. Overall, the coordinated use of SC, BESS, and STATCOM represents an effective and practical strategy for improving the dynamic resilience and operational reliability of modern power systems facing increasing variability and disturbances.

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Appendix A

The tables below detail the parameters used in the DlgSILENT PowerFactory model for this study.

Table A1. IEEE 9-bus parameters retained in this study for DlgSILENT modelling.

Subsystem	Parameter	Value/Setting Used in This Study
System base	Nominal frequency	50 Hz
	Bus voltage levels	230 kV (Line-Line)
Loads	Load A (Bus 5)	125 MW, 50 Mvar
	Load B (Bus 6)	90 MW, 30 Mvar
	Load C (Bus 8)	100 MW, 35 Mvar

Table A2. Transmission line parameters used in the DlgSILENT model.

Line Number	Parameter	Value/Setting Used in This Study
1	Rated voltage	230 kV
	AC Resistance (20 °C)	5.29 Ω
	Reactance	44.965 Ω
2	Rated voltage	230 kV
	AC Resistance (20 °C)	16.928 Ω
	Reactance	85.169 Ω
3	Rated voltage	230 kV
	AC Resistance (20 °C)	4.4965 Ω
	Reactance	28.088 Ω
4	Rated voltage	230 kV
	AC Resistance (20 °C)	6.2951 Ω
	Reactance	53.3232 Ω
5	Rated voltage	230 kV
	AC Resistance (20 °C)	20.631 Ω
	Reactance	89.930 Ω
6	Rated voltage	230 kV
	AC Resistance (20 °C)	8.993 Ω
	Reactance	48.668 Ω

Table A3. Transformer parameters used in the DiGSILENT model.

Transformer	Parameter	Value/Setting Used in This Study
T1	Rated power	250 MVA
	Winding connection	YN-d
	Voltage ratio	230/16.5 kV
T2	Rated power	200 MVA
	Winding connection	YN-d
	Voltage ratio	230/18 kV
T3	Rated power	150 MVA
	Winding connection	YN-d
	Voltage ratio	230/13.8 kV

Table A4. Generator parameters used in the DiGSILENT model.

Subsystem	Parameter	Value/Setting Used in This Study
Generator G1	Plant type	Hydropower plant
	Governor model	HYGOV (PowerFactory standard model)
	Excitation/AVR	1981 IEEE Type AC1
	Rated power	145 MVA
	Rated voltage	16.5 kV
	X _d	0.36 p.u.
	X _q	0.24 p.u.
	X' _d	0.15 p.u.
	X'' _d	0.1 p.u.
	X'' _q	0.1 p.u.
Generator G2	Plant type	Gas-turbine power plant
	Governor model	Gas-turbine governor
	Excitation/AVR	GAST (PowerFactory standard model)
	Rated power	80 MVA
	Rated voltage	18 kV
	X _d	0.36 p.u.
	X _q	0.24 p.u.
	X' _d	0.15 p.u.
	X'' _d	0.1 p.u.
	X'' _q	0.1 p.u.
Generator G3	Plant type	Coal-fired thermal power plant
	Governor model	User-defined (See Table A6)
	Excitation/AVR	1968 IEEE Type 1
	Rated power	190 MVA
	Rated voltage	13.8 kV
	X _d	1.68 p.u.
	X _q	1.61 p.u.
	X' _d	0.23 p.u.
	X' _q	0.32 p.u.
	X'' _d	0.2 p.u.
	X'' _q	0.2 p.u.

Table A5. SC, BESS and STATCOM parameters used in the DiGSILENT model.

Subsystem	Parameter	Value/Setting Used in This Study
Synchronous Condenser	Connection bus	Bus 6
	Excitation/AVR	User-defined (See Table A7)
	Rated MVA	80 MVA
	Q _{min}	−80 Mvar
	Q _{max}	80 Mvar
	AVR gain	150 p.u.
	X _d	1.68 p.u.
	X _q	1.61 p.u.
	X' _d	0.23 p.u.
	X' _q	0.32 p.u.
	X'' _d	0.2 p.u.
	X'' _q	0.2 p.u.
BESS	Connection location	Bus 9
	Converter type	PWM voltage-source converter
	Droop gain (K _f)	0.004 p.u.
	Rated active power	40 MW

Table A5. *Cont.*

Subsystem	Parameter	Value/Setting Used in This Study
STATCOM	Connection bus	Bus 6
	Converter type	Voltage-source converter
	Control structure	Vdc-Q
	Rated power	50 MVA
	Reactive power setpoint	3 Mvar
	Active power control gain (Kp)	10 p.u.
	Active power control time constant (Tp)	0.002 s
	Voltage control gain (Kv)	4 p.u.
	Voltage power control time constant	0.002 s
	Voltage droop	5%
	Minimum current reference limit	−2.67 p.u.
	Maximum current reference limit	2.67 p.u.

Table A6. User-defined governor parameters for the coal-fired power plant generator (G3) model.

Parameter	Value/Setting Used in This Study
Controller Gain (K)	25 p.u.
Governor Time Constant (T1)	0.25 s
Servo Time Constant (T3)	0.1 s
High Pressure Turbine Factor (K1)	0.3 p.u.
Intermediate Pressure Turbine Time Constant (T5)	10 s
Intermediate Pressure Turbine Factor (K3)	0.4 p.u.
Medium Pressure Turbine Time Constant (T6)	0.4 s
Medium Pressure Turbine Factor (K5)	0.3 p.u.
High Pressure Turbine Time Constant (T4)	0.3 s
HP Turbine Rated Power (PNhp)	190 MW
Valve Closing Time (Uc)	−0.1 p.u./s
Minimum Gate Limit (Pmin)	0.3 p.u.
Valve Opening Time (Uo)	0.1 p.u./s
Maximum Gate Limit (Pmax)	1 p.u.

Table A7. User-defined AVR parameters for the SC model.

Parameter	Value/Setting Used in This Study
Measurement Delay (Tr)	0.028 s
Controller Gain (Ka)	150 p.u.
Controller Time Constant (Ta)	0.03 s
Exciter Constant (Ke)	1 p.u.
Exciter Time Constant (Te)	0.266 s
Stabilization Path Gain (Kf)	0.0025 p.u.
Stabilization Path Time Constant (Tf)	1.5 s
Saturation Factor 1 (E1)	4.5 p.u.
Saturation Factor 2 (Se1)	1.5 p.u.
Saturation Factor 3 (E2)	6 p.u.
Saturation Factor 4 (Se2)	2.46 p.u.
Controller Output Minimum (Vrmin)	−12 p.u.
Controller Output Maximum (Vrmax)	12 p.u.

Table A8. Disturbance, event and measurement specifications.

Category	Parameter	Value/Setting Used in This Study
Fault event	Disturbance type	Temporary three-phase fault
	Fault location	Midpoint of Line 5
	Fault impedance	0 Ω
	Fault initiation time	1 s
	Fault clearing time	1.1 s
	Post-fault behaviour	Line 5 remains in service
Load-increment event	Disturbance type	Step load increase
	Step size	30 MW
	Location	Bus 6
	Event time	1 s
	Load power factor	1

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