

An Adaptive Load-Shedding Approach Applying Wide-Area Measurement Systems (WAMS)

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Abstract: Power system collapses are among the primary challenges in modern grids. Today's power grids face stressful conditions day by day. The increase in electricity consumption, the expansion of electrical networks, and the oldness of protective equipment are among the stressful items in today's networks. In this stressful situation caused by the low stability margin in power networks, load shedding (LS) is the last solution to prevent power system collapse. Various conventional and independent LS programs will no longer respond to the existing conditions. Therefore, the load-shedding scheme considering the existing conditions and appropriate to the types of instabilities is very necessary. To improve the load-shedding programs, various methods are suggested in the articles. The expansion of wide-area measurement systems and increasing use in electrical networks have made it possible to be more maneuverable in load-shedding programs than before. Hence, a new adaptive LS approach is proposed based on the combined instabilities, which shows better behavior than the existing programs. Validation of the suggested approach is investigated in a real power grid.

Keywords: adaptive load shedding scheme; combined load shedding; adaptive protection system; wide-area measurement systems (WAMS)

1 INTRODUCTION

With the growing energy demand, power systems are now operating very close to their sustainability limits, leading to a minimal sustainability margin. As a result, network components are functioning near their maximum available capacity [1], [2]. In such circumstances, any significant disruption can cause an imbalance in consumption and production and ultimately jeopardize the power system's stability [3-5]. Therefore, in recent years, there have been numerous reports of various types of instabilities and even overall blackouts in power systems. Voltage instability, frequency instability, and rotor angle instability are the basis of power system instability. To assert such instabilities, several practical measures are implemented [6]. The first action involves activating stability control equipment to maintain the power grid's stability. Load-shedding (LS) is used as a last-resort action to preserve network stability [6].

Frequency is a key indicator in power systems, reflecting the balance between production and consumption of active power. One of the most widely used LS approaches to maintain power grid stability is the under-frequency load-shedding (UFLS) scheme. In this approach, the timing, location, and quantity of loads to be shed for each disturbance, regardless of its intensity, are determined by relying on previous network evaluations. Similarly, the under-voltage LS plan was developed to prevent voltage instability in power grids. Despite the local nature of voltage stability, this plan is also implemented based on offline evaluations [7].

Although conventional load-shedding plans can sometimes restore power systems' stability, they have several drawbacks. These include setting a frequency threshold, determining the shed load amount, the stepping load-shedding plan, selecting loads leaning on previous network studies, and ignoring the combination of different inconsistencies, among other issues [8].

Multiple studies have introduced strategies to address the limitations of traditional load-shedding (LS) programs. Several researchers have suggested various schemes to

minimize the drawbacks of the under-frequency load-shedding plan. These include the reduction of the relay's delay time during major disturbances with significant frequency drops and local LS are among other plans aimed at maintaining the power systems' frequency stability [9]. However, failing to account for the combined instabilities remains a significant defect of the designed plans. In references [10, 11], an LS program has been introduced, but the one-dimensional perspective on instabilities continues to be a major disadvantage of existing approaches. In [12], the authors applied the Thevenin equivalent model to enhance the conventional UFLS plan. However, one of the drawbacks of this approach is its high computational burden. References [13, 14] suggested utilizing voltage changes to precisely determine the locations for load shedding within the voltage load-shedding program. The main defect of many suggested cases is that they rely on the offline evaluation of loads leading to instability, take gradual load increase as the agent of instability, and do not consider the combined instabilities. To accurately determine the active power unbalance, response-based and event-based approaches have been introduced. In reference [15], the voltage stability index (VSI) is utilized to recognize buses as vulnerable to instability. This local indicator is effective for assessing voltage instability but might not be suitable for addressing combined voltage and frequency instabilities. Simultaneously, determining the networks' impedance and generator equivalents to determine the location of shed loads using the Jacobian Matrix is another method that can be applied in power grids. However, the high computational time makes its online application challenging [16]. Seyedi et al. introduced load-shedding methods based on responses and events to determine the amount of load to be removed. In this approach, they proposed the LS plan in specific steps, tailored for both large and small events [17]. Even though computational time has been reduced and stability has relatively improved, the proposed method still faces challenges such as voltage amplitude index and the presence of buses with identical magnitudes.

Voltage instability often does not occur in isolation; it is

frequently intertwined with angle instability, where one can be unstable the other. Similarly, frequency instability may also be highly dependent on either angle or voltage instabilities. Both voltage and frequency instability are critical factors in power system instability, and if not addressed promptly, they can cause other power plant units to trip, potentially leading to a partial or complete blackout of the power grid.

With the growing adoption of WAMS in power grids, control and protection programs have gained greater flexibility. Therefore, in this manuscript, a new adaptive and wide-area load-shedding scheme is proposed that takes into account the combination of various instabilities. This method also considers the impact of rotor angle on instabilities.

The rest of the manuscript structure is as follows: Section 2 introduces both adaptive and conventional UFLS schemes. Section 3 provides a detailed evaluation of the proposed LS scheme. Section 4 briefly introduces and analyzes the studied test system along with the related figures. Finally, Section 5 presents the conclusions.

2 LOAD SHEDDING (LS) APPROCHES

Various LS approaches have been suggested to enhance LS schemes. The conventional UFLS method is the oldest LS plan in power grids, while the modal analysis plan, highlighted in many recent articles, is presented as a new approach and thoroughly reviewed.

2.1 Conventional Under- Frequency LS Method

In this LS approach, when the frequency falls under a specified threshold, it will sequentially disconnect certain loads from specific buses. The overall power imbalance will be calculated using Eq. (1) and Eq. (2).

$$L = \frac{\text{Total Consumption Load} - \text{Total Generation Power}}{\text{Total Generation Power}} \quad (1)$$

$$LD = \frac{\frac{L}{L+1} - d \left[1 - \left(\frac{f_{\min}}{f_n} \right) \right]}{1 - d \left[1 - \left(\frac{f_{\min}}{f_n} \right) \right]} \quad (2)$$

Here, D and LD illustrate the load dependence on frequency changes and the amount of shedded load in specific steps [17].

2.2 Modal Analysis Based Load Shedding Method

To pinpoint the precise location of loads inclined to instability, the Modal analysis approach was suggested in [14]. The active and reactive power (load) is determined using (3). In the following equation, J represents the Jacobian matrix.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \quad (3)$$

Taking into account the significant affiliation of voltage variations with reactive power variation, and considering certain hypotheses, the following equations are obtained.

$$\Delta Q = \left[J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{PV} \right] \Delta V = J_R \Delta V \quad (4)$$

$$\Delta V = J_R^{-1} \Delta Q \quad (5)$$

In this equation, J_R is the reduced Jacobian matrix. Based on Eq. (6) and by breaking it into left and right components, Eq. (7) and Eq. (8) are derived.

$$J_R^{-1} = E_R \xi^{-1} E_L \quad (6)$$

$$\Delta V = E_R \xi^{-1} E_L \Delta Q = \sum_l \frac{E_{R,l} E_{L,l}}{\lambda_l} \Delta Q \quad (7)$$

$$\Delta V_{ml} = \frac{\Delta Q_{ml}}{\lambda_l} \quad (8)$$

In the above equations, E_L and E_R represent the left and right eigenvectors of J_R and also $E_{L,l}$ and $E_{R,l}$ are indicators of the l^{th} row and column of E_R .

Here, λ_l being less than or equal to zero indicates the presence of voltage instability. By decomposing k to the related eigenvectors, the voltage variation due to reactive power variation is represented by Eq. (9).

$$VQS_k = \frac{dV_k}{dQ_k} = \sum_l \frac{\mu_{k,l} \eta_{l,k}}{\lambda_l} \quad (9)$$

Each bus that VQS_k ($V-Q$ sensitivity at bus k) amounts to lean to zero, is more prone to voltage instability.

This approach is reliable. However, it has some disadvantages. For example:

- The high computational burden of the Modal analysis makes it difficult to use this method on online platforms, especially in large or combined disturbances.
- The agent of instability is limited to gradual load growth, while generator trips and line outages have an important role in power system instabilities.

3 THE NEW ADAPTIVE AND WIDE-AREA LS SCHEME

In [18] and [19], two types of methodologies are utilized to precisely quantify the power imbalance. The author proposed two-step thresholds of the frequency to configure the LS plan. However, the voltage magnitude index is proposed to determine the location of the shed loads. While this index can be applied online during disturbances, it is not a reliable measure for identifying buses prone to instability. Often, multiple buses have the same voltage magnitude, complicating the selection process for identifying buses with more instability potential.

In modern grids, the spreading use of WAMS increases the maneuverability of power networks. Hence, this manuscript introduces a combined scheme that considers the

frequency, voltage, and angle of various buses within the power system. Generators' rotor angle variations affect the voltage angle of neighboring buses and can aid the LS scheme. In the newly suggested approach, the exact power imbalance is calculated using wide area measurement systems data and based on the response-based method. As in [17], a two-step adjustment is used to determine the LS frequency threshold. In a network with a nominal frequency of 50 Hz, this threshold is designed based on the rate of change of frequency (ROCOF) in two steps of 49.7 and 49.4 Hz for large and small disturbances. The process of the suggested LS approach is shown in Fig. 1.

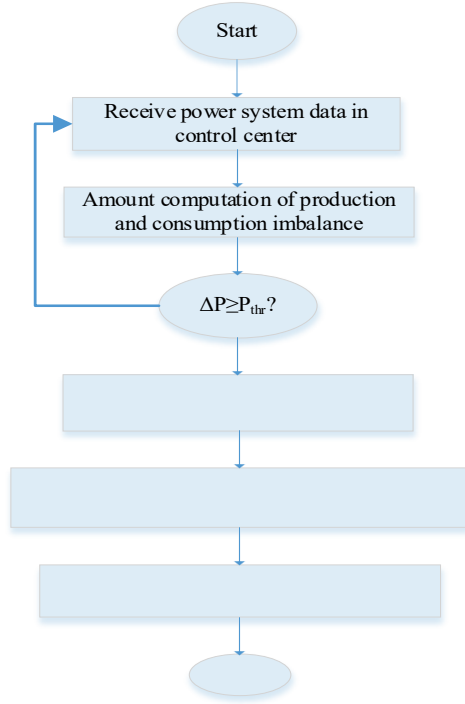


Figure 1 The process of the suggested LS approach

In the suggested approach, power imbalances based on power swing equations are calculated as follows. Here, P_{m_i} and P_{e_i} represent the generator's mechanical and electrical active power on i^{th} the bus.

$$\frac{2H_i}{f_n} \frac{df_i}{dt} = P_{m_i} - P_{e_i} = \Delta P_i \quad (i = 1, \dots, N) \quad (10)$$

To account for the power imbalance across all generators, Eq. (11) can be derived.

$$\Delta P = \sum_{i=1}^N \Delta P_i = \frac{2 \sum_{i=1}^N H_i}{f_n} \frac{df_c}{dt} = \varepsilon \frac{df_c}{dt} \quad (11)$$

Where

$$f_c = \frac{\sum_{i=1}^N H_i f_i}{\sum_{i=1}^N H_i} \quad (12)$$

$$\varepsilon = \frac{2}{f_n} \sum_{i=1}^N H_i \quad (13)$$

Considering the reserve capacity (P_{thr}) of the power plant units, the final load-shedding amount (P_{shed}) is determined using Eq. (15).

$$P_{\text{shed}} = SM \times (\Delta P - P_{\text{thr}}) \quad (14)$$

The tripped units may contribute to the spinning reserve included in the LS program. Therefore, a safety margin (SM) has been weighed into the LS calculations.

Given the localized essence of voltage and the presence of adjacent buses within the similarity limit, selecting buses to shed becomes challenging. To address this issue, a newly adaptive and wide-area LS scheme has been proposed. Fig. 2 illustrates the perspective of an equivalent grid. The voltage magnitude and angle of the bus are key factors in determining the current flow, which subsequently affects the voltage decrease on the power system. Consequently, as reactive and active power flows through the equivalent network, the voltage drop will be intensified, potentially leading to instability and collapse of the power system.

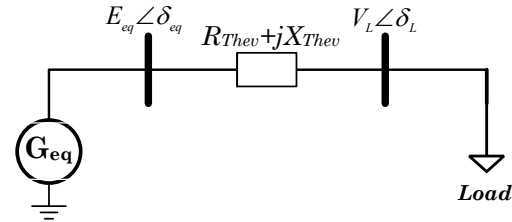


Figure 2 The perspective of an equivalent grid

The load current flow in the equivalent grid (I_L) is derived using Eq. (15).

$$I_L = \frac{E_{\text{eq}} \angle \delta_{\text{eq}} - V_L \angle \delta_L}{R_{\text{Thev}} + jX_{\text{Thev}}} \quad (15)$$

$$S_{\text{GL}} = E_{\text{eq}} I_L^* \quad (16)$$

In the above equations, E_{eq} , R_{Thev} and X_{Thev} illustrate the Thevenin equivalent of power network voltage, resistance and reactance, respectively, and S_{GL} represents the total power transmitted to the load.

Neglecting the line resistance in Eq. (15), the reactive and active power flow to the load from the equivalent network generator (P_{GL} and Q_{GL}) can be expressed as follows.

$$P_{GL} = \frac{E_{eq} V_L}{X_{Thev}} \sin(\delta_{eq} - \delta_L) \quad (17)$$

$$Q_{GL} = \frac{E_{eq}^2}{X_{Thev}} - \frac{E_{eq} V_L}{X_{Thev}} \cos(\delta_{eq} - \delta_L) \quad (18)$$

Because voltage is a local parameter, different buses in the specific area will have almost the same magnitude. Hence, a bus with a higher voltage angle will drag more current through the equivalent grid, leading to increased reactive and active power transfer through the equivalent network, resulting in a greater voltage drop. Simply put, for buses that are of a similar voltage magnitude, if the equivalent network voltage is supposed to be $1\angle 0$, the near the bus voltage angle is 90° , the higher the flow of reactive and active power and the result is the greater voltage falls. Consequently, that bus can unstable the power grid. The same principle applies to generators; the rotor angle in the vicinity of 90° , the more susceptible to outage.

Furthermore, to enhance the validity of the LS scheme, the suggested approach offers an adaptive and wide-area LS with a lower computation burden and a swift mechanism. This adaptive LS approach has improved the voltage and frequency stability of the power system while addressing the shortcomings of previous programs.

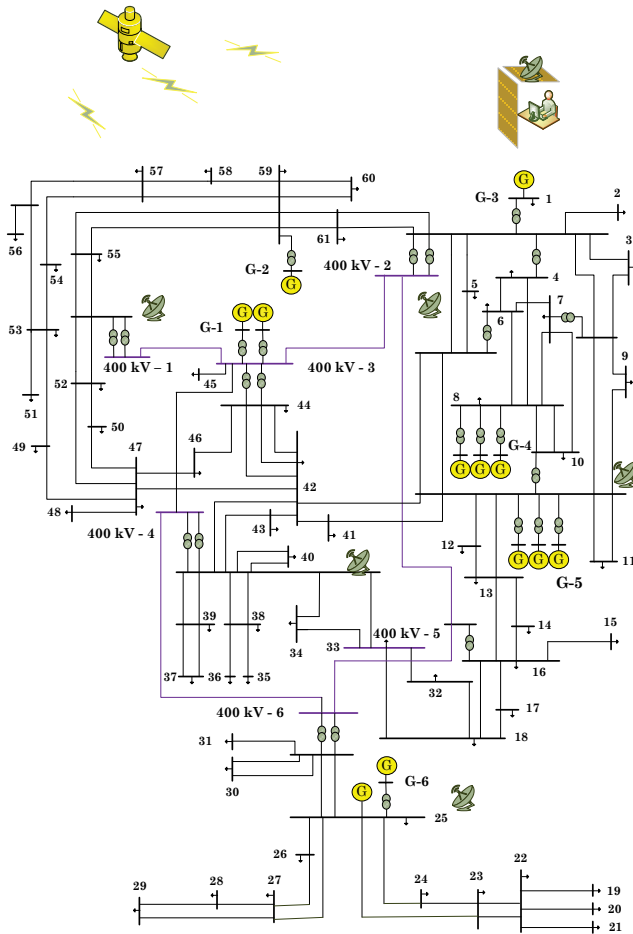


Figure 3 The real Khorasan power grid.

4 NUMERICAL EVALUATION AND DISCUSSIONS

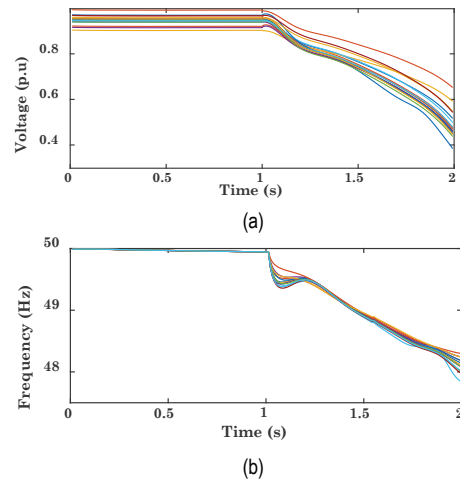
To appraise the effectiveness of the proposed LS approach, the Khorasan power grid (a major part of the Iranian national network) is analyzed using the DigSILENT platform. Fig. 3 depicts the simulated power grid.

This network with 75 buses, a generation capacity of 2370 MW and a spinning reserve of 350 MW, has been evaluated under different scenarios to evaluate the performance of the proposed LS scheme compared to existing approaches. In conventional UFLS relays, the intentional delay time is set at 100 ms, while the implementation time for the proposed scheme and the modal analysis method (assuming real-time implementation without the drawbacks of static analysis and computational load) is set at 200 ms.

The article presents two example scenarios with different characteristics and methods, which can be evaluated in the subsequent sections.

4.1 Major Event: Tripping of all Power Plant Units in G-1

In this disturbance, which occurred on the 1st second, a power of 906 MW was outage from the production capacity. Figs. 4 (a)-(b) illustrate the frequency and voltage changes in different zones without considering the LS approaches. As observed, notwithstanding the grid's spinning capacity and remedial actions, the system experiences concurrent frequency and voltage instabilities, potentially leading to power system collapse. Therefore, to prevent power system collapse, an appropriate load-shedding (LS) scheme must be implemented.

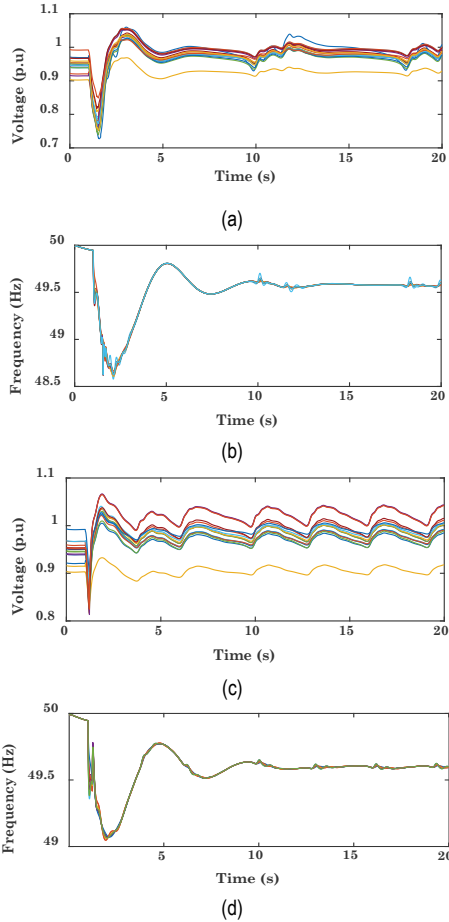


Figures 4 (a)-(b) Frequency and voltage changes in different areas following the major event.

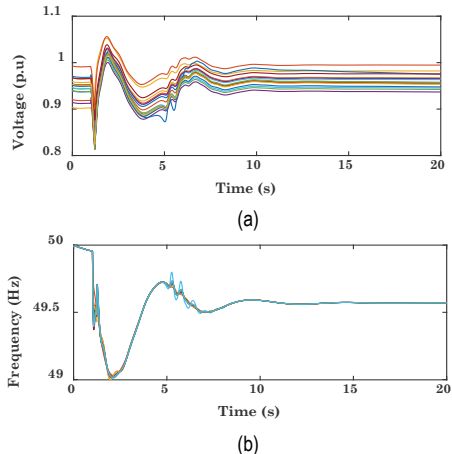
All the LS strategies analyzed, including conventional UFLS, the Modal analysis method, and the suggested approach, have been implemented on the power grid. Figs. 5 (a)-(d) depict the frequency and voltage sample signals in various areas of the grid for conventional UFLS and Modal analysis-based LS approaches. Observing Fig. 5 closely, it becomes evident that although the two simulated load-

shedding methods can restore voltage and frequency stability, there are persistent oscillations in the frequency and voltage waveforms. This indicates that the shed loads might not be optimally distributed.

The frequency and voltage signals for different areas of the power system under the proposed LS approach are depicted in Figs. 6 (a)-(b). Implementing this approach stabilizes the frequency and voltage signals, as evidenced by the absence of persistent state fluctuations.

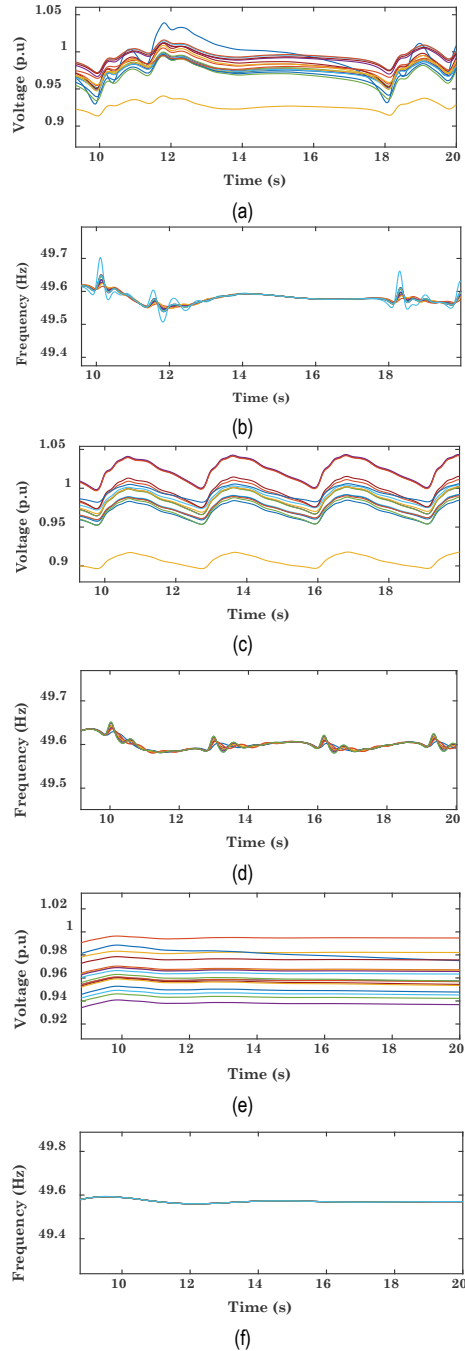


Figures 5 (a)-(b) Stability improvements achieved using the conventional UFLS scheme, (c)-(d) Stability improvements achieved using the Modal analysis scheme.



Figures 6 (a)-(b) Stability improvements achieved using the proposed LS scheme.

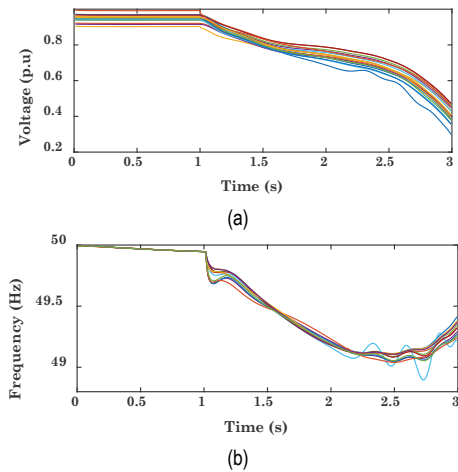
Based on the simulation results and the magnification of the frequency and voltage signals for sample buses in various areas during a near-to-final condition (from the 10th to the 20th second), Figs. 7 (a)-(f) have been derived. Upon close examination, it becomes evident that, notwithstanding their ability to restore frequency and voltage, the conventional UFLS and modal analysis methods also exhibit oscillatory instabilities. In contrast, the proposed scheme achieves better frequency and voltage recovery with less amplitude variation and no oscillation.



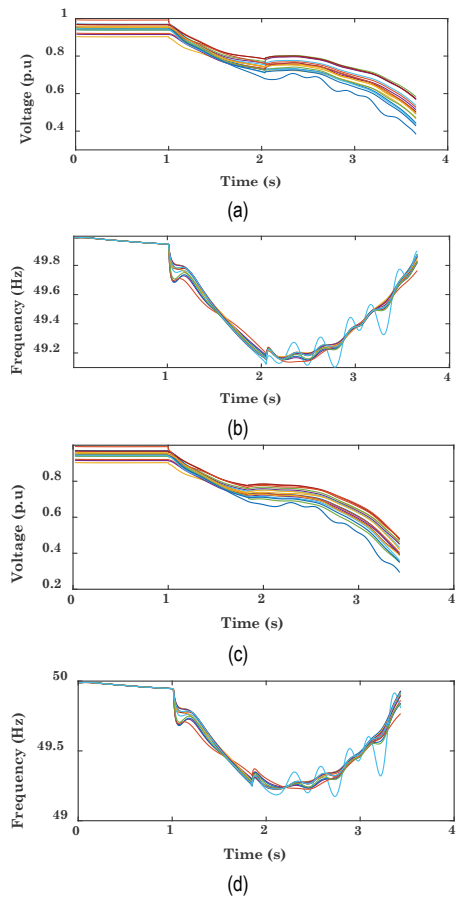
Figures 7 (a)-(b) The magnified frequency and voltage behavior for the conventional UFLS approach, (c)-(d) The magnified frequency and voltage behavior based on the Modal analysis LS approach, (e)-(f) The magnified frequency and voltage behavior based on the proposed LS approach.

4.2 Minor Event: Tripping of all Power Plant Units in G-3 and 2 to 3 Tie-Line

In this disturbance, which occurred on the 1st second, a power of 560 MW was outage from the production capacity. Subsequently, the 400 kV-2 to 3 tie-line is also outage. Figs. 8 (a)-(b) display the frequency and voltage variations across different areas of the network.

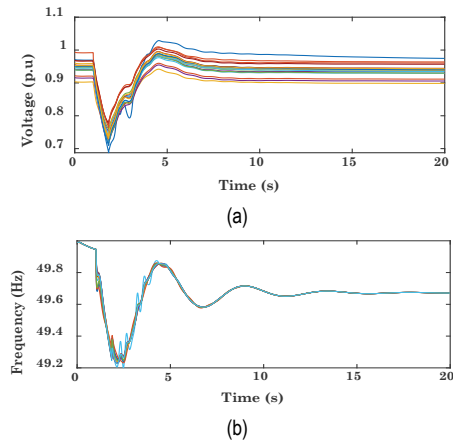


Figures 8 (a)-(b) Frequency and voltage changes in different areas following the minor event.



Figures 9 (a)-(b) Stability improvements achieved using the conventional UFLS scheme, (c)-(d) Stability improvements achieved using the Modal analysis plan.

The frequency and voltage outcomes in various areas of the power system, derived from LS approaches, are illustrated in Figs. 9 (a)-(d) and Figs. 10 (a)-(b).



Figures 10 (a)-(b) Stability improvements achieved using the proposed LS scheme.

As depicted in the corresponding figures, both the conventional UFLS and Modal analysis approaches, despite their efforts to recover frequency, have experienced voltage instability, resulting in the network's collapse. The proposed index demonstrates superior performance among the simulated methods.

4.3 General Discussions

A detailed brief of the simulation results is provided in Tab. 1. For the evaluated network, the threshold value used to identify the severity of large or small events is based on the ROCOF, set at 1.7 Hz/s and 1.4 Hz/s, respectively. In this simulated system, a safety margin is considered at 1.05. Events in this simulation are initiated at the 1st second. If stability is observed around the 20th second, Tab. 1 will display the voltage and frequency magnitude range (V_{min} , V_{max} and F_{min} , F_{max}) of the network's various buses following the different events. In the first event, the conventional load-shedding plan is executed in three steps, resulting in higher shed loads compared to other approaches. However, in the absence of adaptive selection for the shed load locations, voltage and frequency waveforms exhibit fluctuations in various areas during steady states. Similarly, despite the computational burden of the Modal analysis LS approach, it also results in voltage and frequency fluctuations, although with fewer shed loads than the conventional method.

The proposed LS scheme, on the other hand, demonstrates superior and acceptable behavior post-disturbance. With fewer shed loads, it achieves better frequency and voltage restoration across different network areas, exhibiting low variance and no fluctuations.

In the other scenario, the conventional LS approach is activated only in the first step, leading to voltage instability and eventual network collapse despite efforts to restore frequency. The modal analysis plan shows similar behavior, causing network instability and collapse due to voltage issues despite shedding more loads.

The proposed load-shedding scheme, with lower computational demands compared to the modal analysis and more adaptive to the type and location of the incident than conventional methods, performs acceptably in such combined disturbance scenarios. In both modal analysis and conventional UFLS approaches, the network is prone to instability and blackouts.

The proposed LS approach is feasible for implementation in any power network, thanks to the availability of WAMS. Future research can explore the impact of load models and load restoration methods on the load-shedding program following network modifications.

Table 1 Comparison of the simulated LS approaches

Disturbance	LS approach	F_{\min} (Hz)	F_{\max} (Hz)	V_{\min} (p.u)	V_{\max} (p.u)	ΔP_{shed} (MW)	Shedded buses
First scenario	Conventional	49.576	49.625	0.929	1.008	542.9	4-11-14-15-28-36-37-40-43-47-52-53-54-55
	Modal analysis	49.463	49.599	0.903	1.019	583.8	1-2-3-6-9-12-15-17-18-20-21-22-23-25-27-32-34-42-44-50-51-53-54-55-58-59-60
	Proposed	49.569	49.569	0.937	0.995	531.1	6-7-10-37-48-49-51-53-54
Second scenario	Conventional	Unstable	Unstable	Unstable	Unstable	158.7	15-40-47-53-54
	Modal analysis	Unstable	Unstable	Unstable	Unstable	221.5	3-35-46
	Proposed	49.671	49.671	0.899	0.975	219.4	2-16-17-19-20-21-22

5 CONCLUSION

In summary, this study proposes a novel adaptive LS approach designed to enhance power system frequency and voltage stability. Key insights include:

- **WAMS Data:** Fundamental for implementing the scheme, facilitating precise selection of loads prone to instability.
- **Reduced Computational Burden:** By considering another network index for load selection, the method reduces computational demands compared to other adaptive programs.
- **Improved Response:** The adaptive approach effectively addresses various types of disturbances, outperforming constant load-shedding patterns used in conventional methods.
- **Advantages over Conventional UFLS:** Avoids the limitations of fixed load-shedding amounts, timing, and locations.
- **Challenges with Modal Analysis:** Although providing an admitted result, it entails a high computational burden and may not always maintain network stability, because of gradual load growth as an instability factor.
- **Better Performance:** The proposed scheme shows faster and superior behavior in responding to disturbances, aiming to mitigate the shortcomings of existing programs.

The adaptive load-shedding scheme leverages WAMS data and a strategic load selection index to offer a more resilient and efficient solution for maintaining power system stability.

5.1 Notice

The Khorasan network, encompassing 5 large power plants and 75 buses at 400 kV and 132 kV levels, boasts an installed generation capacity of approximately 2700 MW, with a spinning reserve of around 350 MW at peak load. For dynamic network stability studies in this paper, the Khorasan network has been meticulously and dynamically modeled, incorporating an accurate load model that simulates load

behavior under voltage and frequency instability. Additional details about the Khorasan network are available in reference [20].

Nomenclature

L	Total overload amount
LD	Total amount of load to be shed in UFLS
d	Load reduction factor
$f, df/dt$	Frequency and its rate of change (ROCOF)
f_{\min}	Minimum permissible frequency in power network
f_n	Power system nominal frequency
f_c	Frequency of the equivalent inertial centre
f_{setting}	Frequency setting in UFLS scheme
N	Total number of generators
H_i	Inertia constant in i^{th} generator
V	Bus voltage magnitude
i, k	Bus indices

Greek Symbols

ε	Constant value
ΔP	Generation-consumption mismatch
δ_L	Bus voltage angle
ζ	Diagonal eigenvalue of JR
ΔV_{ml}	Variation of l^{th} modal voltage
ΔQ_{ml}	Variation of l^{th} modal reactive power
λ_l	l^{th} eigenvalue of J_R
$\mu_{k,l}$	k^{th} element of $E_{R,l}$
$\eta_{k,l}$	k^{th} element of $E_{L,l}$

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