Optimization of Load Ranking and Load Shedding in a Power System Using the Improved AHP Algorithm

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Abstract-This paper proposes a method of load ranking and load shedding in a power system based on the calculation of the priority weighting continuity of the power supply of loads and the improved AHP algorithm. The proposed method applies the theories of covariance between objects, correlation, and fuzzy preference to develop a fuzzy preference correlation matrix based on the percentage of Vital Load, Semi Vital Load, and Non-Vital Load at each load bus. This matrix replaces the judgment matrix of the traditional AHP algorithm to form the criteria layers and scheme layers of the problem. The priority weighting continuity of the power supply of loads is continuously calculated and updated according to the load profile and is used to distribute the load shedding power to each load bus. This distribution optimizes the objective function and maximizes the load benefits, thereby minimizing the damages due to load shedding. The traditional AHP method and the proposed method are applied to the IEEE 30 bus system and the result comparison demonstrates the effectiveness of the proposed method.

Keywords-optimal load shedding; load ranking; AHP; improved AHP; correlation

I. INTRODUCTION

Load shedding often occurs in order to optimize the operation, in a case of emergency, or due to power shortage of the power system. There are many studies interested in the problem of load shedding in a power system [1-3], however, to the best of our knowledge, the economic loss of load shedding has not yet been taken into account. To ensure the initiative in planned load break or optimal load shedding without unduly affecting the interests of customers and electricity suppliers in the competitive electricity market, the loads of the system are required to be classified and ranked according to priorities in the power supply continuity.

There are many studies on load classification and ranking [4, 5]. A microgrid system constantly evaluates and prioritizes the loads in the system to propose load management strategies to control the power generation dispatch of the power sources in the system. In [6], loads are classified into three types and are considered as schedulable variables based on their characteristics and importance. Thereby, the microgrid optimization reduces the operating costs of the system. The methods used to classify loads in the power system suggest the use of ISODATA algorithm to classify customers based on information supplied by the customers and load profile [7]. In [8], the authors propose a model of load classification according to a five-stage process developed on the summary and analysis of studies on load classification in a smart grid environment. A classification method based on fuzzy c-means (FCM) is presented. In [9], the authors show how to extract Characteristic Attributes of the Frequency Domain (CAFDs) and use these CAFDs to form a hierarchy of load profiles that can be used as system framework for load classification of customers.

The ranking of load shedding is applied quite commonly. In [10], the authors propose load shedding based on the AHP

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method to stabilize the voltage of the power system. Thus, a simple and flexible load shedding model can be developed. This method is based on the assessment of experts from different backgrounds, so it is subjective. In [11], a method for load shedding based on priority demand is proposed with a combination of wind power. Higher priority loads are connected to a wind power source that protects them from shedding under emergency conditions. This is done by real-time monitoring of the power system accompanied by shedding of lower priority loads. In [12], the authors propose the development of a load shedding strategy based on load priority. Thereby, loads with high priority demand will be connected to an emergency power source and at the same time, loads with lower priority demand will be shed.

In this paper, a method of load ranking and shedding in the system based on the improved AHP algorithm to calculate the power supply priority weighting of loads is proposed. This calculation is consistent with the actual load classification, allowing the system operator to be proactive in planned load shedding or load shedding due to system failure. In addition, this method eliminates the expert factor in traditional AHP calculation and incorporates economic conditions. The load shedding strategy of the proposed method is objective, helping to reduce the shedding power and to minimize the damage to the system and the customers while it optimizes the objective function and load benefits.

II. PRIORITY RANKING OF POWER SUPPLY CONTINUITY LOADS BASED ON THE IMPROVED AHP ALGORITHM

Priority ranking of loads in the power system is important in ensuring the reliability of the power supply for the loads that are considered important and are highly ranked in the system. The loads in the power system are classified in three types by their priority level: type 1 (Vital load or priority load type 1), type 2 (Semi-Vital load or priority load type 2), and type 3 (Non-Vital load or priority load type 3) [13, 14]. Type 1 load is a type of load that is continuously power supplied, and in case of power failure, it will cause extremely serious consequences. This type of load includes mines, hospitals, loads of steelworks, blast furnaces, etc. In addition, it also disrupts order and affects international politics, such as loads of embassies, public cultural works, etc. Type 2 load is a type of load that, if the power is lost, will cause economic losses such as production shortage, increase of by-products, waste of work, etc. Type 3 load is a type of load that allows power outage, which are civil works, welfare works, and residential areas. In the grid diagrams, the load buses usually have high capacity. The case of feeder lines including only one priority load type is quite rare. These loads will be actually collected and from there the percentage of each type of loads on those feeder lines will be summarized. From the power percentages of these loads, an improved AHP method based on statistical math, Pearson correlation math, and Spearman correlation will be applied to calculate the optimal weights of each respective load bus. From this result, we can rank priority loads that need to be power supplied uninterruptedly and the load power that needs to be shed at each bus when there are many priority loads.

The improved AHP method applied in this paper is a combination of the traditional AHP method and fuzzy preference relation theory. Based on the percentage of priority load types at each load bus, the theory of variance and covariance is applied to calculate the quantitative value and develop a judgment matrix according to the pairs of load type criteria: Type 1 load, type 2 load, and type 3 load of the criteria layer. From this judgment matrix, the weights of each load type in the criteria layer are determined. The value of variance between elements of each type of load of each criterion is used to develop a fuzzy preference correlation matrix. This matrix is used to replace the judgment matrix of the scheme layer to calculate the weights of the loads of each type. The weights of the criteria layer and the scheme layer are combined to get the power supply continuity priority weighting of each load. The process of calculating the power supply continuity priority weighting and distributing load shedding power of the proposed method is shown in Figure 1.

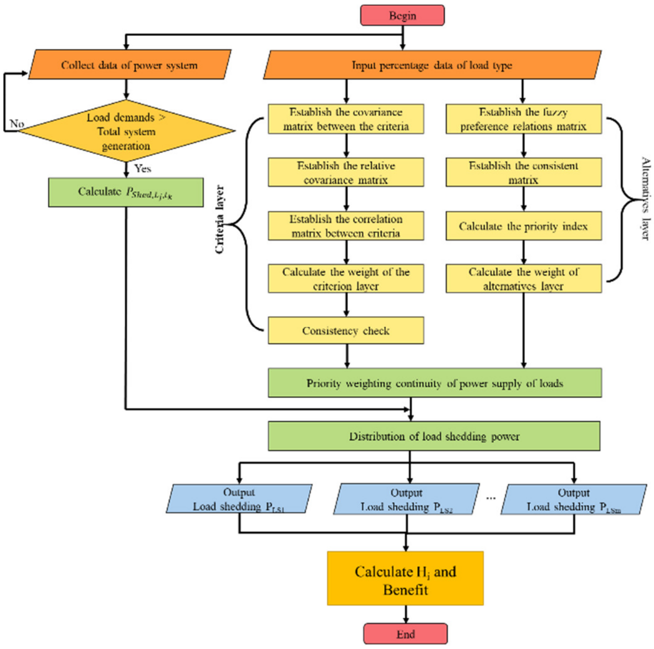

Fig. 1. The process of calculating the power supply continuity priority weighting and distributing load shedding power.

The process of calculating the priority weighting continuity of power supply includes the following steps:

- Develop a hierarchical model of the AHP algorithm, in which the criteria layer includes the load types and the scheme layer includes loads in the power system. The hierarchical model of the AHP algorithm to calculate the power supply continuity priority weighting of loads is presented in Figure 2.
- Calculate the weights of the criteria layer.
- Calculate the weights of the scheme layer.
- Calculate the combined weights.

Details of the process of calculating the weights of the criteria layer and the scheme layer are presented below.

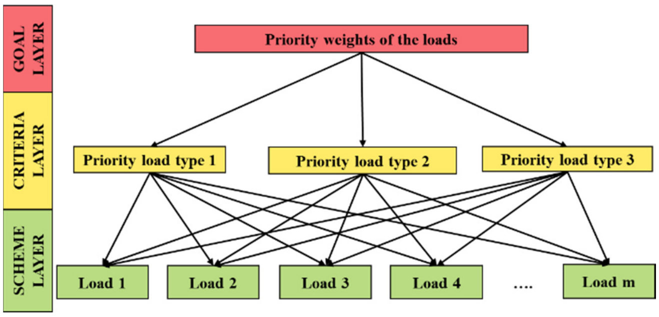

Fig. 2. The hierarchical model of the improved AHP algorithm to calculate the power supply continuity priority weighting of the loads.

A. *Calculating the Weights of the Criteria Layer*

The criteria layer of the model of the calculation of the power supply continuity priority weighting represents the load types in the system. The percentages of the load types of each load show the importance of those loads. The process of calculating the weights of the criteria layer is shown in Figure 1 and is in accordance with the following steps:

1) *Step 1: Set up the Covariance Matrix between the Criteria*

The covariance of the criteria is calculated to form the covariance matrix. The criteria of this problem are the load types (Vital Load, Semi Vital Load, Non-Vital Load) in the power system. The covariance matrix of the criteria ε_{i} and ε_j is expressed as $\varepsilon_{\mathrm{ij}}$ [15]. The model of the steps of calculating the criteria weights is shown in Figure 2. The covariance matrix between the criteria has the following form:

$$\varepsilon=\begin{bmatrix}\varepsilon_{11} & \varepsilon_{12} & \cdots & \varepsilon_{1n}\\ \varepsilon_{21} & \varepsilon_{22} & \cdots & \varepsilon_{2n}\\ \vdots & \vdots & \vdots & \vdots\\ \varepsilon_{n1} & \varepsilon_{n2} & \cdots & \varepsilon_{nn}\end{bmatrix} \quad (1)$$

where the main diagonal elements are calculated using the variance of the criterion data:

$$\varepsilon_{\mathrm{ii}}=\sigma^2=\frac{1}{n}\sum_{i=1}^{n}\left(x_i-\bar{x}\right)^2 \quad (2)$$

and the remaining elements are calculated using the covariance between the criteria. When the covariance between the two criteria is negative, its absolute value will be taken and the values of these elements are symmetric to each other through the main diagonal.

$$\varepsilon_{\mathrm{ij}}=\varepsilon_{\mathrm{ji}}=\left|Cov(X,Y)\right|=\left|\frac{1}{n}\sum_{i,j=1}^{n}\left(x_i-\mu_x\right)\left(y_j-\mu_y\right)\right| \quad (3)$$

2) *Step 2: Set up the Relative Covariance Matrix*

The relative covariance matrix β is obtained by transforming the covariance matrix ε, dividing each covariance column $\varepsilon_{\mathrm{ij}}$ by the covariance $\varepsilon_{\mathrm{ii}}$. The advantage of this transformation is that a matrix whose main diagonal factor is 1 will be gotten. The obtained matrix has the following form:

$$\beta=\begin{bmatrix}1 & \beta_{12} & \cdots & \beta_{1n}\\ \beta_{21} & 1 & \cdots & \beta_{2n}\\ \vdots & \vdots & \vdots & \vdots\\ \beta_{n1} & \beta_{n2} & \cdots & 1\end{bmatrix} \quad (4)$$

3) *Step 3: Set up the Correlation Matrix between the Criteria*

The correlation matrix α shows the relation between the criteria. The elements in the correlation matrix are called relation coefficients and have the form of (5) [16]. These values are obtained from the values of the elements of the matrix β.

$$\alpha_{ij}=\frac{\beta_{ij}}{\sqrt{\beta_{ij}\times\beta_{ji}}},\quad \beta_{ji}=\frac{1}{\beta_{ij}} \quad (5)$$

From (5), the correlation matrix between the criteria has the form of (6):

$$\alpha=\begin{bmatrix}1 & \alpha_{12} & \cdots & \alpha_{1n}\\ \alpha_{21} & 1 & \cdots & \alpha_{2n}\\ \vdots & \vdots & \vdots & \vdots\\ \alpha_{n1} & \alpha_{n2} & \cdots & 1\end{bmatrix} \quad (6)$$

4) *Step 4: Calculate the Weights of the Criteria Layer*

After having the correlation matrix α, the root method will be used to calculate the weights of criteria layer [17].

$$A_{(i)}=\prod_{j=1}^{n}\alpha_{ij}\ \ (i=1,2,3,\ldots\mathrm{n}) \quad (7)$$

$$W_{(i)}^{*}=\sqrt[n]{A_{(i)}} \quad (8)$$

W_i^* will be normalized and the results of the weights of the criteria are calculated by:

$$W_{C(i)}=\frac{W_{(i)}^{*}}{\sum_{i=1}^{n}W_{(i)}^{*}} \quad (9)$$

5) *Step 5: Check the Consistency of the Correlation Matrix*

The consistency of the correlation matrix will be checked by calculating the Consistency Ratio (CR) [17]. A correlation matrix will be called the most consistent matrix when $CR < 0.1$. CR is calculated by:

$$CR=\frac{CI}{RI} \quad (10)$$

with:

$$CI=\frac{\lambda_{max}-n}{n-1} \quad (11)$$

where λ_{max} is the maximal eigenvalue of the correlation matrix and is determined by:

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(\alpha W)_{(j)}}{nW_{(i)}}, j = 1,\ldots,n \quad (12)$$

where $(\alpha W)_i$ represents the i^{th} component of the vector αW in the correlation matrix α.

B. Calculate the Weights of the Scheme Layer

The scheme layer of the model represents the relationship between loads in the same criterion. Subjectivity in decision making is a problem that needs to be minimized, and fuzzy preference theory is applied to solve this problem [15-16]. The process of calculating the weights of the scheme layer is shown in Figure 1 and is described below.

1) Step 1: Calculate the Variance

V_i is the variance between attributes of n-1 objects in a criterion, excluding the i^{th} object. The variance between attributes in the entire set of criteria is used to calculate the elements of the fuzzy preference relation matrix. V_i is calculated according to:

$$V_i = \frac{\sum_{j=1}^{n-1}\left(x_j - \bar{x}\right)^2}{n-1} \text{ with } j \neq i \quad (13)$$

where x_j is the value of the j^{th} object in a criterion, $\bar{x}$ is the corresponding sample mean of the criterion, and n is the size of the sample of the criterion.

2) Step 2: Develop the Fuzzy Preference Matrix

The P_{ij} elements in the fuzzy preference matrix P are determined based on the variance of the object attribute, which is calculated by (14) and (15):

$$p_{ij} = \frac{V_i}{V_i + V_j} \quad (14)$$

$$p_{ji} = 1 - p_{ij} \quad (15)$$

where $i, j \in [1\ n]$, the higher the P_{ij} value, the greater the priority for the i^{th} object. The diagonal elements have a value of 0.5. Based on the calculation of variance, the fuzzy preference matrix is easier to be calculated and the result is unique and certain. The fuzzy preference matrix P has the form of (16):

$$P = \begin{bmatrix} 0.5 & p_{12} & \cdots & p_{1n} \\ p_{21} & 0.5 & \cdots & p_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ p_{n1} & p_{n2} & \cdots & 0.5 \end{bmatrix} \quad (16)$$

3) Step 3: Develop the Fuzzy Preference Relation Consistency Matrix

The weights of the scheme layer will be calculated based on the consistency matrix $\overline{P}$, which is used to replace the pairwise comparison matrix between the attributes of a criterion and the attributes of another criterion. The elements of the consistency matrix $\overline{P}$ are established based on (17):

$$\left(\overline{p}_{ik}\right)_{n\times n} = \left(\frac{1}{n}\sum_{j=1}^{n}\left(p_{ij} + p_{ik}\right) - 0.5\right)_{n\times n} \quad (17)$$

The value of the element of the consistency matrix $\overline{P}$ represents the level of importance between the schemes. If $\overline{p}_{ij} > 0.5$, x_i will be more important than x_j, if $\overline{p}_{ij} < 0.5$, then x_j is more important than x_i, and if $\overline{p}_{ij} = 0.5$, x_i is as important as x_j. According to the above calculation, the main diagonal of the consistency matrix will be 0.5.

4) Step 4: Calculate the Weights of the Scheme Layer

The weights of the scheme layer are calculated based on the pros and cons of the scheme. The values of this level use the values of the elements in the consistency matrix $\overline{P}$. Equation (18) is applied to calculate them:

$$r_{\text{ij}} = \left\{\begin{matrix} 1 \\ 0.5 \\ 0 \end{matrix}\right\} \begin{matrix} x_i > x_j \\ x_i = x_j \\ \text{ortherwise} \end{matrix} \quad (18)$$

where r_{ij} is the priority index in the comparison between the scheme x_i and the scheme x_j. The priority index R_i of the scheme x_i in the set of scheme X is calculated by:

$$R_i = \sum_{j=1}^{n} r_{ij} \quad (19)$$

The weights of the scheme layer $W_{P(j)}$ are calculated based on the priority indexes R_i for the scheme x_i in the set of scheme X and are determined by:

$$W_{P(j)} = \frac{R_i}{\sum_{i=1}^{n} R_i} \quad j \in [1 n] \quad (20)$$

Based on this weight calculation method, it is possible to determine the weights of the scheme layer by solving the fuzzy preference consistency of the relation of alternatives of the matrix P.

C. Calculate the Combined Weights

Based on the calculation results of the weights of the criteria layer and the scheme layer, the aggregate priority weight of the power supply continuity $W_{L,ij}$ of each L_i is calculated by (21):

$$W_{L,ij} = \sum_{i,j=1}^{n} W_{C(i)} \times W_{P(j)} \quad i, j \in [1\ n] \quad (21)$$

The shedding power at the buses is calculated according to:

$$P_{Shed,L_i,t_k} = K_{Shed,L_i,t_k} . P_{Shed,t_k} = \frac{K_{i,t_k}}{\sum_{i=1}^{n} K_{i,t_k}} . P_{Shed,t_k} \quad (22)$$

where P_{Shed,L_i,t_k} is the shedding power of the i^{th} load bus (MW), at the k^{th} time stage (with k=1÷6), P_{Shed,t_k} is the total load shedding power of the system (MW) at the k^{th} time stage, K_{Shed,L_i,t_k} is the load shedding weight of the i^{th} load bus at the k^{th} time stage, and $P_{L_i,k}$ is the load power L_i at the k^{th} time stage. K_{i,t_k} is calculated by:

$$K_{i,t_k} = \frac{W_{L,ij}}{\sum_{i=1}^{n} \frac{1}{W_{\mathrm{L,ij}}}} . \frac{P_{L_i,k}}{\sum_{i=1}^{n} P_{L_i,k}} \quad (23)$$

The distribution of shedding power to the load buses must satisfy the following constraints: First, the smaller the priority weight of the power supply continuity of the load bus, the greater the shedding power and vice versa. In this regard, it should be noted that it is not possible to shed the entire power of the low-priority load buses as to ensure background or base loads and high-priority loads (Vital loads) at these load buses. Second, the shedding power at the load buses P_{Shed,L_i,t_k} is not allowed to be greater than the power of the load bus at the k^{th} time stage, $P_{Shed,L_i,t_k} < P_{L_i,k}$.

III. OBJECTIVE FUNCTION - BENEFIT FUNCTION

The objective function for load shedding using the traditional AHP method is [17]:

$$H_i = \sum_{i=1}^{n} W_{L,ij} . v_{ij} . x_{ik} \quad (24)$$

where x_{ik} is the decision variable (equals to 0 or 1) on load bus i at the k^{th} time stage [17], v_{ij} is the independent load value (or cost) in a specific load bus i at the k^{th} time stage ($/kW or $/MW), and $\mathrm{W}_{L,ij}$ is the aggregate priority weight of the power supply continuity. $W_{L,ij}$, v_{ij} are definite numbers, so the H_i function will reach its maximum value when all x_{ik} are equal to 1. Decision variable x_{ij} equals to 1 if the load demand is satisfied, otherwise it is equal to 0.

In this paper, we propose a method to calculate the objective and benefit functions for load shedding using the improved AHP method presented in equations (25) and (26):

$$H_i = \sum_{i=1}^{n} W_{L,ij} . v_{ij} . (1 - K_{Shed,L_i,t_k}) \quad (25)$$

$$Benefit = \sum_{i=1}^{n} v_{ij} . (P_{L_i,k} - P_{Shed,L_i,t_k}) \quad (26)$$

IV. CASE STUDY AND SIMULATION RESULTS

The IEEE 30 bus system is used for calculations according to the proposed method. The parameters of the system, the capacity of the generators, and the daily load data, including the independent load value/cost at each load site are listed in [17]. Suppose generator G1 is out of service. The total source power is only 225.0MW. This results in limited power supply at some time stages. The total system generation resources P_G and load demands P_L can be seen in [17]. The results of collecting information about power and power percentage of Vital Load, Semi Vital Load, and Non-Vital Load at each load bus are presented in Table I. Implementing the steps of the improved AHP algorithm to determine the priority weights of the load buses in the system, serves as the basis for load shedding. The loads with low priority factors will be prioritized for shedding in order to minimize the damage caused by power outages.

TABLE I. PERCENTAGE LOAD TYPES OF THE SYSTEM LOAD BUSES

Load L_i	**Load name**	**Vital Load (%)**	**Semi Vital Load (%)**	**Non-Vital Load (%)**	**Variance V_i of L_i in**		
					Vital Load criteria	**Semi Vital Load criteria**	**Non-Vital Load criteria**
L_1	PD_2	0.124	0.342	0.534	0.0047	0.0011	0.0024
L_2	PD_3	0.127	0.346	0.527	0.0047	0.0011	0.0024
L_3	PD_4	0.131	0.332	0.537	0.0048	0.0011	0.0024
L_4	PD_6	0.132	0.348	0.52	0.0048	0.0011	0.0025
L_5	PD_7	0.133	0.328	0.539	0.0048	0.0011	0.0024
L_6	PD_8	0.134	0.338	0.528	0.0048	0.0011	0.0024
L_7	PD_{10}	0.135	0.344	0.521	0.0048	0.0011	0.0025
L_8	PD_{12}	0.138	0.324	0.538	0.0048	0.0011	0.0024
L_9	PD_{14}	0.136	0.326	0.538	0.0048	0.0011	0.0024
L_{10}	PD_{15}	0.137	0.313	0.55	0.0048	0.0011	0.0023
L_{11}	PD_{16}	0.242	0.289	0.469	0.0050	0.0011	0.0025
L_{12}	PD_{17}	0.246	0.268	0.486	0.0049	0.0011	0.0025
L_{13}	PD_{18}	0.25	0.256	0.494	0.0049	0.0010	0.0025
L_{14}	PD_{19}	0.252	0.274	0.474	0.0049	0.0011	0.0025
L_{15}	PD_{20}	0.258	0.254	0.488	0.0049	0.0010	0.0025
L_{16}	PD_{21}	0.267	0.282	0.451	0.0048	0.0011	0.0024
L_{17}	PD_{23}	0.276	0.258	0.466	0.0048	0.0010	0.0025
L_{18}	PD_{24}	0.279	0.292	0.429	0.0047	0.0011	0.0023
L_{19}	PD_{26}	0.291	0.276	0.433	0.0046	0.0011	0.0023
L_{20}	PD_{29}	0.294	0.28	0.426	0.0046	0.0011	0.0023
L_{21}	PD_{30}	0.298	0.342	0.36	0.0046	0.0011	0.0016

From the percentages of Vital Load, Semi Vital Load, and Non-Vital Load at the load buses in the system, the theory of Section II is applied to calculate the weights of each criteria layer. The matrices $\varepsilon, \beta, \alpha$ are calculated by (1), (4), and (6) and are presented as follows:

$$\varepsilon = \begin{bmatrix} 0.0048 & 0.0018 & 0.0030 \\ 0.0018 & 0.0011 & 0.0007 \\ 0.0030 & 0.0007 & 0.0024 \end{bmatrix}$$

$$\beta = \begin{bmatrix} 1.0000 & 1.6026 & 1.2756 \\ 0.3649 & 1.0000 & 0.2756 \\ 0.6351 & 0.6026 & 1.0000 \end{bmatrix}$$

$$\alpha = \begin{bmatrix} 1.0000 & 2.0957 & 1.4172 \\ 0.4772 & 1.0000 & 0.6762 \\ 0.7056 & 1.4788 & 1.0000 \end{bmatrix}$$

From the correlation matrix between the criteria α and by applying (7), (8), and (9) we get the weights of the criteria layer. The results are presented in Table II.

TABLE II. EQUIVALENT PARAMETERS OF WIND POWER PLANT

	Vital Load	Semi Vital Load	Non-Vital Load
$W_{C(i)}$	0.4581	0.2186	0.3233

Applying (12) results to $\lambda_{\max} = 3$, and by (11) and (10) we get calculate $CI=0$ and $CR=0$. This shows the high consistency of the correlation matrix. After calculating the weights of the criteria layer, the theory to calculate the weights of the scheme layer is applied. Applying (13) in combination with the data of the percentage of the load type, we get the variances of the characteristics which are shown in Table I. The elements in the fuzzy preference relation matrix P and the fuzzy preference consistency matrix $\bar{P}$ are calculated by (14), (15) and (17). Applying (18) and (19) allows us to calculate the priority index r_{ij} of the scheme layers. The results are presented in Table III.

TABLE III. PRIORITY INDEX R*i* OF THE SCHEMES IN THE *P* MATRICES AND WEIGHTS OF THE SCHEME LAYER

Load L_i	R_i of $\bar{P}_1$	R_i of $\bar{P}_2$	R_i of $\bar{P}_3$	$W_{P(j)}$ of Vital Load	$W_{P(j)}$ of Semi Vital Load	$W_{P(j)}$ of Non-Vital Load
L_1	3.5	8.5	9.5	0.0159	0.0385	0.0431
L_2	4.5	4.5	12.5	0.0204	0.0204	0.0567
L_3	6.5	10.5	9.5	0.0295	0.0476	0.0431
L_4	8.5	3.5	14.5	0.0385	0.0159	0.0658
L_5	9.5	15.5	5.5	0.0431	0.0703	0.0249
L_6	10.5	10.5	10.5	0.0476	0.0476	0.0476
L_7	11.5	6.5	13.5	0.0522	0.0295	0.0612
L_8	14.5	17.5	7	0.0658	0.0794	0.0317
L_9	12.5	16.5	7	0.0567	0.0748	0.0317
L_{10}	13.5	20.5	3.5	0.0612	0.0930	0.0159
L_{11}	20.5	18.5	16.5	0.0930	0.0839	0.0748
L_{12}	19.5	6.5	18.5	0.0884	0.0295	0.0839
L_{13}	18.5	1.5	19.5	0.0839	0.0068	0.0884
L_{14}	17.5	10.5	17.5	0.0794	0.0476	0.0794
L_{15}	16.5	0.5	20.5	0.0748	0.0023	0.0930
L_{16}	15.5	14.5	10.5	0.0703	0.0658	0.0476
L_{17}	7.5	2.5	15.5	0.0340	0.0113	0.0703
L_{18}	5.5	19.5	2.5	0.0249	0.0884	0.0113
L_{19}	2.5	11.5	4.5	0.0113	0.0522	0.0204
L_{20}	1.5	13.5	1.5	0.0068	0.0612	0.0068
L_{21}	0.5	7.5	0.5	0.0023	0.0340	0.0023
$\sum_{i=1}^{n} R_i$	220.5	220.5	220.5			

The weights of the scheme layer are calculated based on the priority index R_i. Applying (20) calculates the weights of the scheme layer. The results are presented in Table III. The hierarchical model showing the results of the weights of the criteria layer and the scheme layer is presented in Figure 3.

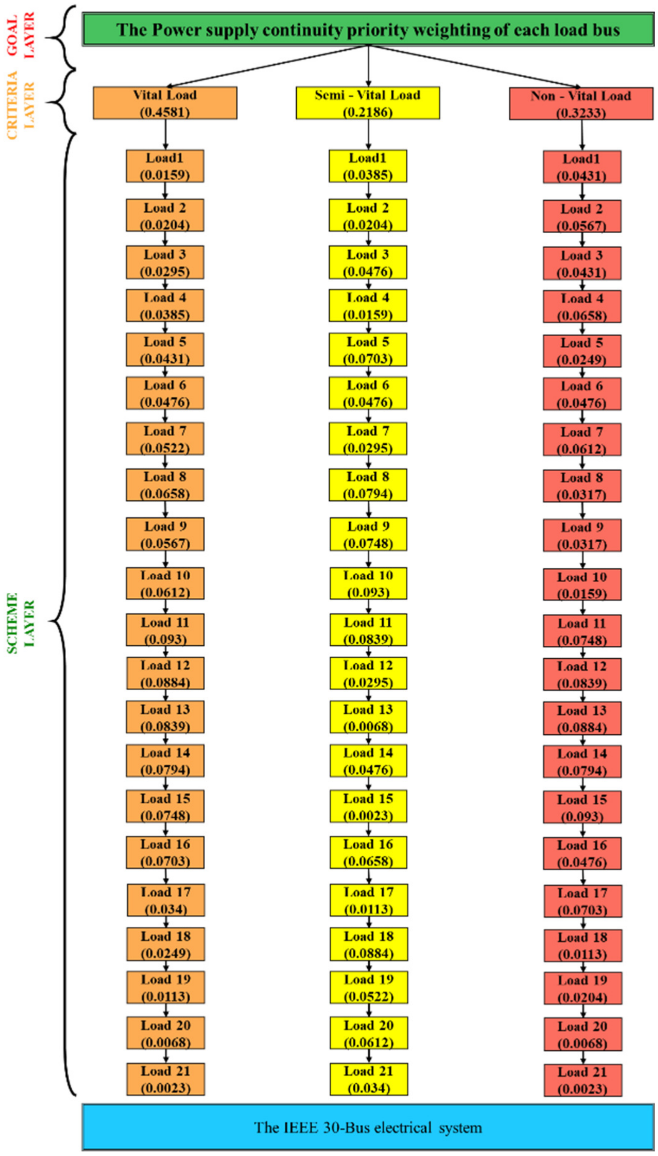

Fig. 3. Weights of the criteria and the scheme layers in the IEEE 30 bus system hierarchy.

After obtaining the weights of the criteria layer (Table II) and the weights of the scheme layer (Table III), we apply (21) to calculate the power supply continuity aggregate priority weights of the load buses. The results of calculating and load ranking are presented in Table IV. Based on the load ranking results the higher $W_{L,ij}$ the load has, the more important it is and the later its order for load shedding is. The more heavily weighted the load, the smaller the power shedding ratio and vice versa.

Equation (22) is applied to calculate the power shedding distribution at the load buses. The values of the objective function H_i and the Benefit function are calculated by (25) and (26). The results are presented in Table IV. The comparison results between the AHP and the improved AHP methods are presented in Table V. The comparison results show that the improved AHP approach is truly optimal. It not only has maximal load benefits and reduces the total load shedding, but also considers the percentages of Vital Load, Semi Vital Load, and Non-Vital Load of the load buses. For example, the improved AHP method has the total load shedding power increased from 10.48% to 69.54% corresponding to time stages of t_2-t_6. Meanwhile, the objective function of the improved AHP method increases from 48.81% to 52.67% and the load benefits also increase from 229$ to 1466$. That shows that the improved AHP method is better than the AHP method.

V. DISCUSSION

In the improved AHP method, the correlation matrix α replaces the pairwise judgment matrix of the traditional AHP method. The elements of the correlation matrix are inversely symmetric across the main diagonal line, just like in the judgment matrix of the traditional AHP method. However, for the improved AHP method, these values are derived from statistical and correlation mathematical processing based on the input as a percentage of the priority load types at each load bus. Therefore, this matrix is objective and reliable. Meanwhile, in the traditional AHP method, these values are obtained from the subjective opinions of experts. When implementing load shedding in the traditional AHP method, the entire loads are shed [17]. This is difficult to do in practice because base loads or very important loads must be maintained. Meanwhile, the improved AHP method, based on the percentages of Vital Load, Semi Vital Load, and Non-Vital Load as the basis for the application of statistical and correlation math based on the AHP algorithm hierarchical model to calculate power supply continuity weights, is feasible and practical. Therefore, if the data collection system of system parameters can satisfy the continuity, this method will be very effective. It ensures less load shedding power while ensuring a higher objective function and higher load benefits compared to the traditional AHP method.

TABLE IV. POWER SUPPLY CONTINUITY PRIORITY WEIGHTS AND LOAD BUS RANKING

Load L_i	**Power supply continuity priority weight of load buses ($W_{L,ij}$)**	**Rank**	**V_{ij} (\$/kW)**	**P_{Shed,L_i,t_1} at t_1 0.00h – 4.00h (MW)**	**P_{Shed,L_i,t_2} at t_2 4.01h – 8.00h (MW)**	**P_{Shed,L_i,t_3} at t_3 8.01h – 12.00h (MW)**	**P_{Shed,L_i,t_4} at t_4 12.01h – 16.00h (MW)**	**P_{Shed,L_i,t_5} at t_5 16.01h – 20.00h (MW)**	**P_{Shed,L_i,t_6} at t_6 20.01h – 24.00h (MW)**
L_1	0.029626441	18	300	0	3.003446	5.828059	3.726798	3.003446	0.209771
L_2	0.032136639	17	300	0	0.344511	0.668509	0.450038	0.344511	0.024062
L_3	0.037842291	15	300	0	0.825931	1.640064	1.101938	0.825931	0.059031
L_4	0.042388041	13	280	0	9.112701	17.68281	11.3498	9.112701	0.636461
L_5	0.043168144	12	280	0	2.165763	4.202572	2.823654	2.165763	0.151264
L_6	0.047619048	11	300	0	2.583331	5.012845	3.249887	2.583331	0.180428
L_7	0.050129246	10	300	0	0.474435	0.92062	0.618553	0.474435	0.033136
L_8	0.057738432	7	280	0	0.795413	1.543465	1.037034	0.795413	0.055554
L_9	0.05259167	9	280	0	0.483408	0.938034	0.630253	0.483408	0.033763
L_{10}	0.053503791	8	245	0	0.628447	1.219475	0.81935	0.628447	0.043893
L_{11}	0.085123456	1	220	0	0.1686	0.327162	0.220146	0.1686	0.011776
L_{12}	0.074080937	2	280	0	0.498168	0.966673	0.649495	0.498168	0.034794
L_{13}	0.068512253	4	220	0	0.187533	0.371643	0.249702	0.187533	0.013377
L_{14}	0.072425184	3	245	0	0.544156	1.043705	0.70164	0.544156	0.037566
L_{15}	0.064831551	5	280	0	0.139148	0.27001	0.181416	0.139148	0.009719
L_{16}	0.061973073	6	280	0	1.157909	2.246874	1.510099	1.157909	0.080872
L_{17}	0.040785013	14	220	0	0.315025	0.6243	0.419459	0.315025	0.022471
L_{18}	0.034424924	16	220	0	1.036301	2.010898	1.351913	1.036301	0.072379
L_{19}	0.023192711	19	300	0	0.618808	1.200771	0.807996	0.618808	0.04322
L_{20}	0.018699685	20	220	0	0.52628	1.021223	0.686147	0.52628	0.036757
L_{21}	0.00920747	21	245	0	4.720686	9.160291	6.15468	4.720686	0.329708
Total	1.00			0	30.33	58.9	38.74	30.33	2.12

TABLE V. SUMMARY AND COMPARISON OF AHP AND IMPROVED AHP (iAHP) LOAD SHEDDING METHODS FOR THE IEEE 30-BUS SYSTEM

Methods	AHP	iAHP	AHP	iAHP	AHP	iAHP	AHP	iAHP	AHP	iAHP	AHP	iAHP
Time stage	t_1	t_1	t_2	t_2	t_3	t_3	t_4	t_4	t_5	t_5	t_6	t_6
Max. system generation (MW)	225.0	225.0	225.0	225.0	225.0	225.0	225.0	225.0	225.0	225.0	225.0	225.0
System demands (MW)	198.69	198.69	255.33	255.33	283.9	283.9	263.74	263.74	255.33	255.33	227.12	227.12
Committed loads (MW)	198.69	198.69	213.8	225.0	218.1	225.0	219.93	225.0	213.8	225.0	220.16	225.0
Total load shedding (MW)	0.0	0.0	41.53	30.33	65.80	58.9	43.81	38.74	41.53	30.33	6.96	2.12
H_i	130.87	254.2	123.87	254.2	120.32	254.2	123.87	254.2	123.87	254.2	130.10	254.2
***Benefit* (×10^3)\$**	55058	55058	60979	62445	62306	62535	62717	62425	60979	62445	61406	62356

In addition, in this paper, we propose (25) to compare the value of H_i function with (24). From there, the advantages of the proposed load shedding distribution method can be seen more clearly. In (24), the entire load at bus i at the k^{th} time stage is cut ($x_{ik} = 0$) and does not consider the ratio of Vital, Semi-Vital, and Non Vital loads. However, in (25), we do not cut the entire load i, we only cut a part of the load i based on the K_{Shed,L_i,t_k} weight. K_{Shed,L_i,t_k} has been calculated by (22) – (23).

VI. CONCLUSION

The calculation of the power supply continuity priority weighting of each load bus by applying the theory of covariance and forming the criteria and scheme layers was conducted in this paper. The calculation of the power supply continuity priority weighting of each load bus by applying the theory of covariance and forming the criteria and scheme layers of the problem avoids the un-objectiveness of experts' opinions and gets consistent results, thus overcoming the disadvantages of the traditional AHP method. Besides, it supports the ranking of the load buses and distributes the shedding power in the power system in a more optimized way. The objective function and the benefits are better than those of the traditional AHP method.

The results of load bus prioritization can serve to set the priority of power cut of load shedding relays or planned power cuts in case of long-term power shortage or load shedding in emergency situations. In further work, more consideration should be given to the continuous variation over time of the percentage of each load type and possible combinations of constraints: the cost of power failure, the cost of fines for power failure, and the load cost for a more optimal distribution of load shedding.

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