Application of AHP algorithm on power distribution of load shedding in island microgrid

An. T. Nguyen[1], Nghia T. Le[2], Anh. H. Quyen[3], Binh T. T. Phan[4], Tan P. Trieu[5], Thien D. Hua[6]
[1,2,3,5,6]Department of Electrical and Electronics Engineering, Ho Chi Minh City University of Technology and Education, Ho Chi Minh City, Vietnam
[4]Department of Electrical and Electronics Engineering, Ho Chi Minh City University of Technology, Vietnam

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ABSTRACT

This paper proposes a method of load shedding in a microgrid system operated in an Island Mode, which is disconnected with the main power grid and balanced loss of the electrical power. This proposed method calculates the minimum value of the shed power with reference to renewable energy sources such as wind power generator, solar energy and the ability to control the frequency of the generator to restore the frequency to the allowable range and reduce the amount of load that needs to be shed. Computing the load importance factor (LIF) using AHP algorithm supports to determine the order of which load to be shed. The damaged outcome of load shedding, thus, will be noticeably reduced. The experimental results of this proposed method is demonstrated by simulating on IEEE 16-Bus microgrid system with six power sources.

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Corresponding Author:

Nguyen Thai An
Department of Electrical and Electronics Engineering
Ho Chi Minh City University of Technology and Education
01 Vo Van Ngan Street, Thu Duc District, Ho Chi Minh City, Vietnam
Email: anthainguyen.hcmute@gmail.com

1. INTRODUCTION

Microgrid is a system that can be operated in both Island and grid-connected mode to ensure stable power supply [1]. In Island mode, the microgrid will act as a single, self-controlling grid so that its frequency and voltage can be adjusted by managing the power distribution of all the energy sources [2]. In addition, the practice of power imbalance between the distributing sources and the electrical loads is expected to occur frequently, which is the case where the total generator power is less than the load power. Consequently, this will lead to a rapid decrease in frequency due to the poor response of the distributed energy resources. The monitoring and control system will immediately implement specific solutions to restore the frequency back to its threshold and quickly improve the system stability.

In [3] an automatic controller restoring the frequency after each disturbance implements managing the primary and secondary controls in such microgrid. Load shedding is considered as a last resort to avoid cascaded tripping and blackout [4-11]. There are many methods to load shedding in the traditional power system [12-16] and in recent years studies of load shedding in microgrid have been conducted, including such conventional methods as in [17] suggesting the permutation of the rate of change of under frequency (ROCOUF) relay. There are available scheduled load shedding strategy and the adaptive one, the former is outlined in [18, 19] and the latter is depicted in [20]. In [21] proposes an efficient multi-layer fuzzy-based load Shedding (MLFLS).

A load shedding strategy is considered as effective when the amount of shed load is the lowest and the stable frequency of microgrid still be restored to its threshold after the load shedding practice. Besides the critical damage caused by that action must also be carefully thought-out. This article presents the method of load shedding in the microgrid system operating in disconnected-Island mode from the main grid by calculating the minimum amount of the load shedding practice taking into account renewable energy sources, primary and secondary control in microgrid. Computing the load importance factor (LIF) using AHP algorithm helps to determine the priority order of which load to be shed.

The method is illustrated by simulating a IEEE 16-bus microgrid system with six power sources including diesel generator, solar power, wind energy generator, battery energy storage all connecting to the main grid. The experimental results of the method are compared with the results using the under-frequency load shedding (UFLS) in order to show the effectiveness of the proposed method.

2. METHODOLOGY

2.1. Determine the minimum value of load shedding power

Microgrid system includes the power supplies and the load units, containing the power received from the main grid, the source components which have a governor, or the droop control of distributed generation (DG) to control the frequency and types of distributed power of renewable energy such as wind energy, solar energy, and battery energy storage. The power balance equation under normal operating conditions without the power loss is presented as:

$$P_{main\ \mathrm{grid}} + P_{Gi} + P_{G_{batt}} + P_{G_{wind}} + P_{G_{solar}} = \sum P_{Lj} \tag{1}$$

where $P_{\mathrm{main\ grid}}$ is the power received from the main grid. P_{Gi} is the power of the i^th^ generator belonging to the source components, which have a governor, or the droop control of DG to control the frequency at the period of a normal operating condition. P_{Lj} is the active power of the j^{th} load unit in the period of a normal operating condition. $P_{G_{batt}}, P_{G_{wind}}, P_{G_{solar}}$ is the power of the battery energy storage, wind power generator and solar energy which are considered as negative load.

When the microgrid system disconnects to the main grid, the initial reaction of the system is the reaction of energy sources which control their power, particularly including a governor, or the droop control of DG that increase the power in relation to the frequency-change [22-24]. The primary and secondary control of the generators are shown in Figure 1.

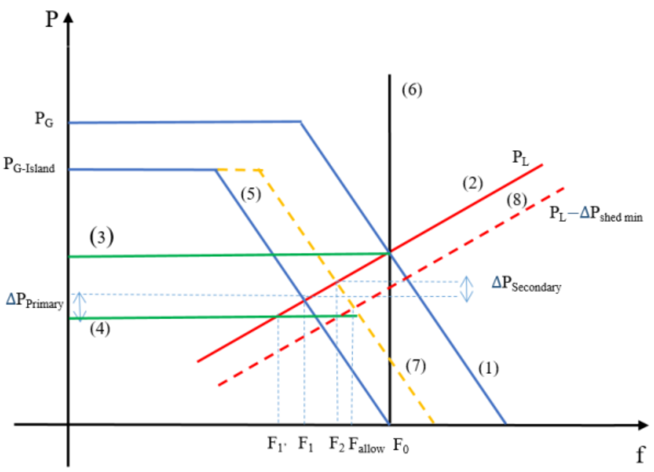

Figure 1. Primary and secondary control

Where F_{allow} is the restored frequency (59.7Hz for power grids with a rated frequency of 60Hz); After the disconnection to the main grid and the primary control, the power balance equation is presented as follows:

$$P_{Gi} + \Delta P_{\mathrm{Primary}} = \sum P_{Lj} - P_{G_{batt}} - P_{G_{wind}} - P_{G_{solar}} - \Delta P_{L(feq)} \tag{2}$$

where, $\Delta P_{Primary} = \sum \frac{-\Delta f_1}{R_i}$ is the value of primary control power, which is the amount of primary control of a system when a problem occurs with the ratio between frequency deviation and power deviation (R), which is featuring for adjusting the slip speed; $\Delta P_{L(feq)} = D \times (-\Delta\omega)$ is the composition of the load depends on the frequency-change (e.g. motors, pumps, etc.). D is a percentage-change coefficient of the load according to a percentage of frequency-change, the value of D is from 1% to 2% and experimentally determined in the power system. E.g. when the value of D = 2% means that a 1% of the frequency-change will cause a 2% in load-change [22].

In the case that the frequency value after the primary control is still out of its threshold, the secondary frequency control is considered as a next implement, the power balance equation is presented as:

$$P_{Gi} + \Delta P_{Primary} + \Delta P_{Secondary} = \sum P_{Lj} - P_{G_{batt}} - P_{G_{wind}} - P_{G_{solar}} - \Delta P_{L(feq)} \quad (3)$$

where $\Delta P_{Secondary} = \sum_{i=1}^{m} P_{Gn,i} - \Delta P_{Primary,i}$ is value of maximum secondary control of the generator for frequency regulation with $P_{Gn,i}$ is the maximum power of the ith generator.

After implementing both processes: primary and secondary control but the frequency has not been restored to the allowed frequency (f_{allow}), load shedding is mandatory and necessary to restore f_{allow}. The power balance equation at this time is presented as follows:

$$P_{Gi} + \Delta P_{Primary} + \Delta P_{Secondary} = \sum P_{Lj} - P_{G_{batt}} - P_{G_{wind}} - P_{G_{solar}} - \Delta P_{L(feq)} - \Delta P_{Shed\min} \quad (4)$$

$$\Leftrightarrow P_{Gi} + \sum \frac{-\Delta f_{allow}}{R_i} + \Delta P_{Secondary} = \sum P_{Lj} - P_{G_{batt}} - P_{G_{wind}} - P_{G_{solar}} - D \times (-\Delta\omega_{allow}) - \Delta P_{Shed\min} \quad (5)$$

From (5), the minimum value of load shedding power is calculated by the (6):

$$\Delta P_{Shed\min} = \sum P_{Lj} - P_{G_{batt}} - P_{G_{wind}} - P_{G_{solar}} - D \times (-\Delta\omega_{cp}) - P_{Gi} - \sum \frac{-\Delta f_{allow}}{R_i} - \Delta P_{Secondary} \quad (6)$$

where $\Delta P_{Shed\min}$ is the minimum value of shed power so that the frequency is restored to its threshold, $\Delta f_{allow} = f_n - f_{allow}$ is the allowed frequency attenuation.

2.2. The coefficient of importance based on the analytic hierarchy process (AHP)

The main purpose of AHP is to circumvent a problem into smaller component parts. The two stages of AHP are designing the hierarchical organization and analyzing its components. AHP is a calculation technique for decision-making, which involves calculating the weights and ranking the importance, which are relative to each other on each criterion in turn, and then the combining of the pairwise-ranking results in order to obtain a measure of support for judging each alternative as the top-ranked alternative overall depending on the purpose of application. Determining the importance factor of the buses in microgrid brings the weight for each bus in a hierarchical level, thereby giving priority of which bus to be shed. The steps of the AHP algorithm can be presented in [25, 26].

Step 1: Set up a hierarchy model, shown in Figure 2.

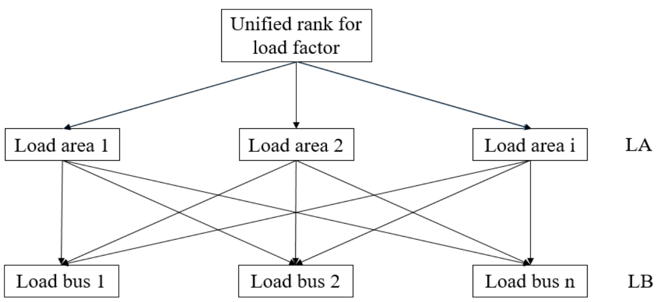

Figure 2. Hierarchical organization of ranking units

Step 2: Form a judgment matrix.

The A-LB and A-LA judgment matrix can be written as follows.

$$A-LB=\begin{bmatrix} w_{D1}/w_{D1} & w_{D1}/w_{D2} & ..... & w_{D1}/w_{Dn} \\ w_{D2}/w_{D1} & w_{D2}/w_{D2} & ..... & w_{D2}/w_{Dn} \\ . & & & . \\ . & & & . \\ . & & & . \\ w_{Dn}/w_{D1} & w_{Dn}/w_{D2} & ..... & w_{Dn}/w_{Dn} \end{bmatrix}, \quad A-LA=\begin{bmatrix} w_{K1}/w_{K1} & w_{K1}/w_{K2} & ..... & w_{K1}/w_{Kn} \\ w_{K2}/w_{K1} & w_{K2}/w_{K2} & ..... & w_{K2}/w_{Dn} \\ . & & & . \\ . & & & . \\ . & & & . \\ w_{Kn}/w_{K1} & w_{Kn}/w_{K2} & ..... & w_{Kn}/w_{Kn} \end{bmatrix} \tag{7}$$

Where: W_{Di}/W_{Dj}, which is the element of the judgment matrix A-LA, represents the relative importance of the ith load compared with the jth load; W_{ki} /W_{kj}, which is the element of judgment matrix A-LB, represents the relative importance of the ith load area compared with the jth load area. The value of W_{Di}/W_{Dj} and W_{ki}/W_{kj} can be obtained from the experience of experts or operators by using 9-scaling method. Therefore, the unified weighting factor of the load W_i can be obtained from the (8).

$$W_{ij} = W_{Kj} \text{ x } W_{Di} \tag{8}$$

where $D_i \in K_j$ means load D_i is located in load center K_j.

The value of the factors in the matrices reflects a user's knowledge of the relative importance between every pair of factors.

Step 3: Calculate the maximal eigenvalue and the corresponding eigenvector of the judgment matrix

Step 4: Hierarchy ranking and consistency check of results

The hierarchical structure can be done according to the value of the components in the eigenvectors, representing the importance of the relationship of the corresponding factor. The consistency index of the hierarchy ranking [20] is determined as (9):

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{9}$$

where, $\lambda_{\max}$ is maximum eigenvalue of the judgment matrix, n is the dimension of the judgment matrix.

The stochastic consistency ratio is defined as:

$$CR = \frac{CI}{RI} \tag{10}$$

where, RI is a set of given average stochastic consistency indices and CR is the stochastic consistency ratio. For matrices with dimensions ranging from one to nine, respectively, the values of RI will be in Table 1.

Table 1. Consistency indexes, which are stochastic, initialized for different sizes of matrix

n	1	2	3	4	5	6	7	8	9
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

It is evident that for a matrix with n = 1 or 2, it is not necessary to check the random consistency ratio. In general, the judgment matrix is satisfied if the stochastic consistency ratio CR < 0.10. To create the judgment matrix in step 2, we will base on the basic principles of AHP as follows:

The basic principle of AHP is to calculate the specific function of the alternatives for each criterion. For qualitative factors such as the relative importance of units and criteria, the respective functions can be obtained by calculating the judgment matrix. The judgment matrix can be formed on the basis of several scaling methods, such as the 9-scaling method. For the two efficiency indicators A and B, their relationship can be expressed as follows using the 9-scaling method [27]. If the opinions of experts are mismatch with each other, to achieve the final judgment matrix, use the following formula:

$$CF_{eq} = \sqrt[n]{CF_1 \times CF_2 \times .... \times CF_n} \tag{11}$$

where n is the number of experts who gave their opinions, CF_n is the scaling factor according to the opinion of the n^{th} expert when considering the importance of A and B, CF_{eq} is the equivalent scaling factor when considering the level of importance of A and B.

The maximum eigenvector values and corresponding eigenvectors of the judgment matrix in step 3 are calculated by the root method [28]. For the judgment matrix A, apply the root method of calculating the eigenvector vector, we get

$$W = \left[W_1, W_2, ..., W_n\right]^T \tag{12}$$

The maximum eigenvalue $\lambda_{\max}$ of judgment matrix A is calculated using the (13):

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(AW)_j}{nW_i}, j = 1,\ldots, n \tag{13}$$

where: $(AW)_i$ represents the i^{th} component of the vector AW.

2.3. Distribution of the minimum value of load shedding based on the importance factor of the load buses

After calculating the minimum amount of load shedding and importance factor of the load buses, the next step is to distribute the shed power to the buses in which the lower value of its importance factor, the higher value of its power to be shed and vice versa. In this shed power distribution, it is not possible to shed all the power of the buses with a low importance factor because it must ensure the baseline load for these buses. The value of shed power of the buses will be calculated by the (14):

$$P_{Shed,i} = \frac{\mathrm{W}_{eq}}{\mathrm{W}_{ij}} \times P_{Shed\min} \tag{14}$$

where, $P_{Shed,i}$ is the load shed power of the i^{th} bus (MW); $P_{Shed\ min}$ is the minimum load shed power to restore frequency back to allowed range (MW); W_{ij} is the importance factor of the i^{th} buses, W_{eq} is the equivalent importance factor of all the buses and W_{eq} is calculated in the (15).

$$\mathrm{W}_{eq} = \frac{1}{\sum_{i=1}^{m} \mathrm{W}_{ij}} \tag{15}$$

3. CASE STUDIES-SIMULATION AND RESULTS

The IEEE 16-bus [29] microgrid system with 6 power sources was chosen as the system to simulate the effectiveness testing of the proposed methods. The microgrid includes a power source at bus-16 is considered as the main grid connecting to the microgrid at bus 1, two diesel generators, one solar energy, one wind power generator and one battery energy storage. The parameters of the generators and the loads are shown in Tables 2 and 3. The experimental case is the system operated in the Island mode and the diesel generator at bus 2 is specified as a bus for secondary control. The experimental cases are supported with simulation using power world simulation 2019.

In this experimental microgrid, two diesel generators participate in frequency control. Using (3) and the parameters of the generators and load in Table 2 and Table 3, we get:

$$5 + 0.9 + \frac{6\times(-\Delta f_1)}{0.05\times 60} + \frac{1\times(-\Delta f_1)}{0.05\times 60} = 11.98 + (-0.3) + (-2) + (-0.5) - \frac{11.98\times 0.02\times(-\Delta f_1)}{60}$$
$$2.3373267(-\Delta f_1) = 3.28$$
$$\Delta f_1 = -1.4033 Hz$$

The frequency after the disconnection to the main grid equals: 60 + (-1.4033) = 58.59668Hz. The frequency waveform after the disconnection to the main grid is depicted in Figure 3. According to Figure 3, the frequency value after the disconnection with the main grid is less than the allowed value.

Table 2. Parameters of generators

Generator	P_G (MW)	P_{Gn} (MW)	R
Grid supply	3.87		
Gen 2 (Diesel)	5.00	6.0	0.05
Gen 8 (Diesel)	0.90	1.0	0.05
Gen 11 (Battery)	0.30	0.5	0.00
Gen 14 (Solar)	0.50	1.0	0.00
Gen 15 (Wind)	2.00	3.0	0.00

Table 3. Load area and active power of load buses

Load	Load 3	Load 4	Load 5	Load 7	Load 9	Load 10	Load 12	Load 13	Total
Load Area (LA)	LA1	LA1	LA2	LA2	LA3	LA3	LA3	LA3	11.98
Active power (MW)	1.06	1.53	1.95	1.17	1.81	2.09	1.20	1.17	

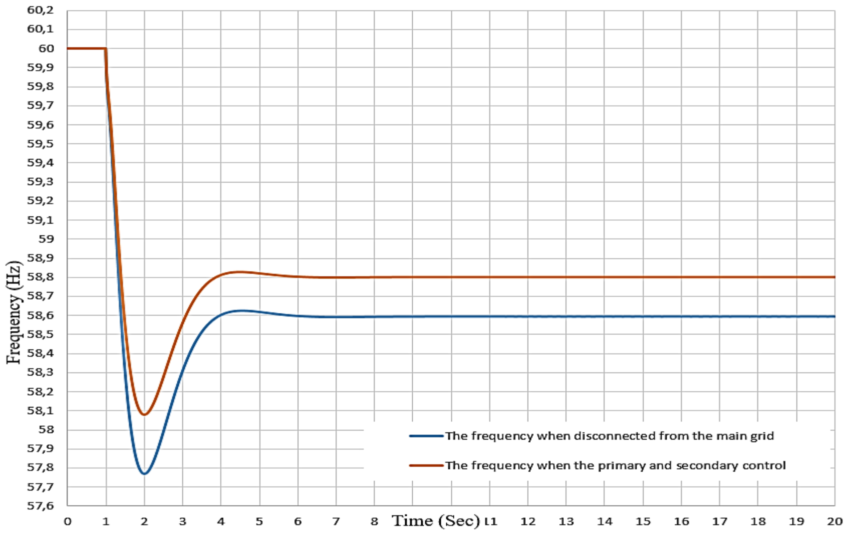

Figure 3. Frequency value of the microgrid after the primary and secondary control

Therefore, it is necessary to carry out the process of primary and secondary frequency control described in section 2.1 to restore the frequency. The primary frequency control is automatically implemented due to the reaction of the turbine governor. Primary power control is calculated as:

$$\sum \Delta P_{Primary} = \frac{-6}{0.05} \times \frac{-0.3}{60} + \frac{-1}{0.05} \times \frac{-0.3}{60} = 0.7MW$$

The value of secondary control power from the diesel generators at Bus-2 the calculated as:

$$\Delta P_{Primary} = 6 - 5 - 0.6 = 0.4MW$$

After calculating the value of the primary and secondary power, the graph of frequency simulation of the grid is shown in Figure 3. According to Figure 3, the frequency value has not restored to its threshold after the primary control. Load shedding practice, therefore, is implemented to effectuate the aforementioned requirement. Using (6), the minimum value of the load shedding power is calculated as follows:

$$\Delta P_{Shed\min} = 11.98 + (-0.3) + (-2) + (-0.5) + \frac{11.98 \times 0.02 \times (-0.3)}{60} - 5 - 0.9 - \frac{-6 \times (-0.3)}{0.05 \times 60} - \frac{-1 \times (-0,3)}{0.05 \times 60} - 0.4 = 2.1788MW$$

the minimum value of the load shedding power is 2.1788 MW.

Implementing the steps of the AHP algorithm to determine the importance of the load units in the system, thereby serving as a fundamental for load shedding. The specific loads, which have low value of importance factor, is preferentially reduced to diminish severe damage. The calculating load importance factor is calculated according to the procedure presented in section 2.2.

Step 1: Identifying the load areas and its loads on the microgrid diagram. Identify three additional load areas corresponding to three regions as shown in Figure 4.

Step 2: Defining hierarchical structure to calculate the importance factor according to load areas and divided loads.

Step 3: Determining the weights of the importance of load areas and its loads using the judgment matrix. Applying the 9-scaling method to initialize judgment matrix of load and load areas. The opinions of the experts are used as a fundamental for initializing judgment matrix. The results are presented in the Tables 4-7.

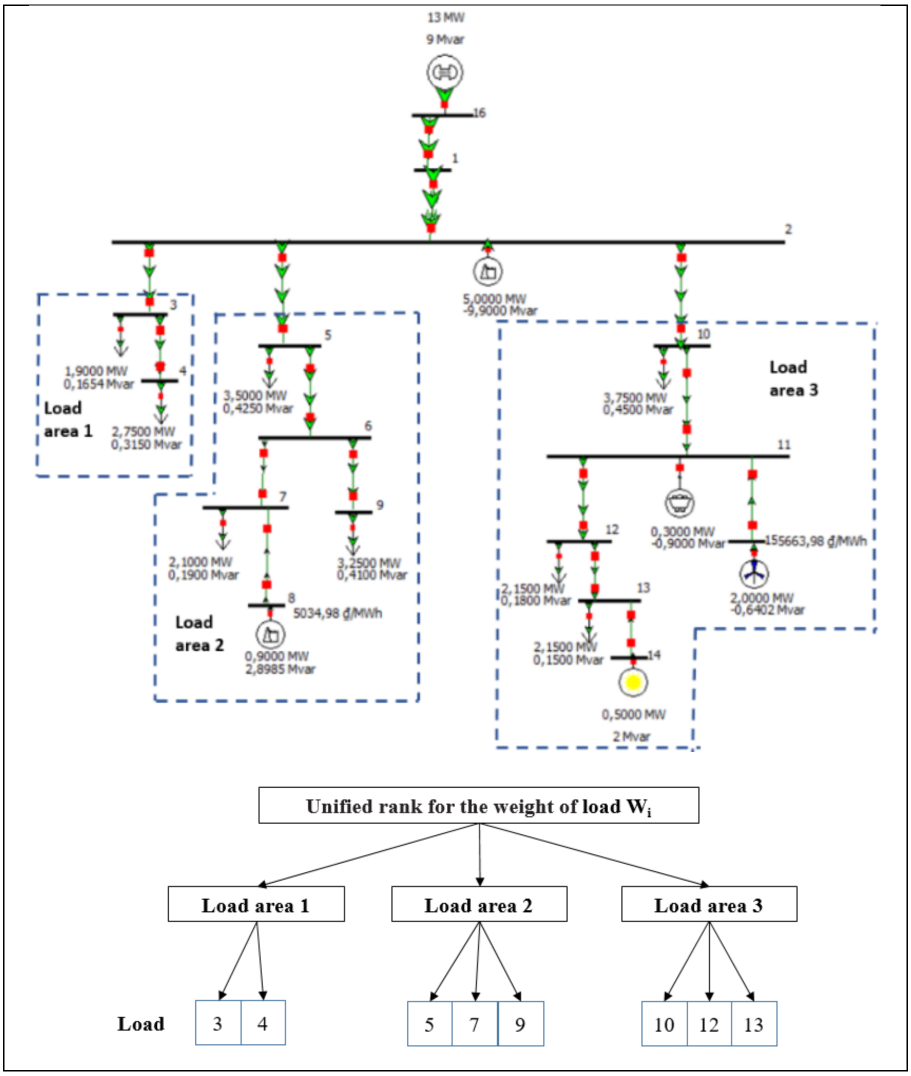

Figure 4. Location of load areas, loads in the microgrid diagram and its hierarchical structure

Table 4. Judgment matrix of load areas (LA_i)

PI	LA1	LA2	LA3
LA1	1/1	2/1	2/1
LA2	1/2	1/1	1/2
LA3	1/2	2/1	1/1

Table 5. Judgment matrix of load area-1 (LB_j-1)

LA1	L3	L4
L3	1/1	2/1
L4	1/2	1/1

Table 6. Judgment matrix of load area-2 (LB_j-2)

LA2	L5	L7	L9
L5	1/1	1/3	1/2
L7	3/1	1/1	2/1
L9	2/1	1/2	1/1

Table 7. Judgment matrix of load area-3 (LB_j-3)

LA3	L10	L12	L13
L10	1/1	1/3	1/4
L12	3/1	1/1	1/2
L13	4/1	2/1	1/1

Step 4: Obtaining the weights of the importance of each load by multiplying the results of the eigenvectors with the result of the judgment matrix of the load areas and its loads.

Using the root method to calculate the eigenvector vector values of the judgment matrices, from the (12) obtained:

$$W_{Load\ Areas} = [0.493;\ 0.196;\ 0.311]^T \quad ; \quad W_{Load-Area-1} = [0.667;\ 0.333]^T ;$$

$$W_{Load-Area-2} = [0.163;\ 0.540;\ 0.297]^T \quad ; \quad W_{Load-Area-3} = [0.163;\ 0.540;\ 0.297]^T$$

After calculating the value of weights, check the consistency level of expert opinions on the elements in the same judgment matrix. Using (9), (10), (13) to calculate the maximum eigenvalues (λ_{max}), the consistency index (CI) and the stochastic consistency ratio (CR). The calculated results are presented in Table 8.

Table 8. The maximum eigenvalues, consistency index and random consistency ratio of the judgment matrices

Judgment matrices	λ_{max}	CI	CR
Judgment matrices of all load areas	3.054	0.027	0.046
Judgment matrices at load-area-1	2.75	0.75	0.000
Judgment matrices at load-area-2	3.009	0.005	0.008
Judgment matrices at load-area-3	3.018	0.009	0.016

From the results presented in Table 8, it is evident that the values of CR are less than 0.1, so the proposed judgment matrices above are acceptable. Multiplying the coefficient of importance of the loads by the load areas to get the final load importance factor. Using (14) to calculate the value of load shedding power at the buses, the calculated results are presented in Table 9.

Table 9. Importance factor and the value of load shedding power of the load buses

Load	Load area	W_{di}	W_{kj}	W_{ij}	Shed power (MW)
L3	LA1	0.667	0.493	0.329	0.0606
L4	LA1	0.333	0.493	0.164	0.1213
L5	LA2	0.163	0.196	0.032	0.6233
L7	LA2	0.540	0.196	0.106	0.1888
L9	LA2	0.297	0.196	0.058	0.3430
L10	LA3	0.122	0.311	0.038	0.5262
L12	LA3	0.320	0.311	0.099	0.2008
L13	LA3	0.558	0.311	0.174	0.1149
	Total			1.000	2.1788

The under-frequency load shedding method using under-frequency load shedding relay (UFLS) is used in order to compare the effectiveness of the proposed method. UFLS is performed when the frequency drops below its threshold. In fact, load shedding is usually carried out step by step based on the load shedding schedule determined based on general rules and experience of the experts. These mentioned tables indicate the amount of power that should be reduced at each step depending on the frequency attenuation [30].

The frequency comparison results showing the efficiency of the proposed method comparing with UFLS method frequency are shown in Figure 5. According to Figure 5, the value of shed power is significantly smaller within the allowed range, by which the effectiveness of the proposed method are highly proved, although the recovery frequency using the proposed method is not as equal as the recovery frequency using UFLS. In addition, the proposed method preferentially reduces loads, which are trivial, thereby reducing the severe damage caused by load shedding practices.

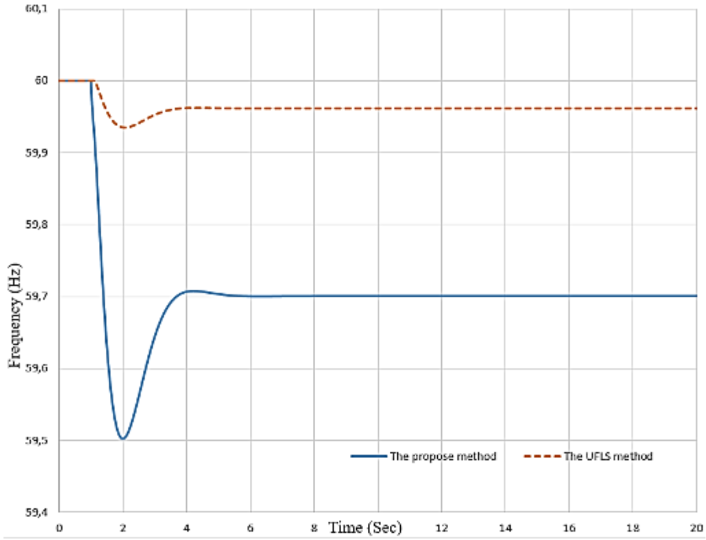

Figure 5. The recovered frequency after using load shedding with propose method and conventional method

4. CONCLUSION

The calculation of the minimum value of shed power allowing for renewable energy sources and the ability to control the generator's frequency in the microgrid system help to reduce the value of load shedding power and restore the frequency within the allowed range. Prioritizing to reduce the loads, which have low coefficient of importance immensely, helps to decline the severe damage caused by load shedding, while ensuring that the frequency of the grid is restored to its threshold. The effectiveness of the proposed method is demonstrated by simulating on IEEE microgrid system diagram of 16-bus with six sources. In terms of further research, load shedding issues in the microgrid system will be implemented by solving the multi-target prediction considering economic and technical factors and applying intelligent algorithms, e.g. GA, PSO, etc.

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BIOGRAPHIES OF AUTHORS

Nguyen Thai An received his Eng. degree in electrical engineering from Ho Chi Minh City University of Technology and Education (HCMUTE), Vietnam, in 2018. Currently, He is pursuing the M.S degree in electrical engineering at HCMC University of Technology and Education, Viet Nam.. His main areas of research interests are load shedding in power systems and Microgrid, power systems stability, and load forecasting, distribution network.

Trong Nghia Le received his M.Sc. degree in electrical engineering from Ho Chi Minh City University of Technology and Education (HCMUTE), Vietnam, in 2012. Currently, he is a lecturer in the Faculty Electrical and Electronics Engineering, HCMUTE. His main areas of research interests are load shedding in power systems, power systems stability, and distribution network.

Quyen Huy Anh received PhD degree in power system from MPIE, Russia in 1993. Currently, he is a professor, lecturer in the Faculty Electrical and Electronics Engineering, HCMUTE. His research interests are modeling power systems, pattern recognition in dynamic stability of power systems, and artificial intelligence.

Phan Thi Thanh Binh received Ph.D. degree in electrical engineering from Kiev Polytechnique University, Ukraine in 1995. Currently, she is a Professor and lecturer in the Faculty Electrical and Electronics Engineering, HCMUT. Her main areas of research interests are power systems stability, power systems operation and control, load forecasting, data mining.

Phung Trieu Tan received M.Sc. degree in electrical engineering from Ho Chi Minh City University of Technology and Education (HCMUTE), Vietnam, in 2020. Currently, he is a Research Assistant with the Faculty Electrical and Electronics Engineering, HCMUTE Viet Nam. His main areas of research interests are artificial neural network, load shedding in power systems, power systems stability, load forecasting and distribution network.

Hua Duc Thien received his Eng. degree in electrical engineering from Ho Chi Minh City University of Technology and Education (HCMUTE), Vietnam, in 2019. Currently, he is a Research Assistant with the Faculty Electrical and Electronics Engineering, HCMUTE Viet Nam. His main areas of research interests are load shedding in power systems, power systems stability, load forecasting and distribution network.