Investigation of Power System Blackouts and Prevention Strategies

Khodani Conjwa[1], *and Best* Khoza[1]

[1]University of Zululand, Department of Engineering, Richards Bay, South Africa

Abstract. Power system blackouts remain a significant grid reliability threat, often resulting from cascading failures triggered by faults, operational errors, extreme weather conditions or cyberattacks. This study investigated the mechanism of power system blackouts and evaluated practical prevention strategies aimed at improving power system resilience. Historically significant blackout events were analysed to identify common failure patterns and key lessons for modern grid operation. A simulation-based approach was adopted using an IEEE 9-bus test system on DigSilent Powerfactory to analyse cascading failures under generator outage conditions. The effectiveness of load reduction and battery energy storage systems (BESS) was assessed using frequency and voltage stability metrics. The simulation results showed that the loss of generator 3, representing approximately 26.6 % of total generation capacity, resulted in voltage and frequency instability that met the study's blackout criteria. Under the load reduction scenario, voltage was restored with a minimum voltage of 0.9515 p.u. and frequency nadir of 49.747 Hz, whereas BESS support achieved faster voltage recovery (4s versus 6s) while maintaining full load supply. These findings demonstrate that BESS provides more effective blackout mitigation strategy than conventional load reduction and can significantly enhance power system resilience.

1 Introduction

Electric power grids represent one of the most vital and complex infrastructures of modern society, facilitating economic development, public security, and social stability. The reliability of these systems is critically important, but the power grids are constantly threatened by enormous disruptions referred to as blackouts. A blackout, which is the uncontrolled and large-scale loss of electric power, can stem from a wide variety of causes, ranging from the failure of components to protection system maloperation, human mistakes, severe weather conditions, and now, cyber-physical attacks [1]. The extreme impacts of blackouts can range from economic losses and damage to strategic infrastructure to the immediate jeopardy to human lives. The transition towards smarter and more sustainable grids introduces additional vulnerability. Integration of renewable energy sources, while being environmentally significant, introduces intermittency and reduces system inertia, causing potential enhancement of dynamic instability issues like voltage collapse and frequency oscillation during disturbances. Second, the intimate relationship between the cyber network and power grid in a smart grid creates an important interdependency, where compromise or failure in the communication system can have a direct impact on physical power system operations, as the 2015 Ukraine cyberattack clearly illustrated in causing a large-area blackout [2]. This research initiative is informed by the pressing need to develop power system resilience. By integrating learnings from previous blackout post-mortems and examination of existing mitigation methods, varying from advanced cascading failure models to grid and system structural enhancements. The longer-term objective is to underpin the design and operation of robust, adaptive grids that can withstand disturbance and thus minimize the risk and catastrophic impact of future blackouts.

2 Power system and blackout mechanism

2.1 Power system overview

Power system refers to a complex network comprising generation, transmission, and distribution components that are required to maintain a precise balance between energy demand and supply on real-time basis. Modern power systems, whose origins can be traced to the innovative work of Edison, Tesla, and Westinghouse in the late 19th century, form critical infrastructure today.

2.2 Operating states of a power system

Understanding the different operating states of a power system is essential for identifying vulnerabilities that may lead to blackouts and for developing effective prevention strategies. Fig. 1 shows a simplified block diagram of these operating states and their transitions. Each state is defined by specific operating conditions and required interventions. In the normal state, the system functions within all technical limits, with stable voltage, frequency, and balanced supply-demand conditions. The alert state indicates increased risk, where early signs such as voltage or frequency deviations and equipment overloading appear, requiring heightened monitoring and preventive action. The emergency state occurs when operational limits are exceeded, demanding immediate corrective measures such as load shedding or network reconfiguration to prevent further deterioration. If emergency conditions are not effectively managed, the system may progress to a blackout state, characterized by partial or complete loss of supply due to cascading failures. Following this, the restoration state involves systematic efforts to re-energize the network using strategies such as black start units and controlled system reconnection.

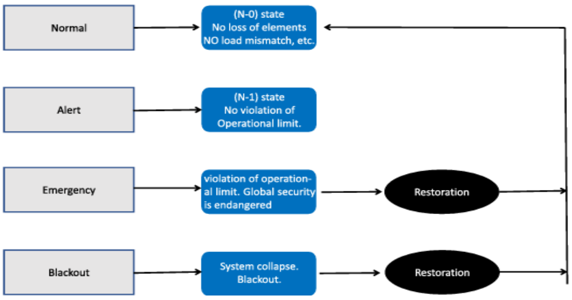

Fig. 1. Various states of an electrical Power System **[3]**

2.3 Cascading failures

Cascading failures represent one of the most critical mechanisms leading to large-scale blackouts in modern power systems. The Power system cascading failures refer to the chain-reaction phenomenon wherein the loss or failure of one component starts a series of subsequent failures in the interconnected network. The phenomenon often results in large blackouts and continues to be a contentious issue in contemporary power system reliability and resilience analysis [3]. With the transition towards the renewable energy integration, new issues have emerged. Low system inertia due to inverter-based resources raises the risk of frequency instability, while widespread digitization and interconnectivity with communications infrastructure introduce cyber-physical vulnerabilities [3].

To study and mitigate cascading failures, some of the modelling methods built include:

- Topological and Statistical Models
- Power Flow and Dynamic Simulation Models
- Cyber-Physical and Composite Infrastructure Models:
- Empirical Analysis and Event Sequence

2.4 Historical overview of power system blackouts

2.4.1 The First Documented Major Blackout

The November 9, 1965, blackout that plunged a large portion of the northeastern United States and Ontario, Canada, into darkness marks a watershed in the history of electric power systems. It lasted for 13 hours and impacted 30 million people, and it was a moment that fundamentally changed the focus of power grid vulnerabilities and led to the creation of modern-day reliability standards [4].

The first fault occurred on the 230 kV transmission system between an Ontario power station and the load centre in Toronto. One of five 230 kV circuits was opened by a backup protective relay, whose operating set point the operators did not know. A chain reaction occurred; several other 230 kV, 115 kV, and 345 kV transmission lines were tripped by protective relay action. Additionally, the ensuing power swings resulted in automatic generator shutdowns: 5 of 16 units at the St. Lawrence plant tripped, followed by 10 units at the Sir Adam Beck plant (due to low governor oil pressure) and 5 of its pumping generators (tripping over-speed control).

As a response, the regulation and engineering communities conducted an in-depth analysis that resulted in seismic changes. Most importantly, the blackout established the National Electric Reliability Council (NERC) in 1968 (now the North American Electric Reliability Corporation), the first organization with a mandate to create and enforce mandatory reliability standards on the bulk power system of North America [4].

2.4.2 Blackouts that Led to Major Advancements of Power Grid Resilience in Different Power Systems

Previously, large-scale power failures have been learning opportunities that have resulted in great leaps in electrical network resilience. Such events expose weakness in the protection schemes, operational procedures, and topological design of the grid that stimulate engineers and researchers to devise innovative solutions.

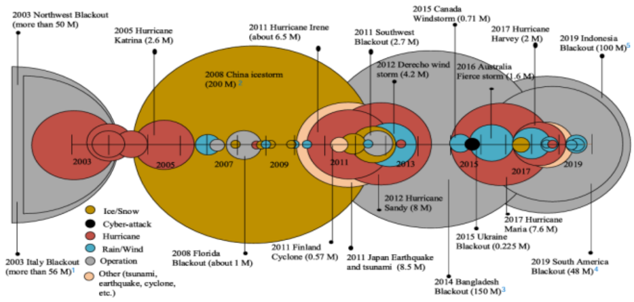

Fig. 2. Examples of major outage events, where M represents the number of customers affected (in millions) **[5]**

Table 1 lists major blackouts that spurred major advancements of power grid resilience in different power systems. This shows how system collapses have had a direct impact on operating and technology enhancements, making contemporary power systems more resilient to cascading collapses.

2.5 Recent Notable Blackouts and Their impacts

2.5.1 The 2021 Texas Winter Storm

The February 2021 Texas blackout is one of the most acute examples of just how badly modern power systems can fail when extreme weather coincides with infrastructure vulnerabilities. This five-day-long event plunged more than 4.5 million households into darkness and claimed between 246 and 978 lives, while economic losses ran to about $130 billion [6].

Table 1. Major power system resilience advancements spurred by different blackouts.

Blackout	Major advancement
1. 2003 Italy blackout	Phasor Measurement Unit (PMU)
2. 2008 China Ice Storm blackout	Ice-resistant transmission lines
3. The 2014 Bangladesh blackout	Automated Under Frequency Load Shedding (UFLS)
4. The 2019 South America blackout	Advance Relay Coordination
5. The 2019 Indonesia blackout	Phasor Measurement Unit (PMU)

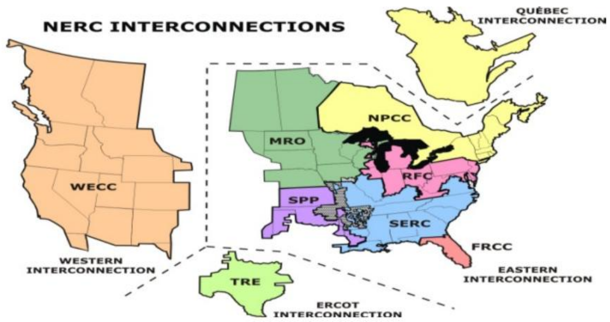

Fig. 3. The four major power grid interconnections in North America **[7]**.

The North American electric power system shown in Fig. 3 consists of four major interconnections in the Eastern, Western, ERCOT (Electric Reliability Council of Texas), and Québec systems, that together constitute one enormous network responsible for the continent-wide reliability of electric supplies. What started off as a weather event rapidly turned into a grid emergency when, on the early morning of February 15, the ERCOT system experienced a precipitous frequency decline that lasted 4 minutes and 23 seconds [6]. This frequency deviation, reaching precariously below operational thresholds, signaled the grid's struggle to balance rapidly deteriorating generation resources against the surging demand.

This event makes it clear that resilience requires more than the weatherization of individual components; it requires holistic techniques such as demand forecasting based on climate science, fuel supply chain redundancy, interconnecti-on for mutual support, and market designs that properly value reliability [6].

2.5.2 The 2015 Ukraine Cyber-Induced Blackout

The 23rd December 2015 Ukraine blackout, was the first publicly confirmed cyberattack to cause a large-scale power outage, a milestone in the history of power system disruption. Fig. 4 shows the three regions that suffered a loss of over 130MW, namely Prykarpattia, Chernivtsi, and Kyiv. Approximately 225,000 customers were in the dark, outages continued for about 6 hours before power could be restored manually [8].

Fig. 4. Regions impacted by the cyber-induced power outage in Ukraine **[8]**

The Ukraine outage was significant, nevertheless, in that it revealed new possibilities for vulnerability in sophisticated power systems, where cyberattacks could lead to actual service disruptions on par with conventional blackouts.

This initial intrusion occurred weeks in advance of the actual blackout attests to the attackers' patience and planning, spear-phishing emails with Black Energy 3 malware were used for the initial intrusion [8]. Attackers then moved laterally to operational systems after establishing a foothold in the IT networks [8]. Each of the affected firms saw staggered power outages: the first at 3:30 p.m. EET, the second at 3:31 p.m., and the third at about 4:00 p.m. Operators resorted to manual switching to restore service once they realized that the SCADA interfaces and VPNs had been hijacked.

The 2015 Ukraine blackout is a stern reminder that the increasing digitalization of power systems must be matched by rigorous cybersecurity integration, operator preparedness, and resilient network design.

3 Blackout Prevention Strategies

3.1 Load Reduction

Load reduction is a planned and controlled disconnection of selected loads from the power system to maintain system stability when available generation and imports are insufficient to meet demand [9]. It is implemented as a corrective action to prevent a complete system collapse (blackout) by restoring the real-time power balance. It is based on the power balance principle that:

$$\sum Generation = \sum Loads + \sum Losses \qquad (1)$$

It is often referred to as load shedding in operational practice. When system demand exceeds available supply, the imbalance results in a system frequency decline. Load reduction is therefore applied to restore equilibrium by reducing demand by an amount P_{shed} to ensure that:

$$P_{gen} \geq P_{load} - P_{shed} \quad (2)$$

In practical power systems, load reduction is implemented through automatic or manual shedding schemes depending on the severity and speed of a disturbance. Managed load shedding has been widely implemented in several developing power systems to support grid operation during supply shortages.

A key distinction exists between operational load shedding and protection-based load shedding. Modern power systems employ automated under-frequency load shedding (UFLS) and Under-voltage load shedding (UVLS). These schemes play a decisive role in blackout prevention by automatically responding to frequency and voltage deviations, respectively. UFLS schemes act as rapid countermeasures against sudden power deficits by using frequency thresholds or adaptive algorithms to disconnect loads in proportion to the detected rate of change of frequency (ROCOF), while UVLS targets regions experiencing voltage instability due to reactive power shortages. The integration of intelligent, adaptive, and decentralized methods, such as those using real-time inertia estimation or combined frequency–voltage criteria, enables faster and more precise responses under diverse grid conditions.

3.2 Battery Energy Storage System

Battery Energy Storage System (BESS) is becoming a crucial part of the modern power systems, providing a fast, flexible, and controllable means of storing and delivering electrical energy. The growing role of intermittent renewable energy sources like solar and wind has introduced volatility and uncertainty into grid operations. This situation calls for quick stabilization solutions that can maintain the grid frequency, voltage, and power quality [10].

The operational flexibility of BESS is established based on its functionality to support both short-term high-power operations as well as long-term energy balancing. For the sub-second range, BESS prevents transient instability. For the minute to hour duration range, it supports peak shaving, load shaping, or smoothing solar intermittency [10]. At present, lithium-ion batteries have been leading in grid-scale storage because of their high round-trip conversion efficiency, high energy density, and ability to ramp up quickly. Table 2 and Table 3 below shows the characteristics of some of the prominent battery technologies.

BESS plays a critical role in enhancing the stability, reliability, and resilience of modern power systems, effectively serving as a preventive measure against large-scale blackouts. By providing fast-response active and reactive power support, BESS mitigates voltage and frequency deviations that often trigger cascading failures during system disturbances.

Table 2. Typical technical performance parameters of different battery technologies adapted from [10].

Battery type	Typical Capacity (MW)	Charging and discharging cycles	Typical Efficiency (%)	Specific energy density (Wh/L)
Lead-Acid	0 - 40	300 – 3000	70 – 90	35 – 40
Lithium-ion	0 – 100	3000	75 – 90	250 – 693
Lithium iron phosphate	0.001 -10	2000 – 10000	85 – 95	90 – 120*
Sodium-sulphur	0.05 – 8	4500	80 – 90	150 -300
Nickel-cadium	0 – 40	3000	60 – 80	46 – 60
Flow battery	0.03 - 3	2000 – 20000	65 – 90	40

*Wh/kg

Table 3. Operational and economic characteristics of different battery technologies adapted from [10].

Battery type	Response time	Charge, discharge times	Estimated cost ($/kWh)
Lead-Acid	5 – 10 minutes	Minutes-days, seconds-hours	200 - 400
Lithium-ion	ms	Minutes-days, minutes - hours	600 - 2500
Lithium iron phosphate	ms	Minutes-days, minutes - hours	600 - 2500
Sodium-sulphur	ms	Seconds-minutes, < 15 minutes	1000 - 1400
Nickel-cadium	ms	Minutes-days, seconds-hours	800 - 1500
Flow battery (Nickel metal hydrate)	ms	Minutes-days, seconds-hours	150 - 1000

4 Methodology

4.1 Study Network and Simulation Environment

All simulations were performed in DIgSILENT PowerFactory 2024, which provides integrated capabilities for steady-state, fault, and RMS dynamic analysis. The IEEE Standard 9-Bus Test System served as the study network for this investigation. It was selected because of its moderate size, well-documented parameters, and suitability for educational and research-based transient stability studies. Since the IEEE 9-Bus system was originally designed for 60 Hz operation, the frequency was adjusted to 50 Hz to align with Southern African grid standards.

4.2 Model Validation

The model was validated using a load-flow (power-flow) study based on the Newton–Raphson iterative method, which will solve the nonlinear power equations representing the balance between generated and consumed power at each bus. The power mismatches will be iteratively minimized using the following mathematical formulation [11]:

$$P_k = |V_k| \sum_{m=1}^{n} |V_m| \{G_{km} \cos(\theta_k - \theta_m) + B_{km} \sin(\theta_k - \theta_m)\} \quad (3)$$

$$Q_k = |V_k| \sum_{m=1}^{n} |V_m| \{G_{km} \sin(\theta_k - \theta_m) - B_{km} \cos(\theta_k - \theta_m)\} \quad (4)$$

Where;
$|V_m|$ = Voltage magnitude at bus m
$|V_k|$ = Voltage magnitude at bus k
θ_m = Voltage phase angle at bus m
θ_k = Voltage phase angle at bus k

Successful load-flow convergence in Fig. 5 validates that the IEEE 9-Bus system is stable and balanced, providing a reliable baseline for the subsequent dynamic simulations.

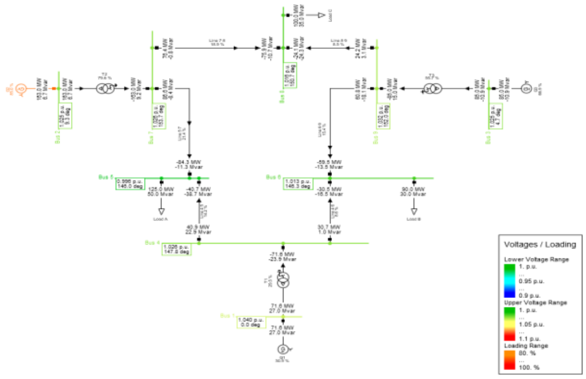

Fig. 5. IEEE Standard 9-Bus Study Network power flow(50Hz)

4.3 Assumptions

To ensure analytical consistency and maintain focus on key stability indicators, three fundamental assumptions will be applied in this study.

- Voltage Stability: It will be assumed that the system's voltage magnitudes will remain within the operational limits of 0.95 to 1.05 p.u. under normal operating conditions.
- Frequency Stability: The nominal system frequency will be maintained at 50 Hz, with an allowable deviation range of 49.7 to 50.3 Hz.
- Blackout Reference Condition: For this research, a blackout event will be defined as a situation where voltage or frequency deviates beyond the specified operational limits for a sustained duration. Specifically, the grid will be considered to have collapsed if voltage drops below 0.95 p.u. or overshoots beyond 1.05 p.u., or if frequency falls below 49.7 Hz or overshoots beyond 50.3 Hz.
- The parameters for the employed battery energy storage system are provided in the appendix of this paper.

4.4 Simulation Scenarios

- Scenario 1: Blackout Reference [Generator 3 (G3) Trip Event]
- Scenario 2: Load-Shedding [G3 Trip Event followed by a load event on Load B]
- Scenario 3: BESS [G3 Trip Event followed by integration of two Battery Energy Storage Systems (BESS) added at Bus 6 and Bus 8]

5 Results and discussion

5.1 Base Case Results

The base case scenario results indicated acceptable voltage range of 0.95-1.05 p.u at all 9 buses as seen in **Fig.** *6* below. The system also exhibited acceptable nominal frequency of 50 Hz as seen in **Fig.** *7*.

5.2 Blackouts and Prevention Strategies Results

Figures 9 and 10 simulate a blackout event where generator 3 is tripped at 2 seconds. This resulted in the loss of 26.6 % of the total generation, leading to both voltage and frequency collapse. For brevity, only the voltage response at Bus 5 is presented. The voltage responses at other buses and the system frequency demonstrated similar characteristics. This is characterized by voltage and frequency that are outside the acceptable ranges.

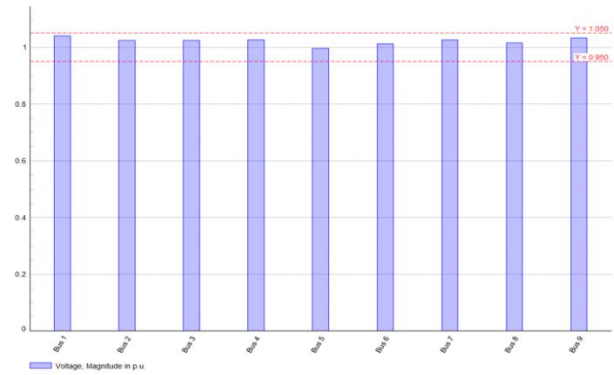

Fig. 6. Steady state bus voltage profiles under normal operating conditions.

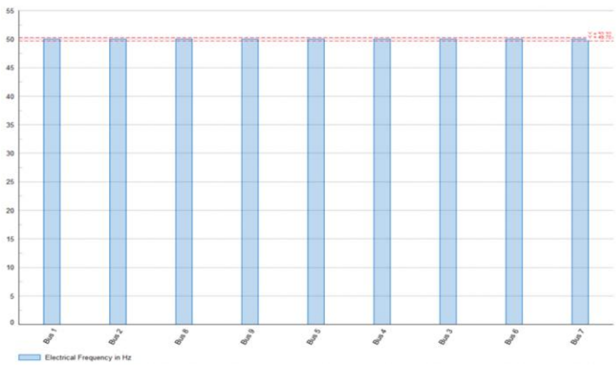

Fig. 7. Power system frequency under normal operating conditions

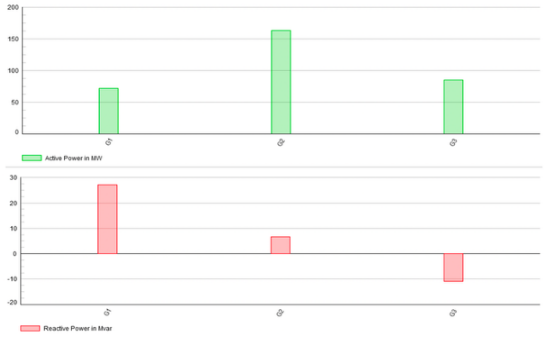

Fig. 8. Active and reactive power for the three generators

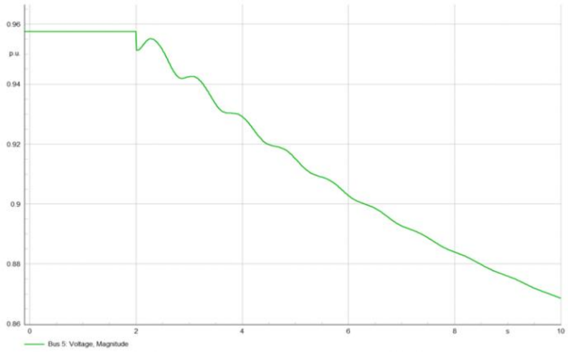

Fig. 9. Bus voltage profile following generator 3 trip under the blackout reference scenario

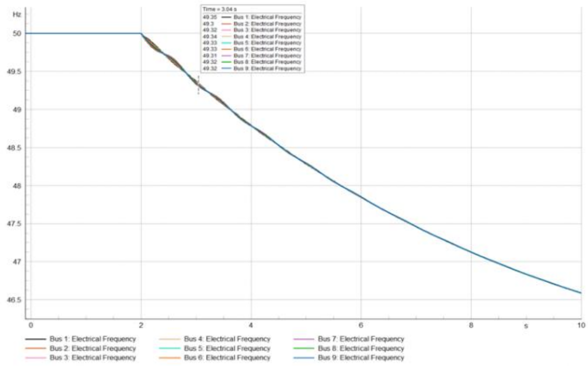

Fig. 10. Frequency profile following a generator 3 trip under blackout scenario

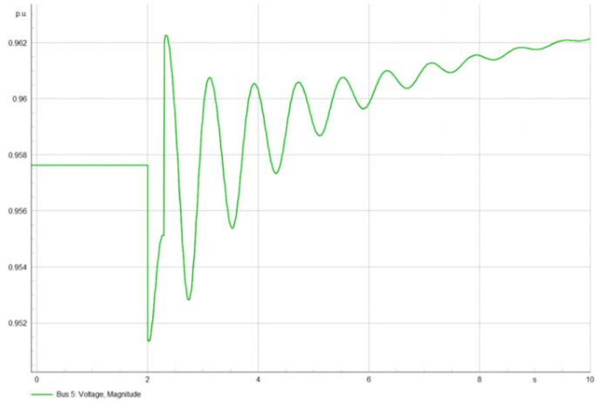

Fig. 11. Bus 5 voltage profile following generator 3 trip and subsequent load shedding.

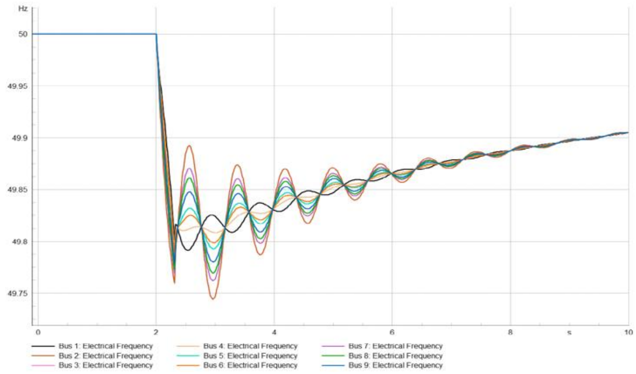

Fig. 12. Power system frequency following generator 3 trip and subsequent load shedding

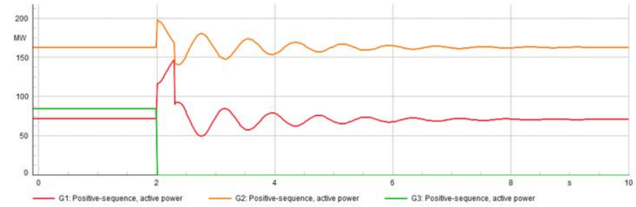

Fig. 13. Active power profiles of all generators following generator 3 trip and subsequent loadshedding.

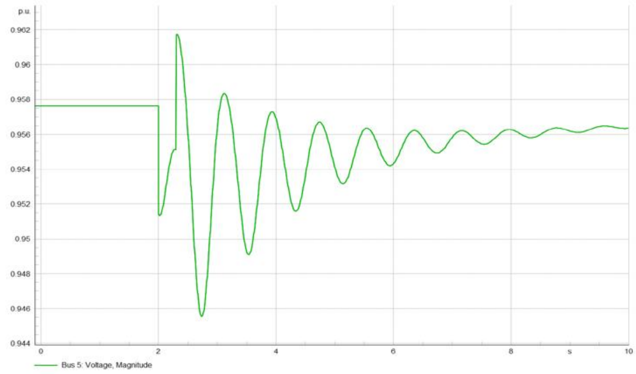

Fig. 14. Bus 5 voltage profile following generator 3 trip with BESS support at buses 6 and 8.

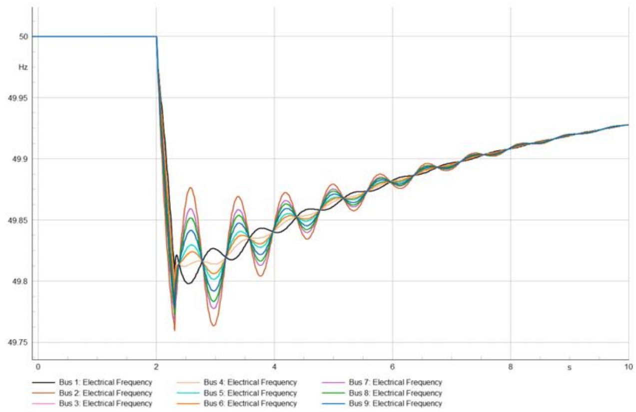

Fig. 15. Power system frequency following generator 3 trip with BESS support at buses 6 and 8

Table 4. Brief comparison of the investigated mitigation strategies

Mitigation Strategy	Minimum bus voltage range (p.u)	Average Voltage recovery time (s)	Frequency Nadir (Hz)
Load shedding	0.9515-0.975	6	49.747
BESS	0.9455-0.9681	4	49.752

6 Conclusion

This study has demonstrated the critical role of blackout mitigation strategies in maintaining power system stability under disturbance conditions. Two key findings emerge from the analysis.

Firstly, the results highlight the inherent limitations of under-frequency load shedding (UFLS) as a mitigation strategy. While UFLS was effective in arresting voltage collapse following a generator outage and restoring system voltages, this was achieved at the expense of system reliability and continuity of supply. The disconnection of approximately 26.6% of the total system demand reduced the frequency nadir to 49.747 Hz, thereby stabilizing the system but introducing significant service interruption. This underscores the paradox of UFLS: although it improves system stability by rebalancing active and reactive power, it remains a reactive and disruptive measure that cannot prevent blackouts without compromising load supply.

Secondly, the study establishes battery energy storage systems (BESS) as a more effective and proactive solution for enhancing system resilience. The integration of BESS enabled simultaneous active and reactive power support, resulting in rapid recovery of both voltage and frequency following generation loss. This behaviour effectively emulates synthetic inertia and advanced voltage support mechanisms characteristic of modern converter-based technologies such as VSC-HVDC, while offering the advantage of distributed and flexible deployment.

BESS reduced the average voltage recovery time by 33.3 % (from 6 seconds to 4 seconds) while maintaining full customer supply. In contrast, load reduction achieved acceptable voltage and frequency recovery only through partial demand curtailment. These results quantitatively demonstrate the operational advantages of BESS for blackout mitigation in low-inertia power system.

The findings indicate that BESS should not be viewed merely as an auxiliary enhancement, but rather as a fundamental component of modern power system design. Its ability to provide fast, coordinated support transforms low-inertia and disturbance-prone networks into more adaptive and self-stabilizing systems. As power systems continue to evolve towards higher penetration of renewable energy sources, the role of BESS becomes increasingly critical in ensuring frequency stability, voltage regulation, and continuity of supply under dynamic operating conditions.

The findings of this study are consistent with the previous research on blackout mitigation strategies. Similar to the work of [12], that revealed that BESS provides fast active power support during disturbances and helps arrest frequency decline after generator outages. Research conducted by [13] highlighted that controlled load shedding can prevent propagation of cascading failures thereby reducing the risk of total system collapse.

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Appendix

The parameters used for the battery energy storage system are as follows:

Table A1. Parameters used for the battery energy storage system

BESS unit	**Power rating (MW)**	**Energy capacity (MWh)**	**SOC limits (%)**	**SOC initial (%)**
Bus 6	50	8,33	20 - 90	80
Bus 8	40	6, 66		
Total BESS	90	15		