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Research Article

Optimize Ranking and Load Shedding in Microgrid Considering Improved Analytic Hierarchy Process Algorithm and Power Stability Index

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This paper proposes a load shedding model for the island microgrid based on the ranking of loads and the power stability index (PSI). Loads are ranked based on the improved analytic hierarchy process (AHP) algorithm. Real-time measurement systems have the function of collecting data for very important, important, and less-important loads at each bus load. From this data, the improved AHP method is applied to rank the loads. The advantage of this method is that the subjectivity is eliminated and not depending on the expertise of the system operator when implementing the traditional AHP method. Besides, the minimum amount of load shedding power is calculated, taking into account both primary and secondary control methods. The objective is to minimize the impact on power consumers and ensure that the frequency returns to an acceptable range. In addition, when implementing load shedding, voltage quality, and stability are considered. The PSI serves as a crucial parameter for assessing the voltage stability of microgrid buses. This index is combined with load ranking weights to obtain combined weights for the load shedding plan. Consequently, the proposed load shedding plan prioritizes minimizing damage to customers, improving voltage quality and stability, and ensuring frequency is within permissible limits. The 16-bus microgrid system is applied to compare with traditional methods and to prove the efficiency of the suggested technique.

1. Introduction

The development of the world's economy has put the operating state of the power grid very close to its stability limit. Therefore, when unexpected situations occur, such as generator and transmission line outage, the grid operates in island mode, and the load changes suddenly.

These situations can lead to frequency instability or collapse and consequent power outages. Moreover, today's power grid is more complex due to the appearance of new loads and generators requiring a higher level of safety and stability. Frequency stability is defined as the ability of the system to keep the frequency in allowable limits on all buses after a failure. There are many methods to keep the frequency stable in the system, such as: primary frequency control, secondary frequency control, voltage regulation, resistance–reactance cooperation, flexible AC transmission systems devices, and so forth. In such situations, the solution of load shedding is considered as a last line of defence to keep the system frequency stable and restore the frequency to an acceptable range [1–3].

Load shedding methods correspond to different operation goals. In which, the two main concerns are the economic aspect and the technical aspect. Awad and Hafez [4], Horri and Mahdinia Roudsari [5], Shen et al. [6], and Hussain and Shakir Al-Jubori [7], technical factors such as frequency and voltage quality were focused on, while economic issues such as compensation for damage caused by disconnected loads have not been mentioned. Besides, the voltage quality after load shedding has not yet been carefully considered. Mogaka et al. [8] and Le et al. [9], the authors optimally solved the problem of economic damage caused by the load reduction, meeting the economic aspects of the problem. However, power quality issues from a technical perspective still have not been effectively evaluated.

In the competitive electricity market, suppliers and customers can be proactive in cutting the load with a plan or optimizing load shedding to minimize risks affecting the interests of both parties. To do that, the loads in the system must be calculated and prioritized appropriately. Moran [10] and Shi et al. [11], the microgrid system with smart meters continuously sent parameters describing the status of the power system at each interval.

From those parameters, the system will continuously evaluate and classify which load is the priority type of power supply and which load is the priority to be removed when system failure occurs. Nawaz et al. [12] load characteristics and structures have been considered and classified based on the characteristics and customer demands for each load, and schedule operations to optimize operating costs in the microgrid.

Besides, the solutions to improve the voltage stability and quality in the power grid are also studied. Wang et al. [13], the authors presented an adaptive dynamic programming method based on the wind/solar equivalence model and Bellman principle to solve the problem of optimizing the control variable, and correctly adjusting the voltage in real time. Power electronics technology has strongly developed and has many applications in improving the stability of power systems. Reducing current can help reduce voltage loss and improve voltage stability and quality. Line resistance and reactance play a very important role in voltage stabilization. A method of determining the stable region based on the line impedance–admittance cooperation for grid-tied inverters in weak grids has been presented in Rui et al. [14]. There, the line impedance matching stable region was solved by Kronecker sum-based map theory. This leads to a simpler calculation process. However, these methods have not yet delved into the power system frequency stability analysis and prioritized load considerations.

The determination of power electronics location such as static VAR compensator (SVC) to improve voltage stability has also been shown in Aydin and Gumus [15]. This study presents a multicriteria decision making technique based on the analytic hierarchy process (AHP) algorithm to determine the optimal location of SVC. However, the problem of establishing a judgment matrix between the criteria of the AHP algorithm is built on the opinion of the power system operator. This matrix is used to determine the priority weight of the implementation decision. As a result, subjectivity still exists and depends on the level of knowledge of the experts who operate the power system.

A load shedding technique based on frequency and voltage stabilization is presented in Nahid-Al-Masood et al. [16]. This study presents a load shedding method to improve the frequency response of low-inertia power grids by achieving voltage stability. Voltage stability is determined based on the reactive power margin and that is the basis for determining the amount of load shedding power. The distribution of load shedding power is done according to the principle: the weaker the bus voltage stability is, the higher amount of load shedding power is. However, this study has not yet considered the ranking and shedding of priority loads.

The ranking for load shedding is also a matter of interest to many researchers. In the paper Bajaj et al. [17], the AHP algorithm is applied to evaluate the power quality of distorted distribution networks. The cause of the distortion is due to the presence of renewable energy DGs. The power quality in this paper is evaluated based on the construction of the unified power quality index to evaluate the overall power quality of individual buses and the entire distribution grid. The evaluation parameters include: voltage harmonics, voltage unbalance (VU), voltage sag, and steady-state voltage characteristics.

The AHP algorithm is also studied and applied widely in the field of power quality analysis and assessment. Bajaj et al. [18], the authors presented a method to apply the AHP algorithm to rank the voltage quality of the intelligent distribution grid. The proposed method in that paper has built a process to evaluate the overall voltage quality in the distribution grid by building a single voltage quality index. Scores for all voltage quality related phenomena are calculated using the AHP algorithm considering multiple consumer impact criteria. These phenomena include: voltage fluctuation (VF), voltage harmonic distortion (VHD), VU, and so forth. In large power grids, through supervisory control and data acquisition systems, parameters of these phenomena are collected and processed as a basis for experts to make judgments and build judgment matrices. Therefore, this method can be applied to large power grids of any size, and the matrix size M will change according to the number of buses of the grid. However, this AHP method still has disadvantages. That is, the judgment matrix M in this article is still built, establishing pairs of important judgments that are still based on expert opinions and are subjective and have not gone into deep data analysis.

The authors of the papers [19, 20] present a simplified method of power quality assessment by combining the important power quality index in different bus groups into a single composite indicator using the AHP methodology. This method is well suited for power quality assessment of systems with renewable energy sources integrated into the grid. In such systems, parameters such as VFs, VHD, current harmonic distortion, frequency fluctuations, VU, power factor, and steady-state voltage profile are designed as components of decision matrix for load bus, DG bus, and grid bus, respectively. The AHP method was applied to calculate the power quality phenomena importance scores of these matrices. From there, the composite index is calculated.

Although these methods calculate the consistency ratio index to evaluate whether the judgment matrix or decision matrix satisfies the requirements of the AHP algorithm. But in reality, the construction of the judgment matrix to calculate the AHP algorithm of these methods is based on surveys of customers, suppliers, or on the opinions of experts and system operators. Therefore, these results may be somewhat subjective and depend on the operator's level of knowledge and expertise in electrical systems. The traditional AHP algorithm is applied to find the overall critical score of all power quality and voltage phenomena. This shows that this method is very reliable in the field of rating and evaluating the quality of distributed network, especially distributed power systems with a high level of integrated renewable energy. However, one of the main drawbacks of the traditional AHP method is the potential for expert bias. This is because the decision-making process heavily relies on the input and opinions of the proposer who may be influenced by personal biases, experiences, and beliefs. Therefore, the final decision may not reflect the objective reality of the situation, leading to potentially suboptimal outcomes. Furthermore, the traditional AHP method assumes that the decision criteria are independent of each other, which may not be the case in complex decision-making scenarios. This can lead to a skewed or inaccurate representation of the decision problem and ultimately result in a poor decision outcome. Hence, it is crucial to be aware of these limitations and to take steps to mitigate the potential for proposed bias in the AHP decision-making process. This can include incorporating multiple perspectives and sources of information, conducting sensitivity analysis, and using improved AHP models that account for interdependent criteria. Ye et al. [21] it has proposed the use of AHP algorithm to shed the loads in order to steady the voltage of the system. However, this method relies heavily on expert opinions from other platforms, so it is subjective. Rosli et al. [22], a method of ranking and load bus shedding using modified discrete evolutionary programming and AHP algorithm is proposed. This method ranks the load buses with the smallest power inequity and the smallest stability index. The article has proposed a ranking and load shedding model with good results, but this model sheds the entire load bus. In practice, this is not satisfactory. Because each load bus includes many feeders and many types of important loads.

In this paper, we propose a load shedding model for the microgrid based on the ranking of the shedding loads and the PSI. The ranking of loads for shedding in the microgrid is done by the improved AHP algorithm. The PSI helps to improve voltage stability at the bus loads. The minimum load shedding capacity for frequency recovery is also computed. The combined weights at the load buses are calculated to deliver the appropriate amount of load reduction power to each load node. This delivery improves voltage quality and minimizes damage to power consumers.

In order to fulfill the imperative of minimizing adverse impacts on electricity consumers during load shedding events, it is crucial to objectively assess the prioritization of loads while concurrently enhancing voltage quality. Consequently, a method for prioritizing loads based on an improved AHP algorithm and the power stability index (PSI) has been introduced, with the following key advantages delineated:

First, the load shedding process incorporates a systematic ranking of loads for shedding. This ranking is predicated on the proportion of various load types—namely, very important, important, and less-important loads—situated on a specific load bus. To establish this ranking, an enhanced AHP algorithm, augmented by statistical and Spearman correlation techniques, is employed to formulate a correlation matrix between load type criteria. This matrix, in turn, facilitates the computation of weights (denoted as W_{ij}) for prioritizing loads to be shed. This approach effectively mitigates the subjective limitations inherent in the traditional AHP method, which is reliant on the interpretative acumen of experts or power system operators.

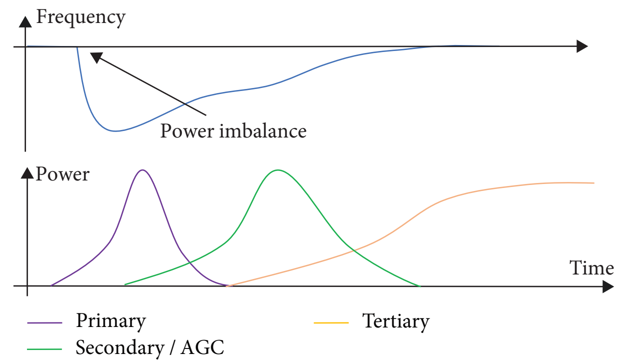

Figure 1: Activate primary, secondary, and tertiary control after power imbalance.

Second, a rigorous assessment is made to ascertain the minimum amount of load shedding power required. This computation duly accounts for both primary and secondary control mechanisms of generators. The objective here is to minimize the quantum of power curtailment necessary, thereby mitigating the adverse consequences on customers, while concurrently ensuring that the frequency is reinstated within permissible thresholds.

Third, the quality and stability of voltage across the microgrid network are methodically factored into the distribution of load shedding power. The PSI serves as a critical parameter for the comprehensive evaluation of voltage stability at various buses within the microgrid. This holistic consideration ensures a judicious allocation of load shedding power while preserving voltage quality and stability.

2. Optimizing the Amount of Shedding Power

When the microgrid system has a problem of interruption to the utility or power grid, the generating capacity is smaller than the load capacity, and is not enough to supply the demand for use. That leads to a quick decline in frequency. The activation of primary, secondary, and tertiary control after power imbalance is shown in Figure 1. Monitors and controllers will immediately operate to restore the frequency. After performing frequency control processes and it is nevertheless outside the allowable bounds, the last thing to do is to reduce the amount of power consumption. This amount of power is calculated according to Equation (1) [23, 24]:

$$P_{\text{Shed}} = \sum P_{Lj} - P_{G_{\text{batt}}} - P_{G_{\text{wind}}} - P_{G_{\text{solar}}} - D \times (-\Delta\omega_{\text{allow}}) - P_{Gi} - \sum \frac{-\Delta f_{\text{allow}}}{R_i} - \Delta P_{\text{Secondary}}, \quad (1)$$

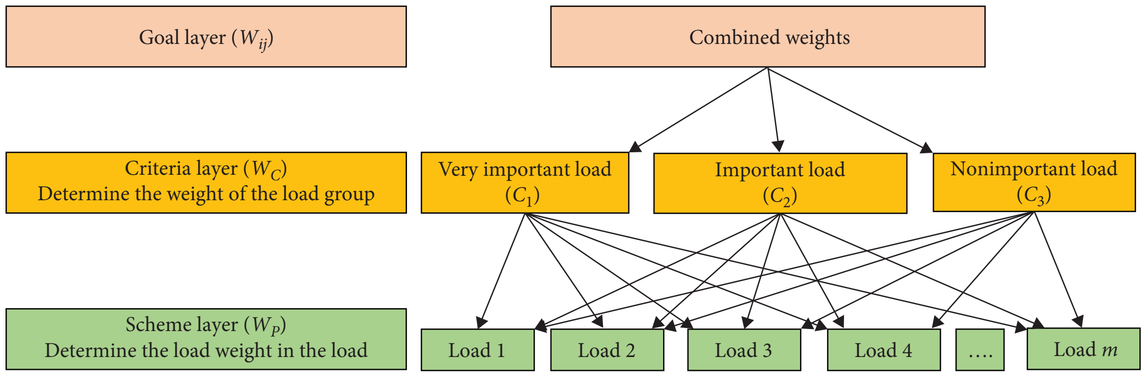

FIGURE 2: Improved AHP algorithm calculation process.

where P_{Shed} is the amount of minimum load power to be shed. P_{Lj} is the real power of the j load unit. $P_{G_{\text{batt}}}$, P_{wind}, P_{solar} are the energy of storage, wind turbine, and solar power, respectively, these forms of energy are considered as negative loads. P_{Gi} is the capacity of the ith generator belonging to the supply machinery, with a regulator or speed controller of distributed generation. $D\times(-\Delta\omega_{\text{allow}})$ is the active power variation of load depending on the frequency adjustment. $\Delta f_{\text{allow}} = f_n - f_{\text{allow}}$ is the allowable frequency change value. $\Delta P_{\text{Secondary}} = \sum_{i=1}^{m} P_{Gn,i} - \Delta P_{\text{Primary},i}$ is the total power value of the secondary control. $\Delta P_{\text{Primary}} = \sum \frac{-\Delta f_1}{R_i}$ is the total power that can be realized in the primary control. R_i is the permanent droop (pu) of ith diesel generator

3. The Load Shedding Ranking in the Microgrid is Established Based on the Improved AHP Algorithm and the Power Stability Index

The load ranking in the microgrid is very important in ensuring power supply reliability for the critical loads or very important loads and the highest ranking in the system. The loads in the microgrid are classified or sorted into three types: very important, important, and less important load groups [25].

Each feeder in the distribution network actually consists of many loads and different types of loads: very important, important, and less important. These load types will be monitored, counted, thereby showing the percentage of load types on the feeder. Depending on the percentage of load types, their importance can be assessed. By the processing steps of statistical science combined with the AHP algorithm, it helps to convert these ratios or sorts into weights to prioritize the loads for the load shedding problem. Thereby, this ranking solves the requirements of the priority load and the economy of the load reduction problem. Besides, the stability of the load bus after shedding should also be considered. The concept of PSI is used to evaluate the load nodes. From there, the requirements of the system's specifications after load shedding are guaranteed.

From the percentages of the load types, the improved AHP technique is applied to compute the significance weights of each load bus. From there, ranking the order of the load reduction buses according to the priority aspect. The stages of the improved AHP algorithm are calculated including the calculation of the criterion layer weights, the goal layer weights, and the schemes layer weights [26]. In which, the criteria layer weights represent the correlation relationship between the very important load groups, the important load groups, and the less important load groups. The scheme layer weights represent the priority relationship between the loads in each subload group. The improved AHP algorithm calculation procedure is shown in Figure 2.

3.1. Criterion Layer Weight Calculation. The criterion class of the load shedding ranking weight calculation model shows the weighting relationship between the load groups: very important load group (C_1), important load group (C_2), and less important load group (C_3). Each data set of this load group includes the percentage values of the respective load categories at every load node or load bus. This data set is considered a data set that sorts three load groups. Calculating the weight of each load group in this sorting data set and applying the improved AHP algorithm model contribute to converting from a sorting problem to a ranking problem. Each load group is calculated and has a defined weight. The calculation procedure follows these steps:

Step 1: Build the covariance matrix C between the load groups C_1, C_2, C_3:

$$C = \begin{bmatrix} \text{Var}(C_1) & |\text{Cov}(C_1, C_2)| & |\text{Cov}(C_1, C_3)| \\ |\text{Cov}(C_1, C_2)| & \text{Var}(C_2) & |\text{Cov}(C_2, C_3)| \\ |\text{Cov}(C_1, C_3)| & |\text{Cov}(C_2, C_3)| & \text{Var}(C_3) \end{bmatrix}, \tag{2}$$

where $\text{Var}(C_1)$, $\text{Var}(C_2)$, $\text{Var}(C_3)$ is the variance of each data set C_1, C_2, C_3, and $\text{Cov}(C_i, Cj)$ is the covariance between the data sets C_1, C_2, C_3 together. When the covariance between the two criteria is not positive, take its absolute value. Because the main purpose of calculating covariance in this method is to consider the distance of the linear relationship of the criteria to each other, the distance result here needs to be a positive number. These values are symmetrical through the main diagonal.

Step 2: Build the relative covariance matrix R. This matrix is taken by converting the covariance matrix C. The matrix R is presented as follows:

$$R=\begin{bmatrix} 1 & \frac{|\mathrm{Cov}(C_1,C_2)|}{\mathrm{Var}(C_1)} & \frac{|\mathrm{Cov}(C_1,C_3)|}{\mathrm{Var}(C_1)} \\ \frac{|\mathrm{Cov}(C_1,C_2)|}{\mathrm{Var}(C_2)} & 1 & \frac{|\mathrm{Cov}(C_2,C_3)|}{\mathrm{Var}(C_2)} \\ \frac{|\mathrm{Cov}(C_1,C_3)|}{\mathrm{Var}(C_3)} & \frac{|\mathrm{Cov}(C_2,C_3)|}{\mathrm{Var}(C_3)} & 1 \end{bmatrix} = R = \begin{bmatrix} 1 & \frac{R_{12}}{R_{11}} & \frac{R_{13}}{R_{11}} \\ \frac{R_{21}}{R_{22}} & 1 & \frac{R_{23}}{R_{22}} \\ \frac{R_{31}}{R_{33}} & \frac{R_{32}}{R_{33}} & 1 \end{bmatrix}. \quad (3)$$

Step 3: Set up the correlation matrix M between the criterions. This matrix shows the correlation between load groups C_1, C_2, C_3. The elements of this matrix are named the correlation factors M_{ij} and are calculated based on Equation (4) [9].

$$M_{ij}=\frac{R_{ij}}{\sqrt{R_{ij}\times R_{ji}}}, M_{ji}=\frac{1}{M_{ij}}. \quad (4)$$

From Equation (4), the correlation matrix M between the criterions is shown in Equation (5):

$$M=\begin{bmatrix} 1 & M_{12} & M_{13} \\ M_{21} & 1 & M_{23} \\ M_{31} & M_{32} & 1 \end{bmatrix}. \quad (5)$$

This correlation matrix M replenishes the judgment matrix of the conventional AHP algorithm. Here, the matrix M is calculated based on the statistical techniques and Spearman linear correlation.

Step 4: Calculate the weight of the criterion layer. From the matrix M, this weight is calculated based on the root method and performed similarly to the traditional AHP algorithm [23, 27, 28].

Step 5: Check the consistency ratio (CR) of the correlation matrix M. The matrix M is considered to be a matrix of consistency when $\mathrm{CR}<0.1$ and the process of calculating this coefficient is described in Nguyen et al. [23] and Zhu [27].

3.2. Scheme Layer Weight Calculation. The scheme layer of the load shedding weighting model signifies the weighting connection between the values of loads in the similar group C_1 or C_2, or C_3. Prejudice in decision making is the question that needs to be reduced, and fuzzy preference theory is used to resolve this question [26, 29]. The method of computing the weight of the project layer (the scheme layer) includes the following steps:

Step 1: Calculate the V_{Li} variance among the parameters of $n-1$ loads in the same criterion C, except for the ith load in the same criterion C. V_{Li} is computed following to Equation (6).

$$V_{Li}=\frac{\sum_{j=1}^{n-1}(x_j-\overline{x})^2}{n-1} \text{ with } j\neq i, \quad (6)$$

where x_j is the parameter of the jth load in the same criterion C, $\overline{x}$ is the corresponding data mean of the loads in group C, and n is the number of loads of each group C.

Step 2: Build the fuzzy priority matrix P. The P_{ij} parameters of the matrix P are calculated by Equations (7) and (8).

$$p_{ij}=\frac{V_{Li}}{V_{Li}+V_{Lj}}, \quad (7)$$

$$p_{ji}=1-p_{ij}, \quad (8)$$

$i,j\in[1\ n]$, the larger the P_{ij} parameter is, the higher importance for the ith load is. The crosswise parts have a parameter of 0.5. In the computation of variance, the matrix P is simpler to compute, and this is the single and convinced solution. The P matrix has the structure of Equation (9):

$$P=\begin{bmatrix} 0.5 & p_{12} & \cdots & p_{1n} \\ p_{21} & 0.5 & \cdots & p_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ p_{n1} & p_{n2} & \cdots & 0.5 \end{bmatrix}. \quad (9)$$

Step 3: Build a fuzzy priority relation consistency matrix $\overline{P}$. The weight of the scheme layer will be computed depending on the $\overline{P}$ matrix, which is used to switch the pairwise relationship matrix between the characteristics of one criterion and that of the other criterion. The parameters of the $\overline{P}$ matrix are computed as Equation (10).

$$(\overline{P}_{ik})_{n\times n} = \left(\frac{1}{n}\sum_{j=1}^{n}(p_{ij}+p_{ik}) - 0.5\right)_{n\times n}. \quad (10)$$

The parameter of the elements of $\overline{P}$ matrix shows the significance among schemes. If $\overline{p}_{ij}>0.5$ then x_i is more significant than x_j, $\overline{p}_{ij}<0.5$ then x_i is less significance than x_j, $\overline{p}_{ij}=0.5$ then x_i is as significance as x_j. Following to the over computation, the primary crosswise value of the consistency matrix is 0.5.

Step 4: Compute the weight of the scheme layer. This weight is calculated and depends on the level of advantages and disadvantages of the scheme. The parameters of this level get through the parameters of the components in the $\overline{P}$ matrix. Equation (11) is used to compute them.

$$r_{ij} = \begin{Bmatrix} 1 \\ 0.5 \\ 0 \end{Bmatrix} \begin{matrix} x_i > x_j \\ x_i = x_j \\ \text{otherwise} \end{matrix}, \quad (11)$$

where r_{ij} is the priority index that scheme x_i compares to scheme x_j. The priority index R_i of project x_i in the set of project C is computed according to Equation (12).

$$R_i = \sum_{j=1}^{n} r_{ij}. \quad (12)$$

The weight of the scheme layer $W_{P(j)}$ is computed by Equation (13):

$$W_{P(j)} = \frac{R_i}{\sum_{i=1}^{n} R_i} j \in [1n]. \quad (13)$$

3.3. The Combined Load Shedding Ranking Weighting Calculation of Each Load. The load shedding ranking weighting of each load is calculated depending on $W_{C(i)}$ and $W_{P(j)}$ as Equation (14):

$$W_{ij} = \sum_{i,j=1}^{n} W_{C(i)} \times W_{P(j)}. \quad (14)$$

3.4. Power Stability Index Calculation. To consider the voltage stability of all load buses, this study also considers the PSI. Consider a two-bus system with and without load shedding in the microgrid shown in Figure 3.

From Figure 3, we have:

$$S_L = P_L + jQ_L = V_L I_L^*, \quad (15)$$

$$\overline{V_L} = \overline{V_S} - \overline{I_L Z}, \quad (16)$$

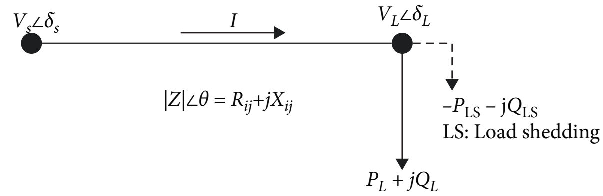

Figure 3: A two-bus system.

where:

$$I_L = \frac{P_L - jQ_L}{V_L^*}. \quad (17)$$

If the network has load shedding, then Equation (17) is rewritten as:

$$I_L = \frac{(P_L - P_{\text{shed}}) - j(Q_L - Q_{\text{shed}})}{V_L^*}, \quad (18)$$

where P_{shed} is the load shedding power at the j node. i is the power transmission bus. j is the power obtaining bus. R_{ij} is the line resistance connecting the two buses i and j. P_L is the load power at bus j.

Substituting I_L from Equation (18) into Equation (16), we get:

$$\overline{V_L} = \overline{V_S} - \frac{\overline{[(P_L - P_{\text{shed}}) - j(Q_L - Q_{\text{shed}})]}}{V_L^*}. \quad (19)$$

Separate into real and imaginary parts, we get:

$$P_L - P_{\text{shed}} = \frac{|V_L||V_S|}{Z}\text{Cos}(\theta - \delta_S + \delta_L) - \frac{|V_L|^2}{Z}\text{Cos}(\theta), \quad (20)$$

$$Q_L - Q_{\text{shed}} = \frac{|V_L||V_S|}{Z}\text{Sin}(\theta - \delta_S + \delta_L) - \frac{|V_L|^2}{Z}\text{Sin}(\theta). \quad (21)$$

From Equation (20), we have:

$$|V_L|^2 - \frac{|V_S||V_L|\text{Cos}(\theta - \delta)}{\text{Cos}(\theta)} + \frac{Z(P_L - P_{\text{shed}})}{\text{Cos}(\theta)} = 0, \quad (22)$$

with $\delta = \delta_S - \delta_L$ is the angle of the phase difference between the two buses i and j. θ is the polar argument angle of the line ij. V_L is the node voltage and needs to be a real value. Equation (22) is a quadratic equation. In this equation, the uppercase delta (Δ) in algebra represents the discriminant of a quadratic equation. The discriminant of this equation presents in Equation (23).

$$\Delta = \left[\frac{V_S\text{Cos}(\theta - \delta)}{\text{Cos}(\theta)}\right]^2 - \frac{4Z(P_L - P_{\text{shed}})}{\text{Cos}(\theta)}. \quad (23)$$

For Equation (22) to have a solution V_L, it must satisfy the condition $\Delta \geq 0$ and this problem is presented in Equation (24):

$$[V_S \mathrm{Cos}(\theta - \delta)]^2 - 4Z(P_L - P_{\mathrm{shed}})\mathrm{Cos}(\theta) \geq 0, \tag{24}$$

$$Z = \frac{R_{ij}}{\mathrm{Cos}(\theta)}. \tag{25}$$

In the microgrid, because the voltage is not too high and due to the distribution grid's characteristics, the R/X value is relatively high. Therefore, the X_{ij} value can be neglected.

$$[V_S \mathrm{Cos}(\theta - \delta)]^2 - \frac{4R_{ij}(P_L - P_{\mathrm{shed}})\mathrm{Cos}(\theta)}{\mathrm{Cos}(\theta)} \geq 0, \tag{26}$$

$$[V_S \mathrm{Cos}(\theta - \delta)]^2 - 4R_{ij}(P_L - P_{\mathrm{shed}}) \geq 0, \tag{27}$$

$$4R_{ij}(P_L - P_{\mathrm{shed}}) \leq [V_S \mathrm{Cos}(\theta - \delta)]^2, \tag{28}$$

$$\mathrm{PSI} = \frac{4R_{ij}(P_L - P_{\mathrm{shed}})}{[V_S \mathrm{Cos}(\theta - \delta)]^2} \leq 1. \tag{29}$$

From Equation (23), it can be seen that the larger the P_{shed} (i.e., the larger the amount of power load shedding) is, the closer to 0 the PSI coefficient (i.e., the more stable the system) is. In other words, the closer to 0 the PSI value of the bus is, the more stable the bus is. It should be noted that, in the PSI value calculation equation, the P_{shed} value can include the amount of load shedding power and the power of the distributed generator DG (if any) at the j bus [22, 30].

PSI weights are calculated to indicate the relative stability of the load buses. The higher the PSI is, the more unstable the system is. From that data, this paper considers the stability of the nodes, and calculates the weights of the load shedding priority. Therefore, in this paper, we prioritize load shedding for the load buses with high PSI values to bring it back to the stable level when there are failure situations in the microgrid system. PSI is calculated for each load bus applying Equation (29). The improved AHP weighting will rank the shedding of loads in order from small to large. In that case, the PSI will rank the unstable load bus from large to small. For the convenience of calculation and homogenization, this paper will convert the PSI index into PSI weight. This weight is calculated according to Equation (30):

$$W_{\mathrm{PSI}} = I - \mathrm{PSI}. \tag{30}$$

4. The Proposed LoadShedding Method Uses the Improved AHP Algorithm and PSI

For the load shedding problem, many stages need to be calculated and implemented to ensure optimal load shedding. In this study, there are three main stages that are carried out: load ranking, load shedding capacity calculation, and load shedding capacity classification. The steps are presented in Figure 4.

From the outcome of the weight calculation of the criterion layer, the project layer, and the PSI weight, the combined load shedding weight $\mathrm{W}_{L,i}$ of each L_i load object is calculated by Equation (31):

$$W_{L,i} = W_{ij} \times W_{\mathrm{PSI}(i)} i, j \in [1n], \tag{31}$$

where the $W_{\mathrm{PSI}(i)}$ value is the PSI weight of the ith respective load buses.

The amount of load shedding capacity at the load nodes is calculated according to the following Equation (32):

$$P_{\mathrm{Shed},L_i} = K_{\mathrm{Shed},L_i}.P_{\mathrm{Shed}} = \frac{K_i}{\sum_{i=1}^{n} K_i}.P_{\mathrm{Shed}}, \tag{32}$$

whereP_{Shed,L_i} is the capacity of load shedding of the ith load node (MW); P_{Shed} is the minimum total load shedding capacity (MW); K_{Shed,L_i} is the load shedding weight of the ith load node; P_{L_i} is the load power L_i. K_i is calculated using the following equation:

$$K_i = \frac{W_{L,i}}{\sum_{i=1}^{n} \frac{1}{W_{\mathrm{L},i}}} \cdot \frac{P_{L_i}}{\sum_{i=1}^{n} P_{L_i}}. \tag{33}$$

The delivery of the load shedding power to the load nodes must satisfy the following constraints: The load shedding capacity at the load nodes P_{Shed,L_i} must not be larger than the capacity of the load node $P_{\mathrm{Shed},L_i} < P_{L_i}$; the smaller the load bus with the combined load shedding ranking weighting is, the larger the load shedding capacity is and vice versa. The loads belonging to the Very important load group are treated as base load and cannot be reduced.

5. Testing System Model—Results

The microgrid system is applied for calculation with the suggested technique. This system has 16 buses, 6 sources, and 8 loads [23, 24]. The single-line diagram of the microgrid is shown in Figure 5.

The case study is that the microgrid suddenly disconnects from the main grid, and operates in island mode. This interruption causes the frequency quality to degrade. After implementing frequency control solutions, but the frequency has not recovered to the suitable range, load shedding must be done. The minimum amount of shedding power is calculated according to Equation (1).

$$\begin{aligned}\Delta P_{\mathrm{Shed}} = {} & 11.98 + (-0.3) + (-2) + (-0.5) \\ & + \frac{11.98 \times 0.02 \times (-0.3)}{60} - 5 - 0.9 - \frac{-6 \times (-0.3)}{0.05 \times 60} \\ & - \frac{-1 \times (-0,3)}{0.05 \times 60} - 0.4 = 2.1788\ \mathrm{MW}.\end{aligned} \tag{34}$$

Through the measurement and data acquisition system, the results of the percentages of the load types at the load nodes are presented in Table 1.

Based on the percentage of each type of load. Equations from (2) to (5) are applied to calculate the matrices C, R, M. The values of the criterion layer weights are presented in Table 2.

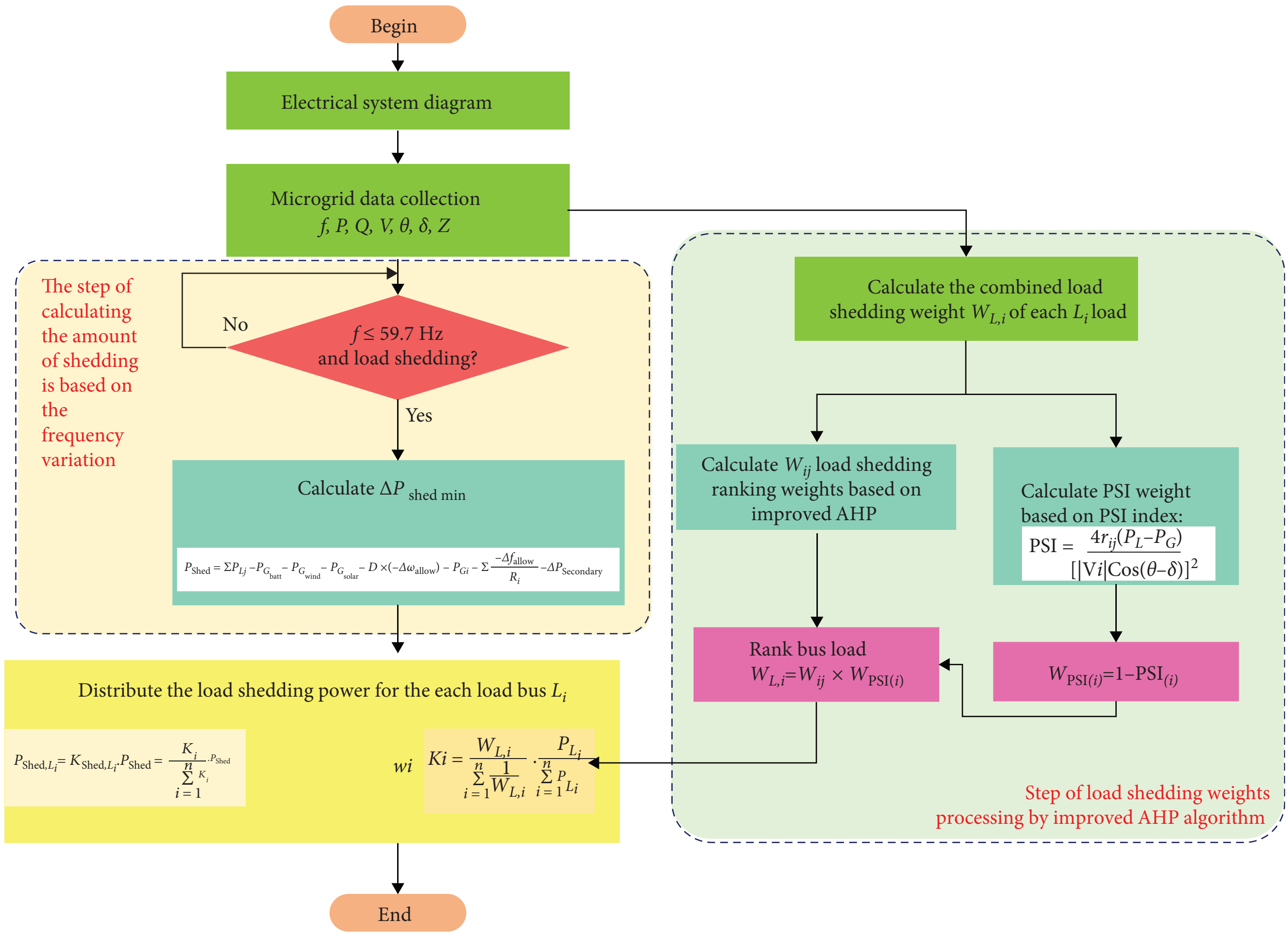

FIGURE 4: Flowchart for calculating the combined load shedding weighting and distribution.

$$C = \begin{bmatrix} 0.0017 & 0.0013 & 0.0003 \\ 0.0013 & 0.0016 & 0.0003 \\ 0.0003 & 0.0003 & 0.0006 \end{bmatrix}$$
$$R = \begin{bmatrix} 1.0000 & 0.8247 & 0.5325 \\ 0.8051 & 1.0000 & 0.4675 \\ 0.1949 & 0.1753 & 1.0000 \end{bmatrix} \quad (35)$$
$$M = \begin{bmatrix} 1.0000 & 1.0121 & 1.6518 \\ 0.9880 & 1.0000 & 1.6330 \\ 0.6050 & 0.6124 & 1.0000 \end{bmatrix}.$$

CR of the correlation matrix M is checked by applying [23, 27]. The results show that $\lambda_{\max} = 3$, CR = 0, CI = 0. The fact that CR is always absolute zero, which shows the outstanding advantage of the improved AHP method. In traditional AHP, the CR check step indicates the consistency of the judgment matrix, if this value is not met, it is necessary to repropose the judgment matrix and perform all calculation steps again. Hence, that shows the superior efficiency of the improved AHP method compared with the traditional AHP method.

From the values of the loads in Table 1, Equations from (6) to (13) of the scheme layer weight calculation process are applied to calculate the values: the variance V_{Li}, the fuzzy priority matrix P, the fuzzy priority relation consistency matrix $\overline{P}$, the priority index R_i of the scheme layer, the weight of scheme layer. The results are performed in Table 3.

Equation (14) is used to calculate the load shedding ranking weighting W_{ij} of each load. Equations (29) and (30) are applied to calculate the PSI index and the PSI weight. The calculated data of the test system are extracted from PowerWorld software [31]. Equations (31) and (32) are used to calculate the combined load shedding weight $W_{L,i}$ of each L_i load for the ranking and distribution of the amount of shedding power at the load buses. The results are presented in Table 4.

To express the efficiency of the suggested technique, the voltage and frequency quality values are checked. Two cases will be included in the test simulation as follows:

Case study 1: Compares the recovery frequency of the proposed method and the under-frequency load shedding method (UFLS). For the case study, the load shedding capacity according to the UFLS method [32, 33] and the proposed technique are 4.0732 and 2.1788 MW, respectively. The results of frequency assessment show the effectiveness of

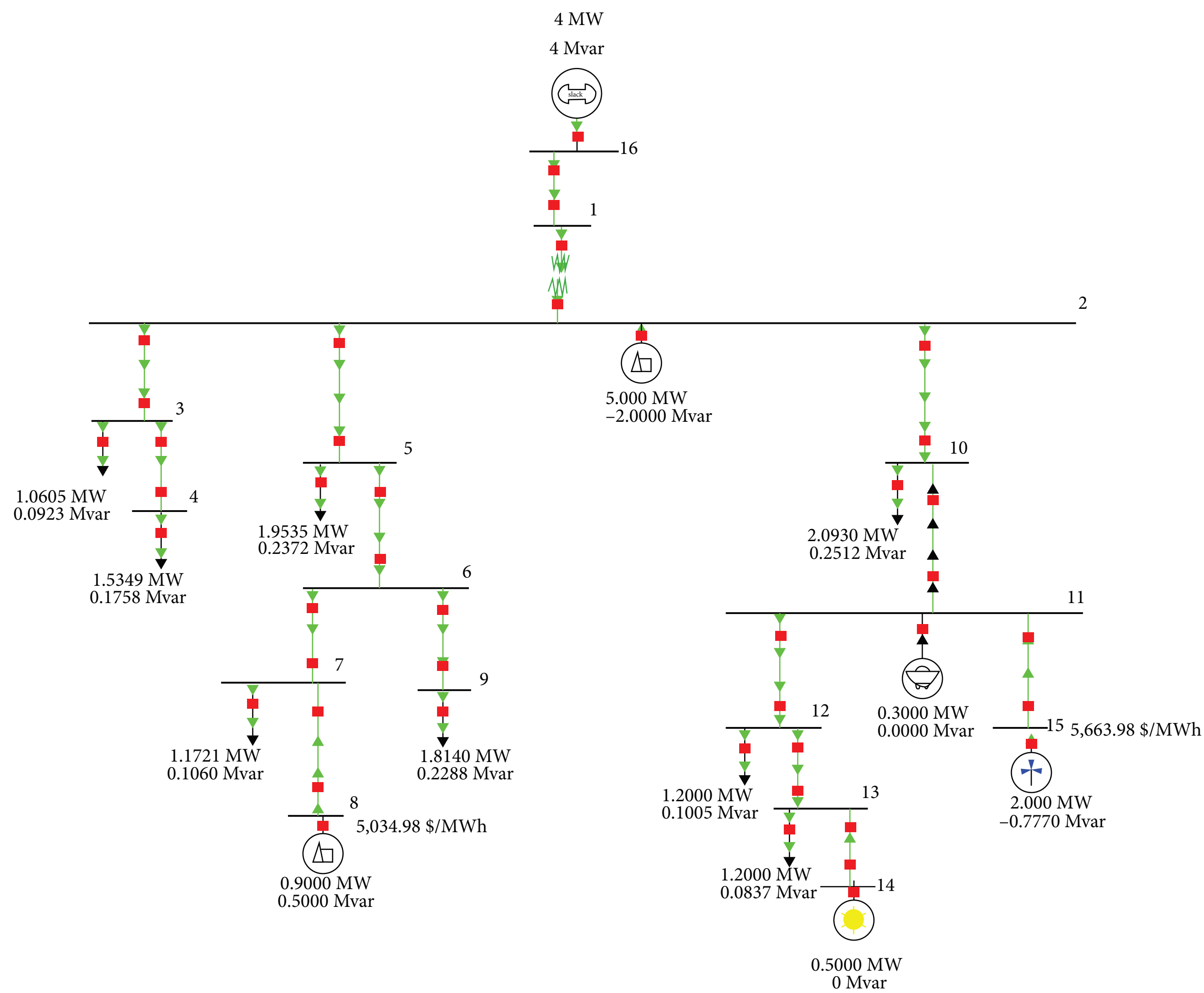

Figure 5: The single-line diagram of the IEEE microgrid system 16 bus.

Table 1: The percentage of loads in the system.

Load bus Li	Very important load (C_1) (%)	Important load (C_2) (%)	Less important load (C_3) (%)
Load 3	0.170	0.291	0.539
Load 4	0.220	0.245	0.535
Load 5	0.290	0.232	0.478
Load 7	0.280	0.163	0.557
Load 9	0.220	0.228	0.552
Load 10	0.180	0.272	0.548
Load 12	0.260	0.182	0.558
Load 13	0.240	0.206	0.554

Data for calculating criterion layer weights

Data for calculating scheme layer weights

Table 2: The values of the criterion layer weights.

	C_1	C_2	C_3
$\omega(i)$	0.3856	0.3810	0.2333

Table 3: Project priority index and scheme layer weights.

Load Li	Ri of $\overline{P_1}$	Ri of $\overline{P_2}$	Ri of $\overline{P_3}$	$W_{P(j)}$ of very important load	$W_{P(j)}$ of important load	$W_{P(j)}$ of less important load
Load 3	0.5	1.5	7.5	0.0156	0.0469	0.2344
Load 4	6	5.5	6.5	0.1875	0.1719	0.2031
Load 5	1.5	6.5	0.5	0.0469	0.2031	0.0156
Load 7	3.5	0.5	2.5	0.1094	0.0156	0.0781
Load 9	6	7.5	4.5	0.1875	0.2344	0.1406
Load 10	2.5	3.5	5.5	0.0781	0.1094	0.1719
Load 12	4.5	2.5	1.5	0.1406	0.0781	0.0469
Load 13	7.5	4.5	3.5	0.2344	0.1406	0.1094
$\Sigma_{i=1}^{n} R_i$	32	32	32			

Priority index of each load in each load group

Scheme layer weight

Table 4: Calculation results of weights: W_{ij}, W_{PSI}, and $W_{L,i}$, the rank of the buses, and the amount of shedding power at the load buses.

Load bus L_i	W_{ij}	PSI	W_{PSI}	$W_{L,ij}$	Rank	$P_{\mathrm{shed},Li}$ (MW)
Load 3	0.0786	0.0205	0.9795	0.0770	7	0.27501
Load 4	0.1852	0.0526	0.9474	0.1755	2	0.17418
Load 5	0.0991	0.0235	0.9765	0.0968	5	0.40248
Load 7	0.0664	0.0044	0.9956	0.0661	8	0.35351
Load 9	0.1944	0.0181	0.9819	0.1909	1	0.18940
Load 10	0.1119	0.0403	0.9597	0.1074	4	0.38875
Load 12	0.0949	0.0045	0.9955	0.0945	6	0.25371
Load 13	0.1695	0.0274	0.9726	0.1649	3	0.14176
Total						2.1788

the proposed technique compared to the UFLS technique. These outcomes are displayed in Figure 6.

In case study 1, the UFLS method is compared with the proposed method in terms of load shedding power and frequency recovery. Although the recovery frequency of the UFLS method is better than that of the proposed method, the amount of load shedding power is 86.95% larger, which causes economic loss due to the shedding. Besides, the frequency after shedding according to the proposed method has recovered to the allowable range (59.7–60.3 Hz).

The simulation results show that: although the recovery frequency of the suggested technique is not as good as that of the UFLS technique, these parameters still recover to the allowable range. The amount of load shedding power is less than the UFLS method. That supports to reduce the economic losses affected by load shedding for electricity customers.

Case study 2: Compares the recovery voltage parameter between the suggested technique (Improved AHP_PSI) and the improved AHP method. The voltage value at buses when comparing the suggested technique and the improved AHP method is shown in Figure 7.

In case study 2, the recovery voltage of buses when shedding load by the proposed method is better than the original improved AHP method. With the same amount of shedding power, when applying the shedding method based on the

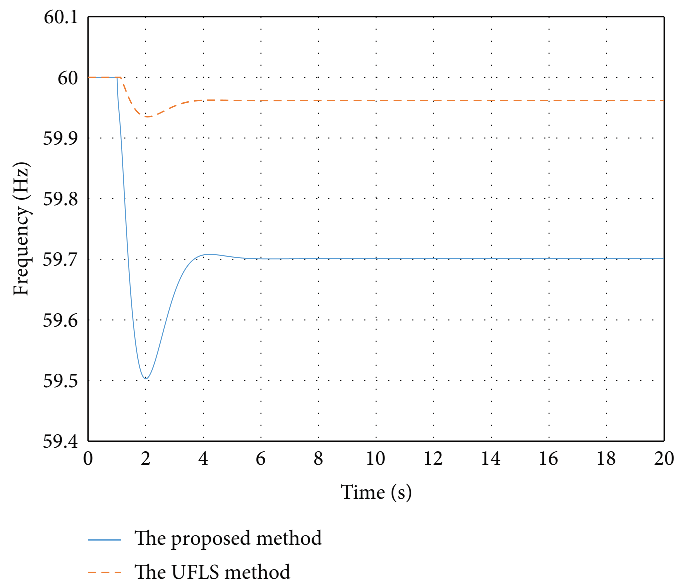

FIGURE 6: Microgrid recovery frequency after implementing load shedding according to the proposed method and UFLS method.

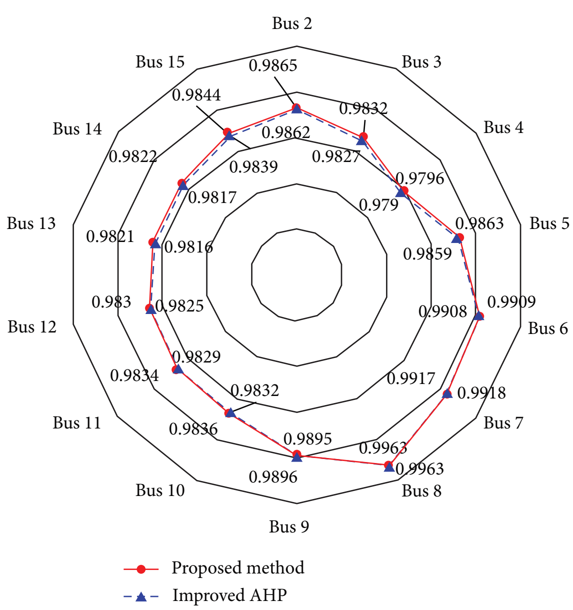

FIGURE 7: The comparison of the recovery voltage parameter at the load buses between the proposed method and the improved AHP method.

improved AHP and PSI, the recovery voltage values at all load buses are higher than the load shedding method based on the improved AHP. Specifically, according to the improved AHP and PSI method, the voltage values after shedding at the buses are as follows: Bus 3 (0.9832 pu), Bus 4 (0.9796 pu), Bus 5 (0.9863 pu), Bus 7 (0.9918 pu), Bus 9 (0.9896 pu), Bus 10 (0.9836 pu), Bus 12 (0.9830 pu), Bus 13 (0.9831 pu). Meanwhile, according to the improved AHP method, the voltage values after shedding at the buses are as follows: Bus 3 (0.9827 pu), Bus 4 (0.9790 pu), Bus 5 (0.9859 pu), Bus 7 (0.9917 pu), Bus 9 (0.9895 pu), Bus 10 (0.9832 pu), Bus 12 (0.9825 pu), and Bus 13 (0.9816 pu).

Therefore, it can be said that the technical factor of PSI considered in the study is effective and can meet the technical aspect of the load shedding power distribution technique. In addition, to check the voltage stability region, the *P*–*V* characteristics of the research cases: no load shedding when island, shedding according to the improved AHP method, and shedding according to the improved AHP method combined with PSI value, are presented in Figure 8.

From Figure 8, it can be seen that the voltage stability region of the shedding method based on the improved AHP and PSI is better than the improved AHP and the case of no load shedding. Therefore, the proposed method will help the system have a better voltage stability reserve.

6. Discussion

The traditional load shedding method uses UFLS relays, when the frequency drops below the frequency threshold setting, the relay will shed a predefined amount of power. This makes the load shedding can exceed the amount of power required to be shed under certain circumstances (due to load shedding as a percentage of the load) and lead to a large frequency difference, which causes more waste and damage to customers. Because of the higher amount of shedding power, the recovery frequency value of this method is higher than that of the proposed method. Meanwhile, the amount of shedding power of the proposed method ensures that the frequency will recover to the allowable value, so the amount of shedding power and the frequency recovery value will be less. However, this value is still within the allowable range. As a result, due to less power shedding, there is less damage to customers. In addition, the proposed shedding method also considers the types of priority load and the index of power stability to enhance the voltage quality when shedding. Moreover, even if the amount of power shedding of the proposed method and that of the UFLS

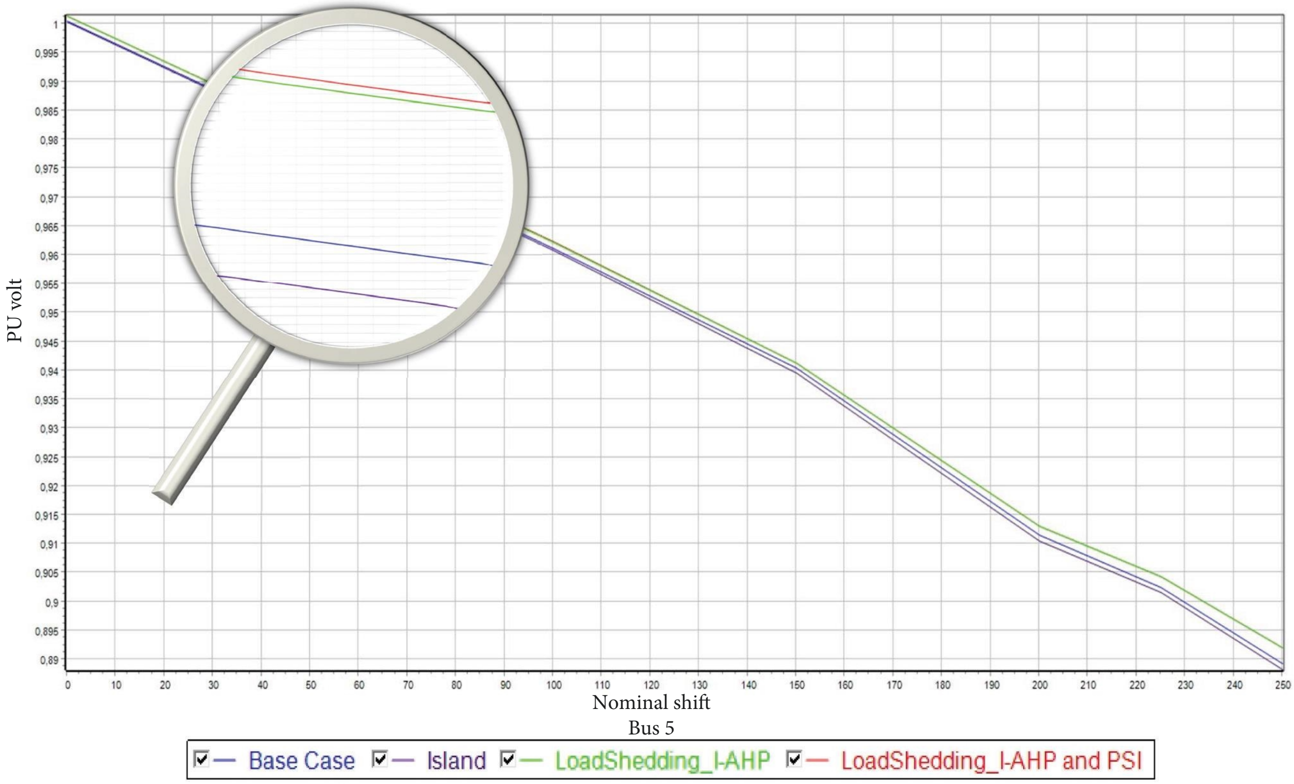

FIGURE 8: P–V characteristics of case studies: no loads shedding, i-AHP, i = AHP_PSI.

method are equal, the proposed method still has the advantage that it considers the priority of loads, or the critical loads in order to rank the shedding priority. In parallel with that, it also takes more PSI index into account to improve the voltage quality. Meanwhile, the UFLS method has not received interest.

In practice, the proposed load shedding model requires a measurement system in order to quickly and accurately collect parameters of the power of the loads in the system. From the measured values collected, it helps to calculate the power ratio of the priority load types. Then, depending on Spearman correlation transformation and improved AHP algorithm to calculate the load ranking. Meanwhile, load shedding based on power flow distribution can still be done to restore the system's frequency and reduce the current or power transmitted on the lines, which helps to improve the stability of the power system. However, this method does not consider the priority loads in the system as well as the damage caused by the load shedding. The error and reliability of the measurement system, which collects data for the improved AHP algorithm, determine the error and reliability of the problem's solution. Therefore, it is necessary to have solutions to limit the errors caused by measurement and eliminate noise parameters in the data collection process. This will be an interesting research topic in future works.

The improved AHP method and the traditional AHP method both use the AHP hierarchical model to calculate the priority weights. The improved AHP method uses Spearman correlation and statistical techniques, thus ensuring high reliability and absolute consistency. The improved AHP method improves some of the following issues:

(1) First, in the traditional AHP method, the elements in the judgment matrix are derived from the opinions of experts or operators in the power system, so these opinions depend heavily on their understanding. One of the main drawbacks of the traditional AHP method is the potential for operator bias. This is because the decision-making process heavily relies on the input and opinions of the operator, who may be influenced by personal biases, experiences, and beliefs. For the improved AHP, the data will be collected and processed by using statistical techniques and correlation, especially Spearman correlation, so reliability is increased, and subjectivity is significantly reduced. Hence, this method does not depend on the opinion of experts, but the ratio of priority loads collected by each load node.

(2) Second, for the traditional AHP method, after calculating the weights of the object, there is a need to check the consistency of the judgment matrix, if the consistency is not reached (i.e., greater than 0.1), it is necessary to repropose the judgment matrix. For the improved AHP, the data processed by statistical techniques creates a correlation matrix, which has absolute consistency (i.e., the CR is zero). This shows the objectivity of the improved AHP method and proves the effectiveness of the improvement.

(3) Third, the improved AHP algorithm is quickly calculated based on statistical and correlation expressions.

The recovery voltage value at the load buses shows that the load shedding according to the proposed method has a better recovery value. This is due to the effect of load shedding distribution considering the PSI, thereby proving the efficiency of the suggested technique. In addition, the suggested technique has prioritized load reduction with low WL, *j* weight and high PSI weight, so it can ensure the economic and technical aspects of the load reduction problem at the same time.

The PSI index affects to the recovery voltage value and the ability expand the voltage stability region. In this study, because the amount of load shedding power of the two cases study is equal, the proposed method has a better value of recovery voltage, and a better voltage stability region. However, this magnitude is not very much. Therefore, depending on the priority and the research problem is frequency stability or voltage stability, the PSI weight in the overall weight formula is more or less. This issue needs to be studied more in future studies.

7. Conclusions

The proposed load shedding technique is built on the improved AHP algorithm and the PSI index. The improved AHP method is applied to reduce subjectivity by replacing the judgment matrix based on expert opinions with a fuzzy priority correlation matrix based on statistical techniques and Spearman correlation. This algorithm used a combination of data analytics and traditional multicriteria decision analysis to transform data from a sorting problem to a ranking problem. This method is applicable to the case where the system implements load shedding taking into account the percentages of load types. It accurately, objectively, and consistently calculates load shedding weights, which will help reduce the damage to electricity customers and suppliers. The outstanding advantage of the improved AHP method compared to the traditional AHP method is that the consistency of the criteria comparison matrix is absolute. Therefore, there is no need to waste time checking for consistency and reproposing the criteria comparison matrix when the original matrix is not consistent. Besides, the combination with the PSI index aims to improve the stability of the system and optimize both economic and technical aspects.

In future work, the weight calculation will be computed and updated continuously according to the forecast of the load graph. From there, the load shedding plan will be executed proactively and accurately to ensure that the cost affected by the load shedding is minimized in all situations.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors' Contributions

All authors contributed to the study conception and design. Topical guidance was performed by Trong Nghia Le. Material preparation, data collection, and analysis were performed by Hoang Minh Vu Nguyen, Thai An Nguyen, Trieu Tan Phung, Thi Thu Hien Huynh, and Quang Tien Nguyen. The first draft of the manuscript was written by Trong Nghia Le, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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