Emergency Control of Load Shedding Based on Fuzzy- AHP Algorithm

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Abstract—Load shedding is considered one of the methods used in emergency situations to avoid instability and quickest recovery. In load shedding, anti-instability and spreading, it is important to quickly propose a reasonable load shedding strategy that will allow rapid recovery frequencies and the frequency values are acceptable. This paper presented the building of load shedding strategy that includes pre-designed rules based on the Fuzzy-AHP algorithm. The Fuzzy-AHP algorithm calculates the importance factor of the load in the electrical system. Load shedding are performed with low priority loads to help reduce the economic losses. When the electrical system is determined to be unstable, immediately, the load shedding control commands is executed, so the decision-making time is shortened and the damage caused by the load shedding is reduced compared to the traditional methods. The effectiveness of the proposed method is checked on the IEEE 39-bus system.

Keywords— Load Shedding; fuzzy-AHP; power system stability; UFLS

1. INTRODUCTION

Controlling the load shedding in the electrical system requires both economic and technical efficiency. Thereby, it must ensure the power system continues to maintain stability and cause the least damage when the load has to be shed. The method of load shedding by under frequency relay (R81), or under voltage relay (R27) is the most commonly used method for frequency and voltage stability control, and maintenance stability of the system under the necessary conditions [1,2].

In conventional load-shedding, when the frequency or voltage fluctuates outside the pre-set operating range, the under frequency/under voltage relay will cut the load. Therefore, it will prevent the frequency/voltage reduce and its effects. The under frequency load shedding relays are set to cut a predetermined load capacity of 3-5 steps when the frequency reduce below the set threshold in order to keep the power system stable.

To improve the effectiveness of the load shedding, some load shedding methods are based on the declining frequency (df/dt) [3], or are used the second derivative to forecast the frequency and load shedding [4]. These methods mainly restore the frequency of allowable values and prevent the black out. To optimize the amount of load shedding, some intelligent methods were proposed such as: artificial neural networks (ANNs) [5,6], fuzzy logic, neuro-fuzzy, particle swarm optimization (PSO), genetic algorithm (GA) [7-9]. These publications are focused on under frequency load shedding in the steady state of operation of the power system. However, due to the complexity of the electrical system, in the emergency operating mode, these cases had a problem of the burden of calculation; the processing speed of the algorithm program was slow or has to shed the passive load after the frequency was under the threshold. It took much time and caused delay in load shedding decision leading to the unstable power system. In particular, in the electricity market today, the need to ensure quality of power and reduce the economic losses associated with load shedding should be addressed.

In order to overcome the limitations of traditional methods, it is necessary to propose a new model for load shedding control based on rules that pre-design according to the Fuzzy-AHP algorithm. When the power system is unstable, the load shedding control commands immediately executes, so the decision-making time is shortened. The effectiveness of the proposed method is test on the IEEE 39-bus electrical system diagram.

II. MATERIALS AND METHODS

A. Analytic Hierarchy Process (AHP)

Analytic Hierarchy Process (AHP) is one of Multi Criteria decision making method that was originally developed by Prof. Thomas L. Saaty. In short, it is a method to derive ratio scales from paired comparisons [10, 11]. This method presents assessment method and criteria, and works collectively to arrive at a final decision. AHP is particularly well suited for case studies involving quantitative and analytical, making decisions when there are multiple standards-dependent alternatives with multiple interactions.

The steps of the AHP algorithm can be expressed as follows:

Step 1: Set up a decision hierarchy model.

Fig. 1. AHP model of the arrangement of units
Step 2: Build judgment matrix $LC$ and $LN$ that show the important factor between load centers ($LC$) and load nodes ($LN$) each other of the power system. The value of elements in the judgment matrix reflects the user’s knowledge about the relative importance between every pair of factors.

$$
LC = \begin{bmatrix}
    w_{11}/w_{12} & w_{11}/w_{13} & \cdots & w_{11}/w_{1n} \\
    w_{21}/w_{22} & w_{21}/w_{23} & \cdots & w_{21}/w_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    w_{n1}/w_{n2} & w_{n1}/w_{n3} & \cdots & w_{n1}/w_{nn}
\end{bmatrix}
$$

$$
LN = \begin{bmatrix}
    w_{11}/w_{12} & w_{11}/w_{13} & \cdots & w_{11}/w_{1n} \\
    w_{21}/w_{22} & w_{21}/w_{23} & \cdots & w_{21}/w_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    w_{n1}/w_{n2} & w_{n1}/w_{n3} & \cdots & w_{n1}/w_{nn}
\end{bmatrix}
$$

(1)

where, $w_{ij}/w_{ij}$ is the relative importance of the $i$th load node compared with the $j$th load node; $w_{ij}/w_{ij}$ is the relative importance of the $i$th load center compared with the $j$th load center. The value of $w_{ij}/w_{ij}$, $w_{ij}/w_{ij}$ can be obtained according to the experience of electrical engineers or system operators by using some “1 – 9” ratio scale methods. According to the principle of AHP, the weighting factors of the loads can be determined through the ranking computation of a judgment matrix, which reflects the judgment and comparison of a series of pair of factors. Therefore, the unified weighting factor of the load nodes of the power system can be obtained from the following equation:

$$
w_{ij} = w_{ij} \times w_{Di} \quad D_i \in K_j
$$

(2)

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

**Step 3**: Calculate the largest eigenvalue and corresponding eigenvectors of judgment matrix.

To calculate the eigenvalue of matrix largest judgment, we use the root methods.

(1) Multiply all the components in each row of the judgment matrix.

$$
M_i = \prod_{j=1}^{n} X_{ij} \quad i = 1, \ldots, n; j = 1, \ldots, n
$$

(3)

Here, $n$ is the dimension of the judgment matrix $A$, $X_{ij}$ is the element of the matrix $A$.

(2) Calculate the $n$th root of $M_i$

$$
M_i = \sqrt[n]{M_i} \quad i = 1, \ldots, n
$$

(4)

Vector $W^*$: $W^* = [W_1^*, W_2^*, \ldots, W_n^*]^T$

(5)

(3) Standardize vector $W^*$

$$
W_i = \frac{W_i^*}{\sum_{j=1}^{n} W_j^*}, \quad i = 1, \ldots, n
$$

(6)

In this way, there are eigenvectors of matrix $A$,

$$
W = [W_1, W_2, \ldots, W_n]^T
$$

(7)

(4) Calculation of the largest eigenvalues of matrix $A$

$$
\lambda_{max} = \sum_{j=1}^{n} (AW)_j, \quad j = 1, \ldots, n
$$

(8)

Where, $AW_i$ represents the $i$th component of the vector $AW$.

Step 4: Hierarchy ranking and check the consistency of the results.

**B. The definition of the triangular fuzzy number and the operational laws of triangular fuzzy numbers [12]**

The membership function $M(x): R \rightarrow [0,1]$ of the triangular fuzzy number $M = (l,m,u)$ defined on $R$ is equal to

$$
\tilde{M}(x) = \begin{cases} 
\frac{x - l}{m - l}, & x \in [l, m] \\
\frac{x - u}{m - u}, & x \in [m, u] \\
0, & \text{otherwise}
\end{cases}
$$

(9)

Where, $l \leq m \leq u$ and, $l$ and $u$ are respectively lower and bound values of the support of $M$. According to Zadeh extension principle given two triangular fuzzy numbers $\tilde{M_1} = (l_1, m_1, u_1)$ and $\tilde{M_2} = (l_2, m_2, u_2)$ ($l_1$ and $l_2 \geq 0$).

**Fig. 2. The comparison of two fuzzy numbers $\tilde{M_1}$ and $\tilde{M_2}$**

The extended addition is defined as:

$$
\tilde{M_1} \oplus \tilde{M_2} = (l_1 + l_2, m_1 + m_2, u_1 + u_2)
$$

(10)

The extended multiplication is defined as:

$$
\tilde{M_1} \otimes \tilde{M_2} = (l_1l_2, m_1m_2, u_1u_2)
$$

(11)
The inverse of triangular fuzzy number $M_i$ is defined as:

$$M_i^{-1} = \left[ \frac{1}{u_i}, \frac{1}{m_i}, \frac{1}{l_i} \right]$$

(12)

C. Fuzzy - AHP Model

The conventional AHP approach may not fully reflect a style of human thinking. One reason is that decision makers usually feel more confident to give interval judgments rather than expressing their judgments in the form of single numeric values. As a result, fuzzy AHP and its extensions are developed to solve alternative selection and justification problems. Fuzzy-AHP method determines the significance of the load units in the power system, is performed by following these steps [12]:

Step 1: Identify main factors and sub-factors.

Step 2: Develop an AHP model based on these factors determined in Step 1.

Step 3: Calculate the weighting of the important factor of these load centers together and the important factor of load units in the same load center based on the judgment matrix was been fuzzy. Percentage of fuzzy about the important factor to measure the relevant weighting is given in Fig 3 and Table I. This rate was proposed by Kahraman [13] and was used to resolve the problems fuzzy implementation of decisions [13,14].

![Linguistic scale for relative importance](image-url)

Fig. 3. Linguistic scale for relative importance

### Table I. Linguistic Scales for Difficulty and Importance

<table>
<thead>
<tr>
<th>Linguistic scale for difficulty</th>
<th>Linguistic scale for importance</th>
<th>Triangular fuzzy scale</th>
<th>Triangular fuzzy reciprocal scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Just equal</td>
<td>Just equal</td>
<td>(1,1,1)</td>
<td>(1,1,1)</td>
</tr>
<tr>
<td>Equally difficult (ED)</td>
<td>Equally important (EI)</td>
<td>(1/2,1,3/2)</td>
<td>(2/3,1,2)</td>
</tr>
<tr>
<td>Weakly more difficult (WMD)</td>
<td>Weakly more important (WMI)</td>
<td>(1,3/2,2)</td>
<td>(1/2,2/3,1)</td>
</tr>
<tr>
<td>Strongly more difficult (SMD)</td>
<td>Strongly more important (SMI)</td>
<td>(3/2,2,5/2)</td>
<td>(2/5,1/2,2/3)</td>
</tr>
<tr>
<td>Very strongly more difficult (VSMD)</td>
<td>Very strongly more important (VSMI)</td>
<td>(2,5/2,3)</td>
<td>(1/2,3/2,5/2)</td>
</tr>
<tr>
<td>Absolutely more difficult (AMD)</td>
<td>Absolutely more important (AMI)</td>
<td>(5/2,3,7/2)</td>
<td>(2/7,1/3,2/5)</td>
</tr>
</tbody>
</table>

Step 4: Calculate the weights in the sub-factors (load units) for the whole system. This weight is calculated by multiplying the numerator by the weighted coefficients by the weight of the respective principal factors.

According to Chang’s Fuzzy-AHP method [15-17],

$$S_i \approx \sum_{j=1}^{m} M_{ji}^{-1} \otimes \left( \sum_{j=1}^{m} \sum_{i=1}^{n} M_{ji}^{-1} \right)^{-1}$$

(13)

where,

$$\sum_{j=1}^{m} M_{ji}^{-1} = \sum_{j=1}^{m} I_j \otimes \sum_{i=1}^{n} M_{ij} \otimes \sum_{j=1}^{m} u_j$$

(14)

The degree of possibility of

$$M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$$

is defined as:

$$V(\sim M_2 \geq \sim M_1) = \text{sum}[\min(\sim M_1(x), \sim M_2(y))]$$

$$V(\sim M_2 \geq \sim M_1) = \text{hgt}(\sim M_1 \cap \sim M_2) = M_3(d) = \begin{cases} 1, & \text{if } m_2 \geq m_1 \\ 0, & \text{if } l_2 \geq u_1 \end{cases}$$

(15)

See Fig. 3 $V(\sim M_2 \geq \sim M_1)$ in case $m_2 < l_1 < u_2 < m_1$ where $d$ is the ordinate of the highest intersection point $D$ between $M_1$ and $M_2$. To compare $M_i$ and $M_j$, need to both the values of $V(\sim M_i \geq \sim M_j)$ and $V(\sim M_j \geq \sim M_i)$. The degree possibility for a convex fuzzy number to be greater than k convex fuzzy numbers $M_i (i = 1, 2, ..., k)$ can be defined by

$$V(\sim M \geq \sim M_1, \sim M_2, ..., \sim M_k) = \min V(\sim M \geq \sim M_i), i = 1, 2, ..., k$$

(16)

Finally,

$$W = (\text{min } V(S_1 \geq S_k), \text{min } V(S_2 \geq S_k), ..., \text{min } V(S_n \geq S_k))^T$$

(17)

is the weight vector, for $k = 1, 2, ..., n$.

The weighting importance of the load units of the system is calculated by multiplying the weights of the load nodes with the weight of the corresponding load center.

Step 5: Sort by descending order of importance of each load unit to implement load shedding strategy by priority.
TABLE II.  SORT BY DESCENDING ORDER OF IMPORTANCE OF THE LOAD UNITS

<table>
<thead>
<tr>
<th>Load Center</th>
<th>Load</th>
<th>W</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC1</td>
<td>L1</td>
<td>W1</td>
<td>W1 &gt; W2 &gt; ....</td>
</tr>
<tr>
<td>LC1</td>
<td>L2</td>
<td>W2</td>
<td></td>
</tr>
<tr>
<td>LC3</td>
<td>...</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>LC4</td>
<td>...</td>
<td>...</td>
<td></td>
</tr>
</tbody>
</table>

**D. Proposed method**

![Flowchart of steps using Fuzzy-AHP method to load shedding](image)

**III. SIMULATIONS AND RESULTS**

To compare the effectiveness of load shedding base on Fuzzy-AHP, we simulation the proposed algorithm on the IEEE 39 bus system for using case proposed method and using traditional method.

Considering the loss of a generator causes the system to become unstable (frequency decreases less than 59.7 Hz or rotor deviation greater than 180° at the bus). Corresponding to each case, it will develop a "control strategy" in the load shedding to restore the parameters back to the initial stable state. This paper simulations using PowerWorld and observes the results obtained when applying the proposed load shedding.

Calculate the importance factor of load based on the Fuzzy - AHP algorithm:

![Diagram of the power system 39 bus 10 generators for case study](image)

**Fig. 5.** Diagram of the power system 39 bus 10 generators for case study

Based on the grid of the elements and the number of the loads, divide the system into 4 load centers. This system is similar to a National grid, in which each loading area is a province (or possibly a cluster of provinces). The number of loads in the area is the transformer stations in that province.

Use the Fuzzy - AHP method to determine load and load center weights in the system. Follow the steps of the Fuzzy-AHP algorithm model:

Step 1: Identify the load centers and load units in the load center (main factors and sub-factors).

In this model, the system has four load centers LC1, LC2, LC3, LC4 and has 19 load units as shown in Table III.

**TABLE III. SYNTHESIZE DIVISION OF LOAD CENTERS, GENERATORS AND LOADS**

<table>
<thead>
<tr>
<th>Load Center</th>
<th>GEN</th>
<th>LOAD</th>
<th>N. OF LOAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC1</td>
<td>G30,31,32</td>
<td>L4, 7, 8, 12, 31, 39</td>
<td>6</td>
</tr>
<tr>
<td>LC2</td>
<td>G33, 34, 35, 36</td>
<td>L15, 16, 20, 21, 23, 24</td>
<td>6</td>
</tr>
<tr>
<td>LC3</td>
<td>G38</td>
<td>L26, 27, 28, 29</td>
<td>4</td>
</tr>
<tr>
<td>LC4</td>
<td>G37, 39</td>
<td>L3, 18, 25</td>
<td>3</td>
</tr>
</tbody>
</table>

Step 2: Develop a hierarchical AHP model based on load centers and units Load identified in Step 1.

![Color diagram illustrating the IEEE system with 39 buses and 10 generators](image)

**Fig. 6.** Fuzzy-AHP model includes load centers and load units

Step 3: Determine the weighting coefficients of importance of load centers and load units using the judgment matrix. To do that, the matrices should be constructed between the load centers and between the loads together in each load center. Based on Table I and the experienced operators of electrical systems determine the main and the sub-factors. These factors were shown in the tables Table IV, Table V, Table VI, Table VII, and Table VIII.
Where, $C_i$ is the center of load $i, i = 1 - 4$. This is the 4 row x 4 column, with the value in each row consists of the main position in the middle row and two sub values in the two adjacent rows it. Similarly, the judgment matrices of load in LC1, LC2, LC3, LC4 load centers are calculated.

Load Center 1 includes 6 loads: L4, L7, L8, L12, L31, L39, matrix obtained for load center 1 is matrix 6 rows x 6 columns.
\[ V(S_1 \geq S_2) = \frac{0.15 - 0.29}{(0.20 - 0.29) - (0.23 - 0.15)} = 0.80 \]; similar
\[ V(S_1 \geq S_3) = 0.53; V(S_2 \geq S_3) = 0.55; \]
\[ V(S_2 \geq S_3) = 1; \quad V(S_3 \geq S_1) = \frac{0.19 - 0.36}{(0.23 - 0.36) - (0.29 - 0.19)} = 0.76; \]
similar \[ V(S_2 \geq S_4) = 0.77; \]
\[ V(S_3 \geq S_4) = 1; V(S_4 \geq S_3) = 1; V(S_4 \geq S_2) = 1; \]
\[ V(S_4 \geq S_1) = 1. \]

Using (16):
\[ d(C_1) = V(S_1 \geq S_2, S_3, S_4) = \min(0.80, 0.53, 0.55) = 0.53 \]
\[ d(C_2) = V(S_2 \geq S_1, S_3, S_4) = \min(1.0, 0.76, 0.77) = 1 \]
\[ d(C_3) = V(S_3 \geq S_1, S_2, S_4) = \min(1.1, 1) = 1 \]
\[ d(C_4) = V(S_4 \geq S_1, S_2, S_3) = \min(1.1, 1) = 1 \]

Thus, \[ W = (0.53, 0.76, 1, 1) \], from which the weights or vectors are calculated \[ W = (0.16, 0.23, 0.30, 0.30) \] based on the formula
\[ W_i = \sum W_i^* \cdot \]

Similar to such calculation, find the weights of each load center and of each load in the center. The results for the remaining cases are shown in Table IX.

| TABLE IX. WEIGHT OF LOADS IN EACH CENTER. |
|------------------|------------------|------------------|------------------|
| Weight | LC1 | LC2 | LC3 | LC4 |
| W1 | 0.1519630935 | 0.0992308192 | 0.1371793201 | 0.2895529185 |
| W2 | 0.2152410974 | 0.2162023778 | 0.3872652285 | 0.662567390 |
| W3 | 0.0566022057 | 0.1111338061 | 0.1122063232 | 0.047893425 |
| W4 | 0.1767634341 | 0.1002503983 | 0.3634941282 | - |
| W5 | 0.2023422316 | 0.2294871676 | - | - |
| W6 | 0.1976879287 | 0.2436954311 | - | - |

After obtaining the values \[ W_{ij} \] and \[ W_{ik} \], compute the coefficients of gross coefficient combined \[ W_{ij} \] of each load. The value is calculated by the formula \[ W_{ij} = W_{ik} \times W_{ik} \], that is, multiply by two the weighted values of the load and the weight of the center together. Weights \[ W_{ij} \] in the same load center is the same and equal to the value \[ W_{ij} \]. After calculating the important factor of each load unit at each stage from Fuzzy-AHP calculations, arrange loading units in descending order of priority as shown in Table X. The more important loads are, the greater the \[ W_{ij} \] are.

| TABLE X. ARRANGE LOADING UNITS BY THE WEIGHT FACTOR OF THE LOAD FACTOR \[ W_{ij} \] |
|------------------|------------------|------------------|------------------|
| No | Loads | The important factor of load units | LC | The important factor of load centers | The important factors |
|------------------|------------------|------------------|------------------|------------------|
| 1 | L18 | 0.6625677390 | LC4 | 0.3037660388 | 0.2012655775 |
| 2 | L27 | 0.3872652285 | LC3 | 0.3037660388 | 0.1176380244 |
| 3 | L29 | 0.3633491282 | LC3 | 0.3037660388 | 0.1103731254 |
| 4 | L3 | 0.2895529185 | LC4 | 0.3037660388 | 0.0879563431 |
| 5 | L24 | 0.2436954311 | LC2 | 0.2318391143 | 0.0564981329 |
| 6 | L23 | 0.2294871676 | LC2 | 0.2318391143 | 0.0532041017 |

From Table X, it is found that load L8 has the largest order number (19th) that is the load has the lowest priority and will be cut off first. Load L18 with the smallest ordinal number (numbered 1st), meaning that this load has the highest priority and will be cut off in the end in any case.

From here, the following order can be given: L8, L25, L15, L21, L4, L20, L12, L39, L31, L28, L7, L26, L16, L23, L24, L3, L29, L27, L18.

The Fuzzy-AHP method is used to determine the arrangement of load units in priority order at all times and the load shedding system will cut the load on the system smallest number before.

Apply the proposed method proceed to load shedding the load until the frequency of recovery return to a value greater than 59.7Hz. The results of frequency simulation were shown in Fig. 7.
Compared the load shedding methods based on traditional method (under frequency load shedding) and Fuzzy-AHP algorithm, in both cases the frequencies were restored to allowed values. However, the load shedding according to Fuzzy-AHP algorithm had total load shedding capacity lower than under frequency load shedding. Especially, the frequency recovery time and rotor angle of Fuzzy-AHP method are faster than traditional method.

IV. CONCLUSIONS

Load shedding based on Fuzzy-AHP algorithm is applied in the emergency situations to maintain stability of the power system. This paper proposed a new method to build load shedding strategies according to the pre-designed rules based on Fuzzy-AHP algorithm. The implementation of load shedding was made immediately after evaluating the instability of the power system, helping the system to recover faster in emergency. Simulation results on the IEEE 39 bus system showed that the effectiveness of the proposed method.

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