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Reliability Evaluation of Electrical Distribution Network Containing Distributed Generation Using Directed-Relation-Graph

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Abstract – This paper presents an analytical technique for reliability evaluation of electrical distribution network (EDN) containing distributed generation (DG). Based on hierarchical levels of circuit breaker controlling zones and feeder sections, a directed-relation-graph (DRG) for an END is formed to describe the hierarchical structure of the EDN. The reliability indices of EDN and load points can be evaluated directly using the formed DRG, and the reliability evaluation of an EDN containing DGs can also be done without re-forming the DRG. The proposed technique incorporates multi-state models of photovoltaic and diesel generations, as well as weather factors. The IEEE-RBTS Bus 6 EDN is used to validate the proposed technique; and a practical campus EDN containing DG was also analyzed using the proposed technique.

Keywords: Reliability evaluation, Electrical distribution network, Distributed generation, Directed-relation-graph

1. Introduction

In recent years, renewable energy sources have been integrated into electrical distribution network (EDN) in order to reduce the emission of environmentally harmful substances from use of conventional energy sources [1, 2]. The integration of renewable energy sources changes the operational modes of conventional EDN [3, 4]. Therefore, it is necessary to evaluate and analyze the impact of distributed generation (DG) to the reliability of EDN.

Considerable works have been done in developing reliability evaluation of EDN containing DG. Failure mode and effect analysis (FMEA) [5, 6] is a traditional and extensively-used technique for reliability evaluation of EDN. However, it is difficult to use FMEA to evaluate a complex EDN directly due to the difficulty in forming FMEA table. A network equivalent technique [7] for complex EDN reliability evaluation is proposed to simplify the evaluation process. However, when a complex EDN with many sub-feeders is considered, it is difficult to obtain an equivalent network for a complex EDN [8]. The shortest path algorithm for reliability evaluation of complex EDN is proposed in [9]. Simulation and analytical techniques [10] are used in the reliability evaluation of EDN containing DG with grid connected mode and islanding mode. An analytical method for reliability evaluation of EDN containing DG is proposed [11] for the standby mode of DG operations. A probabilistic technique [1] has been used to evaluate the reliability of EDN containing wind-based DG with the islanding operation mode. Weather factors [12, 13] are incorporated into component failures for EDN reliability evaluation, and the results show that bad weather condition has a significant effect on EDN reliability performance.

Based on the reliability evaluation techniques described above, this paper presents an analytical technique that can calculate reliability indices of an EDN containing DGs only by a directed-relation-graph. In this paper, controlling zone (CZ) of feeder circuit breaker (CB) and feeder section of each CZ are classified into different hierarchical levels. A DRG is formed to describe an EDN on the basis of the hierarchical levels. According to the proposed technique, the reliability indices of the EDN with DGs can be obtained by only modifying the average failure rates and average annual outage times of the load points that are connected to the DG. In other words, it does not need to re-form the DRG. The IEEE-RBTS Bus 6 system and a practical campus EDN with DG are used to validate the proposed technique.

2. Multi-state Models of DG and Weather Factors

Photovoltaic (PV) array and diesel generator are the most popular DGs that are connected to an EDN. Therefore, in order to accurately analyze the reliability of the EDN, it is necessary to properly model them, and consider the weather factors as well.

2.1 Historical output power series of PV station

Fig. 1 illustrates an hourly output power series of a

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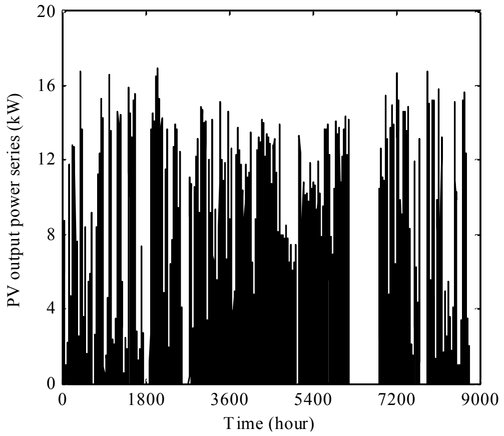


Fig. 1. PV power output series for one year

campus PV station for one year. It can be seen that PV often operates in de-rated states due to insufficient solar radiation. In order to accurately evaluate the reliability of power system with PV station, the historical observed output power data for a few years are incorporated into the reliability model in this paper.

2.2 Two-state diesel generator model

When a customer outage occurs, automatic transfer switch should be activated for start up of a diesel generator to supply the lost power to the customer. However, once power from grid is restored, automatic transfer switch should transfer the outage customer back to power grid.

Fig. 2 shows a two-state Markov model of a diesel generator. λ_d and μ_d are the failure rate and repair rate of a diesel generator, respectively. p_{Ud} and p_{Dd} are the probabilities of the diesel generator in up and down states, respectively.

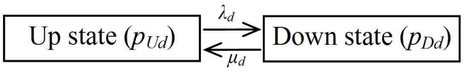


Fig. 2. Two-state Markov model of diesel generator

2.3 Two-state weather model

Fig. 3 shows a two-state weather model. The transition rates (λ_{na} and λ_{an}) between normal and adverse weather conditions are calculated in (1) and (2).

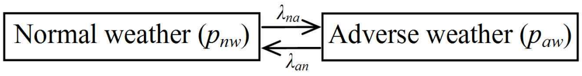


Fig. 3. Two-state Markov model of weather conditions

$$\lambda_{na} = 1 / t_{nw} \tag{1}$$

$$\lambda_{an} = 1 / t_{aw} \tag{2}$$

where t_{nw} and t_{aw} are the average duration of normal and adverse weather conditions.

The failure rate of component (λ_{cw}) considering weather conditions is calculated by:

$$\lambda_{cw} = p_{nw}\lambda_N + p_{aw}\lambda_F \tag{3}$$

where p_{nw} and p_{aw} are the probabilities of normal and adverse weather conditions, and λ_N and λ_F are failure rates of component under normal and adverse weather conditions.

3. Formation of DRG of EDN

A simple EDN shown in Fig. 4 is used to illustrate the proposed technique for reliability analysis of EDN.

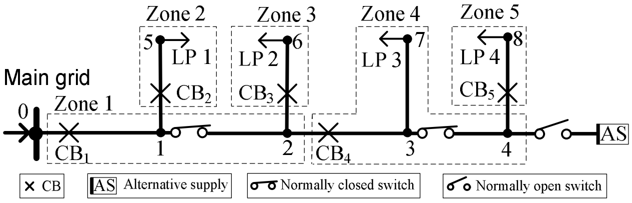


Fig. 4. A simple EDN

In order to improve the efficiency of reliability evaluation process, the equivalent of a complex feeder section is introduced. As a diesel generator can be used as an alternative supply (AS), the effect of AS on reliability is also analyzed. Then a directed-relation-graph (DRG) can be formed.

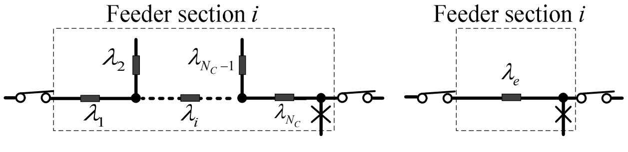
3.1 Feeder section equivalent

Fig. 5 shows the equivalent process of a feeder section. If a feeder section contains several components, the equivalent failure rate (λ_e) and equivalent repair time (γ_e) of the section can be calculated by the basic formulae of the series elements:

$$\lambda_e = \sum_{i=1}^{N_C} \lambda_i \tag{4}$$

$$\gamma_e = \frac{\sum_{i=1}^{N_C} \lambda_i \gamma_i}{\lambda_e} \tag{5}$$

where N_C is the number of components in the feeder



(a) Original section (b) Equivalent section

Fig. 5. Feeder section containing several components

section; λ_i and γ_i are the failure rate and repair time of component *i* in the feeder section.

3.2 Effects analysis of AS

Fig. 6 shows two interconnected CZs of an EDN. The node *n* is a junction node of UCZ and DCZ.

Assume that there is no alternative supply in an EDN. If the failure of a component occurs in the *i*th section or upstream hierarchical level sections of the *i*th section in UCZ, the outage times of components in DCZ equals the repair time of the failed component. However, if the failure of a component occurs in downstream hierarchical level sections of the *i*th section, the outage times of components in DCZ equals the disconnecting time.

Assume that there is an AS connected to the end of the EDN. If the failure of a component occurs in the *i*th section in UCZ, the outage times of components in DCZ equals the repair time of the failed component. However, if the failure of a component occurs in downstream hierarchical level sections of the *i*th section, the outage times of components in DCZ equals the disconnecting time. If the failure of a component occurs in upstream hierarchical level sections, the outage times of components in DCZ equals the sum of the disconnecting time and the switching time.

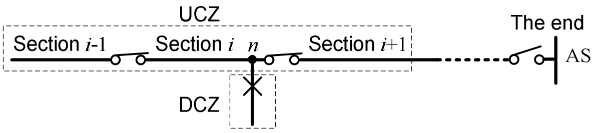


Fig. 6. Two interconnected CZs

3.3 Formation of DRG containing controlling zone levels

Based on the power flow direction, the components located upstream of component *i* are defined as upstream components. Similarly, downstream components can also be defined.

Obviously, when a failure occurs at downstream components of a CB, it does not affect the operational state of upstream components of the CB. However, if a failure occurs at upstream components of a CB, all downstream components of the CB will stop working. Based on the failure effect relation between components in an EDN, CBs and their CZs are classified into various hierarchical levels in the following steps:

Step 1) A CB directly connected to the main grid is designated as the first hierarchical level CB, e.g., CB_1 shown in Fig. 4.

Step 2) Search components from CB_1 following the EDN power flow direction in normal state using the depth-first-search (DFS) [14]. The spreading process is similar to the process of the water wave when a stone is cast into a pool. If a CB at a feeder or at a terminal of the feeder is searched, the search process for this direction is stopped. Then continue to search components at other direction, until all search processes are stopped. The traversed components form a CZ, e.g., Zone 1 shown in Fig. 4. This CZ is designated as the first hierarchical level CZ.

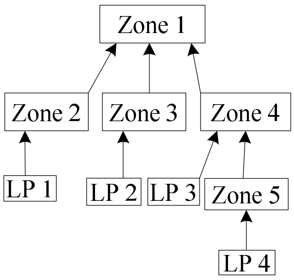


Fig. 7. DRG with CZ levels

Step 3) Search other CBs connected directly to Zone 1. The searched CBs are designated as the second hierarchical level CBs, e.g., CB_2, CB_3, and CB_4 shown in Fig. 4. Then, search each CZ of the second hierarchical level CBs using the DFS, and designated the CZs as the second hierarchical level CZs, e.g., Zone 2, Zone 3, and Zone 4 shown in Fig. 4.

Step 4) Similarly, continue to search other CBs and their CZs using the steps above until all the CBs are traversed and all CZs are formed.

Step 5) Form an DRG consisting of upstream CZ (UCZ) and downstream CZ (DCZ), e.g., DRG shown in Fig. 7.

Fig. 7 shows that Zone 1 is an UCZ of Zone 2, Zone 3, Zone 4, and Zone 5, whereas Zone 5 is a DCZ of Zone 4 and Zone 1, and Zone 2, Zone 3 and Zone 4 are the DCZs of Zone 1.

A failure of any component in UCZ should lead to a outage of all components in DCZ, whereas failures of components in DCZ do not affect the operational state of any component in UCZ.

3.4 Formation of DRG containing controlling zone and feeder section levels

When a component failure occurs in a CZ containing disconnect switches, the failed component can be isolated by disconnect switches. Then the section between the power supply and the disconnect switches can be restored. Therefore, component outage times in different sections are different. Feeder in each CZ is classified into different sections based on the locations of disconnect switches. The feeder section forming algorithm is described as follows:

Step 1) Assume that all feeders in each CZ are in the first hierarchical level section.

Step 2) Search disconnect switches following the EDN normal power flow direction in a CZ. If the *i*th disconnect switch is traversed, all downstream feeder of the *i*th disconnect switches in the CZ are modified as the (*i*+1)th

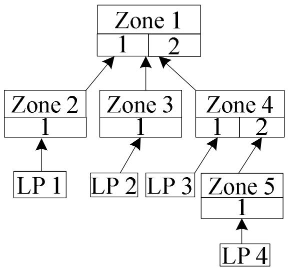


Fig. 8. DRG with CZ and feeder section levels

hierarchical level section.

Step 3) Search other disconnect switches based on Step 2) until all disconnect switches are traversed in the CZ.

Step 4) Search in the next CZ until all the CZs are traversed. Record hierarchical levels of sections which are located at the junction node of two mutually connected CZs.

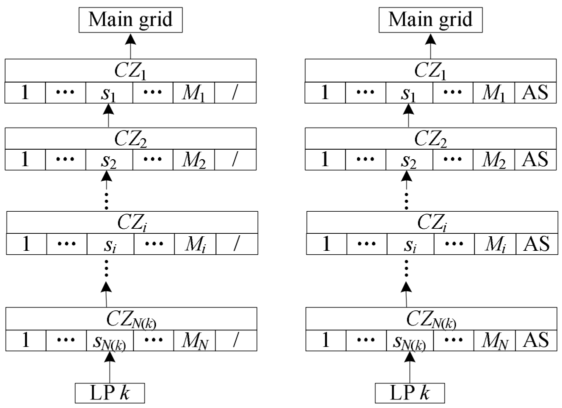
Based on the algorithm described above, the feeder in Zone 1 in Fig. 4 is classified into 2 sections, and the first hierarchical level section has components branch 0-1, and the second hierarchical level section is branch 1-2. Zone 2, Zone 3 and Zone 5 have only one section, and Zone 4 has two sections.

Based on the analysis above, a DRG of an EDN can be formed. Fig. 8 shows the DRG of the simple EDN shown in Fig. 4.

4. Reliability Indices of Load Points and System

4.1 Indices of load points with or without AS

Reliability indices of load points and system can be evaluated based on the formed DRG. Fig. 9 shows a part of DRG and illustrates the calculation of reliability indices of load points. M_i is the number of sections in the ith CZ (CZ_i), $N(k)$ is the number of UCZ of load point k, and s_i is the junction node between the ith CZ and the (i+1)th CZ.



(a) DRG without AS (b) DRG with AS

Fig. 9. DRG of load point k with or without AS

Reliability indices of load point k with AS can be calculated using (6) and (7); otherwise, without AS using (6) and (8).

$$\lambda(k)=\sum_{i=1}^{N(k)}\sum_{j=1}^{M_i}\lambda_{ij}+\lambda_{mg} \tag{6}$$

$$\begin{aligned}U(k)=&\sum_{i=1}^{N(k)}\sum_{j=1}^{j=s_{i-1}}\lambda_{ij}(t_{ds}+t_{sw})+\sum_{i=1,j=s_i}^{N(k)}\lambda_{ij}\gamma_{ij}\\&+\sum_{i=1}^{N(k)}\sum_{j=s_{i+1}}^{M_i}\lambda_{ij}t_{ds}+\lambda_{mg}\gamma_{mg}\end{aligned} \tag{7}$$

$$U(k)=\sum_{i=1}^{N(k)}\sum_{j=1}^{s_i}\lambda_{ij}\gamma_{ij}+\sum_{i=1}^{N(k)}\sum_{j=s_{i+1}}^{M_i}\lambda_{ij}t_{ds}+\lambda_{mg}\gamma_{mg} \tag{8}$$

where $\lambda(k)$ and $U(k)$ are the average failure rate and average annual outage time of load point k, respectively; λ_{ij} and γ_{ij} are the failure rate and the outage time of the jth section in the ith CZ, respectively; t_{ds} and t_{sw} are the disconnecting time and the switching time; λ_{mg} and γ_{mg} are the failure rate and the outage time of main grid.

4.2 Indices of load points connected to PV

In (6)-(8), $\lambda(k)$ and $U(k)$ are the indices of load point k without a DG connected. Let P_{ak} denotes the average load (in kW) at load point k. When a PV is connected to load point k, historical PV output power series can be used to calculate the average failure rate $\lambda'(k)$ and average annual outage time $U'(k)$ of load point k with the integration of PV.

The integration of PV has a contribution on reducing the average failure rate and average annual outage time of load point k. The degree of contribution depends on the lost load. Therefore, when an hourly PV output power series for a few years is considered, $\lambda'(k)$ and $U'(k)$ at load point k can be modified as follows:

$$\lambda'(k)=\frac{1}{N_{pv}}\sum_{j=1}^{N_{pv}}\frac{\max\{P_{ak}-P_j,0\}}{P_{ak}}\lambda(k) \tag{9}$$

$$U'(k)=\frac{1}{N_{pv}}\sum_{j=1}^{N_{pv}}\frac{\max\{P_{ak}-P_j,0\}}{P_{ak}}U(k) \tag{10}$$

where P_j (j=1, 2, …, N_{pv}) is output power of PV for the jth hour; N_{pv} is the total number of hours.

4.3 Indices of load points with diesel generator connected

A diesel generator as an alternative supply is connected to important customers by automatic transfer switch devices. Because diesel generators may be started only after the occurrence of EDN failures, thus the integration of diesel generator does not reduce the outage frequency. However, the integration of diesel generator can reduce the outage time. Therefore, for a two-state model of diesel generator, the average failure rate $\lambda''(k)$ and average annual outage time $U''(k)$ at load point k with the integration of diesel generator can be calculated by:

$$\lambda''(k) = \lambda(k) \tag{11}$$

$$U''(k) = p_{Ud}\lambda(k)t_{di} + p_{Dd}U(k) \tag{12}$$

where t_{di} is the duration of diesel from starting to stable operation.

By replacing $\lambda(k)$ and $U(k)$ in (11) and (12) with $\lambda'(k)$ and $U'(k)$, the average failure rate and average annual outage time with the integration of PV and diesel generator can be obtained.

4.4 System reliability indices

System reliability indices, such as System Average Interruption Frequency index (SAIFI, fr/syst.cust), System Average Interruption Duration index (SAIDI, hr/syst.cust), Customer Average interruption Duration index (CAIDI, hr/cust), Average Service Availability Index (ASAI), and Average Energy Not Supplied (AENS, kWh/yr), can be calculated by:

$$SAIFI = \frac{\sum_{k\in R}\lambda(k)C_k}{\sum_{k\in R}C_k} \tag{13}$$

$$SAIDI = \frac{\sum_{k\in R}U(k)C_k}{\sum_{k\in R}C_k} \tag{14}$$

$$ASAI = \frac{\sum_{k\in R}8760C_k - \sum_{i\in R}U(k)C_k}{\sum_{k\in R}8760C_k} \tag{15}$$

$$CAIDI = \frac{\sum_{k\in R}U(k)C_k}{\sum_{k\in R}\lambda(k)C_k} \tag{16}$$

$$AENS = \frac{\sum_{k\in R}P_{ak}U(k)}{\sum_{k\in R}C_k} \tag{17}$$

where C_k is the number of customers at load point k; R represents the set of load points in the system.

In (13)-(17), $\lambda(k)$ and $U(k)$ can be replaced by $\lambda'(k)$ and $U'(k)$ or $\lambda''(k)$ and $U''(k)$ to calculate the system indices when PV or diesel generator are connected to load point k.

Changing rate of $ASAI$ index before and after integration of DG is defined in (18).

$$CR_{ASAI} = \frac{ASAI_{DG} - ASAI_0}{ASAI_0} \tag{18}$$

where $ASAI_0$ and $ASAI_{DG}$ are $ASAI$ before and after integration of DG.

Fig. 10 shows the flow chart of the proposed technique for evaluating the reliability of an EDN.

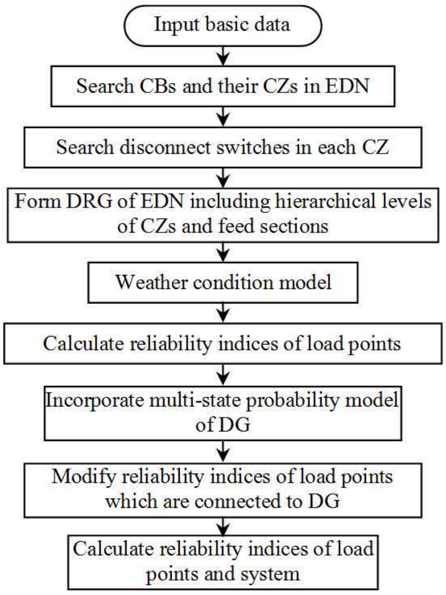


Fig. 10. Flow chart for evaluating the reliability of an EDN

5. Case Studies

The IEEE-RBTS Bus 6 system and a practical campus EDN with DG are studied to validate the proposed technique for reliability evaluation of EDN.

5.1 RBTS Bus 6 system

The configuration, electrical and reliability data of the IEEE-RBTS Bus 6 system can be found in [15, 16]. Tables 1 and 2 list reliability indices at some load points and the system evaluated by the proposed technique. The data in the tables show that the reliability evaluation results are valid.

Table 1. Load point reliability indices of the RBTS Bus 6

Load point	Proposed technique		In [15]	
	λ(f/yr)	U(hr/yr)	λ(f/yr)	U(hr/yr)
LP1	0.33025	3.666	0.3303	3.67
LP4	0.33025	3.666	0.3303	3.67
LP8	0.3725	3.761	0.3725	3.76
LP12	0.3595	3.696	0.3595	3.7
LP16	0.2405	1.008	0.2405	1.01
LP18	1.6725	8.402	1.673	8.402
LP23	1.7115	8.597	1.712	8.597
LP26	1.7115	11.483	1.712	11.483
LP32	2.589	12.984	2.589	12.984
LP37	2.560	15.724	2.56	15.724
LP40	2.511	15.480	2.511	15.48

Table 2. System reliability indices of the RBTS Bus 6

Method	*SAFI*	*SAIDI*	*CAIDI*	*ASAI*(%)
Proposed technique	1.00665	6.66878	6.62473	99.9239
In [15]	1.0067	6.6688	6.6247	99.9239

5.2 Campus EDN with DG

Fig. 11 shows the configuration of a practical campus EDN. The EDN load consists of six teaching buildings (B1, B2, B3, B5, B6, B7), three dormitory buildings (D1, D2, D3), a gym building (GM), and a fitness centre building (FC). A PV array with 20 kW rated capacity was installed on the roof of B7, and 9 diesel generators as AS were installed in all buildings except the gym and fitness centre. Only when the main grid fails, the diesel generator is started, and the diesel only supplies power to important customer power equipments, such as elevators, pumps, or air-conditioners.

Table 3 lists the basic data of the campus EDN. Effect of the main grid is considered in the reliability evaluation of the campus EDN. Weather conditions are considered only in the main grid because overhead lines are in the main grid only and cables in campus EDN only.

The average load of each load point is obtained from the energy management system of the campus EDN. Based on the statistical data, the average duration of normal weather and adverse weather are 720 hours and 4 hours, respectively. The switching time of disconnect switches is 1 hour. The disconnecting time of a diesel generator from start-up to stable operation is 0.5 minute to 1 minute.

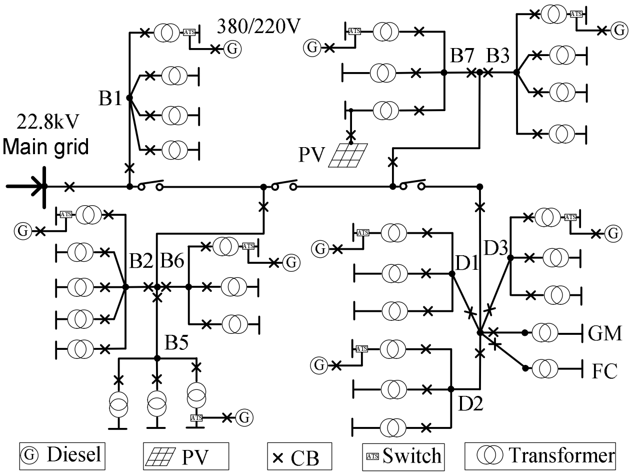


Fig. 11. A practical campus EDN with PV and diesel

Table 3. Basic data of campus EDN

Components		Failure rate(f/yr)	Repair time(hr)
Cable (per km)		0.035	10
Transformer		0.015	48
Main grid	Normal weather	1	6
	Adverse weather	4	6

5.2.1 Reliability of campus EDN without DG

Table 4 lists the system reliability indices of buildings and campus load points. The *ASAI* index in Table 4 shows that B1 has a highest reliability performance, and reliability performances of the three dormitories, gym and fitness centre are the lowest. This is because B1 is located at the beginning of the campus EDN, whereas D1, D2, D3, GM, and FC are located at the end of the campus EDN. Since B5 is with the largest average load among all load points, the value of *AENS* is, therefore, the biggest.

Table 4. System reliability indices of buildings and campus

System	*SAFI*	*SAIDI*	*ASAI* (%)	*AENS*
B1	1.0765	7.4127	99.9154	498.4270
B2	1.0782	7.4774	99.9146	537.5650
B3	1.0775	7.5019	99.9144	394.2440
B5	1.0775	7.4704	99.9147	1042.1000
B6	1.0782	7.4774	99.9146	495.0040
B7	1.0775	7.5019	99.9144	848.6900
D1	1.0800	7.6839	99.9123	659.6120
D2	1.0800	7.6839	99.9123	318.9080
D3	1.0800	7.6839	99.9123	612.3560
GM	1.0800	7.6839	99.9123	218.7610
FC	1.0800	7.6839	99.9123	670.8050
Campus	1.0784	7.5430	99.9139	578.123

5.2.2 Reliability of campus EDN with PV

Since PV only supplies energy to the load of B7, the system reliability indices of buildings except for B7 do not change when PV is incorporated into system. Therefore, Table 5 only lists the system reliability indices of campus and B7. The reliability indices of other buildings are the same as that in Table 4.

It can be seen from Tables 4 and 5 that reliability levels of B7 and campus have a slight improvement with the integration of PV.

Table 5. System reliability indices of campus and B7

System	*SAFI*	*SAIDI*	*ASAI* (%)	*AENS*	CR_{ASAI} (%)
B7	1.06800	7.4355	99.9151	843.927	0.0007
Campus	1.07753	7.5369	99.9140	577.690	0.0001

5.2.3 Reliability of campus EDN with PV and diesel

Assume that the forced outage rate of the diesel generator is 0.02. Table 6 lists the system reliability indices of buildings and campus with the integration of PV and diesel generators.

Table 6 demonstrates that the integration of PV and diesel generators improves the system reliability of campus EDN. However, diesel generator as alternative supply does not reduce the system outage frequency, but reduce the system average annual outage time. The buildings located at the end of system have the largest improvement from a reliability point of view.

Table 6. Reliability indices of buildings with PV and diesel

System	*SAFI*	*SAIDI*	*ASAI* (%)	*AENS*	CR_{ASAI} (%)
B1	1.07648	5.60104	99.9361	453.607	0.0207
B2	1.07823	6.01542	99.9313	432.011	0.0167
B3	1.07753	5.66842	99.9353	386.396	0.0209
B5	1.07753	5.03605	99.9425	496.948	0.0278
B6	1.07823	5.04077	99.9425	235.016	0.0279
B7	1.06800	4.99091	99.9430	499.209	0.0286
D1	1.07998	5.17982	99.9409	304.183	0.0286
D2	1.07998	5.17982	99.9409	242.658	0.0286
D3	1.07998	5.17982	99.9409	476.159	0.0286
GM	1.07998	7.68390	99.9123	218.761	0
FC	1.07998	7.68390	99.9123	670.805	0
Campus	1.07753	5.52559	99.9369	399.156	0.0230

6. Conclusions

This paper presents an analytical technique for reliability evaluation of electrical distribution network (EDN). According to the failure effect relation between circuit breaker controlling zones, the protection zones are classified into different hierarchical levels. Similarly, feeder sections are also classified into different hierarchical levels according to the number and location of disconnect switches. Then a directed relation-graph (DRG) of EDN can be formed based on the classified hierarchical levels, which can be used to directly evaluate the reliability of load points and the system.

Multi-state models of distributed generation (DG), weather factors, and the forced outage rate of DG are incorporated into the proposed technique, which makes the reliability evaluating results of EDN closer to the actual reliability performance. The integration of DG does not need to reconfigure the formed DRG of EDN. Therefore, this technique increases the efficiency of reliability evaluation. Case studies of the IEEE-RBTS Bus 6 system is used to validate the proposed technique. A practical campus EDN containing DG is also analyzed using the proposed technique.

The proposed technique for evaluating the reliability of EDN is not only applied to the integration of PV and diesel generators, but also to other renewable energy sources.

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