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Adaptive Preventive Load Shedding Using FVSI and Fuzzy Logic in Power Systems

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ABSTRACT

In power systems, protection mechanisms such as Load Shedding (LS) are implemented to mitigate the risk of voltage collapse (Blackout). This study is dedicated to the investigation of preventive LS, a strategy aimed at alleviating power transits before they reach critical levels, thereby ensuring voltage stability. The methodology employed leverages a Fuzzy Logic (FL) algorithm to optimise the process. A key aspect of this research is the identification of optimal locations for LS, which involves pinpointing network branches that are particularly vulnerable to voltage collapse. This is achieved through the application of the Fast Voltage Stability Index (FVSI), which guides the strategic reduction of loads and power flows in critical branches. A series of case studies carried out on a typical IEEE 30-bus power system shows that the proposed approach exhibits a significant improvement over conventional LS techniques. The results underscore the efficacy of this method in enhancing the reliability and stability of the power system, particularly in scenarios where voltage stability is at risk. This research contributes to the ongoing development of more advanced and responsive LS strategies in power systems, offering a significant enhancement in power system protection and stability.

1. INTRODUCTION

Contemporary electric power systems face significant challenges due to rising demand and heavy loading conditions, leading to voltage instability and widespread power outages worldwide. These challenges arise from the need to meet growing electricity consumption, maximise economic benefits, and optimise transmission efficiency. Addressing these issues requires a comprehensive strategy that includes enhancing grid infrastructure, implementing advanced monitoring and control technologies, encouraging demand response programmes, incorporating various Renewable Energy Sources (RES), and utilising energy storage technologies. Such measures aim to improve system resilience and stability in the face of increasing demand and operational complexities [1].

Voltage instability results from the demand exceeding the power system's capacity, leading to potential failures that are crucial triggers for power outages. Key factors include inadequate transmission infrastructure, diverse electrical loads, and the geographical gap between power generation and consumption. Mitigating this instability requires strategies like Load Shedding (LS), capacity enhancement, and integrating RES, which are essential for a reliable electricity supply amidst growing demand and the shift towards renewable sources [2].

The effectiveness of Undervoltage Load Shedding (UVLS) as a mechanism for maintaining system stability critically depends on accurately determining the LS's magnitude, timing, and geographic specificity. If these decisions are not made correctly, they can worsen voltage instability, collapse, or go over frequency, which can manifest as too much or too little shedding. According to the literature [3], LS that is not precisely targeted can also cause unnecessary service interruptions. This can hurt customer trust and lower utility revenues. The significance of timely execution in load-shedding interventions, highlighting its pivotal role in ensuring voltage stability, is further underscored in the study [4].

Voltage profiles significantly impact voltage stability in electrical power systems, with instability risks increasing as voltage drops due to reactive power changes [5]. UVLS is highlighted as a key measure to counteract such instabilities and prevent blackouts, emphasising the importance of reactive power management [6]. The success of UVLS depends on accurately determining the load to shed, its timing, and its location to avoid voltage collapse or frequency issues, as per [3]. The critical nature of timing in LS is further underscored [4], pointing to the need for precise execution of UVLS for power system stability.

Power system optimisation has significantly improved thanks to progress in AI. Various optimisation and AI techniques have been applied for UVLS, each with its own advantages and drawbacks. Key players in this improvement are meta-heuristic algorithms like Genetic Algorithms (GA), which have been used for optimising UVLS parameters, but they have a slow convergence rate and are not adaptable to real-time variation in grid conditions. However, Particle Swarm Optimisation (PSO) has been applied to determine optimal LS locations and amounts; nonetheless, it is prone to getting stuck in local optima and has difficulty adapting to dynamic grid fluctuations. These techniques have enhanced LS optimisation while maintaining load and voltage stability margins [7-10]. Adding Artificial Intelligence (AI), especially Machine Learning (ML), to UVLS strategies has complicated them. AI, especially ML, has piqued attention for improving UVLS strategies. ML techniques, including Neural Networks (NNs) with traditional analytical methods, have been applied to predict voltage instabilities and optimise LS. These approaches offer data-driven decision-making and can identify complex patterns in voltage behaviour that traditional rule-based methods may overlook.

However, AI and ML approaches have major limitations restricting their applicability in real-world UVLS implementations. Here, ML models depend greatly on large-scale historical data sets that are not always available, like in rapidly changing power systems with fluctuating RES. The lack of transparency and explainability is a significant challenge in practical situations that frequently demand a clear explanation for LS decisions. Additionally, applying Fuzzy Logic (FL) and neuro fuzzy systems has further enhanced performance [11-13]. This progression reflects a shift towards more accurate and efficient management of power systems by utilizing cutting-edge computational techniques.

Advanced optimization techniques such as GA and PSO improve UVLS precision, enabling smart grid management and resilience in modern power systems [14].

These methods balance load, voltage, and stability, helping power systems adapt to evolving demands.

Recent advancements in UVLS research, particularly those in studies [15-18], have redefined it as an optimisation problem ideal for meta-heuristic algorithms. Despite their efficacy, many current methods need more flexibility across different operational scenarios and overlook real-time considerations in using Artificial Neural Networks (ANN) for prediction. ANNs have been applied to predict voltage stability and to improve adaptive UVLS strategies. However, their effectiveness is restricted because they require extensive training data and are essentially "black box" that render their decision-making process largely uninterpretable. Additionally, LS decisions are frequently based on a single Stability Index (SI), which assesses the proximity between buses and power sources, limiting the depth of analysis and often resulting in uneven load distribution. This points to a critical need for UVLS solutions that are dynamic and robust.

New research, such as that in the study [19], suggests two creative ways to deal with these problems. The first uses a coevolution algorithm in UVLS relays, which is based on NN, to help people learn to work together and make better decisions. The second improves bus prioritisation by combining different classification methods that use different SI measures. This multi-index approach provides a more comprehensive assessment and ensures a more balanced LS process. Together, these developments mark substantial progress in tailoring UVLS strategies to the complex demands of modern power systems, paving the way for more adaptable and effective network stability management.

Previous studies have been cited to have employed decentralised decision-making systems in which each LS relay makes decisions based on the parameters available at the bus to which it is connected and the load it serves. Most of them use a single parameter, such as voltage, to determine amount load that should be shed. But it can be potentially improved by incorporating other parameters, like stability indices, for better precision and performance.

The main contributions to this manuscript can be identified as follows:

The approach applies an FL algorithm to improve the decision-making process in LS, thereby increasing accuracy and efficiency.

The Fast Voltage Stability Index (FVSI) is used to identify critical network branches for voltage failure.

The proposed approach has been validated using case studies on the standard IEEE 30 bus system, which shows its practicality and effectiveness.

Together, these contributions promote understanding and implementation of preventive load-shedding strategies and provide a more stable and reliable power system.

The structure of this paper is organized as follows: Section 2 provides a comprehensive overview of preventive load shedding. Section 3 delves into problem modeling, discussing in detail the objective function, constraints, and the proposed techniques. Section 4 presents the technical approach to the proposed load shedding strategy. Section 5 shows the simulation results. Section 6 presents the comparison study results. Finally, Section 7 provides the conclusion.

2. PREVENTIVE LOAD SHEDDING

This section summarizes the existing preventive LS schemes proposed in the literature:

2.1 Conventional preventive Load Shedding

This type of LS prevents potential overloads on critical network branches through several key actions. Power transients are continuously monitored and compared against technical limits, accounting for factors such as cable capacity and equipment switching. Early detection identifies branches nearing or exceeding these limits. Progressive LS redistributes loads, adjusts generator outputs, or modifies consumption patterns to maintain network stability. Selective LS reduces the load on critical branches, keeping power transients within safe limits by redirecting loads or activating control devices.

The determination of the amount of load to be shed, S_{shed}, using the conventional technique of preventive LS can be summarized by the following equations:

$$\text{Threshold 1: } if \quad S_{i-j} \geq 90\% \, S_{limit\,(i-j)}, \quad S_{Shed\,(i-j)} = 30\,\% \, S_{Load\,(j)} \tag{1}$$

$$\text{Threshold 2: } if \quad S_{Shed\,(i-j)} > 50\% \, S_{Load\,(j)}, \quad S_{Shed}(\text{i, j}) = 50\% \, S_{Load\,(j)} + 30\% \, S_{Load\,(j+1)} \tag{2}$$

$$\text{Threshold 3: } if \quad S_{Shed\,(i-j)} > 50\% \, (S_{Load\,(j)} + S_{Load\,(j+1)}), \quad S_{Shed}(\text{i, j}) = 50\% \, S_{Load\,(j)} + 50\% \, S_{Load\,(j+1)} + 30\% \, S_{Load\,(j+1)} \tag{3}$$

Conventional preventive LS employs fixed voltage thresholds at designated buses to initiate shedding events. Suppose the initial shedding is insufficient to satisfy the required load reduction from a branch-level perspective. In that case, additional load is shed from downstream buses along the same power transfer path, as shown in Figure 1. While methodologically simple, this scheme exhibits limited adaptability, as it applies fixed shedding quantities without evaluating the disturbance severity or considering load prioritisation. As emphasised in studies [20, 21], the use of static thresholds and the absence of real-time responsiveness significantly constrain its effectiveness, thereby reinforcing the need for more flexible and adaptive LS strategies tailored to system conditions.

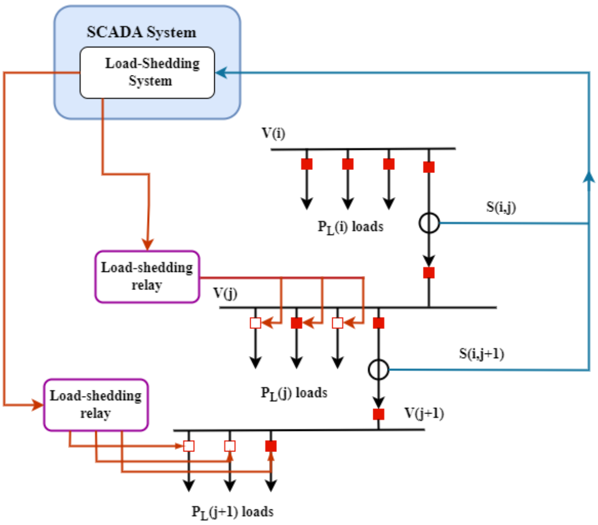

Figure 1. Principle of preventive Load Shedding (LS)

2.2 Intelligent preventive Load Shedding

Effective load management in a power system is crucial for maintaining system stability and preventing outages. An innovative approach involves developing an optimal LS strategy, using simulation to assess and refine outcomes. This strategy, as illustrated in Figure 2, is based on the following principle:

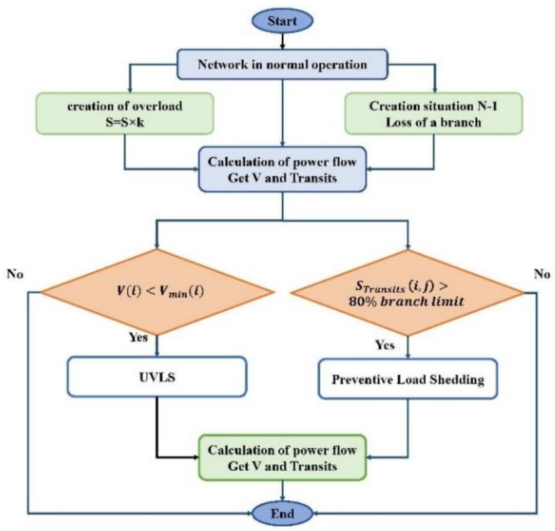

Figure 2. Flowchart of preventive load shedding in the face of Undervoltage Load Shedding (UVLS)

Intelligent preventive LS with optimal thresholds already set aims to lower power flows in branches, which also lowers the voltage difference with the 1 Pu voltage level. If preventive LS does not meet the voltage stability conditions, a UVLS is applied [22]. Evaluating each solution may involve simulating the power system to estimate power transits and the voltage discrepancy resulting from allocating the load to be shed. This simulation objectively assesses each solution's performance under real conditions.

3. PROBLEM FORMULATION

The main objectives of this study are to ensure, in critical operating situations (overload and N-1 state), the following main objectives:

- The voltage profile of the nodes of the entire network must be improved within the stability margin.
- Maintaining the power transits of branches within their tolerable margins.
- The amount of LS should be as minimal as possible at each node.
- The first part of Eq. (4) defines the problem of preventive LS in general. The first is that the process's flow reaches a certain level in relation to the branch's limit.

✓ Minimisation of S_{Shed} (i, j)

$$S_{Shed}(i,j) = \sum_{j \neq i}^{Nbus} X_j(\%) \times \Delta S(\mathrm{i,j}) \tag{4}$$

✓ Minimisation of ΔV

$$\Delta V = \sum_{i=1}^{Nbus} \Delta V(\mathrm{i}) \tag{5}$$

- The minimization of the voltage deviation (ΔV) is adopted as a secondary objective to enhance service quality within the network we used Eq. (5). This parameter is based on the results from the power flow analysis. With

$$X_j(\%) = \frac{S_{Shed}(i,j)}{S_{Load}(\mathrm{j})} \times 100\% \tag{6}$$

$$\Delta S(i,j) = S_{limit}(\mathrm{i,j}) - \mathrm{S(i,j)} \tag{7}$$

$$\mathrm{S\,(i,j)} \geq \mathrm{K}\,(\%) \times S_{limit}(\mathrm{i,j}) \tag{8}$$

$$S_{Load}(j) = P_{Load}(j) + jQ_{Load}(j) \tag{9}$$

$$\Delta V(\mathrm{i}) = |1 - V(\mathrm{i})| \tag{10}$$

$S_{Shed}(i,j)$: Quantity to be shed in MVA per branch, X_j: Quantity to be shed in (%) at node j and j+1 respectively, $\Delta S(i,j)$: Difference between the transit of branch (i, j) and the limit power of this branch, $S(i,j)$: Transit of branch (i, j), $K(\%)$: Level in (%) of the transit of branch (i, j) compared to the limit, $S(j)$: Apparent power of the load of node j. $S_{limit}(i,j)$: Technical limit of the branch in MVA, $S_{Load}(i,j)$: Apparent power called by the load in MVA, and P and Q are the active and reactive powers, respectively.

It is essential to categorize loads according to their category, also referred to as tiers. The entire set of medium voltage feeds is divided into several subsets. Each of these tiers is characterized by an order of priority number, with the highest number corresponding to the non-shedable tier (priority load) [19].

In our work, we adopt four levels of tiers based on the type of load and its economic significance (cost of interruption) and technical importance: residential loads (1), commercial loads (2), industrial loads (3), and non-interruptible loads (4), such as hospitals, military factories, banks, etc.

➢ **Constraints**

The amount of load to be shed (in percentage), represented by Eq. (11), is always constrained by thresholds prescribed by the grid code, where the limits generally range from 5% to 40% and can go up to 50% depending on the type of load departure at the node.

$$X_{j.min}(\%) < X_j(\%) < X_{j.max}(\%) \tag{11}$$

Eq. (12) describes the transit level (in %) reached by a branch, which is constrained by a minimum threshold, K_{min}, representing the onset of overload estimation on the branch generally 80 to 90% of its limit. K_{max} serves as both the setting threshold for protections like Max I and the upper limit of the branch's tolerance, which can reach 120% of its limit.

$$K_{min}(\%) < K(\%) < K_{max}(\%) \tag{12}$$

This work also considers the voltage stability margin in the network, which typically ranges from 0.9 Pu to 1.1 Pu. Eq. (13) details this.

$$V_{i\,min}(pu) < V_i\,(pu) < V_{i\,max}\ \ (pu) \tag{13}$$

$V_{i\,min}$ Et $V_{i\,max}$: minimum and maximum voltage, respectively.

In this work, LS must ensure that the power transit in the branch becomes lower than the technical limit of the branch, as outlined in Eq. (14).

$$\mathrm{S}\,(\mathrm{i,j}) < S_{limit}(\mathrm{i,j}) \tag{14}$$

Eqs. (15) and (16) define the balance between production and consumption. These equations are used to solve the power flow problem, ensuring that the amount of electricity generated matches the amount consumed within the network.

$$P_{gi} - P_{Li} = V_i \sum_{j=1}^{Nbus} V_j Y_{ij}\cos\left(\delta_i - \delta_j - \theta_{ij}\right) \tag{15}$$

$$Q_{gi} - Q_{Li} = V_i \sum_{j=1}^{Nbus} V_j Y_{ij}\sin\left(\delta_i - \delta_j - \theta_{ij}\right) \tag{16}$$

Researchers have developed various stability indices to evaluate the stability of branches, nodes, and other network elements, focusing on variables such as voltage and frequency. This paper analyses the impact of N − 1 contingencies, or line disconnections, using the FVSI index as the main stability metric. The FVSI provides a direct measure of each branch's proximity to instability [23]. Its main advantage is clarity: values near 1 indicate a line is close to the stability threshold, while values near 0 indicate normal operation. Eq. (17) shows how this index is calculated. where Q_{j-i} is the reactive power received at node j. V_i is the voltage size at the sending node. X_{i-j} is the reactance of line $i-j$, and Z_{i-j} is the impedance of line $i-j$.

$$FVSI_{i-j} = \frac{4Z_{i-j}Q_{j-i}}{V_i^2 X_{i-j}} \tag{17}$$

4. TECHNICAL APPROACH TO THE PROPOSED LOAD SHEDDING STRATEGY

The proposed LS strategy aims to enhance the reliability and stability of the power network by introducing a more dynamic and intelligent system for managing power surges and potential overloads.

This section outlines the technical approach of the strategy by analysing the unsuitability of the conventional approach. We can propose some ideas to invent a more intelligent and adaptive approach, such as:

- Variable or dynamic LS thresholds, or the estimate of the overload, depend on the branch's overload level, the deviation from its trigger threshold, and even the voltage level of the transmitter and receiver nodes.
- Variable or dynamic thresholds of quantity to be released.
- Several parameters will be monitored, namely the branch's power transit and its critical state or less critical classification via an indicator that evaluates the latter.

To address this issue, in our work, we have conceived a centralized controller which, following its analysis, implements a more intelligent preventive LS by ensuring an enhanced voltage profile, reduced power transit, and a minimized total LS amount. This controller is equipped with the following parameters:

Inputs

✓ The difference between branch transits and their limits.

✓ The FVSI of the network branches.

Outputs

✓ The amount of load to be shed per branch and subsequently per node.

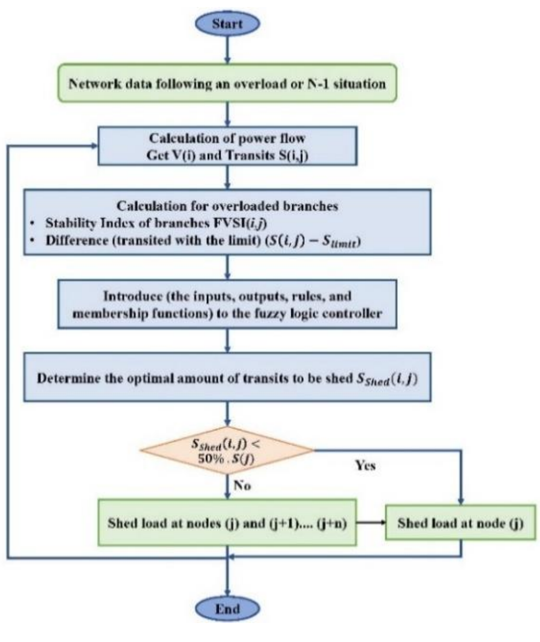

Figure 3. Proposed load-shedding strategy flow chart

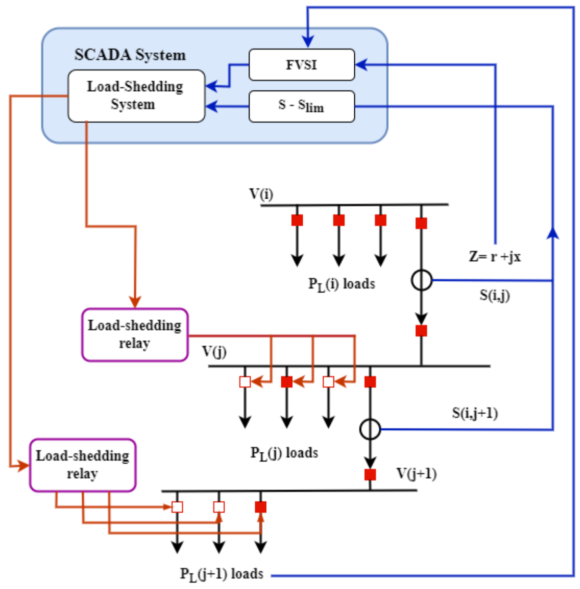

Figure 4. Synopsis of the proposed Load Shedding (LS) strategy

Figure 3 illustrates the proposed LS system. The synoptic diagram of the proposed load-shedding strategy, illustrated in Figure 4, provides a comprehensive overview of this study's approach.

Following the initiation of an incident in the power system (due to overload or an N-1 situation), an initial power flow calculation is conducted. The evaluation of voltage results at nodes and transits in branches informs the appropriate LS decision. However, a UVLS is implemented when the voltage drops below its stability margin. Preventive LS occurs when:

- ✓ The power transit of a branch reaches a threshold close to the trigger limit,
- ✓ The node or branch is evaluated as being in a critical (sensitive) or non-critical state of stability,
- ✓ The FVSI's estimate of the branch's sensitivity determines how much to shed. This quantity pertains to the transit in branches, which is subsequently distributed to the receiving nodes.

4.1 Proposed Load Shedding strategy optimisation algorithm

The centralized LS system is modelled as a controller based on FL as shown in Figure 5, with a command implemented at each LS relay at the network nodes. This system functions as a multifaceted tool similar to a SCADA system; it can measure various network parameters in real time and predictively (through simulation). In our case, it measures the voltage values at the transmitting and receiving nodes, the transit in the branch connecting them, and the development of the FVSI.

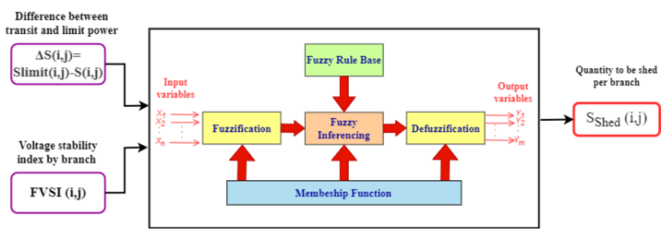

Figure 5. Fuzzy logic controller for the proposed approach

4.2 Implementation of preventive Load Shedding

Conventional preventive LS is based on the principle that a certain amount of load will be shed at the receiving nodes (according to the direction of power flow) of the overloaded branches. This overload is defined as exceeding 95% of the branch's capacity, and the amount to be shed must be sufficient to keep the branch within its operational limits.

- Principle of the Proposed Conventional Preventive LS

If $S_{i\text{-}j} \geq 0.95 \times S_{lim}$ LS $\Delta S_j = 1.05 \times [S_{i\text{-}j} - S_{lim}]$

It can be observed that, like all conventional load-shedding methods, the foundation specifies a fixed threshold for a fixed percentage amount.

- Principle of Preventive LS (Proposed Approach)

The Fuzzy Inference System (FIS) editor displays general information about the fuzzy inference system, as shown in Figure 6.

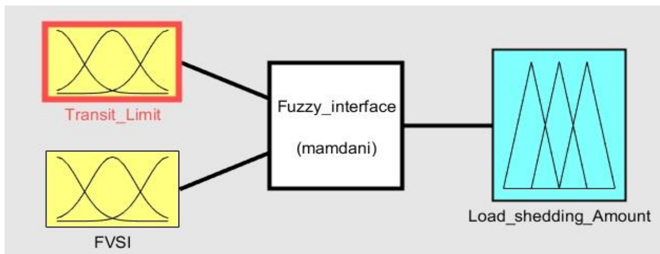

Figure 6. Fuzzy Inference System (FIS) load-shedding editor

The FL controller is structured as follows:

A. Two (02) inputs: the deviation (difference) between the power transients and the technical limit of the branch (ΔS) and the voltage stability index (FVSI), as shown in Figure 7 and Figure 8 respectively.

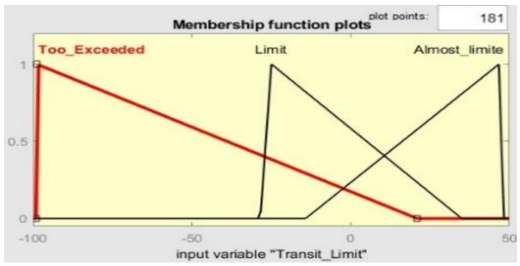

Figure 7. The input variable 1 transient-limit (ΔS)

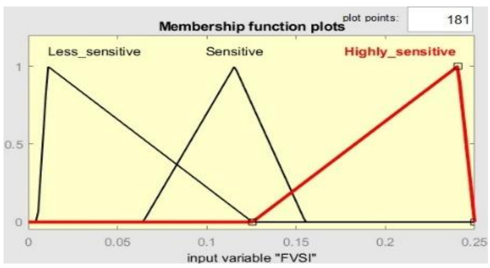

Figure 8. Input variable 2 Fast Voltage Stability Index (FVSI) function

- ✓ Transit-limit (ΔS) rules
  - The (Too Exceeded) function reflects the case where there is a very high exceedance of the branch's technical limit.
  - The (Limit) membership function illustrates the case

where the branch's transient is in the range [90-110%], close to the technical limit.

- The (Almost Limit) function represents the case where the transient is less than or equal to the branch's limit.

✓ FVSI rules

- The FVSI is an effective parameter for identifying the most critical nodes and the corresponding critical branches.
- The (Less Sensitive) function reflects the branch's stability, while the other two functions represent the branches' degrees of sensitivity.

B. One (01) output: The amount of LS in (%) as presented in Figure 9.

- The (Low) function starts at 0.05 (5%) and goes up to 20-25%.
- The (Medium) function applies when the amount exceeds 20% up to 30%.
- The (Excessive) function applies when the LS exceeds 30% up to 50%, which is the limit of LS.

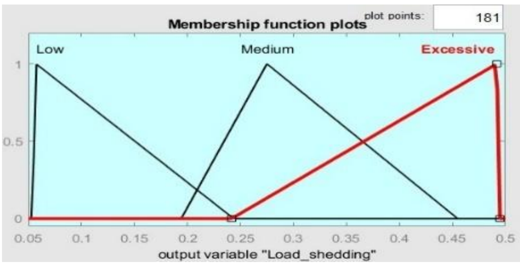

Figure 9. The output variable – (Load Shedding (LS) quantity)

Table 1. Fuzzy controller rules

Rule Number	If Transit-limit (△S)	And FVSI	Then Shedding Amount
01	Too Exceeded	Highly sensitive	Excessive
02	Too Exceeded	Sensitive	Excessive
03	Too Exceeded	Less sensitive	Medium
04	limit	Highly sensitive	Excessive
05	limit	Sensitive	Medium
06	At limit	Less sensitive	Low
07	Almost Limit	Highly sensitive	Medium
08	Almost Limit	Sensitive	Low

Table 1 represents the FL conditions for obtaining an optimal amount of LS, which are as follows:

• ***R1–R2***: If the branch is severely overloaded and voltage stability is critical, implement excessive LS.

• ***R3***: If the branch is highly overloaded but voltage stability remains acceptable, apply moderate LS.

• ***R4***: If the branch operates near its limit and the FVSI shows high sensitivity, apply aggressive shedding to maintain system stability.

• ***R5***: If both overload and voltage sensitivity are moderate, apply medium shedding.

• ***R6***: If the system operates near its limit but remains stable, apply minimal shedding.

• ***R7***: If the branch is not overloaded but voltage sensitivity is high, apply preventive medium shedding to address potential fluctuations.

• ***R8***: If loading is near the limit and sensitivity is moderate, apply low shedding.

5. SIMULATION RESULTS

This part concerns several simulations reflecting the power system's behaviour via voltage variation. To achieve this, we adopt three approaches, conventional, preventive, and intelligent, based on the FL described in the preceding section. These simulations demonstrate the effectiveness of intelligent LS.

5.1 Presentation of the system under study

Simulations were performed using MATLAB and the MATPOWER toolbox to validate the cases studied. The adaptive LS was determined using a fuzzy logic controller (FLC) implemented with MATLAB's Fuzzy Logic Toolbox. These simulations were conducted on the standard 30-bus IEEE test network, as illustrated in Figure 10.

Note*:*

For the rest of the simulations, the 132 kV network will be referred to as the transmission network, and the 33 kV network will be referred to as the distribution network [24].

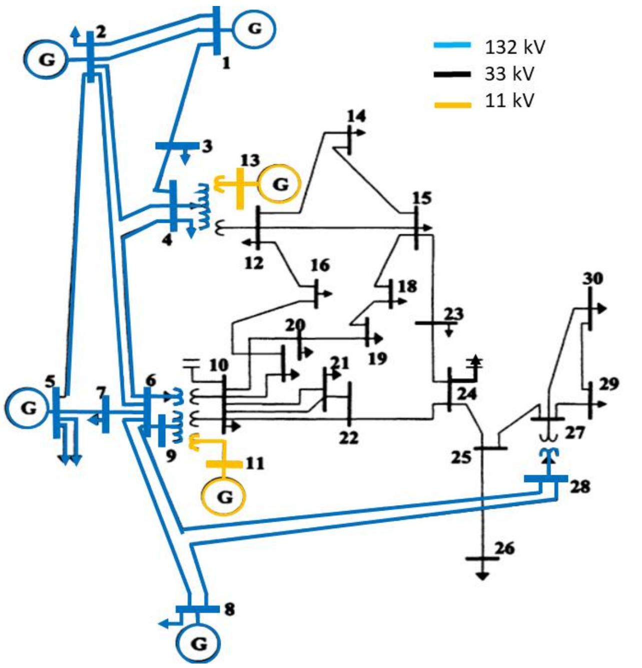

Figure 10. IEEE 30 bus system test

5.2 Definition of case studies

The following scenarios are applied to the responses of the electricity network studied:

- *Basic case:* No overload and no fault.
- *Overload on the whole network:* The applied overload is 50% beyond the normal consumption, i.e., 1.5x the initial power.
- *Loss of one branch at overload:* Specifically, branch 22-24.

For each case study, we are interested in evaluating the network behaviour following the scenarios defined in terms of voltage profile and transits of the network branches and after the LS.

The simulations proposed in this phase are divided into two parts:

a) **Case 1** (simulations following faults before LS),
b) **Case 2** (simulations following faults after intelligent preventive LS using the proposed approach).

a) Case 1 (Before Load Shedding)

1. Base case

The initial simulation, which serves as the baseline scenario, illustrates the behaviour of bus voltages and branch flows under normal operating conditions.

Figure 11 presents the voltage profile of a 30-bus system. The graph represents the voltage variation for each bus in the power system. It is observed that the voltage is within the acceptable operating range, defined between 0.94 and 1.01 p.u. This range represents the voltage limits allowed to ensure the stable and secure operation of the power system.

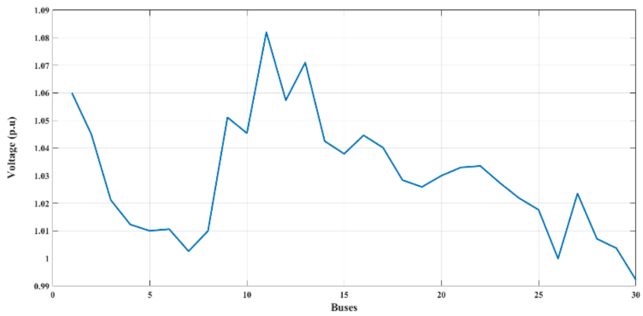

Figure 11. Voltage profile of the IEEE 30-bus system without faults

Figure 12 shows the transiting powers in the branches without any defect. The power flow does not exceed the maximum branch limits for the 41 branches of the network. It is not an overload for branch 01, which connects nodes 1 and 2. The 175 MVA value represents the sum of the flows in the two parallel branches, which is 85 + 85 = 170 MVA. Thus, 85 MVA is still below the 130 MVA limit for each branch.

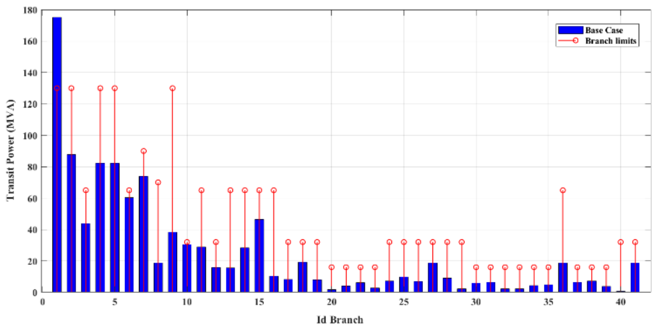

Figure 12. Power flows in the 30-bus system without faults

2. General Overload Case

Figure 13 shows the voltage profile (in p.u.) behaviour of each node in the network under normal consumption and overload conditions. Following the overload on the entire network, there is a considerable drop in voltage at all nodes. This includes nodes furthest from the source nodes, such as nodes 15 to 30, and the antenna nodes, such as node 26. The source nodes, such as nodes 1, 2, 5, 8, 10, and 13, maintain the same voltage as before the overload.

Remember that this network's minimum permissible voltage for normal, stable operation is 0.94 Pu. Thus, despite the overload, the voltage profile is still stable, so there is no need for UVLS. Figure 14 illustrates the effect of network overload on branch transits.

It is observed that due to high consumption, there is an increase in power transits that exceed the capacity of particular branches, particularly on the transport network side, specifically branches No. 01 to branch 07 and even branch No. 10.

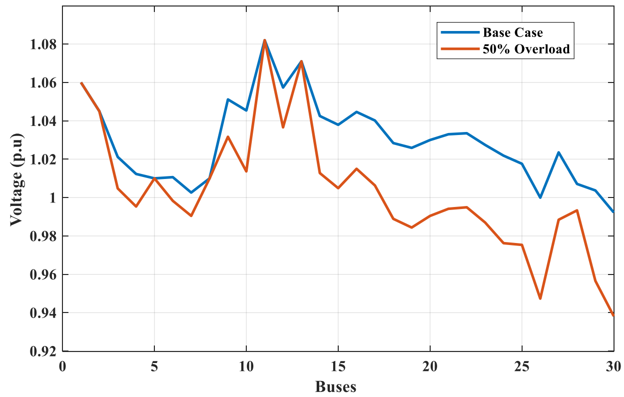

Figure 13. Voltage profile of a 30-bus system with and without overload

In this case, we must relieve the overloaded branches through preventive LS to prevent them from tripping due to the max I protection and to avoid cascading overloads and, at worst, a voltage profile collapse (blackout).

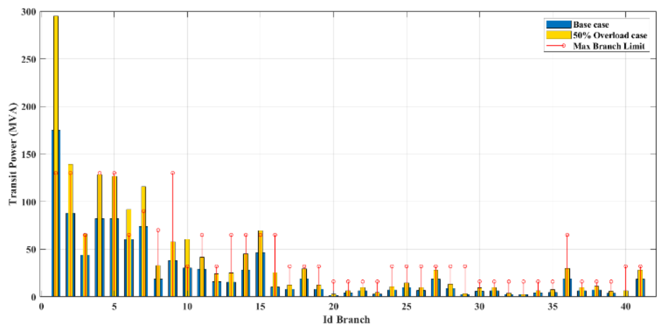

Figure 14. Power transits of the 30-bus system following the system overload

3. Loss of branch due to overload

To evaluate the network's N-1 state, we test triggering a listed branch of the distribution network, specifically branch 22-24, following the overload described above. Figure 15 below illustrates the network when branch 22-24 was lost. Figure 16 below illustrates the voltage profile following the loss of branch 22-24.

We note that some nodes have experienced a drop in voltage while others have experienced an increase. We also see that the voltage disruption has affected the area where the fault exists, namely the distribution network, while the transmission side is not affected.

The interpretation of this is:

- Nodes 24, 25, and 26 are expected to experience a voltage drop because they are connected and primarily fed radially through node 22, which is the closest node to sources 10 and 11.
- Their power supplies now come from other source

nodes, either from 28 or 23. According to the principle that voltage decreases with greater distance from the source, this drop is anticipated.

- The increase in voltage of nodes 21 and 22 is explained by the loss of power to receiving nodes 24, 25, and 26. This is equivalent to losing a load, causing the voltage to increase.

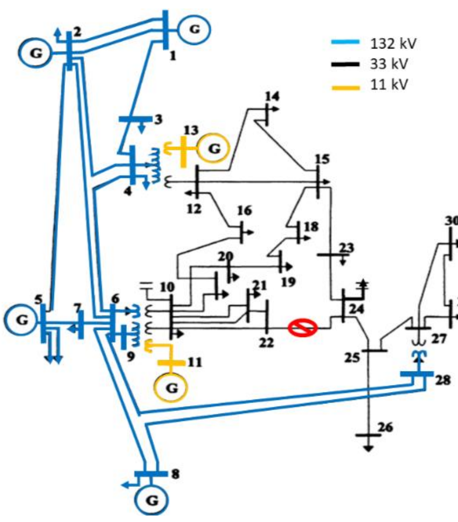

Figure 15. IEEE 30 bus system test with loss of branch 22-24

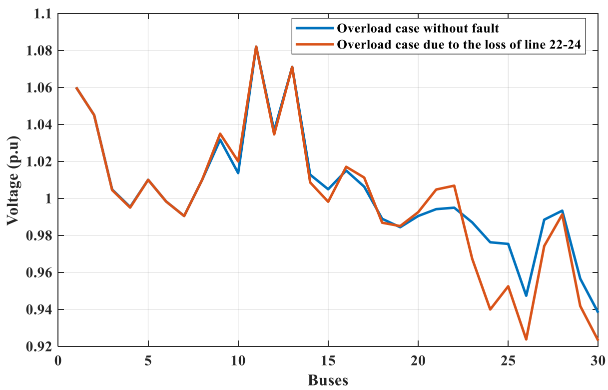

Figure 16. Voltage profile during overload with loss of a branch 22-24

Figure 17 shows the behaviour of the transit powers in the case of overload and the loss of branch 22-24.

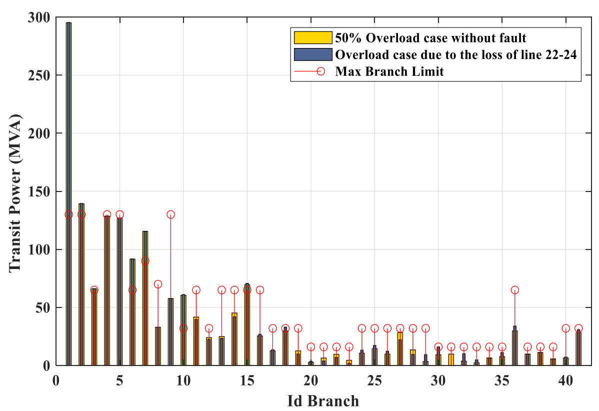

Figure 17. Transit powers during the loss of branch 22-24

In the case of transiting power, this disturbance does not affect the transmission network, whereas a change in transit is evident on the distribution side, as shown in Figure 18. We observe the following:

- The transit in branch 31, equivalent to line 22-24, is zero.
- The transit increases in branches 16 (12-13), 24 (19-20), 25 (10-20), 26 (10-17), 29 (21-22), 32 (23-24), 33 (24-25), 35 (25-27), 36 (28-27), and 41 (6-28) without exceeding the maximum limit.
- The transit increases in branches 18 (12-15) and 30 (15-23) exceed the maximum limit, which necessitates preventive LS.
- The transits decrease in branches 19, 21, 22, 23, and 28.

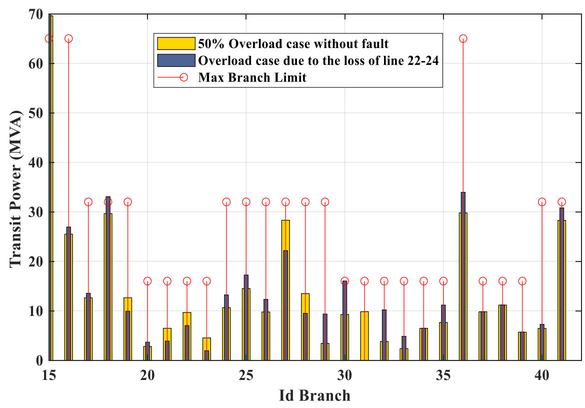

Figure 18. A zoom on the transiting powers of branches near branch 22-24

b) Case 2 (Application of Preventive Load Shedding)

The proposed preventive LS approach uses a fuzzy logic controller designed and implemented in MATLAB's Fuzzy Logic Toolbox. The FLC was configured in the FIS Editor using a Mamdani-type inference system to make real-time load-shedding decisions based on input conditions.

After conducting the simulations, Figure 19 presents the FVSI calculation for each branch across the three case studies. This analysis aims to identify the branches' sensitivity, thereby facilitating optimal LS.

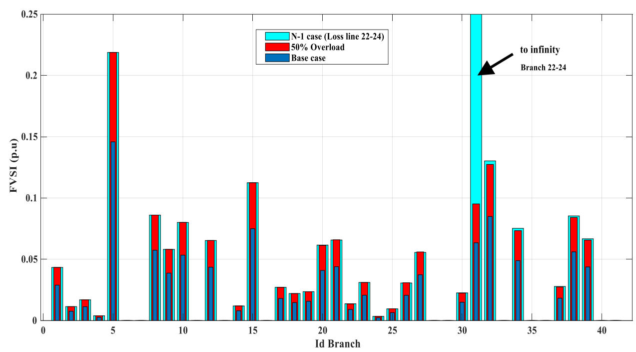

Figure 19. Fast Voltage Stability Index (FVSI) across branches

The results obtained following the application of the proposed approach are as follows:

1. Case of general overload

By carrying out several simulation tests, it is clear that shedding certain loads relieves the transit and, therefore, decreases the network's overload, making it more stable. Figure 16 shows the voltage profile of each node following the load shunting.

The amount of load to be shed must be optimal and sufficient to restore the branch's transit to its safe state while ensuring a stable voltage profile. Figure 20 illustrates the amounts shed at each node.

The red bars show consumption during overload, and the green bars show consumption after LS. The approach has provided us with the precise quantity to be shed and critical nodes and branches. Figure 21 illustrates the updated transit following the LS.

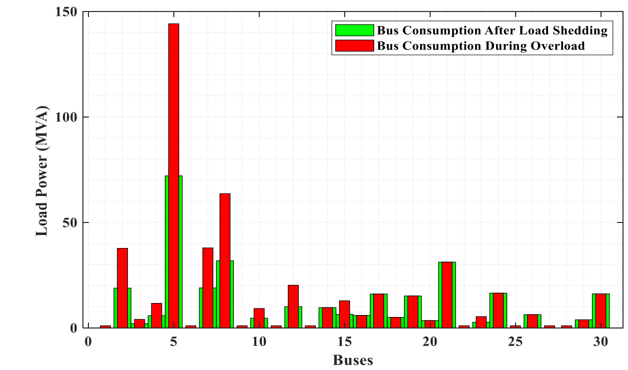

Figure 20. Load power of buses before and after Load Shedding (LS)

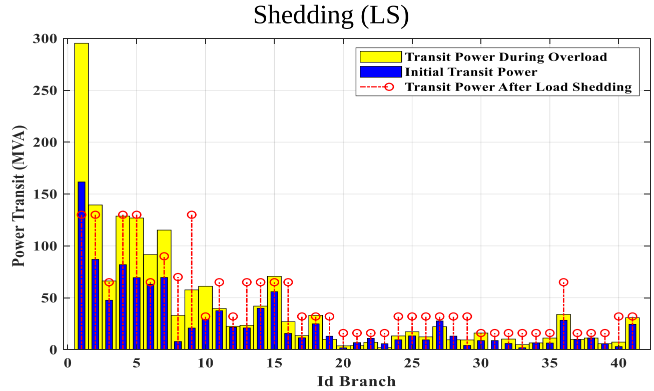

Figure 21. Transits power before and after load-shedding

Figure 22 illustrates three voltage curves. The blue curve shows the voltage profile in the initial case, the red curve shows the voltage profile in the overload case, and finally, the green curve represents the voltage profile after intelligent LS with the FL method. A voltage profile at acceptable levels (stability) is observed even at nodes without LS.

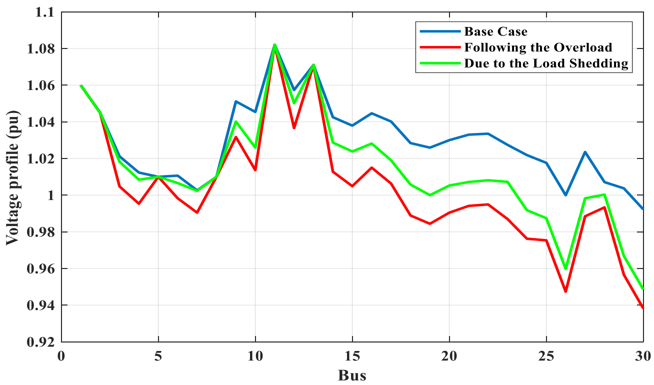

Figure 22. Voltage profile with the intelligent method

2. Loss of a branch at the time of overload

Figure 20 illustrates the updated power flow in the network, comparing the conditions before and after LS in response to line loss 22-24 and overloading. The quantity of load to be shed must be optimal and sufficient to restore the voltage to its steady state.

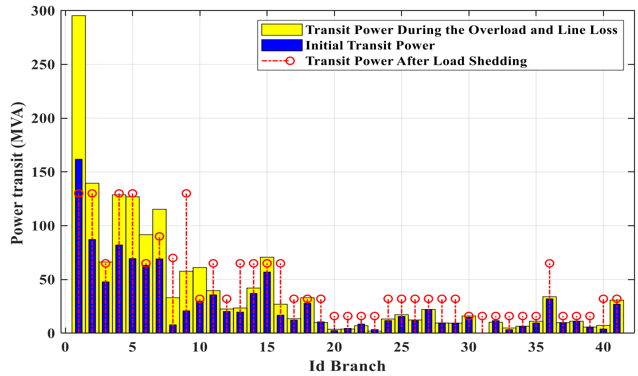

Figure 23. Power flow before and after Load Shedding (LS) following the line loss

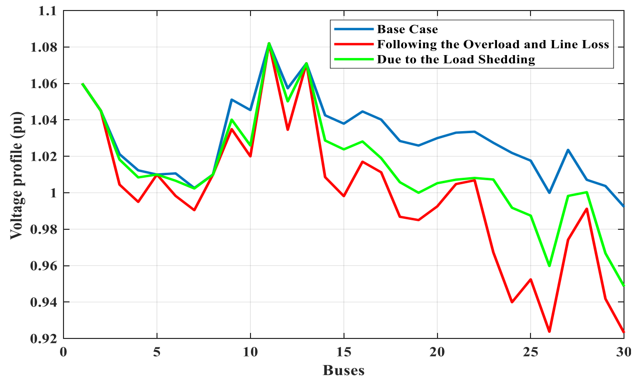

Figure 24. Voltage profile following intelligent Load Shedding (LS) with line 22-24 loss

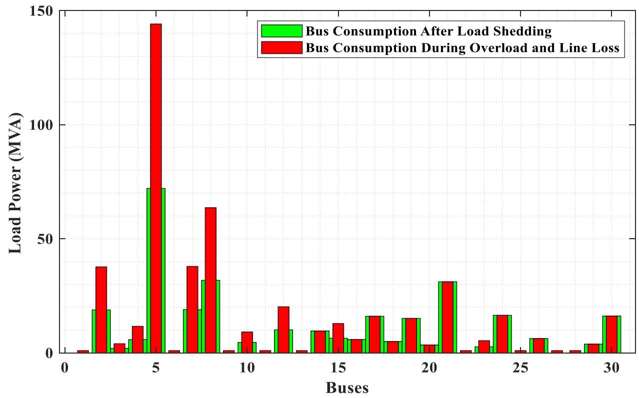

Figure 25. Node consumption after Load Shedding (LS) following the loss of line 22-24

Figure 23 illustrates the power flow before and after LS following a line loss. Figure 24 shows the voltage profile of each node for the 30-bus system with intelligent LS. The graphical representation in Figure 24 illustrates the voltage profile before and after LS. We observe an improvement in the voltage profile at the majority of nodes, in particular those that suffered the voltage drop following the incident (loss of branch 22-24), namely nodes 24, 26 and 30, a voltage below the stability limit of 0.925 Pu before LS, calling for UVLS, becomes more stable around 0.94 Pu the minimum voltage stability limit of this network.

The graphical representation in Figure 25 shows the consumption of nodes before and after LS.

The proposed approach provides the precise amount to be shed and the critical nodes and branches, i.e., those that require LS. However, it can be concluded that shedding one or two loads leads to automatic stabilization of the network. Thus, it is evident that not all nodes requiring LS need to be shed. This is the objective of our study, where FL is identified as the optimal solution to achieve the best result.

Through extensive simulation trials, it is clear that shedding specific loads alleviates congestion and thereby reduces network overload, resulting in improved stability. This section presented several case studies demonstrating the effectiveness of the proposed load-shedding approach.

Following the presentation of the standard IEEE 30-node application network, we studied its behaviour through power flow analysis under normal load conditions, overall overload, and N-1 state during a load loss event.

In the latter two scenarios, no means were available to alleviate the overload of the transit lines except for a preventive load-shedding approach capable of mitigating the overload cascade and temporarily reducing the risk of triggering protective measures that threatened the network's stability.

6. COMPARISON STUDY RESULTS

This section presents a summary of results comparing the proposed adaptive LS strategy with conventional methods in the overload case and under line losses.

Table 2 compares the conventional and proposed LS methods. The amount to be shed by the proposed method is 231.92 MVA, whereas the conventional method sheds 268.56 MVA, indicating improved efficiency. For instance, branch [1-2] sheds 91.5 MVA using the proposed method, compared to 163.50 MVA with the conventional approach.

The conventional technique results in a significantly higher LS than the proposed approach. As illustrated in Table 3, the conventional method requires a total of 271.47 MVA to be shed, whereas the proposed method requires only 232.30 MVA. This reduction in LS is a clear indicator that the proposed method is more efficient in managing system stability, shedding less load while still maintaining network performance.

Table 2. Summary of results for branch limits and Load Shedding (LS) amounts under overload conditions

Id Branch	Transit Overload (MVA)	Branch Limit (MVA)	Exceeding Limit (MVA)	To be Shed (MVA)	
				Conventional	Proposed
1 [1-2]	285.72	130	155.72	163.50	91.5
2 [1-3]	139.25	130	9.25	9.71	27.67
3 [2-4]	66.01	65	1.01	1.059	13.19
4 [3-4]	128.56	130	1.44	1.512	-
5 [2-5]	126.86	130	3.14	3.297	-
6 [2-6]	91.62	65	26.62	27.94	25.19
7 [4-6]	115.60	90	25.59	26.86	31.79
10 [6-8]	60.45	32	28.45	29.87	21.01
15 [4-12]	69.60	65	4.60	4.81	21.58
			Total	268.56	231.92

Table 3. Summary of results for branch limits and Load Shedding (LS) amounts under line loss conditions

Id Branch	Transit Overload (MVA)	Branch Limit (MVA)	Exceeding Limit (MVA)	To be Shed (MVA)	
				Conventional	Proposed
1 [1-2]	295.06	130	155.72	163.50	81.22
2 [1-3]	139.25	130	9.25	9.71	27.73
3 [2-4]	66.01	65	1.20	1.26	13.17
4 [3-4]	128.56	130	1.44	1.51	-
5 [2-5]	126.86	130	3.14	3.3	-
6 [2-6]	91.62	65	26.66	27.99	25.20
7 [4-6]	115.60	90	25.24	26.50	31.69
10 [6-8]	61.1	32	29.09	30.54	21.48
15 [4-12]	70.69	65	5.68	5.96	21.95
18 [12-15]	33.07	32	1.07	1.12	6.60
30 [15-23]	16.02	16	0.02	0.02	3.2646
41 [6-28]	30.79	32	-1.21	0.06	-
			Total	271.47	232.30

7. CONCLUSION

This research investigation focused on enhancing network load-shedding tactics, underscoring their role in maintaining the effective and dependable operation of electrical systems. We began by examining methods to assess progress and identify gaps in the field. After that, we looked at network modelling to help us decide when to reduce the electricity we use. We devised a way to improve system performance using an FL algorithm as a safety measure. The paper presents several case studies that demonstrate the effectiveness of the proposed de-charging approach. Following the presentation of the IEEE 30-bus standard application network system, we studied its behaviour via power flow during operation under a normal load, global overload, and state N-1 with a line loss. In the latter two cases, there was no way to relieve transit overloading other than preventive measures that could dampen the overloading cascade and temporarily reduce the risk of triggering works that threaten the network's stability.

The simulation results demonstrated the efficacy of our proposed approach compared to other methods. Noteworthy advantages included decreased LS quantities and enhanced voltage stability, both pivotal in mitigating the effects of transit risks on the network.

This study contributes to understanding LS practices and provides a robust method for optimising them. Future studies could expand on this work by examining algorithms, multi-agent systems, improved stability, and the use of theoretical models for load distribution. These avenues show promise for advancing LS strategies and fortifying network resilience. Despite promising results, some limitations require consideration.

The proposed approach was validated only on the IEEE 30-bus test system, and its scalability for extensive power networks may entail increased computational effort, mainly due to the centralised FLC and the computation of FVSIs for each network branch. Additionally, the method was assessed under standard operating conditions and does not directly address substantial renewable energy integration.

The variability and uncertainty of renewable generation can alter power flow and voltage stability margins, possibly necessitating adaptive or predictive controls. Future work will aim to adapt the strategy for extensive systems, examine decentralised or hierarchical models, and incorporate renewable variability, storage systems, and uncertainty-tolerant control schemes.

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NOMENCLATURE

$S_{Shed}(i, j)$	Quantity of load to be shed per branch (i, j), in MVA
X_j	Quantity to be shed in percentage (%) at node j and j+1
$\Delta S(i, j)$	Difference between the actual branch power flow and its technical limit, in MVA
$S(i, j)$	Actual power flow (transit) of branch (i, j), in MVA
K(%)	Loading level of branch (i, j) expressed as a percentage of its limit
$S_{limit}(i, j)$	Technical limit of the branch (i, j), in MVA
$S_{Load}(j)$	Apparent power demanded by the load at node j, in MVA
$P_{Load}(j)$	Active power at node j, in MW
$Q_{Load}(j)$	Reactive power at node j, in MVAr
$\Delta V(i)$	Voltage deviation at bus i
$V(i)$	Voltage magnitude at bus i (p.u.)
P_{gi}	Active power generated at bus i, in MW
P_{Li}	Active power load (demand) at bus i, in MW
Q_{gi}	Reactive power generated at bus i, in MVAr
Q_{Li}	Reactive power load (demand) at bus i, in MVAr
V_j	Voltage magnitude at bus j, in per unit (p.u.)
Y_{ij}	Magnitude of the admittance between buses i and j, in Siemens (S)
N_{bus}	Total number of buses in the network
δ_i	Voltage phase angle at bus i, in radians
δ_j	Voltage phase angle at bus j, in radians
θ_{ij}	Phase angle of the admittance between buses i and j, in radians