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Interval Approach to Distribution System Reliability Evaluation with Constraint of Available Capacity

[1] Yongli Liu, [2] Wenping Qiu, [1] Sha Liu, [1] Wentao Kang
[1] Shenzhen Power Bureau, Shenzhen, China
[2] Shanghai University of Electric Power, Shanghai, China;
E-mail: qwp_425951@163.com

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Abstract: The paper presents a new reliability-evaluation method to distribution system, based on interval analysis. In this method, the available capacity of feeder is defined and is considered when evaluation the load-point reliability. By utilizing the minimal-path method, the element is divided treatment principle is established. The basic interval formulas for the load point are presented, considering the uncertainty of the time-varying. The procedure is illustrated by application to a relatively simple but practical system example. *Copyright © 2014 IFSA Publishing, S. L.*

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1. Introduction

As the key link between transmission and customer, distribution system reliability evaluation is closed bound up to power consuming [1-3]. Utility statistics show that distribution system failures account for approximately 80 % of failures happened in power system, so distribution system reliability evaluation is extremely necessary.

The analytical techniques required for distribution system reliability evaluation are highly developed. Nowadays, the Conventional approach is failure-mode-and-effect analysis (FMEA), however, which used to enumerate the list that if the distribution network system is complexity, the statistics computation will be great. Against this weak point, other new methods are put forward based on arborescence structure, such as the minimal-path method, minimal-cut method and network-equivalent method and so on [4, 5]. Since the uncertainty of load variation in system, interval reliability evaluation is presented and come up with new formula for distribution system, based on FMEA, which handle uncertainty reasonably [6] using Monte Carlo simulation method to calculate probability distribution of reliability indexes, portion thought is introduced in distribution system with complexity [7]. The assumption those method make, mentioned above, is that load point get sufficient power supply capacity or achieve load transfer switch operation, where the voltage and current is not out of their limitations, reliability need to be consider afresh.

To get the load point reliability indexes, usually, the overall system reliability indexes must calculate first in previous assessment algorithms, which make calculation process is more complex, time-consuming. A new interval method to load point reliability, therefore, is introduced in this paper to process variation uncertainty of it.

2. Available Capability of Feeder

As for complex distribution system which made up of main feeders and auxiliary feeders, feeder is basic unit and is connected with the high-voltage

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substations from the same root node. It is assumed that the refusing action of circuit breaker in high-voltage substations, then reliability of feeder can be decoupled to calculate. Feeder is only channel to connect to the customer directly, mentioned above, the constraint of available capacity of feeder must be under consideration when doing the reliability evaluation of load point. So this paper introduces the concept of available capacity firstly.

2.1. Definition of Available Capacity

The available capacity of feeder is defined as the capacity that it can supply the power to load, continuously. Feeder has reserve capacity, when designed. At the same time, used capacity of feeder is sum of all load capacity on it. On the basis of definition above, there is such relationship as follows:

$$S_{av} = S_{uv} + S_{rv}, \tag{1}$$

where S_{av} is the available capacity of feeder; S_{uv} is the used capacity of feeder; S_{rv} is the reserve capacity of feeder.

Furthermore, used capacity of feeder is related to the state of each load point which is supplied by the relevant, relationship shown as follows:

$$S_{uv} = \sum_{i=1}^{N} \alpha_i S_i, \tag{2}$$

where α_i is the operation state of load point i, if it operates in normal state, α_i=1 and it operates in outage state, α_i=0; N is the number of load point of the feeder.

In practical engineering, the available capacity of feeder is affected by load rate of distribution transformer and load coincidence factor, formulas is shown as follows:

$$[S_{AV}] = \frac{\sqrt{3} \times U_N \times I_{\max} \times [\delta]}{[\eta] \times [\alpha]}, \tag{3}$$

where $[S_{av}]$ is the interval value of available capacity of feeder; U_N is the rated line voltage; I_{max} is the he maximum allowable line current; $[\eta]$ is the interval value of distribution transformer load rate from statistics; $[\alpha]$ is the interval value of load coincidence factor; $[\delta]$ is the margin coefficient, which considers line losses and capacity reserved margin that meet engineering requirements.

2.2. Available Capacity of Typical Distribution Networks

According to transformer capacity and distribution, geographic and environmental conditions, typical distribution networks are divided into radial network, radial network with alternative supply, and looped network. The available capacities of those networks are described in below, respectively. First of all, assuming load points are operating in normal state, taking the interval time-varying characteristic of load point into account, which is most likely to operate in 70 %-90 % of rated capacity of distribution transformer and processed as interval value $[0.7S_i, 0.9S_i]$, which reflects changes range of the load.

2.2.1. Single Radial Network

Fig. 1 shows the single radial network is the most basic form of the distribution system adopted to supply power to customers. Under normal circumstances, available capacity of radial network must meet:

$$S_l \geq \sum_{i=1}^{5} [S_{li}] + [S_{lb}], \tag{4}$$

where S_l is the available capacity of feeder; $[S_{li}]$ is the interval value of used capacity of feeder; $[S_{lb}]$ is the interval value of reserve capacity of feeder.

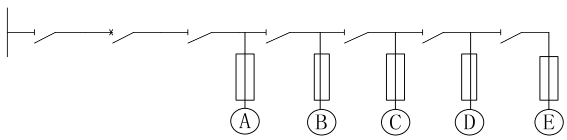

Fig. 1. Single radial network.

2.2.2. Single Radial Network with Alternative Supply

Usually, alternative supply is connected with isolation feeder by disconnect switch or circuit breaker, shown in Fig. 2. If failure happens to load point, alternative supply AS can supply power to other load points as long as switching operation goes well. Available capacity of radial network with alternative supply must meet:

$$S_l \geq \sum_{i=1}^{5} [S_{li}] + [S_{lb1}] + [S_{lb2}], \tag{5}$$

where $[S_{lb1}]$ is the interval value of available capacity of feeder; $[S_{lb2}]$ is the interval value of available capacity of alternative supply.

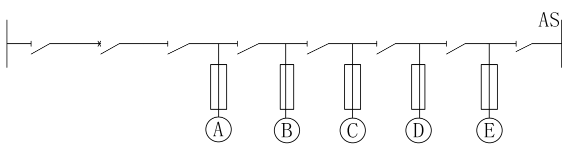

Fig. 2. Single radial network with alternative supply.

2.2.3. Single Looped Network

Although the structure of the distribution system is generally closed loop, it operates in open loop, where is equal to the two feeders which operate in parallel, shown in Fig. 3. Available capacity of looped network must meet:

$$S_l \geq \frac{\sum_{i=1}^{5}[S_{li}]+[S_{L1b}]+[S_{L2b}]}{2}, \tag{6}$$

where $[S_{L1b}]$ is the interval value of available capacity of feeder $L1$; $[S_{L2b}]$ is the interval value of available capacity of feeder $L2$.

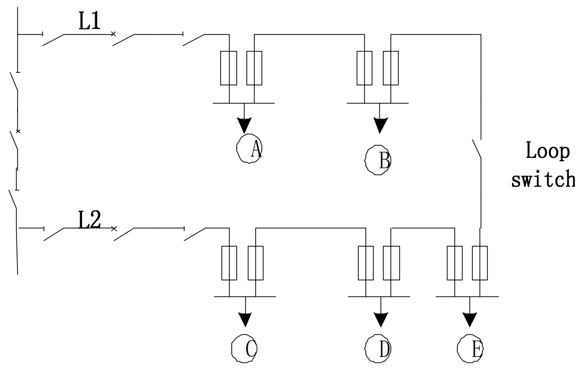

Fig. 3. Single looped network.

Table 1. Treatment principle of element.

Category	Constraint	Available capacity	Outage time
Minimal-path element	Without alternative supply	$S_l \geq \sum_{i=1}[S_{li}]$	$t_u = t_r$
	With alternative supply	$S_l \geq \sum_{i=1}[S_{li}]$ & $S_{lb} \geq \sum_{i=1}[S_{li}]$	$t_u = \max(t_f, t_b)$
Non-minimal-path element	With the protector in feeder	$S_l \geq \sum_{i=1}[S_{li}]$	$t_u = t_r$
	Without the protector and the location of first element is in minimal path and With alternative supply	$S_l \geq \sum_{i=1}[S_{li}]$ & $S_{lb} \geq \sum_{i=1}[S_{li}]$	$t_u = \max(t_f, t_b)$
	Without the protector and the location of first element is in minimal path and Without alternative supply	$S_l \geq \sum_{i=1}[S_{li}]$	$t_u = t_r$
	Without the protector and the location of first element is out of minimal path	$S_l \geq \sum_{i=1}[S_{li}]$	$t_u = t_f$

3. Interval Evaluation of Load Point Reliability Induces

3.1. Minimal-Path Method with Constraint of Available Capacity

The core of minimal-path method is to find minimal-path set where load point is treated as outset and power point is terminal point. In this way, the elements in distribution system is divided into minimal-path set and non-minimal-path set, which are treated differently when calculating the reliability of load point. The treatment principle of element is shown in Table 1

Where t_u is the outage time of load point; t_r is the repair time of fault element; t_f is the operation time of switches; t_b is the operation time of alternative supply.

3.2. Basic Formulas of Load Point

It is assumed that the relationship of elements in minimal-path belongs to series connection. Besides the influence of non-minimal-path elements is handled into their equivalent by the equivalent method to the minimum path, which belongs to series connection with minimal-path components.

According to the previous principle of element, elements can be classified in two sorts and a set of interval formulas of the three basic load point indexes of load point failure rate λ_i, average outage duration γ_j and average annual outage time U_i for the load point i is as follows:

$$[\lambda_i] = \sum_{j=1}^{n}[\lambda_j]\bullet\prod_{k=1}^{m}(1-[p_k]), \tag{7}$$

$$[U_i] = \sum_{j=1}^{n}[\lambda_j]\bullet\prod_{k=1}^{m}(1-[p_k])\bullet[\gamma_j], \tag{8}$$

$$[r_i] = \phi([\lambda_i],[U_i]), \tag{9}$$

where $[p_k]$ is the interval value of reliability rate of element; if $[\lambda_i]=[\underline{\lambda_i},\overline{\lambda_i}]$ and $[U_i]=[\underline{U_i},\overline{U_i}]$, then $\phi([\lambda_i],[U_i])=[(\underline{U_i}/\underline{\lambda_i}),(\overline{U_i}/\overline{\lambda_i})]$.

3.3. Calculations of Distribution System Reliability Indexes

The interval calculations of distribution system reliability indexes are proposed in this paper to make the point that the variation of system reliability indexes because of the uncertainty of distribution system and load point. Equations are shown as follows:

$$[S_{AIFI}] = \frac{\sum_{i=1}^{n}[\lambda_i]N_i}{\sum_{i=1}^{n}N_i}, \tag{10}$$

$$[S_{AIDI}] = \frac{\sum_{i=1}^{n}[U_i]N_i}{\sum_{i=1}^{n}N_i}, \tag{11}$$

$$[C_{AIDI}] = \phi\left(\sum_{i=1}^{n}[\lambda_i]N_i, \sum_{i=1}^{n}[U_i]N_i\right), \tag{12}$$

$$[RS-1] = \left(1 - \frac{\sum[U_i]N_i}{\sum M_i \times 8760}\right) \times 100\%, \tag{13}$$

$$[RS-3] = \left(1 - \frac{\sum[U_i]N_i - [M_{ORi}]\bullet[M_{Ti}]}{\sum M_i \times 8760}\right) \times 100\%, \tag{14}$$

where N_i is the number of customers of load point i; M_i is the number of customers when failure happen to load point i; M_{ORi} is the average inspection rate of load point i; M_{Ti} is the average repair time of load point i.

4. Application Analysis

The following illustrates an application to a practical test system known as the RBTS [8], which is contains six local distribution systems. Fig. 4 shows part of these systems, which consist of feeder F1, F2 and F3. The data used in these studies are given in Table 2 and Table 3. The detailed procedure followed in the interval method is illustrated by taking LP5 as example.

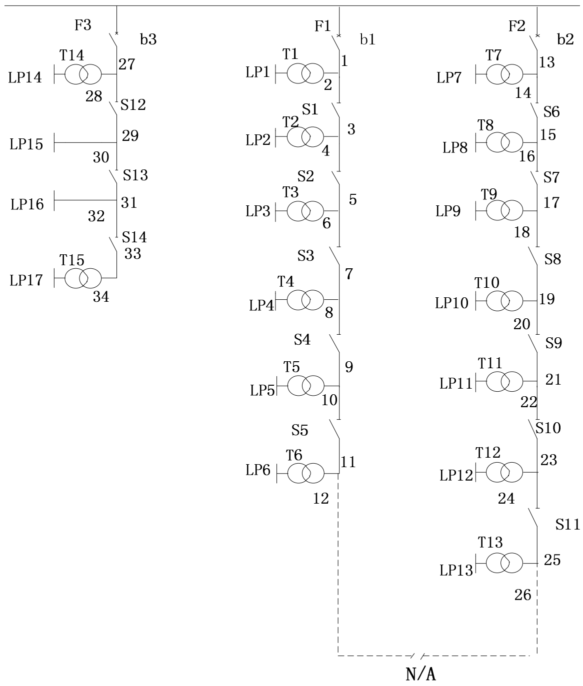

Fig. 4. Example distribution system.

Table 2. Interval information of example feeders.

Sectional area/mm^2	Available capacity/kVA	Number
240	[14100, 15300]	3, 5, 8, 11, 13, 15, 18, 20, 23, 26, 31, 33
150	[12700, 13600]	1, 4, 7, 9, 12, 16, 19, 22, 24, 27, 29, 32
95	[11300, 12600]	2, 6, 10, 14, 17, 21, 25, 28, 30, 34
The rated voltage of feeders is 10 kV, the interval value of distribution transformer load rate is [0.6-0.65], the interval value of load coincidence factor is [0.8-0.85]; the margin coefficient of feeders is [0.90-0.96].		

Table 3. Interval reliability parameter of elements.

Element	Failure rate (occ/year)	Repair time (h)	Maintain rate (int/year)	Maintain time (h)	Switching operation time (h)
Transformer	[0.025, 0.03]	[9, 12]	1	[9, 10]	–
Breaker	[0.006, 0.0065]	[4, 5]	1	[9, 10]	[1, 2]
Disconnect	[0.0065, 0.0068]	[4, 4.5]	1	[9, 10]	[1, 1.5]
Fuse	[0.022, 0.025]	[3.5, 4]	1	[9, 10]	[0.5, 1]
Feeder	[0.04, 0.045]	[7, 8]	1	[9, 10]	–
"–" means that Switching operation time of element is not under consideration.					

Here it is assumed that the limitation of capacity of load point is 1800 kVA. First find the minimal path is T5→L8→L9→S4→L7→S3→L5→ S2→L3→S1→L1→b1 and the non-minimal-path elements are T1–T4, T6. If feeders F1, F2 operate in closed loop, T7-T13, S6-S11, L10-L26 also belongs to non-minimal-path elements.

Since feeders F1, F2 connect each other to make a looped network and operate in open loop, usually.

In the case that failure happen to S4, the protector will cut part of F1, automatically, which get power by S4, LP5 and LP6 can get power again from F2, as long as feeders F1, F2 operate in closed loop. At the same time, the available capacity of feeder F2 need to be checked. Assumed limit case that all load point operate in maximum capacity requirements, meanwhile. Because L10, L12, L14, L16, L16, L20, L22, L24, L26 connect to load point directly, available capacity must be met with the requirements of Table 2. Then check the main feeders L11, L25, L23, L21, L19, L17, L15, L13. The result shows that only L13 is out of its limitation, practical capacity of which is 16200 kVA is greater than the maximum available capacity, 15300 kVA. To make the system safety, load must be cut properly. With the consideration of losses from line flow, the cutting strategy is that cut load point LP5 by disconnecting S5 and S6. After the consideration of available capacity, the load-point and system indexes can be calculated. Table 4 shows a representative sample of the load-point-reliability indexes. Table 5 shows the system indexes.

Table 4. Interval reliability indices of typical load points.

Load point	Failure rate (occ/year)	Repair time (h)	Outage time (h/year)
LP5 (open loop)	[0.3190, 0.3587]	[3.1498, 0.3227]	[1.0048, 1.1577]
LP9 (open loop)	[0.2260, 0.2551]	[3.5871, 3.5367]	[0.8107, 0.9022]
LP5 (closed loop)	[0.1493, 0.1854]	[2.5285, 2.8387]	[0.8254, 0.8971]
LP9 (closed loop)	[0.1227, 0.1493]	[3.1393, 3.5284]	[0.7533, 0.8254]
LP15	[0.1545, 0.1733]	[4.6751, 4.8317]	[0.7465, 0.8102]
LP27	[0.2725, 0.3069]	[4.0684, 4.1310]	[1.1257, 1.2486]

Table 5. Interval reliability indices of example system.

	[SAIFI] (int./cus.year)	**[SAIDI] (h/cus.tear)**	**[CAIDI] (h/int)**	**[RS-1]**	**[RS-3]**
Open loop	[1.5212, 1.8105]	[6.1865, 6.2354]	[4.0669, 4.3259]	[0.997866, 0.998127]	[0.998924, 0.999033]
Closed loop	[1.4352, 1.5822]	[5.6684, 5.8962]	[3.9496, 4.2371]	[0.998713, 0.998822]	[0.999154, 0.999233]

It can be seen by comparing the results in Table 5 that the more system elements connect in series, the greater the difference between the interval value limitations of system failure rate. However, the outage time of system in closed loop get a reduction from that of system in open loop, because of the existence of transferring supply way.

5. Conclusions

This paper illustrates a practical method for distribution-system reliability evaluation. Available capacity of feeder is defined and the constraint of it is under consideration when evaluating the distribution-system reliability. Faced with the uncertainty of distribution system reliability parameters and load parameters and time-varying characteristic, interval analysis method is introduced and deals with uncertainty very well with minimal-path method. Based on the calculation of the reliability indexes of the load point, the evaluation of distribution-system reliability can be rapid.

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