Distribution Network Reliability Evaluation with Load Importance Degree and Isolated Island Operation

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Abstract. Supply power for important load in priority is the fundamental principle during power shortage. For the reason that the existing power load classification principle is too simple to compare the importance degree of loads at the same level, this paper proposed a comprehensive evaluation method of load importance degree. First, an indicator system is established to measure load importance. Then a comprehensive evaluation model is designed basing on improved rank correlation analysis method, which sets weights based on subject and object analysis and calculates the importance degree value according 4 indicators, including outage cost. Finally, evaluating the distribution network reliability with load importance degree. Simulation results on IEEE-RBTS BUS6 system shows the validity and practicality.

1. Introduction

Reliable power supply is the basic function of power system. Under the influence of load fluctuation, power output change and equipment failure, ensuring the balance between power supply and demand is difficult. When power supply is insufficient, appropriate load shedding to restore balance is necessary. In some strategies, in order to support more power customers, removing some of the important load is inevitable, which brings influence to economic, safe and stable operation of power system [1-2].

To ensure the uninterrupted power supply for important load, electrical load is divided into three levels [3], according to the loss or influence caused by power interruption. This method is simple, and can subjectively select important load in a region. But in actual operation process, it mainly has following problems: (1) as this division principle is rough, it is lack of necessary basis to determine the relative importance between loads in same level; (2) there is no quantification of load importance degree. It can only roughly obtain importance order, without further analysis of gap size. Because of them, at present stage, decisions making often only considers supporting load as much as possible, while ignoring load importance degree. It results that some important load cannot be powered in this case. Therefore, it is necessary to quantify load importance degree, and then sort each load in the region. When power supply is insufficient, a reasonable and effective strategy should be adopted to ensure the priority of important load.

This paper puts forward a comprehensive evaluation method for load importance degree. Firstly, an index system is established, including outage cost, load density, load factor, and utilization hours of annual maximum load; secondly, the weight of each index is determined through improved rank correlation analysis method (RCAM), which can not only use objective law of data, but also fully...
reflect expert opinion; thirdly, the importance degree evaluation value of load points are calculated, to
determine the importance rank within the region and to quantify their load importance degree; finally,
power supply reliability considering load importance degree is evaluated, discussing the influence
of this method on the result of distribution network reliability evaluation, and confirming its validity and
practicability via the IEEE simulation system.

2. Comprehensive evaluation method of load importance degree
The comprehensive evaluation method of load importance degree proposed in this paper, establishes
the index system as foundation, determines weights of indexes through improved RCAM [4], and then
calculates importance degree evaluation values of loads.

2.1. Evaluation indicator system
This evaluation index system can comprehensively evaluate load importance degree in an area by
reflecting characteristics of load and impact of load interruption. It includes 4 indexes, outage cost,
load density, load factor, and utilization hours of annual maximum load. Meanings of indexes are as
follows:
(1) Outage cost refers to the economic losses of users caused by electricity outage or restriction.
Obviously, the load which has greater outage cost is more important.
(2) Load density refers to average load per unit power supply area, in the maximum load case. It
represents the quantitative parameters of load distribution. Area with high load density is usually
located in the centre of city, which has frequent commercial and financial activities.
(3) Load factor refers to the percentage of ratio of average load to maximum load in statistical
period. High load factor means that the load curve is smooth, and the peak valley difference is small.
Therefore, this load is at a relatively stable level, and difficult to be cut or interrupted. In addition,
smaller load regulating capacity that it requires also means a positive effect on safe operation and
economic benefit of power system.
(4) Utilization hours of annual maximum load refers to the time required to consume power l
load throughout the year, when power load continues to run at the maximum annual load. Generally
speaking, the utilization hours of annual maximum load of large industrial enterprises and urban
comprehensive power load is larger, and demand of reliability of them is also relatively high.

2.2. Comprehensive evaluation algorithm
In this paper, a calculation model is designed to quantify load importance, using improved RCAM to
determine weights of indexes. Traditional RCAM is flexible and easy to operate, which can
adjust weights according to characteristics of different regions, and fully reflect experts' opinions. But
it is lack of the utilization of objective law of data, and the subjectivity of weights is strong. Therefore,
an improved RCAM is adopted, and the process is as follows:
(1) Set \( n \) evaluation objects, \( m \) evaluation indexes. The original data is converted into dimensionless
profit index \( \{ x_{ij} \} \). Then, weights of indexes are preliminarily determined by traditional method;
(2) According to formula (1), the contribution rate of each index is calculated, as well as the rank
correlation. In order to remain generality, record the rank correlation of contribution rate as
\( C_1 > C_2 > \cdots > C_m \);
\[
c_j = \frac{w_j \sum_{i=1}^{n} x_{ij}}{\sum_{j=1}^{m} w_j x_{ij}} \quad i = 1, 2, \cdots, n, \quad j = 1, 2, \cdots, m
\]
(3) Determine the relative contribution \( r_k \) between \( C_{k-1} \) and \( C_k \);
\[
\frac{c_{k-1}}{c_k} = r_k \quad k = m, m-1, \cdots, 3, 2
\]  
(2)

(4) In order to eliminate strong consistency, contribution rate \(c_j\) is calculated again, as:

\[
\begin{align*}
\max f &= \sum_{k=2}^{m} (c_{k-1}c_k) = c_1 - c_m \\
\text{s.t.} \quad &c_{k-1} - c_k r_k \leq 0 \quad k = m, m-1, \cdots, 3, 2 \\
&c_k - c_{k-1} \leq 0 \quad k = m, m-1, \cdots, 3, 2 \\
&c_1 - 1.8c_m \leq 0 \\
&\sum_{k=1}^{m} c_k = 1
\end{align*}
\]

(3)

(5) The contribution rate \(c_j\) of each index can be obtained by the optimal solutions of above planning problems, and then the weight coefficient is calculated as:

\[
w_m = \left(1 + \frac{\sum_{k=2}^{m} \frac{c_{k-1}}{c_m}}{c_k} \right)^{-1}
\]

(4)

\[
\omega_{k-1} = \omega_k \frac{l_{k-1}c_{k-1}}{c_k l_{k-1}} \quad k = m, m-1, \cdots, 3, 2
\]

(5)

Where, \(l_j = \sum_{i=1}^{n} x_{ij}\).

(6) The weight of each index is obtained by using RCAM. The comprehensive evaluation value \(T\) of each load is calculated, as:

\[
T = \sum_{k=1}^{m} w_k x_k
\]

(6)

It can reflect the load importance degree of different loads in the area. Greater the value of \(T\) is, more important the load is. So it has priority of power supply, in the case of insufficient power supply.

3. Distribution network reliability evaluation process

3.1. Isolated island operation scheme of distribution network

In this paper, the maximum power supply range of isolated island (II) is determined by its DG power. When fault occurs, according to II's DG output, load within II is reduced to meet its power balance. The principle of II formation is: under the premise that load inside II is not larger than its total DG output, it should contain as much load and important load as possible. In traditional process, maximum available power supply capability is targeted as objective function. In order to ensure power supply for important load in priority, the product of load and its importance degree evaluation value is taken as the objective function in this paper. The mathematical model of II formation is as follow:

\[
\begin{align*}
z &= \max \sum_{i=1}^{N} T_i L_i \\
\text{s.t.} \quad &\sum_{i=1}^{N} L_i \leq P_{DG}
\end{align*}
\]

(7)

Where \(T_i\) is the importance degree evaluation value of each load; \(L_i\) is active power of each load; \(N\) is quantity of load in II.

3.2. Distribution network reliability evaluation process
Assuming that superior substation capacity is not limited, blackouts happen only when other elements have failures. To accelerate simulation speed, improved sequential Monte Carlo method \[5\] is adopted for distribution network reliability evaluation. Before evaluation, elements in the same feeder area are equivalent to a single sampled element, using formula (8) and (9).

\[
\lambda_s = \sum_{i \in S} \lambda_i \tag{8}
\]

\[
\gamma_s = \sum_{i \in S} \frac{\lambda_i \gamma_i}{\lambda_s} \tag{9}
\]

In this process, sequential sampling and state sampling are applied to equivalent feeder areas and DG output respectively. Simple steps are as follows:

1. Read element and load parameters to initialize system parameters. Set simulation year period \(NY\) and start time \(t = 0\);
2. Use sequential sampling results to determine the fault area;
3. Find affected load points by failure consequence analysis. Judge whether there are load points being power supported by II. If so, use random sampling to determine DG output. Judge whether it is power balance. If not, establish isolated island operation scheme according to section 2.1. Collect interruption frequency, interruption duration and other indicators.
4. Repeat step (2) and step (3), until simulation time is greater than the set term.
5. Calculate reliability indices of each load point and system.

The overall reliability evaluation process is shown in Figure 1.

**4. Case analysis**

In this paper, case analysis is based on the main feeder F4 of IEEE-RBTS Bus6 system \[6-7\]. 2 DG, with 1MW each, are added in branch line 19 and 25 respectively, as shown in Figure 2. When upstream supply path failure, through circuit breaker operation, II 1 and 2 can form and continue their power supply internally. This test system includes 23 load points, 1 isolation switch, 23 transformers, 6 circuit breakers, and 23 fuses (installed at the head end of load lines). The reliability parameters of equipment and lines are taken from reference \[8\]. The parameters of load points are shown in Table 1. Isolation switch is assumed to be 100% reliable. Switch operating time is 20 minutes.

![Figure 1. The flow chart of distribution network reliability evaluation.](image1)

![Figure 2. Simulation system.](image2)
Assuming that superior substation capacity is not limited, blackouts happen only when other elements have failures. DG only supports load in II, therefore, only load importance degree of load in II is evaluated and sorted. Results are shown in Table 2.

### Table 1. Parameters of each load point.

| Load point number | quantity of users | Load/MW | Outage cost | Load density | Annual load rate | Utilization hours of annual maximum load |
|-------------------|------------------|---------|-------------|--------------|-----------------|--------------------------------------|
| 2                 | 126              | 0.1808  | 10.50       | 60           | 0.4850          | 2200                                 |
| 5                 | 132              | 0.2070  | 75.67       | 200          | 0.5785          | 4000                                 |
| 1,6               | 1                | 0.1659  | 157.53      | 200          | 0.6520          | 7000                                 |
| 15,20             | 20               | 0.1929  | 180.12      | 50           | 0.7369          | 6437                                 |
| 4,18              | 147              | 0.2431  | 11.37       | 65           | 0.6875          | 3000                                 |
| 7,23              | 15               | 0.2101  | 10.02       | 50           | 0.3614          | 3157                                 |
| 9,21              | 79               | 0.2831  | 10.55       | 80           | 0.6875          | 3000                                 |
| 3,13,17           | 35               | 0.2501  | 9.45        | 40           | 0.3614          | 3157                                 |
| 10,12,16,22       | 76               | 0.1585  | 75.85       | 160          | 0.5355          | 4678                                 |
| 8,11,14,19        | 10               | 0.1554  | 147.35      | 60           | 0.7368          | 6437                                 |

### Table 2. Results of load sorting and importance degree evaluation values.

| Sorting (II 1) | Load point number | importance degree evaluation value | Sorting (II 2) | Load point number | importance degree evaluation value |
|----------------|-------------------|-----------------------------------|----------------|-------------------|-----------------------------------|
| 1              | 15                | 0.7629                            | 1              | 20                | 0.7414                            |
| 2              | 14                | 0.7249                            | 2              | 19                | 0.7051                            |
| 3              | 16                | 0.5845                            | 3              | 22                | 0.5839                            |
| 4              | 18                | 0.2445                            | 4              | 21                | 0.2587                            |
| 5              | 17                | 0.0099                            | 5              | 23                | 0.0099                            |

According to section 2.1 and results shown in Table 2, the isolated island operation scheme is determined as Scheme 1. Results of distribution network reliability evaluation considering load importance degree for Scheme 1 and 2 (isolated island operation scheme targeting maximum available power supply capability) are compared, as shown in Table 3. In addition, wind power is used as DG in this simulation, with output model from reference [8].

### Table 3. Distribution network reliability evaluation results of load points.

| Load point | Scheme 1 | Scheme 2 |
|------------|----------|----------|
|            | \(\lambda\) (times/year) | \(r\) (hours/time) | \(U\) (hours/year) |
|            | \(\lambda\) (times/year) | \(r\) (hours/time) | \(U\) (hours/year) |
| LP1        | 1.280    | 4.707    | 6.026 |
| LP8        | 1.280    | 6.194    | 7.928 |
| LP14       | 1.290    | 5.483    | 7.076 |
| LP16       | 1.547    | 5.049    | 7.811 |
| LP17       | 1.842    | 4.598    | 8.468 |
|            | 1.280    | 4.752    | 6.083 |
|            | 1.279    | 6.167    | 7.891 |
|            | 1.479    | 5.149    | 7.616 |
|            | 1.613    | 4.836    | 7.798 |
|            | 1.588    | 4.951    | 7.864 |

According to Table 3, as importance degree evaluation value of LP14 is high, its reliability is obviously improved. What’s more, its failure frequency in annual evaluation is decreased from 1.479 in Scheme 2 to 1.290, reduced by 13%. While load of LP17 is large, its importance degree evaluation value is small. Therefore, effect of LP17’s shedding is also small, so it has higher priority to shed when power supply is insufficient. As a result, its failure frequency in annual evaluation is increased from 1.588 in Scheme 2 to 1.842. For LP1 and LP8, load outside II, their importance degree evaluation...
values remain unchanged. The calculation of system reliability index, SAIFI and SAIDI, is 1.456 times/(user•year) and 7.665 hours/(user•year) respectively in Scheme 1, while 1.424 times/(user•year) and 7.509 hours/(user•year) respectively in Scheme 2. So, the change between them is little. Therefore, using isolated island operation scheme considering load importance degree proposed in this paper can maximize the availability of power supply for important load, with little change in system reliability.

5. Conclusions
In this paper, a comprehensive evaluation method of load importance degree is proposed, from which order of load importance degrees and their importance degree evaluation values in the region can be obtained by subject and object analysis. Compared with traditional isolated island operation scheme targeting maximum available power supply capability, the scheme proposed in this paper can supply power for important load in priority according to load importance degree. Therefore, it is more in line with the practical needs. Validity and practicability of this method is verified by IEEE system’s simulation results.

Acknowledgement
Foundation item: Supported by the Technical Projects of China Southern Power Grid (No. GD KJQQ20161015)

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