Application of the Fuzzy DEMATEL – ANP VIKOR Method to Rank Loads for Load Shedding in Microgrids

Tung Giang Tran
Faculty of Electrical and Electronics Engineering, HCMC University of Technology and Education, Vietnam
giangtt@hcmute.edu.vn

Thai An Nguyen
Faculty of Electrical and Electronics Engineering, HCMC University of Technology and Education, Vietnam
ntan@hcmute.edu.vn (corresponding author)

Hoang Minh Vu Nguyen
Ho Chi Minh City University of Architecture, Vietnam
vu.nguyenhoangminh@uah.edu.vn

Huy Anh Quyen
Faculty of Electrical and Electronics Engineering, HCMC University of Technology and Education, Vietnam
anhqh@hcmute.edu.vn

Ngoc Au Nguyen
Faculty of Electrical and Electronics Engineering, HCMC University of Technology and Education, Vietnam
ngocau@hcmute.edu.vn

Van Hien Truong
Faculty of Electrical and Electronics Engineering, HCMC University of Technology and Education, Vietnam
hientv@hcmute.edu.vn

Tuyet Dan Bui Thi
Faculty of Electrical and Electronics Engineering, HCMC University of Technology and Education, Vietnam
danbtt@hcmute.edu.vn

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ABSTRACT

This paper presents a multi-criteria decision-making method to rank loads for load shedding in microgrids. The proposed Fuzzy VIKOR technique is based on the Fuzzy Decision-Making Test and Evaluation Laboratory (DEMATEL) model and the Analytical Network Process (ANP). The load ranking for load shedding in a microgrid is an issue that requires balancing economic and technical criteria, both of which are often in conflict with each other when considering comparative objects. The proposed Fuzzy VIKOR technique aims to solve problems related to conflicting criteria. Fuzzy numbers theory is utilized

to handle uncertainty and relativity. Furthermore, the DEMATEL method also establishes Network Relationship Maps (NRM) and normalizes the unweighted supermatrix of ANP for weight values that match the criteria. The proposed method provides a comprehensive approach to evaluate the importance of criteria by determining the correlation and influence between factors, calculating their weights, and then ranking and selecting optimal loads based on the weights of load factors that serve the purpose of load shedding. A microgrid system with 16 buses was deployed to validate the proposed method.

Keywords-fuzzy DEMATEL; ANP ; VIKOR; ranking load; load shedding; microgrid

I. INTRODUCTION

Modern society is highly dependent on a secure energy supply. Today, there is growing concern about the availability of electric energy and the aging infrastructure of current transmission and distribution networks, which increasingly challenge the safety, reliability, and quality of power supply. Therefore, the most effective way to meet social needs is to combine technological solutions and the innovative development of the grid infrastructure. Microgrids are examples of such smart grid solutions.

In the event of a fault or poor power quality, a microgrid system autonomously disconnects from the main power grid, switching to the island mode for continuous power supply [1]. Operational challenges arise, particularly in islanded mode, due to increased load demand that affects the reliability of the power supply. Power imbalance leads to a decrease in frequency and voltage. When preventive measures fail, corrective actions such as source switching and load shedding are necessary. The elimination of loads is a cost-effective method to preserve the integrity of the microgrid [2]. However, its implementation requires a thorough evaluation and prioritization of all loads, marking the initial and pivotal step in the process. Ranking of loads in a microgrid is the process of assessing and prioritizing the importance of loads within the system. This helps ensure that critical loads, namely hospitals, broadcasting stations, or other essential devices, are prioritized for power supply in case of limitations. Supporting resource management and efficiently coordinating power supply ensures the stability of the microgrid system [3]. Several Multi-Criterion Decision Making (MCDM) methods [4-7] can be applied to evaluate and rank alternative choices, such as the Elimination and Choice Translating Reality (ELECTRE) method based on the elimination and choice expressing the reality process. ELECTRE has limitations in determining criteria and cutoff thresholds, is sensitive to changes in weights, cannot handle uncertainty, and cannot address complex correlations between criteria [8]. In [9-10], the PROMETHEE I method provided a central solution, while PROMETHEE II provided complete rankings. However, both methods do not calculate weights for evaluation criteria but rely on pairwise comparisons between alternative choices. The MOORA method independently evaluates criteria with many subjective factors. Determining the weights of the criteria can be challenging, leading to inaccurate results [11].

In [12-15] the fuzzy VIKOR technique was employed, and in [16-17] the TOPSIS method was proposed for multi-criteria ranking, both based on the objective function of approaching the ideal solution. The VIKOR method provides specific measures for the closeness to the ideal of alternative solutions and uses linear normalization. Although TOPSIS faces difficulties in using vector normalization, the normalized value depends on the evaluation unit. The results of TOPSIS yield the shortest and farthest distances for the ideal and worst solutions, respectively [18]. However, both methods do not consider the correlation between criteria and other sub-factors, leading to subjective evaluations.

According to [19-22] the Analytic Hierarchy Process (AHP) method forms judgment matrices and uses simple row-wise normalization, resulting in independent weight values without addressing the correlation relationship between criteria. The AHP method also faces difficulties in managing comparison matrices when problems involve a large number of criteria/factors. AHP mainly calculates the criterion and alternative weights based on judgment matrices, without obtaining any result close to the ideal solution. The Analytic Network Process (ANP) was proposed to address interdependencies and feedback issues between criteria and alternative choices [23], although adjusting these dependencies is incomplete.

Load rankings are assessed based on various criteria that combine economic and technical aspects, involving interdependencies and mutual relationships. This study introduces the VIKOR technique to obtain ranking indices based on specific measures of proximity to the ideal solution, improving and selecting alternative options when there are conflicting criteria and disproportionate discrete decisions. The Fuzzy VIKOR technique relies on the ANP and Fuzzy DEMATEL methods to address issues related to criteria that are inconsistent with this dependence and feedback. The use of fuzzy numbers theory handles uncertainty and relativity, while DEMATEL is employed to establish Network Relationship Maps (NRM) and normalize the unweighted supermatrix of ANP for appropriate weight values for the criteria. The final result is the prioritized ranking values for the loads, and from the distance values, the priority weights for the discharge can be inferred to calculate a reasonable amount of discharge power to minimize the maximum damage to the operator in the event of a system failure.

II. THE PROPOSED METHOD FOR LOAD RANKING

Prioritizing loads is a crucial aspect of overseeing electrical consumption in a microgrid, particularly in one that incorporates renewable energy sources. It helps operators understand the electricity usage of different components, allowing for a judicious energy distribution and stable power supply. Efficient management of load priorities improves operational efficiency, reducing the likelihood of power loss and system failures. To address these concerns, a hybrid MCDM model is proposed, employing the fuzzy DEMATEL - ANP VIKOR technique. Figure 1 illustrates the processes of this model.

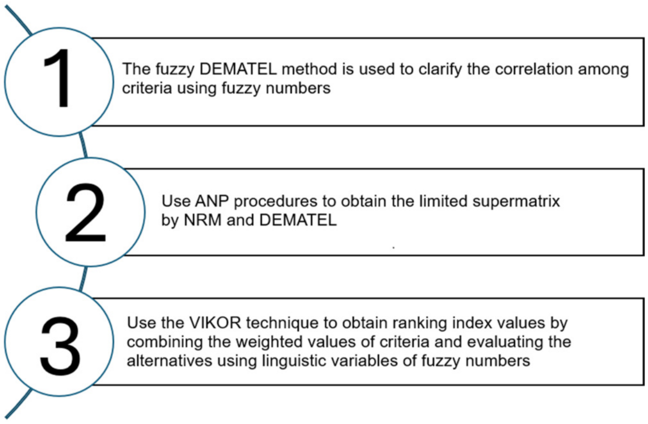

Fig. 1. Conducting rankings using the Fuzzy DEMATEL - ANP VIKOR method.

A. Selecting the Criteria and determining their Dependent Factors

The selection of criteria for evaluating load rankings must ensure both technical requirements and economic benefits. This study utilizes data and computational results based on [20] to choose and evaluate criteria and dependent factors as follows:

- Criteria 1 (C_1): Load Importance Factor (W_{LIF}):

  Element 1 (e_1): Load location. This is a factor assessed based on the location and importance of the load.

  Element 2 (e_2): Load power. This is a factor assessed based on the corresponding power capacity at each load.

  Element 3 (e_3): Penalty cost. This factor is determined based on the penalty amount that the operator must compensate when the power supply is interrupted.

- Criteria 2 (C_2, e_4): Voltage Electrical Distance (W_{VED}).
- Criteria 3 (C_3, e_5): Voltage Sensitivity Index (W_{VSI}).

B. Fuzzy DEMATEL Method

The DEMATEL method is deployed with the VIKOR technique, utilizing applications based on DEMATEL and ANP to establish relationships among factors/criteria and construct the impact of an NRM, as follows [24-25]:

1) Step 1: Set up the Direct Matrix according to the Scoring Evaluations for the Criteria

Each expert evaluator will create a matrix, which is then derived through the average values of similar criteria in the numerous matrices from different expert evaluators. The matrix is represented by:

$$\tilde{A} = \begin{bmatrix} \alpha_{11} & \cdots & \alpha_{1j} & \cdots & \alpha_{1n} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ \alpha_{i1} & \cdots & \alpha_{ij} & \cdots & \alpha_{in} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ \alpha_{n1} & \cdots & \alpha_{nj} & \cdots & \alpha_{nn} \end{bmatrix} \quad (1)$$

where $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ represents fuzzy triangular numbers indicating the degree of importance in the relationship between criteria i and criteria j [24], with $i = j = 1,2,\ldots,n$. These fuzzy triangular numbers are expressed using the linguistic variables in [26].

2) Step 2: Normalize into the Initial Direct Influence Matrix $\tilde{X}$

The initial direct influence matrix $\tilde{X}$, $\left(\tilde{X} = [\tilde{x}_{ij}]_{n\times n}\right)$, can be obtained by normalizing the direct matrix $\tilde{A}$ [24]. Specifically, the matrix $\tilde{X}$can be obtained by multiplying each element of $\tilde{A}$ by a scalar s using (2) and (3).

$$\tilde{X} = s \cdot \tilde{A} \quad (2)$$

$$s = min\left[\frac{1}{\max\limits_i \sum_{j=1}^{n}|\tilde{a}_{ij}|}, \frac{1}{\max\limits_j \sum_{i=1}^{n}|\tilde{a}_{ij}|}\right] \quad (3)$$

With:

$$\sum_{j=1}^{n}|\tilde{a}_{ij}| = \left(\sum_{j=1}^{n}|l_{ij}|, \sum_{j=1}^{n}|m_{ij}|, \sum_{j=1}^{n}|u_{ij}|\right)$$

and

$$max_i \sum_{j=1}^{n}|\tilde{a}_{ij}| = max_i \sum_{j=1}^{n}|u_{ij}|$$

3) Step 3: Calculate the Matrix of Total Direct/Indirect Influences $\tilde{T}$.

The values of the direct relationship matrix A are normalized to $\tilde{X}$, and $\tilde{X}^k$ is referred to as the indirect influence k, continuously reducing indirect impacts based on the value of $\tilde{X}$, for example, $\tilde{X}^2, \tilde{X}^3, \ldots, \tilde{X}^k$, and $\lim_{k\to\infty} \tilde{X}^k = [0]_{n\times n}$ when $\tilde{X} = [\tilde{x}_{ij}]_{n\times n}$, $0 \le \tilde{x}_{ij} \le 1$. The matrix of total influences $\tilde{T}$ is presented as:

$$\tilde{T} = \tilde{X} + \tilde{X}^2 + \cdots + \tilde{X}^k = \tilde{X}\left(I + \tilde{X} + \tilde{X}^2 + \cdots + \tilde{X}^{k-1}\right)$$

$$= \tilde{X}\left[\left(I + \tilde{X} + \tilde{X}^2 + \cdots + \tilde{X}^{k-1}\right)\left(I - \tilde{X}\right)\right]\left(I - \tilde{X}\right)^{-1}$$

$$= \tilde{X}\left(I - \tilde{X}\right)^{-1} \quad (4)$$

where:

$$\left(I - \tilde{X}\right)\left(I - \tilde{X}\right)^{-1} = I, \tilde{T} = [\tilde{t}_{ij}]_{n\times n},$$

$$\tilde{t}_{ij} = (l_{ij}, m_{ij}, u_{ij}),$$

$$\text{Matrix}[l_{ij}] = \tilde{X}_l \times \left(I - \tilde{X}_l\right)^{-1},$$

$$\text{Matrix}[m_{ij}] = \tilde{X}_m \times \left(I - \tilde{X}_m\right)^{-1},$$

$$\text{Matrix}[u_{ij}] = \tilde{X}_u \times \left(I - \tilde{X}_u\right)^{-1}.$$

In addition, the presentation method for each row sum and column sum of the total matrix $\tilde{T}$ is:

$$r = (r_i)_{n.1} = \left[\sum_j^n \tilde{t}_{ij}\right]_{n.1} \quad (5)$$

$$c = (c_j)_{n.1} = (c_j)'_{1.n} = \left[\sum_{i=1}^{n} \tilde{t}_{ij}\right]'_{1.n} \quad (6)$$

From the matrix $\tilde{T}$ with three fuzzy triangular numbers L, M, and U, a defuzzification process is carried out to obtain the total influence matrix T with sharp values as expressed in [24]:

$$\tilde{N}_k^{def} = L + \Delta \times \frac{(m-L)(\Delta+u-m)^2(R-l)+(u-L)^2(\Delta+m-l)^2}{(\Delta+m-l)(\Delta+u-m)^2(R-l)+(u-L)(\Delta+m-l)^2(\Delta+u-m)} \quad (7)$$

where $L = min(l_k)$, $R = max(u_k)$, and $\Delta = R - L$, with $\tilde{T} = (l, m, u)$ being the total influence matrix.

4) Step 4: Set the Threshold Value α and Form the Network Relationship Map (NRM)

Utilizing matrix T, each coefficient t_{ij} offers network insights into the impact of factor i on factor j. Introducing a threshold value α filters out minor effects in matrix T, which is essential for elucidating the relationship structure among factors. Transferring all T information to the NRM yields an overly intricate display for decision-making. To streamline the NRM complexity, decision-makers establish a threshold for influence levels: only factors with T values surpassing the threshold are chosen for transformation into the NRM. Expert assessments typically guide threshold determination, with α often selected as in [27]. Once the threshold and NRM are established, the NRM can be visualized.

The new matrix with the cross-section α is called the total influence matrix at the cross-section α, denoted as T_α. The form of the T_α matrix is:

$$T_\alpha = \begin{bmatrix} t_{11}^\alpha & \cdots & t_{1j}^\alpha & \cdots & t_{1n}^\alpha \\ \vdots & \ldots & \ldots. & \ldots & \vdots \\ t_{i1}^\alpha & \cdots & i & \cdots & t_{in}^\alpha \\ \vdots & \ldots & \ldots & \ldots & \vdots \\ t_{n1}^\alpha & \cdots & t_{nj}^\alpha & \cdots & t_{nn}^\alpha \end{bmatrix} \quad (8)$$

C. ANP Method

1) Step 5: Compare the Criteria Across the Entire System to Create the Supermatrix W

The primary supermatrix of characteristic column vectors is obtained from the pairwise comparison matrices of the criteria. Relative importance values are assessed on a scale of 1 to 9, denoting the degree of importance, varying from equal to highly significant [23]. The general structure of the supermatrix is:

$$W = \begin{array}{cc} & \begin{array}{cccc} C_1 & C_2 & \cdots & C_n \\ e_{11}\cdots e_{1m_1} & e_{11}\cdots e_{1m_1} & \cdots & e_{11}\cdots e_{1m_1} \end{array} \\ \begin{array}{cc} C_1 & \begin{array}{c} e_{11} \\ \vdots \\ e_{1m_1} \end{array} \\ C_2 & \begin{array}{c} e_{21} \\ \vdots \\ e_{2m_2} \end{array} \\ \vdots & \vdots \\ C_n & \begin{array}{c} e_{n1} \\ \vdots \\ e_{nn} \end{array} \end{array} & \begin{bmatrix} W_{11} & W_{11} & \cdots & W_{11} \\ W_{11} & W_{11} & \cdots & W_{11} \\ \vdots & \vdots & \ddots & \vdots \\ W_{11} & W_{11} & \cdots & W_{11} \end{bmatrix} \end{array} \quad (9)$$

where C_n represents the n^{th} cluster, e_{nm} represents the m^{th} criterion within the n^{th} cluster, and W_{ij} is the main feature vector function indicating the influence of criteria in cluster j on cluster i. Additionally, if cluster j does not influence cluster i, then $W_{ij} = [0]$.

2) Step 6: Create the Weighted Matrix W_w by Multiplying the Supermatrix with the Normalized Matrix, which is Derived using the NRM based on the DEMATEL Method

The total cross-sectional influence matrix α T_α needs to be normalized (10). Therefore, it is possible to normalize the total cross-sectional influence matrix α and represent it as a matrix T_s, as in (11).

$$d_i = \sum_{j=1}^{n} t_{ij}^\alpha \quad (10)$$

$$T_s = \begin{bmatrix} \frac{t_{11}^\alpha}{d_1} & \ldots & \frac{t_{1j}^\alpha}{d_1} & \ldots & \frac{t_{1n}^\alpha}{d_1} \\ \vdots & \ldots & \vdots & \ldots & \vdots \\ \frac{t_{i1}^\alpha}{d_i} & \ldots & \frac{t_{ij}^\alpha}{d_i} & \ldots & \frac{t_{in}^\alpha}{d_i} \\ \vdots & \ldots & \ldots & \ldots & \vdots \\ \frac{t_{n1}^\alpha}{d_n} & \ldots & \frac{t_{nj}^\alpha}{d_n} & \ldots & \frac{t_{nn}^\alpha}{d_n} \end{bmatrix} = \begin{bmatrix} t_{11}^s & \cdots & t_{1j}^s & \cdots & t_{1n}^s \\ \vdots & \ldots & \vdots & \ldots & \vdots \\ t_{i1}^s & \cdots & t_{ij}^s & \cdots & t_{in}^s \\ \vdots & \ldots & \vdots & \ldots & \vdots \\ t_{n1}^s & \cdots & t_{nj}^s & \cdots & t_{nn}^s \end{bmatrix} \quad (11)$$

This study uses the normalized total cross-sectional influence matrix α T_s (called the normalized matrix) and the unweighted super-matrix W utilizing (12) to calculate the weighted supermatrix W_w. The weighted supermatrix is the result of synthesizing the influence matrices and the connectivity matrix among factors in the network, namely between the unweighted supermatrix W of the subcriteria (e_1, e_2, ..., e_5) and the normalized total cut influence matrix T_s.

$$W_w = \begin{bmatrix} t_{11}^s \cdot W_{11} & t_{21}^s \cdot W_{12} & \cdots & \cdots & t_{n1}^s \cdot W_{1n} \\ t_{12}^s \cdot W_{21} & t_{22}^s \cdot W_{22} & \ldots & \ldots & \vdots \\ \vdots & \cdots & \ldots & \ldots. & t_{ni}^s \cdot W_{in} \\ \vdots & \ldots & \ldots & \ldots & \vdots \\ t_{1n}^s \cdot W_{n1} & t_{2n}^s \cdot W_{n2} & \ldots & \ldots & t_{nn}^s \cdot W_{nn} \end{bmatrix} \quad (12)$$

3) Step 7: Limit the Weighted Supermatrix by raising it to a Large enough Power k until the Supermatrix Converges and Becomes a Long-Term Stable Supermatrix to Receive Global Priority Vectors or Weights

$$\lim_{k\to\infty} W_w^k \quad (13)$$

The expression (13) is applied to find the convergent matrix to obtain the convergence value of the matrix, which represents the weights of the criteria. The convergent matrix is a concept in linear algebra and matrix theory. It is defined as a matrix for which, when repeatedly multiplied by itself, the result gradually approaches a constant value.

If the constrained supermatrix is not unique, for example, if there are N supermatrices, then the average value of the obtained values is calculated by summing the N supermatrices and dividing by N. For instance, if N = 3 and $\lim_{k\to\infty} W_w^k =$

$\{W^1, W^2, W^3\}$, then the constrained supermatrix with the final weights is formed as:

$$W_f = \frac{1}{3}W^1 + \frac{1}{3}W^2 + \frac{1}{3}W^3 \quad (14)$$

Finally, the weighted super-matrix is constrained until it converges and becomes a stable long-term supermatrix, as in (13).

D. Fuzzy VIKOR Method

The VIKOR method is employed to address ranking and multi-criteria evaluation problems, where factors are assessed based on multiple criteria. In particular, this method is suitable for object evaluation under uncertain or information-deficient conditions, where traditional methods cannot be applied. The implementation process of the VIKOR method was presented in [15].

III. RESULTS

To demonstrate the effectiveness of the proposed approach, the IEEE 16-bus microgrid system, consisting of six power sources and eight loads, was used as a computational test model [15, 20]. Based on previous research, the load characteristic information according to three criteria (LIF, VED, and VSI) and the dependent factors (penalty and power capacity) were presented in [20]. The proposed method forms a direct matrix $\tilde{A}$. This matrix is provided in Tables I and II based on the linguistic variable proposed in [26].

TABLE I. DIRECT MATRIX ACCORDING TO LINGUISTIC VARIABLES

	C_1	C_2	C_3
C_1	N	VL	L
C_2	E	N	FL
C_3	E	VL	N

TABLE II. DIRECT MATRIX ACCORDING TO FUZZY NUMBERS

	C_1			C_2			C_3		
	L	M	U	L	M	U	L	M	U
C_1	0.00	0.00	0.10	0.00	0.10	0.20	0.10	0.20	0.30
C_2	0.90	1.00	1.00	0.00	0.00	0.10	0.20	0.30	0.40
C_3	0.90	1.00	1.00	0.00	0.10	0.20	0.00	0.00	0.10

Equations (2) and (3) are used to normalize the direct matrix into a direct influence matrix and Table III shows the results. The total direct/indirect influence matrix from (4) is calculated and displayed in Table IV. Equations (5) and (6) are applied to calculate influence values between criteria. After that, equation (7) is applied to defuzzify the fuzzy numbers *L*, *M*, and *U*, and the results are portrayed in Table V. Table VI depicts the defuzzied total direct/indirect influence matrix.

TABLE III. STANDARDIZED DIRECT INFLUENCE MATRIX

	C_1			C_2			C_3		
	L	M	U	L	M	U	L	M	U
C_1	0.00	0.000	0.048	0.000	0.048	0.095	0.048	0.095	0.143
C_2	0.429	0.476	0.476	0.000	0.000	0.048	0.095	0.143	0.190
C_3	0.429	0.476	0.476	0.000	0.048	0.095	0.000	0.000	0.048

TABLE IV. TOTAL DIRECT/INDIRECT INFLUENCE MATRIX

	C_1			C_2			C_3		
	L	M	U	L	M	U	L	M	U
C_1	0.021	0.080	0.229	0.000	0.057	0.144	0.049	0.111	0.213
C_2	0.479	0.592	0.752	0.000	0.038	0.160	0.118	0.205	0.345
C_3	0.438	0.542	0.690	0.000	0.076	0.188	0.021	0.063	0.191

TABLE V. CAUSE VALUE AND INFLUENCE VALUE BETWEEN CRITERIA

	r_i			c_i			$(r_i+c_i)_{defuzzy}$	$(r_i-c_i)_{defuzzy}$
	L	M	U	L	M	U		
C_1	0.07	0.25	0.59	0.94	1.21	1.67	1.51	-0.93
C_2	0.60	0.83	1.26	0.00	0.17	0.49	1.10	0.63
C_3	0.46	0.68	1.07	0.19	0.38	0.75	1.15	0.28

TABLE VI. DEFUZZIFIED TOTAL DIRECT/INDIRECT INFLUENCE MATRIX

	C_1	C_2	C_3
C_1	0.099	0.066	0.123
C_2	0.591	0.057	0.211
C_3	0.544	0.084	0.083

Figure 2 is formed by calculating the influence values of the criteria based on (5) and (6). Equation (7) is utilized to defuzzify the fuzzy numbers *L*, *M*, and *U*. The results of defuzzifying the influence values of the criteria are presented in the two right cover columns of Table V. These values are the basis for forming Figure 2. The results in Table V exhibit that the value $(r_i-c_i)_{defuzzy}$ of criterion C_2 is the most positive, so this is the criterion that has the greatest influence on the other criteria. Criteria C_2 and C_3 are cause criteria. Criterion C_1 has a value $(r_i+c_i)_{defuzzy}$ greater than criteria C_2 and C_3, so it is the most central criterion (prominent). Therefore, the relationship of the criteria is demonstrated in Figure 2, which is a causal model drawn by the point $(r_i+c_i; r_i-c_i)$.

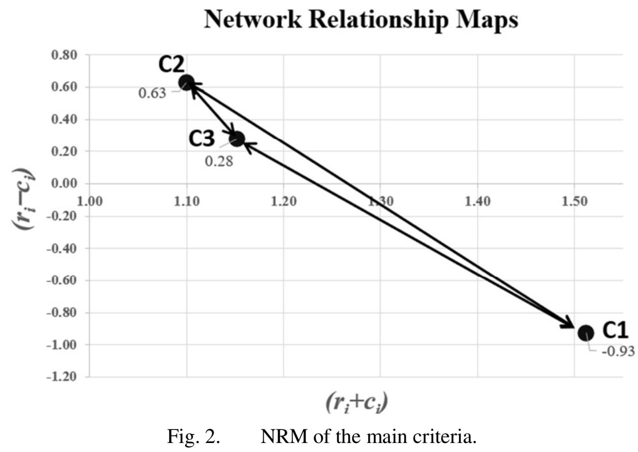

Fig. 2. NRM of the main criteria.

Based on the total influence matrix T, the cross-sectional value α = 0.06 is selected to reduce the complexity of the NRM, because the α value is chosen to be very small, so the influence on the weights of factors is negligible. From the NRM in Figure 3 and the total cross-sectional influence matrix $\alpha - T_\alpha$ (Table VII), a relationship map between the main criteria and their dependent factors can be built. Figure 3 is the

NRM of this ranking problem. This map illustrates the relationships between the main criteria and subcriteria within each main criterion. As previously presented, criterion C_1 - Importance, will include the factors e_1 - location, e_2 - capacity, and e_3 - price. Criterion C_2 - Voltage distance is factor e_4 and criterion C_3 - Voltage sensitivity is factor e_5. The main targets will interact with each other. The subcriteria will affect their main criteria. Therefore, the NRM network model is formed as evidenced in Figure 3.

TABLE VII. THE TOTAL CROSS-SECTIONAL INFLUENCE MATRIX

	C_1	C_2	C_3
C_1	0.099	0.066	0.123
C_2	0.591	0	0.211
C_3	0.544	0.084	0.083

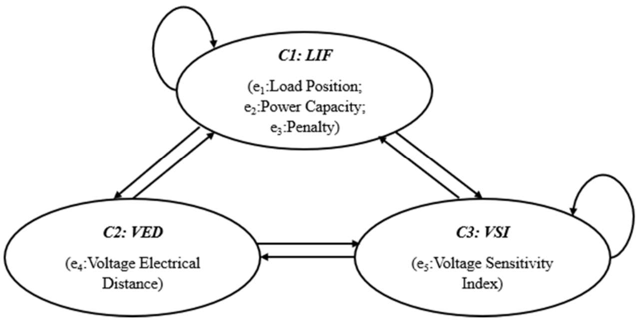

Fig. 3. NRM of the main criteria and the element.

Using the structure of the NRM relational network diagram in Figure 4, the unweighted supermatrix W is obtained, as observed in Table VIII, with the total weight of W_{ij} being 1. Based on the network diagram, it can be seen that criterion C_2 does not affect C_2, deducing W_{22} = [0]. Figure 4 shows the W_{ij} matrices included in the unweighted supermatrix W. The values in Table VIII are obtained from the NRM in Figure 3. Because criterion C_1 has subcriteria e_1, e_2, and e_3, the weight W_{11} is formed according to the framework of all three subcriteria, similarly because criteria C_2 and C_3 have subcriteria themselves.

TABLE VIII. THE UNWEIGHTED SUPER-MATRIX W

W	e_1	e_2	e_3	e_4	e_5
e_1	1	0	0	0.8	0.8
e_2	0	1	0	0.1	0.1
e_3	0	0	1	0.1	0.1
e_4	1	1	1	0	1
e_5	1	1	1	1	1

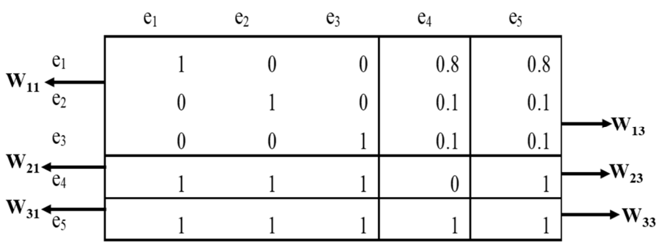

Fig. 4. Matrix W_{ij} in the unweighted supermatrix W.

Applying (10) and (11) to normalize the matrix T_α into the total matrix T_s, the results are presented in Table IX.

TABLE IX. THE MATRIX OF TOTAL NORMALIZED T_S

	C_1	C_2	C_3
C_1	0.344	0.229	0.427
C_2	0.737	0.000	0.263
C_3	0.765	0.118	0.117

The weighted supermatrix W_w is built based on (12). Using (13) to reach the limit of the supermatrix and obtain the weights for the factors, the results are disclosed in Table X.

TABLE X. THE LIMITS OF THE SUPER-MATRIX W_F

W_f	e_1	e_2	e_3	e_4	e_5
e_1	0.428	0.428	0.428	0.428	0.428
e_2	0.054	0.054	0.054	0.054	0.054
e_3	0.054	0.054	0.054	0.054	0.054
e_4	0.159	0.159	0.159	0.159	0.159
e_5	0.306	0.306	0.306	0.306	0.306

Then the calculation process of the VIKOR method is applied [15]. Based on the collected load characteristics, the decision matrix is evaluated according to the linguistic variable proposed in [28]. The decision matrix is presented in Table XI. Next, matrix defuzzification is performed, and the results are displayed in Table XII. Then, the best and worst values of the criterion function are chosen, and the results are portrayed in Table XIII. Here, factors e_1, e_4, and e_5 are the benefit functions, and factors e_2 and e_3 are the cost functions. The r_{ij} ranking matrix is provided in Table XIV.

TABLE XI. DECISION MATRIX EVALUATED ACCORDING TO TZFNS

Load	e_1	e_2	e_3	e_4	e_5
L3	(0.8, 0.9, 1.0, 1.0)	(0.2, 0.3, 0.4, 0.5)	(0.0, 0.0, 0.1, 0.2)	(0.5, 0.6, 0.7, 0.8)	(0.8, 0.9, 1.0, 1.0)
L4	(0.2, 0.3, 0.4, 0.5)	(0.5, 0.6, 0.7, 0.8)	(0.0, 0.0, 0.1, 0.2)	(0.8, 0.9, 1.0, 1.0)	(0.5, 0.6, 0.7, 0.8)
L5	(0.0, 0.0, 0.1, 0.2)	(0.7, 0.8, 0.8, 0.9)	(0.8, 0.9, 1.0, 1.0)	(0.5, 0.6, 0.7, 0.8)	(0.8, 0.9, 1.0, 1.0)
L7	(0.1, 0.2, 0.2, 0.3)	(0.4, 0.5, 0.5, 0.6)	(0.1, 0.2, 0.2, 0.3)	(0.8, 0.9, 1.0, 1.0)	(0.8, 0.9, 1.0, 1.0)
L9	(0.0, 0.0, 0.1, 0.2)	(0.7, 0.8, 0.8, 0.9)	(0.4, 0.5, 0.5, 0.6)	(0.8, 0.9, 1.0, 1.0)	(0.7, 0.8, 0.8, 0.9)
L10	(0.0, 0.0, 0.1, 0.2)	(0.8, 0.9, 1.0, 1.0)	(0.5, 0.6, 0.7, 0.8)	(0.5, 0.6, 0.7, 0.8)	(0.8, 0.9, 1.0, 1.0)
L12	(0.1, 0.2, 0.2, 0.3)	(0.4, 0.5, 0.5, 0.6)	(0.1, 0.2, 0.2, 0.3)	(0.7, 0.8, 0.8, 0.9)	(0.8, 0.9, 1.0, 1.0)
L13	(0.2, 0.3, 0.4, 0.5)	(0.4, 0.5, 0.5, 0.6)	(0.0, 0.0, 0.1, 0.2)	(0.8, 0.9, 1.0, 1.0)	(0.8, 0.9, 1.0, 1.0)

TABLE XII. DEFUZZIFY THE DECISION MATRIX

Load	e_1	e_2	e_3	e_4	e_5
L3	0.92	0.35	0.08	0.65	0.92
L4	0.35	0.65	0.08	0.92	0.65
L5	0.08	0.80	0.92	0.65	0.92
L7	0.20	0.50	0.20	0.92	0.92
L9	0.08	0.80	0.50	0.92	0.80
L10	0.08	0.92	0.65	0.65	0.92
L12	0.20	0.50	0.20	0.80	0.92
L13	0.35	0.50	0.08	0.92	0.92
W	**0.498**	**0.028**	**0.028**	**0.103**	**0.344**

TABLE XIII. SELECTION OF THE BEST AND WORST VALUES

Load	e_1	e_2	e_3	e_4	e_5
f_i^*	0.922	0.350	0.078	0.922	0.922
f_i^-	0.078	0.922	0.922	0.650	0.650

TABLE XIV. RANKING MATRIX R_{ij}

Load	e_1	e_2	e_3	e_4	e_5
L3	0.000	0.000	0.000	1.000	0.000
L4	0.678	0.524	0.000	0.000	1.000
L5	1.000	0.786	1.000	1.000	0.000
L7	0.855	0.262	0.145	0.000	0.000
L9	1.000	0.786	0.500	0.000	0.449
L10	1.000	1.000	0.678	1.000	0.000
L12	0.855	0.262	0.145	0.449	0.000
L13	0.678	0.262	0.000	0.000	0.000

Finally, the S_i, R_i, and Q_i values for the loads were calculated and ranked in ascending order. Table XV shows the load ranking index values.

TABLE XV. S_i, R_i, AND Q_i RANKING INDEX VALUES

Load	S_i	Rank S	R_i	Rank R	Q_i	Rank Q
L3	0.159	1	0.159	1	0.000	1
L4	0.624	5	0.306	3	0.718	5
L5	0.683	8	0.428	6	1.000	8
L7	0.388	3	0.366	4	0.604	3
L9	0.634	6	0.428	6	0.954	6
L10	0.677	7	0.428	6	0.994	7
L12	0.459	4	0.366	4	0.672	4
L13	0.304	2	0.290	2	0.383	2

With the two compromise conditions according to the VIKOR method, consider that the *DQ* distance between L13 and L3, L7 and L13, and L9 and L4 is larger than:

$$\frac{1}{m-1} = \frac{1}{8-1} = 0.14,$$

So, the rank positions of these load pairs satisfy conditions 1 and 2. In addition, considering that the *DQ* distance between loads L4, L12, and L7 is less than 0.14, condition 1 is not met, and loads L5, L10, and L9 are also similar. Therefore, the set of compromise conditions that can obtain load rating results according to the Fuzzy DEMATEL-ANP and VIKOR methods are:

$$L3 \succ L13 \succ \{L7, L12, L4\} \succ \{L9, L10, L5\}$$

However, the relative distances Q_i are only a measure of the distance between the evaluated alternative and the ideal solution. Loads with smaller Q_i values are closer to the ideal solution. After all, between the loads in the proposed microgrid system, there are still different distance values from the ideal solution, and no load has the same distance value. Therefore, the load ranking position in the proposed microgrid model can be concluded as:

$$L3 \succ L13 \succ L7 \succ L12 \succ L4 \succ L9 \succ L10 \succ L5$$

The ranking results of the Fuzzy DEMATEL-ANP VIKOR method were compared with the AHP [20] and Fuzzy VIKOR [15] methods. This comparison was carried out with the same set of input data, and the ranking results are disclosed in Figure 5. The results indicate that L3 is identified as the highest ranking for all three methods. However, in subsequent rankings, there are differences between the methods. This difference is attributed to the less effective resolution of conflicting criteria issues in both the AHP and Fuzzy VIKOR methods. The proposed method combines these approaches, each method addressing the limitations of the other, thus providing a ranking technique capable of overcoming their respective constraints. The Fuzzy VIKOR technique relies on Network Process Analysis and the Fuzzy DEMATEL method to address conflicts among criteria. Fuzzy set theory was employed to handle uncertainty and relativity. Additionally, the DEMATEL method establishes the NRM and normalizes the weightless ANP supermatrix for appropriate weight values corresponding to the criteria.

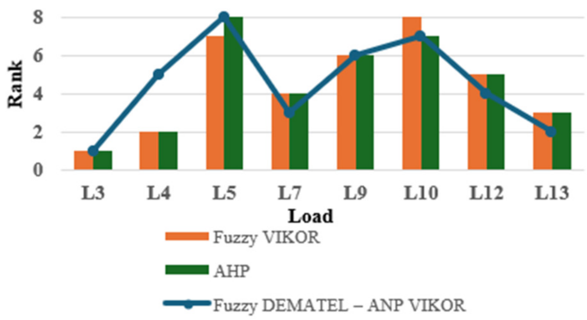

Fig. 5. Comparison of ranking results between the proposed, AHP, and Fuzzy VIKOR methods.

IV. DISCUSSION

This study collected evaluations from multiple experts within the system. Each expert's evaluation created a matrix, which was then consolidated by averaging the values of similar criteria from the different expert matrices. However, when expert opinions are inconsistent, they can affect the consistency and quality of the ranking problem. To address this issue, several methods can be applied to minimize the subjectivity of the ranking problem, such as:

- Use empirical data: Collect and utilize objective data from reliable sources.
- Apply statistical techniques: Use statistical methods to process and analyze data to ascertain objectivity.
- Check and compare results: Compare the results of different methods to ensure consistency and objectivity in the decisions.
- Analyze evaluations from multiple experts: Aggregate opinions from various experts and use statistical methods, such as the mean, median, or Delphi method, to achieve a comprehensive result and reduce individual biases.
- Applying Data Envelopment Analysis (DEA): This method evaluates the relative efficiency of decision-making units based on inputs and outputs, providing a more objective perspective.

- Use random weighting methods: Instead of using fixed weights, employ random weights to assess the sensitivity of criteria and reduce subjectivity.
- Test consistency: Check the consistency of the expert evaluations using the consistency index to ensure that the evaluations are not overly contradictory.

V. CONCLUSIONS

The Fuzzy DEMATEL method forms the relationship between the main criteria in load ranking by processing the evaluation utilizing triangular fuzzy numbers. From there, a network diagram of the relationship between the criteria for the ANP method is formed. This resolves the influential relationships between the main criteria and the secondary factors included in the main criteria to form a weight supermatrix for the criteria/factors. The VIKOR technique is applied to find the load's level of influence and importance compared to other loads. The advantage of the VIKOR method based on Fuzzy DEMATEL and ANP is its ability to integrate correlation assessment between factors and determine their level of importance. Fuzzy DEMATEL allows modeling fuzzy correlations and dealing with uncertainty during evaluation. ANP allows for a multicriteria assessment and determines the degree of correlation between factors. The combination of VIKOR and ANP helps to weigh important factors and correlate them, creating a reliable and effective load ranking method. In the future, the Fuzzy DEMATEL - ANP VIKOR ranking technique will be combined with statistical and data processing techniques for input criteria/factors. This can help to completely eliminate subjectivity caused by experts' opinions in the process of forming judgment matrices and evaluating criteria/factors.

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REFERENCES

[1] P. Taylor, M. Yao, and M. Zhao, "Intelligent Automation & Soft Computing Cooperative Attack Strategy of Unmanned Aerial Vehicles in Adversarial Environment," 2013.

[2] T. Madiba, R. C. Bansal, J. J. Justo, and K. Kusakana, "Optimal Control System of Under Frequency Load Shedding in Microgrid System with Renewable Energy Resources," in *Smart Energy Grid Design for Island Countries: Challenges and Opportunities*, F. M. R. Islam, K. A. Mamun, and M. T. O. Amanullah, Eds. Springer International Publishing, 2017, pp. 71–96.

[3] L. T. H. Nhung, T. T. Phung, H. M. V. Nguyen, T. N. Le, T. A. Nguyen, and T. D. Vo, "Load Shedding in Microgrids with Dual Neural Networks and AHP Algorithm," *Engineering, Technology & Applied Science Research*, vol. 12, no. 1, pp. 8090–8095, Feb. 2022, https://doi.org/10.48084/etasr.4652.

[4] C. Lin, H. Liang, T. Su, and M. A. Tefera, "Multi-Criteria Decision-Making Approach for Analyzing Competency Model of Technology Managers," *Mathematical Problems in Engineering*, vol. 2022, no. 1, 2022, Art. no. 1909851, https://doi.org/10.1155/2022/1909851.

[5] C. T. Chang, K. H. Tan, and H. C. Lu, "Multiple Criteria Decision Making Theory, Methods, and Applications in Engineering," *Mathematical Problems in Engineering*, vol. 2014, 2014, https://doi.org/10.1155/2014/431037.

[6] M. Soba, Y. Ersoy, A. Tarakcioğlu Altınay, B. Erkan, and E. Şik, "Application of Multiple Criteria Decision-Making Methods in Assignment Place Selection," *Mathematical Problems in Engineering*, vol. 2020, no. 1, 2020, Art. no. 6748342, https://doi.org/10.1155/2020/6748342.

[7] M. D. Nguyen, P. Q. Tran, and H. B. Nguyen, "An Application of Analytic Network Process (ANP) to Assess Critical Risks of Bridge Projects in the Mekong Delta Region," *Engineering, Technology & Applied Science Research*, vol. 13, no. 3, pp. 10622–10629, Jun. 2023, https://doi.org/10.48084/etasr.5802.

[8] B. Roy, "The outranking approach and the foundations of electre methods," *Theory and Decision*, vol. 31, no. 1, pp. 49–73, Jul. 1991, https://doi.org/10.1007/BF00134132.

[9] J. P. Brans and Y. De Smet, "PROMETHEE Methods," in *Multiple Criteria Decision Analysis: State of the Art Surveys*, S. Greco, M. Ehrgott, and J. R. Figueira, Eds. New York, NY, USA: Springer, 2016, pp. 187–219.

[10] B. Mareschal, Y. De Smet, and P. Nemery, "Rank reversal in the PROMETHEE II method: Some new results," in *2008 IEEE International Conference on Industrial Engineering and Engineering Management*, Singapore, Dec. 2008, pp. 959–963, https://doi.org/10.1109/IEEM.2008.4738012.

[11] S. Chakraborty, "Applications of the MOORA method for decision making in manufacturing environment," *The International Journal of Advanced Manufacturing Technology*, vol. 54, no. 9, pp. 1155–1166, Jun. 2011, https://doi.org/10.1007/s00170-010-2972-0.

[12] T. H. Chang, "Fuzzy VIKOR method: A case study of the hospital service evaluation in Taiwan," *Information Sciences*, vol. 271, pp. 196–212, Jul. 2014, https://doi.org/10.1016/j.ins.2014.02.118.

[13] S. Musani and A. A. Jemain, "Ranking Schools' Academic Performance Using a Fuzzy VIKOR," *Journal of Physics: Conference Series*, vol. 622, no. 1, Feb. 2015, Art. no. 012036, https://doi.org/10.1088/1742-6596/622/1/012036.

[14] R. Jeya Girubha and S. Vinodh, "Application of fuzzy VIKOR and environmental impact analysis for material selection of an automotive component," *Materials & Design*, vol. 37, pp. 478–486, May 2012, https://doi.org/10.1016/j.matdes.2012.01.022.

[15] T. A. Nguyen *et al.*, "Applying Fuzzy VIKOR algorithm in load ranking for load shedding problem in Microgrid," in *2023 International Conference on System Science and Engineering (ICSSE)*, Ho Chi Minh, Vietnam, Jul. 2023, pp. 271–275, https://doi.org/10.1109/ICSSE58758.2023.10227249.

[16] F. Kutlu Gündoğdu and C. Kahraman, "Spherical fuzzy sets and spherical fuzzy TOPSIS method," *Journal of Intelligent & Fuzzy Systems*, vol. 36, no. 1, pp. 337–352, Jan. 2019, https://doi.org/10.3233/JIFS-181401.

[17] E. S. Saleh and A. M. Kimiagari, "Ranking Tehran's Stock Exchange Top Fifty Stocks Using Fundamental Indexes and Fuzzy TOPSIS," *Engineering, Technology & Applied Science Research*, vol. 7, no. 4, pp. 1863–1869, Aug. 2017, https://doi.org/10.48084/etasr.1252.

[18] S. Opricovic and G. H. Tzeng, "Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS," *European Journal of Operational Research*, vol. 156, no. 2, pp. 445–455, Jul. 2004, https://doi.org/10.1016/S0377-2217(03)00020-1.

[19] T. L. Saaty, "Decision making with the analytic hierarchy process," *International Journal of Services Sciences*, vol. 1, no. 1, pp. 83–98, Jan. 2008, https://doi.org/10.1504/IJSSCI.2008.017590.

[20] A. T. Nguyen, T. N. Le, H. A. Quyen, M. V. Nguyen Hoang, and P. B. L. Nguyen, "Application of AHP Algorithm to Coordinate Multiple Load Shedding Factors in the Microgrid," *IETE Journal of Research*, vol. 69, no. 8, pp. 5276–5288, Sep. 2023, https://doi.org/10.1080/03772063.2021.1962744.

[21] T. N. Le, H. M. V. Nguyen, T. A. Nguyen, T. T. Phung, T. T. H. Huynh, and Q. T. Nguyen, "Optimize Ranking and Load Shedding in Microgrid Considering Improved Analytic Hierarchy Process Algorithm and Power Stability Index," *Mathematical Problems in Engineering*, vol. 2023, no. 1, 2023, Art. no. 6074287, https://doi.org/10.1155/2023/6074287.

[22] H. I. Mohammed, Z. Majid, Y. B. Yamusa, M. F. M. Ariff, K. M. Idris, and N. Darwin, "Sanitary Landfill Siting Using GIS and AHP: A Case Study in Johor Bahru, Malaysia," *Engineering, Technology & Applied Science Research*, vol. 9, no. 3, pp. 4100–4104, Jun. 2019, https://doi.org/10.48084/etasr.2633.

[23] T. L. Saaty, Decision making with dependence and feedback: The analytic network process. Pittsburgh, PA, USA: RWS Publications, 1996.

[24] R. K. Mavi and C. Standing, "Critical success factors of sustainable project management in construction: A fuzzy DEMATEL-ANP approach," *Journal of Cleaner Production*, vol. 194, pp. 751–765, Sep. 2018, https://doi.org/10.1016/j.jclepro.2018.05.120.

[25] T. M. Yeh and Y. L. Huang, "Factors in determining wind farm location: Integrating GQM, fuzzy DEMATEL, and ANP," *Renewable Energy*, vol. 66, pp. 159–169, Jun. 2014, https://doi.org/10.1016/j.renene.2013.12.003.

[26] G. Büyüközkan and G. Çifçi, "A novel hybrid MCDM approach based on fuzzy DEMATEL, fuzzy ANP and fuzzy TOPSIS to evaluate green suppliers," *Expert Systems with Applications*, vol. 39, no. 3, pp. 3000–3011, Feb. 2012, https://doi.org/10.1016/j.eswa.2011.08.162.

[27] G. H. Tzeng and J. J. Huang, Multiple Attribute Decision Making: Methods and Applications. CRC Press, 2011.

[28] S. Opricovic and G. H. Tzeng, "Multicriteria Planning of Post-Earthquake Sustainable Reconstruction," *Computer-Aided Civil and Infrastructure Engineering*, vol. 17, no. 3, pp. 211–220, 2002, https://doi.org/10.1111/1467-8667.00269.