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Reliability Evaluation Technique for Electrical Distribution Networks Considering Planned Outages

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Abstract – The reliability evaluation of the electrical distribution networks (EDN) requires sufficient consideration of the effects of planned outages. The planned outages of the EDN can be divided, by outage models and their effects on the reliability into two major categories: by equipment and by feeder. After studying the characteristics of different categories of planned outages, this paper expands the classification of load points by outage time from 4 types to 7 types and defines corresponding reliability parameters for the different types. By using the section algorithm, this paper proposes a reliability evaluation technique of EDN considering equipment random failures and two categories of planned outages. The proposed technique has been applied to the RBTS-BUS6 test system and some practical EDNs in China. The study results demonstrate that the proposed technique is of higher practical value and can be used for evaluating the reliability performance of EDN more efficiently considering the planned outages.

Keywords: Electrical distribution network, Planned outages, Reliability evaluation, Section technique

1. Introduction

In order to meet the continuous growth of load demands and increasing requirement for higher reliability level of power supply, many large scale projects of construction and upgrade of electrical distribution networks (EDN) are in progress across all urban areas in China. Although people in many utility companies believe that the planning, construction, and upgrade of EDN must be focused to improve the reliability performance of power systems, people in some areas are not aware of the importance of reliability evaluation and analysis of EDN. Facing the challenges in planning, construction, and upgrade, they can only take stopgap measures without guidance of scientific and rational planning principles. Since the construction and upgrade of metropolitan EDN involve a huge amount of capital investment, decision makers in different levels must pay close attention on the questions: How to combine short-term demands and long-term development and how to utilize the investment funds and natural resources to maximize economical and social benefits.

Performing reliability evaluation and analysis before the construction and upgrade of metropolitan EDN can achieve a rational construction plan and proper upgrade measures. This will be of importance to improve the reliability performance of EDN, guarantee quality of power supply, and enhance economical and social benefits.

Many techniques [1-9] have been developed to evaluate the reliability of EDN. The key process of reliability evaluation for a large-scale and complex EDN is the selection of system states and the failure analysis for the selected system states. There are several methods for system state selection: Monte Carlo [1], Markov [2] and simulation state enumeration, which include failure mode and effect analysis (FMEA) [3, 4], the shortest path [5], Bayesian Network [6], and etc. The network-equivalent [7, 8] and section technique [9] have been proposed to simplify the process of failure analysis. Unfortunately, there are relatively little researches on the reliability evaluation of EDN considering the planed outages. A simultaneous decomposition simulation approach has been proposed [10] to evaluate the reliability of interconnected power systems including planned outages.

In developed countries such as the United States, United Kingdom, and Canada, the majority of outages in EDN are planned outages rather than random failures, because equipment failures rarely occur in these countries. However, the similar situation exists in developing countries such as China, India, and Brazil. The ratio of planned outages over total outages are quite large due to fast growth of load demands, and large scale projects for construction and upgrade of EDN are in progress as economic grows fast in these countries. The impacts of planned outages on the EDN system reliability performance cannot be ignored.

References [11] indicates that the ratio of planned outage time over total outage time in China during 2005-2009 is above 70%, even as large as 79.18% in 2009. Therefore, planned outages must be taken into account in reliability evaluation of EDN.

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This paper has studied the classification of planned outages of EDN and their effects on system reliability, and presented a technique for reliability evaluation of EDN considering planned outages based on the section algorithm. More practical and accurate reliability level can be achieved by using the proposed technique.

2. Classifications of EDN Outages and Analysis of Their Effects on Reliability

2.1 Switching devices and their functions in EDN

The following are the types of switching devices in the EDN classified by their functions:

Circuit Breaker (CB): located at the 10 kV outlet spacing of a substation (e.g. the sending end of the feeders) or sending end of long branches. Usually, a CB is a SF_6 breaker or a vacuum breaker that can cut off short circuit current and is equipped with rely protection devices.

Sectionalizing Switch: usually located at a feeder and used to divide the feeder into sections. It uses a SF_6 breaker or a vacuum breaker that can cut off load current.

Disconnect Switch: usually located at the short branches, and can only separate the outaged equipment and cannot cut off load current.

Tie Switch: located at the connecting part between feeders. Usually open during normal operations. Closing tie switches can transfer load from outaged feeder to other feeders when a feeder is outaged.

Fuse: usually located at the high voltage side of 10 kV transformers or ending side of branches. Fuse will automatically melt when the current through the fuse exceeds the rated value.

2.2 Analysis of random failures of equipment

Equipment failures of EDN are resulted from the following causes: equipment own defect, short circuit by foreign objects, external damage, animal activity, lightning, and other nature disasters.

When a certain piece of equipment suddenly fails, the following switching operations are taken:

1) Automatic Tripping: the first CB in the direction against the current flow through the failed equipment (or the forward direction CB) is automatically tripped.
2) Fault Location: locate the failure using a fault locator or by manual inspection.
3) Fault Isolation and Power Supply Recovery: first open the sectionalizing or disconnect switches to disconnect the failed portion of EDN from the remaining portion, then close the forward direction CB to recover power supply to the portion for which the recovery conditions are met.
4) Fault Isolation and Power Supply Transfer: close the corresponding tie switches to transfer power supply to the portion in which the power transfer conditions are met.
5) Fault Repairing: repair the failed equipment and recover all the switches and breakers to their normal operation state.

2.3 Classification of planned outages and their effects to reliability

Outages of EDN can be grouped into two categories: random failures and planned outages as shown in Fig. 1.

The planned outages of EDN usually results from the following causes: maintenance, upgrade projects, constructions, customer request, inadequate power source, and etc.

Maintenance is to maintain a whole feeder or individual equipment in the EDN. Upgrade means the upgrade of load distribution equipment and utility network equipment. Upgrade projects include installation of new equipment or capacity expansion of existing equipment. Outages are also planned for constructions and renovations of EDN and external grid, and other public utility constructions. Constructions include large-scale ones and small-scale ones. Sometimes, customers may request planned outages for their own reasons. Load shedding is usually caused by inadequate system resources or limited capacity of EDN.

The planned outages can also be grouped into two categories by their characteristics: by equipment and by feeder.

Planned Outages by Equipment: outages of a portion of a feeder, including maintenance of individual equipment, small scale construction, upgrade of customer load equipment, and customer requests.

Planned Outages by Feeder: outages of a whole feeder, such as large scale construction, upgrade of public utility equipment, and maintenance of a whole feeder.

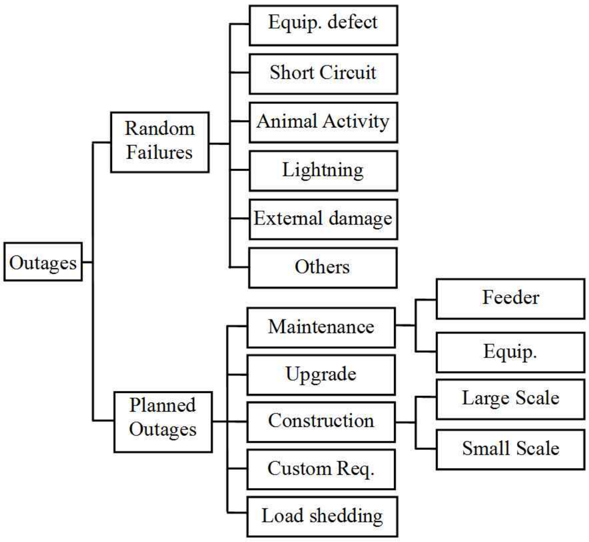

Fig. 1. Classification of equipment outages

Based on the description above, the outages of EDN can be grouped into three categories:

Category I : random failures
Category II : planned outages by equipment
Category III : planned outages by feeder

The following switching operations are taken for planned outages by equipment:

1) Cut off the Power manually: manually open the first CB or sectionalizing switch in the direction against the current flow through the outaged equipment.
2) Outage Isolation and Power Supply Recovery: first open the sectionalizing or disconnect switches to disconnect the outaged portion of EDN from the remaining portion; then close the forward direction CB or sectionalizing switch to recover power supply to the portion for which the recovery conditions are met.
3) Outage Isolation and Power Supply Transfer: close the corresponding tie switches to transfer power supply to the portion in which the power transfer conditions are met.
4) Completion of Planned Outages: recover all the switches and breakers to their normal operation state.

The reliability parameters for planned outages by equipment represent equipment properties, such as outage rate (ooc./yr.km) and average outage time (hr) of planned outages of overhead lines, and outage rate (ooc./yr) and average outage time (hr) of planned outages of switching devices.

The reliability parameters for planned outages by feeder represent feeder properties, such as outage rate (ooc./yr) and average outage time (hr) of planned outages of feeders.

3. Reliability Evaluation Method for EDN Considering Planned Outages

The section technique is used in evaluating the reliability of EDN considering planned outages. The first step is to decompose the system into a few sections of branches (SOB). The equivalent reliability parameters of each SOB and system reliability indices for category I and II outages are calculated. Then the reliability indices considering random failures and all planned outages can be formed by including the effects of category III outages.

3.1 Section technique of EDN and node classification

The section technique is used in this paper to simplify load shedding procedure, reduce analytical simulating times, and enhance efficiency of reliability evaluation of EDN.

Forming a SOB of an EDN starts from the source node.

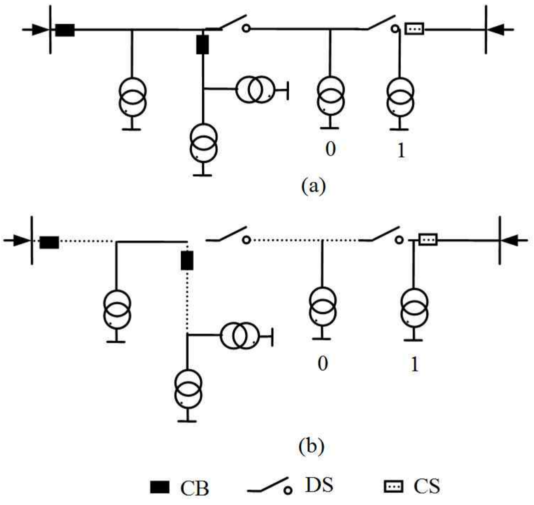

Fig. 2. Forming the section of branches

The depth-first search [12] is used to traverse the EDN. If there is a CB, sectionalizing switch, tie switch, or fuse installed at the terminals of a branch, the branch is deleted from the original EDN. The traversing process splits the original connected EDN into several sections, and each section is a SOB [9].

Figs. 2 (a) and (b) show a simple EDN and its split by deleting the branches in dashed line respectively. It can be seen from Fig. 2 (b) that there are four SOBs in the split EDN. Let $C_{i\text{-}j}$ represent the branch *i-j* (a transmission line or a transformer), and S_k the *k*th SOB. The component sets of the four SOBs are S_1 ($C_{1\text{-}2}$, $C_{2\text{-}3}$, $C_{2\text{-}7}$), S_2 ($C_{3\text{-}6}$, $C_{6\text{-}8}$, $C_{6\text{-}9}$), S_3 ($C_{3\text{-}4}$, $C_{4\text{-}5}$, $C_{4\text{-}10}$), S_4 ($C_{5\text{-}11}$), respectively.

In reference [9] the nodes are classified by outage time into 4 types: (A) Healthy nodes with zero out-of-service duration. (B) Nodes with out-of-service duration equal to the switching / sectionalising time. (C) Nodes with out-of-service duration equal to the switching / sectionalising time plus the reclosure time of a tie switch and (D) Nodes with out-of-service duration equal to the repair time of the failed component. After considering the planned outages, the classification of fault nodes can be expanded from 4 types to 7 types as shown in Table 1.

Since equipment failures are random emergency events that occur suddenly, the outage time of failures is relatively longer (0.5-5 hr). The outage time of planned outages is usually shorter (0.03-2 hr) because the outages are pre-

Table 1. Classification of nodes

Node type	Outage type		Outage time
	Failure	Planned	
a			0
b	√		Fault location + Fault isolation
c	√		Fault location + Fault isolation + Power transfer
d	√		Fault repair
e		√	Isolation
f		√	Isolation + Power transfer
g		√	Planned outage

planned so that feasibility of power transfer must be guaranteed during planned outages, and the time for fault location is not needed.

3.2 Calculation of SOB reliability parameters of category I and II outages

Based on the actual results of equipment outages, whether an equipment outage in a SOB is a random failure or a planned one, its effects to the entire EDN and the switching operations of the system are basically the same. Therefore, the reliability of EDN can be evaluated using SOB as a unit.

Let equivalent outage rate and outage time of random failure in SOB *k* be λ_{ISk} and r_{ISk}, equivalent outage rate and outage time of planned outage λ_{IISk} and r_{IISk}. These parameters can be obtained from the equipment in the SOB *k* using "series" model in [3] as follows.

$$\lambda_{\mathrm{ISk}} = \sum_{i\in \mathrm{S}_{Ck}} \lambda_{\mathrm{I}_i} \tag{1}$$

$$r_{\mathrm{ISk}} = \frac{\sum_{i\in \mathrm{S}_{Ck}} (\lambda_{\mathrm{I}_i} \times r_{\mathrm{I}_i})}{\lambda_{\mathrm{ISk}}} \tag{2}$$

$$\lambda_{\mathrm{IISk}} = \sum_{i\in \mathrm{S}_{Ck}} \lambda_{\mathrm{II}_i} \tag{3}$$

$$r_{\mathrm{IISk}} = \frac{\sum_{i\in \mathrm{S}_{Ck}} (\lambda_{\mathrm{II}_i} \times r_{\mathrm{II}_i})}{\lambda_{\mathrm{IISk}}} \tag{4}$$

where S_{Ck} is the component set contained in SOB *k*. λ_{I_i}, r_{I_i}, λ_{II_i}, and r_{II_i} are failure rate and repair time of random failure, outage rate and repair time of planned outage by equipment, respectively.

The SOB equivalent outage rate λ_{ESk} and outage time r_{ESk} considering category I and II outages can be obtained from (1)-(4) above:

$$\lambda_{\mathrm{ESk}} = \lambda_{\mathrm{ISk}} + \lambda_{\mathrm{IISk}} \tag{5}$$

$$r_{\mathrm{ESk}} = \frac{\lambda_{\mathrm{ISk}} \times r_{\mathrm{ISk}} + \lambda_{\mathrm{IISk}} \times r_{\mathrm{IISk}}}{\lambda_{\mathrm{ESk}}} \tag{6}$$

3.3 SOB load shedding strategies

It is often necessary to transfer power between feeders when outages occur in EDN. In many cases a load shedding is required when de-rate of feeder capacity and / or node voltage violation result from the power transfer. Since load shedding area is bounded by switching devices, the smallest unit of load shedding is a SOB.

Since most switching operations in EDN are not automated and manual operations on site are inevitable, the load shedding requires as less switching operations as possible. The following steps are taken for load shedding:

Step 1: Select the end node of the feeder with the longest logical electrical length from the 10 kV busbar using the shortest path technique.

Step 2: Search for the main feeder lines, which are traversed from the source to the end node based on the normal load flow direction. Other feeders are the lateral feeder lines.

Step 3: Each SOB extracts power from only one main feeder line, which can be determined by the normal load flow direction. Once a main feeder line is outaged, the load in all the SOBs that extract power from the main feeder line would be shed. The load shedding process is performed by omitting the main feeder line from the end node to the source. The load shedding process is not stopped until the feeder satisfied the restricting conditions.

Based on the description above, the reliability of EDN considering category I and II outages, or outages by random failure and planned outages by equipment, can be evaluated using the section technique. Therefore, the reliability indices of each load point, such as outage rate, outage time, availability, and energy not supplied (ENS), can be calculated.

3.4 Calculation of reliability of EDN under category I, II, and III outages

Let the outage rate, outage time, and ENS of load point *i* accounting for category I, II and III outages be λ_{I_i}, r_{I_i}, ENS_{I_i}, λ_{II_i}, r_{II_i}, ENS_{II_i}, λ_{III_i}, r_{III_i}, and ENS_{III_i} respectively.

Because the effects of planned outages by feeder on the reliability of each load point of the feeder are the same, the reliability indices of load point *i* considering category I, II and III outages are:

$$\lambda_{\mathrm{LP}_i} = \lambda_{\mathrm{I}_i} + \lambda_{\mathrm{II}_i} + \lambda_{\mathrm{III}_i} \tag{7}$$

$$r_{\mathrm{LP}_i} = \frac{\lambda_{\mathrm{I}_i} \times r_{\mathrm{I}_i} + \lambda_{\mathrm{II}_i} \times r_{\mathrm{II}_i} + \lambda_{\mathrm{III}_i} \times r_{\mathrm{III}_i}}{\lambda_{\mathrm{LP}_i}} \tag{8}$$

$$ENS_{\mathrm{LP}_i} = ENS_{\mathrm{I}_i} + ENS_{\mathrm{II}_i} + ENS_{\mathrm{III}_i} \tag{9}$$

Where λ_{LP_i}, r_{LP_i}, and ENS_{LP_i} are outage rate, outage time, and *ENS* of load point *i* considering category I, II, and III outages, respectively. L_i is the load power at load point *i*.

Based on formula in reference [3], various reliability indices of feeder and system, including system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), expected energy not supplied (EENS), customer average interruption duration index (CAIDI), and average service availability index (ASAI), can be calculated using reliability indices of all load points.

3.5 Reliability evaluation algorithm considering planned outages

The following steps are performed to evaluate the reliability of EDN considering planned outages:

Step 1: Read the primary data, and compute the steady state load flow of EDN;
Step 2: Form SOBs using the method described in section III.A and calculate equivalent reliability parameters for each SOB;
Step 3: Enumerate SOBs and evaluate the EDN reliability considering category I and II outages. For each SOB, do Steps 3.1-3.5;
  Step 3.1: If the SOB is in outage state by failure, determine outage type for each fault node;
  Step 3.2: If the SOB is in planned outage state, determine outage type for each outage node;
  Step 3.3: Compute the load flows for failure state and planned outage state, respectively. Check for violation on node voltage and branch flow limit. If any violation is detected, process load shedding based on the method described in section III.C;
  Step 3.4: Calculate reliability indices of load points;
  Step 3.5: If enumeration finished then continue. Other-wise, for next SOB go Step 3.1;
Step 4: Evaluate the effects of planned outages by feeder to reliability indices of each feeder;
Step 5: Update reliability indices of load points using formula (7)-(9);
Step 6: Obtain system reliability indices and output results.

4. Case Studies

The proposed algorithm was coded in VC++. The test system is designed as RBTS-BUS6 developed at the University of Saskatchewan [13-15] and a large number of practical EDN have been studied.

The RBTS-BUS6 is a typical complex rural/urban configuration with sub-feeders that has 4 feeders, 40 load points, 122 nodes, and 2938 customers. The average load of this EDN is 10.72 MW. The electrical data, reliability parameters and the network structure are given in [13-15]. The following cases are studied:

Case A: Consider category I outage only;
Case B: Consider category II outage only and the outage rate equals the failure rate for category I outage;
Case C: Consider category I and II outages and the outage rate of category II equals the failure rate of category I;
Case D: Consider outages of category I, II, and III. The outage rate of category II equals the failure rate of category I. The outage rate for category III outages is 0.15 (occ./yr) and average outage time is 6 (hr);
Case E: Consider outages of category I, II, and III. The outage rate of category II is 3 times of the failure rate of category I. The outage rate for category III outages is 0.15 (occ./yr) and average outage time is 6 (hr).

With respect to five cases (A, B, C, D and E) of RBTS-BUS6 test system, the reliability parameters of Category I outage cite from reference [13-15]. Reliability parameters of Category II outage are for intensifying comparison among cases. Based on Category I outage, Category II outage and Category III outage statistical data of EDN in China from 2007 to 2012, Category II outage rate is 3 times higher than that of Category I in Case E, thus making it closer to engineering practice. Reliability parameters of Category III outage are evaluated according to the average statistical value of Category III outage rate and outage time in China from 2007 to 2012.

For all the cases above, the equipment planned outage time equals the fault repair time, both are 6 hr, fault location time is 0.5 hr, fault isolation time is 0.5 hr, power transfer time is 0.5 hr, and switching operation time for planned outages is 0.1hr.

Table 2 below lists the reliability indices of RBTS-BUS6 system using the method in section III.E.

Comparison of the results of cases A and B in Table 2 shows that equipment failures have larger effects on planned outages for the same equipment failure rate, planned outage rate, and outage time. The reasons are: 1) Equipment failures will automatically trip the forward CBs and involve a larger extension of outages while planned outages can cut off the load current by opening the forward sectionalizing switches. 2) Since additional fault location time is necessary, equipment failures require longer switching operation time than that of planned outages.

Table 2. Reliability indices of RBTS-BUS6 system

Case	SAIFI (occ/cust.yr)	SAIDI (hr/cust.yr)	CAIDI (hr/cust.occ)	ASAI (%)	EENS (MWh/yr)
A	1.0067	6.675	6.630	99.9238	72.67
B	0.7546	6.422	8.511	99.9267	70.28
C	1.7613	13.097	7.436	99.8505	142.95
D	1.9113	13.997	7.323	99.8402	152.60
E	3.5104	26.842	7.646	99.6936	293.16

Table 3. Basic data for the EDN of the three districts in Guangdong

EDN	Number of feeders/ substations	Load (MW)	Number of switches	Number of tie switches	Length of all lines (km)
DS1	250/11	626.92	1577	70	1233.78
DS2	200/8	530.35	754	45	900.40
DS3	59/2	162.55	312	14	368.97

Table 4. Reliability indices for the distribution systems of the three districts

System	Planned outages	SAIFI (occ/cust.yr)	SAIDI (hr/cust.yr)	CAIDI (hr/cust.occ)	ASAI (%)	EENS (MWh/yr)
DS1	N	0.6711	2.920	4.351	99.9667	1483.63
	Y	1.5379	6.817	4.433	99.9222	3498.19
DS2	N	0.8142	2.639	3.241	99.9699	1162.30
	Y	2.4695	7.959	3.223	99.9091	3759.59
DS3	N	0.8443	3.583	4.243	99.9591	344.99
	Y	2.3117	10.436	4.514	99.8809	1296.27

The reliability indices for Case C can be obtained from superposition of results of Cases A and B. The reliability indices of Case D can be obtained by including the effects of planned outages by feeder into Case C. Table 2 also shows that SAIFI and SAIDI of Case D are increased by 8.5% and 6.9%, respectively, comparing with Case C.

Case E represents the conditions in China closely. By including the effects of planned outages, SAIFI and SAIDI of Case E increases by 248% and 302%, respectively comparing with Case A.

The technique presented in this paper is also applied to reliability evaluation of EDN of three load districts in Guangdong province, China. Table 3 shows the basic data and Table 4 shows the results of reliability evaluation for these three load districts (DS_1, DS_2, and DS_3).

Table 4 shows that for the three load districts, the ratios of SAIDI by planned outages over the average total yearly SAIDI are 57.2%, 66.8%, and 65.7%, respectively. The calculation results above, which basically consistent with the statistical results for these three load districts, demonstrate the effectiveness of the proposed algorithm. Since planned outages play an important role, the reliability evaluation of EDN must take the effects of planned outages into account.

5. Conclusions

Based on their engineering characteristics and different effects on reliability, the planned outages are classified into two categories: outages by equipment and outages by feeder. The corresponding reliability parameters for these two categories are also defined in this paper.

After considering the planned outages and using the section technique in reliability evaluation of EDN, the classification of fault nodes by outage time can be expanded from 4 types to 7 types. A reliability evaluation technique for EDN considering planned outages has been proposed.

This technique evaluates the effects of equipment failures and two categories of planned outages on reliability of EDN respectively, and the total indices can be obtained by accumulation.

The proposed technique has been applied to the RBTS-BUS6 test system and EDN of three load districts in Guangdong province. The case study results indicate:

1) The reliability evaluation of EDN must take planned outages into account because planned outages have significant effects on system reliability.
2) Classifying the planned outages into two categories will make the reliability evaluation of EDN more efficient and practical.

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