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Investigating Impacts of Sustainable Repair Time and Circuit Breaker Model on Meshed Distribution Networks Reliability Assessment

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ABSTRACT

Generally, the failure rate and the repair time of system components are constant parameters in reliability assessment of electric distribution systems. A failure of component is resulted from failing in the operation or overloading. In addition, there exist cases where, the repair times of components are small and tolerable from customer point of view. Thus, tolerable repair times may be overlooked in the reliability evaluation of distribution systems. Therefore, by omitting the tolerable failures, reliability indices that are more reasonable, will be gained. In this paper, impacts of omitting customer tolerable repair time on electric distribution system reliability are studied. A simple model of circuit breaker, which differs from other components, is included. Monte Carlo simulation method is used for calculating reliability indices. A meshed distribution system is selected as a test system and simulations are performed and analyzed. Simulation results show that unavailability of load points are decreased resulting from omitting sustainable repair time, and also, it is required to include breaker model in distribution reliability evaluation.

KEYWORDS: Distribution system, Reliability, Sustainable repair time, Breaker model.

1. INTRODUCTION

1.1. Motivation and literature review

Reliability assessment is one of the important topics in the power system studies. Consumer satisfaction and economics of power systems are two important issues that are treated in reliability evaluation of distribution networks. Statistical studies show that distribution system has the most individual contribution in the customer's outages [1]. Therefore, reliability of distribution system is evaluated independently, instead of its combining with generation and transmission systems. In the distribution systems, failure rate, average repair time and annual unavailability are basic reliability indices.

Distribution companies perform several tasks to decrease the number of faults and reduce the repair time in order to improve system reliability [2]. In this respect, distribution companies have to upgrade the network to response to the customers' expectation. On the other hand, companies need to manage costs of installation, control, operation and maintenance of equipment. Therefore, accurate evaluation of system reliability is very important to fulfill the necessary standards as well as economic saving.

Generally, methods for assessing reliability of engineering systems are classified into analytical and simulation techniques [3, 4]. Analytical techniques use the mathematical model of the system and have low computation time. However, they have limitations in implementing the complex systems, because of their computational burden. Furthermore, unsuitable simplifications are performed in the mathematical modeling process. Thus, computational accuracy is reduced in analytical techniques. On the other hand, simulation methods are based on the random investigations of safety or faulty components using probability distribution functions. These methods are the most commonly used in

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systems where there are some difficulties to model analytically, such as load uncertainty, input energy and a large number of components. However, many simulations are required to obtain acceptable outputs, and they need long time.

Two different repair times are considered in [5, 6], due to repairing the failed component by two different author. In [7], waiting time to repair has been considered to calculate the reliability of standby system. In [8], outages of two parallel units are included by one traveling time to repairing team. In order to include the travel time associated with each unit, error bound is calculated. Moreover, the travel time only extends the repair time of the first unit. Two states of the operation and failure for components are considered in [9] for a complex system, such that the states depend on each other. In addition, failures occur randomly, while several repairing teams contribute in the repairing process. Changes in maintenance programs affect the operation sequence of equipment and then system reliability. In [10], a probabilistic approach is presented to modify repairing schedule. In [11], aging characteristic of components is included in reliability assessment. In [12], a model is presented for calculating reliability of power system, while protection system failure is considered. In [13], impacts of automatic switches on the distribution system reliability are investigated. It is assumed that there are some negligible repair times, which can be neglected. By omitting of tolerable repair time, the reliability indices are improved and the related costs are reduced. In [14], modified failure rate and repair time is included into the reliability model, instead of omitting the repair time. Outages due to component failures and overloading are included in an analytical framework. In [15], it is assumed that components of meshed and triple-bus distribution systems have negligible repair times. In [16], reliability is evaluated by accounting the repair time omission and the only outages due to the component failures. Monte Carlo simulation is used to calculate mean up and down time.

1.2. Approach and contributions

In this paper, impacts of omitting customer tolerable repair time on electric distribution system reliability are studied. Simulation method is applied to calculate reliability indices. It should be noted that factors affecting component failures have not been considered in the previous researches. Unlike the previous works, different tolerable time has been included in this paper. Breaker model is also included into this paper since the correct modeling of components can help the accurate and reasonable reliability indices. Circuit breaker is considered as simple model of its switching mission and complexities as described in [1]. The main contributions of this paper are therefore:

1) Outages is considered due to both failure of components and overloading since, the only component failure resulted from fault in operations has been reported in previous works.

2) The breaker model is inserted into the meshed distribution networks reliability assessment. Breaker was considered similar to the other components consist of two states.

3) An integrated model is developed in order to evaluate impacts of omitting tolerable customer repair time on reliability indices.

4) Different tolerable time for fault occurrence is considered in different segments. In the previous works, a constant tolerable time was used for all faults and all segments.

Monte Carlo simulation is performed systematically to calculate random values of time to repair and time to failure. As a case study, a meshed distribution system is selected as a test system and simulations are performed and analyzed.

2. MODELING OF REPAIR TIME OMISSION

Distribution systems are composed of different load points having different types of customers. Moreover, there exist specific repair times which are tolerable for some customers. These repair times can be eliminated in the reliability assessment. Repair time omission has economic advantage, because unnecessary costs will be removed to improve system reliability. This idea can be used in designing, operation and preventive maintenance scheduling of distribution system.

The system considered in this paper is a meshed distribution system consisting series and parallel components. Failure rate and unavailability of a load point, are calculated by (1) and (2), for series components [16].

$$\lambda_{s,k} = \sum_{i \in s} \lambda_i \tag{1}$$

$$u_{s,k} = \sum_{i \in s} \lambda_i . r_i \tag{2}$$

where, s is a set of components that are series in the path of load point k and source; λ_i is the failure rate of component i; $u_{s,k}$ is unavailability of load point k, and r_i is the repair time of component i. Equation (3) computes average outage duration of each load point.

$$r_{s,k} = \frac{u_k}{\lambda_k} \tag{3}$$

If there are two parallel components in the path between a load point and source, reliability indices will be calculated by (4)-(6).

$$\lambda_p = \frac{\lambda_1 . \lambda_2 (r_1 + r_2)}{8760} \tag{4}$$

$$r_p = \frac{r_1 . r_2}{r_1 + r_2} \tag{5}$$

$$u_p = \lambda_p . r_p \tag{6}$$

where, λ_p, r_p and u_p are the equivalent failure rate, repair time and unavailability the load point, respectively. In a complex system, reliability indices are calculated by the minimal cut-set concept and using the mentioned equations.

Omitting algorithm of the tolerable repair time is based on random number generation in each step of the Monte Carlo simulation. In each step of simulation, random numbers is generated to determine time to failure and time to repair of components, by equations (7)- (8).

$$TTF_i = \frac{-\ln(u)}{\lambda_i} \tag{7}$$

$$TTR_i = \frac{-\ln(u')}{\mu_i} \tag{8}$$

where, TTF_i and TTR_i are time to failure and time to repair of component i, respectively. μ_i is repair rate of component i and u and u' are random numbers between [0,1]. After calculating TTF and TTR for each components, the smallest TTF value is considered as time to failure for related step of the simulation. In this way, the related component is considered as failed component. Afterwards, load points affected by component interruption, are addressed. In the next step, TTR of the failed component is compared with the customer sustainable repair time. If TTR is less than the sustainable time, then the repair time will be fixed zero, and TTF will be calculated by summation of TTF and TTR; otherwise TTF and TTR will be unchanged, as mentioned by (9).

$$\begin{aligned} &If\ TTR_i \le T \\ &TTR_{new,i} = 0\ ,\ TTF_{new,i} = TTF_i + TTR_i \\ &otherwise \\ &TTR_{new,i} = TTR_i\ ,\ TTF_{new,i} = TTF_i \end{aligned} \tag{9}$$

where, T is customer sustainable TTR, $TTF_{new,i}$ and $TTR_{new,i}$ are modified TTF and TTR. Note that T is generated randomly, based on normal distribution function, defined by (10).

$$\psi_k(T) = \frac{1}{\sqrt{2\pi}\sigma_k} . e^{-0.5\left(\frac{t-\mu_k}{\sigma_k}\right)^2} \tag{10}$$

where, μ_k and σ_k are mean and standard deviation of customer sustainable repair time in load point k.

In the next step of simulation, another number is generated to be converted to TTF. If the summation of the new and the old TTF and TTR are equal or greater than the respected time, the total number of failure and repair time is calculated for each load point; otherwise the procedure is repeated until each hour has been analyzed. At the end of simulation, the average of load point failure rate and failure duration is calculated for all samples of simulations.

3. BREAKER MODELING

In this paper, all components are considered as two sates of operating (up) and failure (down). Such model is not precise for circuit breaker, since its switching function is disregarded during fault conditions. Therefore, different states are included in modeling of circuit breaker. In this study, the model explained in [1], is used. Some assumptions are adopted to model breaker in the simplest way. The probability of malfunctioning in breaker is small, and therefore probability of successfully opening is considered unity. Breakers are usually located at the sending end of a radial feeder, or at both ends of a branch in meshed networks. For circuit breaker, probability of open circuit is very smaller than short circuit. Thus, probability of open circuit for the breaker is negligible. By these assumptions, breaker can be modeled in two ways.

- If the breaker does not clear short circuit fault, then it is not included as a component. Thus, short circuit indices are considered as series components with the bus which is connected.
- If the breaker clears its short circuit, then it will be considered as a component and its short circuit indices associated with bus and line side, are considered as series components.

In this paper, breaker is modeled such that it can clear its short circuit. Figure 1 illustrates this concept.

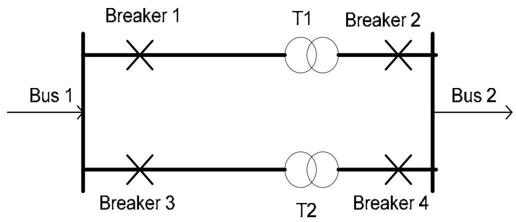

Fig. 1. Sample system for breaker model explanation.

In Fig. 1, it is assumed that the failure rate and the repair time for bus 1 are 0.01 and 5 hours, respectively. Failure rate and repair time for the breaker are assumed equal 0.05 and 20 hours, respectively. Suppose the breaker failure is due to 20% of failure related to the inadvertent opening, 40% related to bus, and 40% related to the line side. Thus, failure rate of bus 1 consists of failure due to bus failure and failure of breaker in the side of bus 1. Also, failure rate of breaker 1 consists of failure due to inadvertent opening and failure of line side of the breaker. Therefore, the failure rate and the repair time for bus and breaker will be changed as below:

$$busbar\ 1 \quad \lambda = (40\% \times 0.05) + (0.01) = 0.03 f\ / yr$$

$$u = (0.01 \times 5) + (40\% \times 0.05 \times 20) = 0.45 hour / yr$$

$$r = \frac{u}{\lambda} = 15 hour$$

$$breaker 1 \quad \lambda = 20\% \times 0.05 + 40\% \times 0.05 = 0.03 f\ / yr$$

$$r = 20 hour$$

4. SIMULATION AND ANALYSIS

4.1. Introducing test system

We have used the test system introduced by [14], in our case study. The system has 18 distributor segments. However, since the circuit breakers have been modeled as an independent component here, the distributor has 25 segments and 4 load points. Figure 2 shows topology of the system. Table 1 shows the failure rate and the repair time of segments, which are related to the fault in operation. Parameters of table1 are computed by separating the breaker from other components in the basic model. Two components are considered series, and then failure rate and repair time are computed for two separated components. Thus, the parameters become similar to the basic parameter of the main test system by combining the separated segments in Table 2.

Figure 3 shows the reliability model of the considered system comprising 25 segments. Table 2 shows information of segments involved in block diagram, as view of load points. Reliability indices can be calculated for each load point using (1)-(6), Table 2 and Fig. 3.

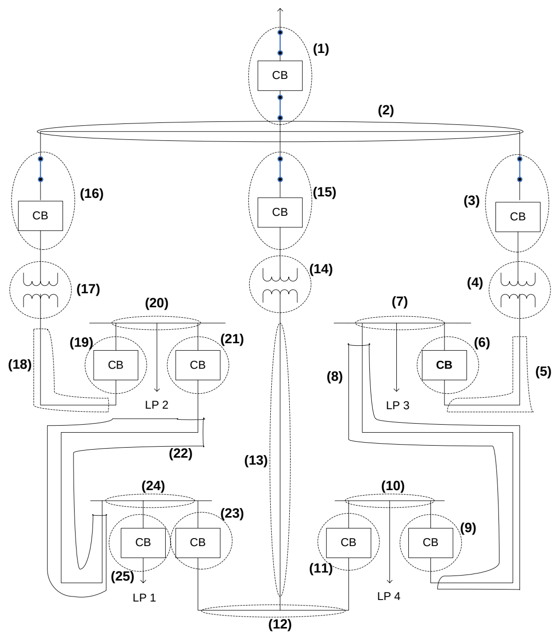

Fig. 2. Meshed distribution test system.

4.2. Overloading model of segments

As it was mentioned earlier, both failure in operation and overloading are considered as failures of components. Outage due to overloading means that the faulted section is removed by system protection in overloading state, and then it is restored. It should be noted that common failures and cascading outages caused by overloading are not considered in this paper. Therefore, in this paper, overloading of a component is considered identical to the failure caused by fault in operating. Equations (11) and (12) calculate the failure rate and the average outage duration.

$$\lambda_i = \frac{1}{(1-p_i)d_i} \tag{11}$$

$$r_i = p_i . d_i \tag{12}$$

Table 1. Data of test system.

Distribution segment	Fail/year (λ)	Average repair time , (r) hours
1	0.3104	10.280412
2	0.3	10
3	0.1276	5.010658
4	0.07	33.985714
5	0.01352	14.335503
6	0.05	13.86320032
7	0.0346	5.780346821
8	0.01764	13.555102
9	0.005	13.86320032
10	0.00346	5.780346821
11	0.05	13.19600012
12	0.056	7.142857143
13	0.0846	15.8
14	0.069	27.565217
15	0.1552	6.865979
16	0.1552	6.865979
17	0.07	33.985714
18	0.01352	14.335503
19	0.05	13.42368059
20	0.0566	5.929287541
21	0.05	13.42368059
22	0.01764	13.5551
23	0.05	13.19600012
24	0.0346	5.780346821
25	0.05	13.86320032

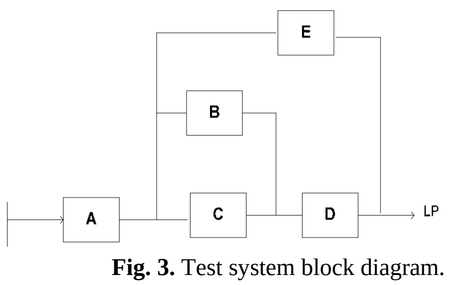

Fig. 3. Test system block diagram.

where, p_i is the probability of overloading of the i'th segment and d_i is average cycle time.

Table 3 shows the failure rate and the repair time due to overloading for 25 segments. Since both overloading and failure can result in the down state of a component, these two elements are series elements. Thus, series equations are used for reliability calculations.

Table 2. Block diagraminformation.

Load point	Blocks	Segments involved
1	A	1, 2, 24, 25
	B	12,13,14,15
	C	3,4,5,6,7,8,9,10,11
	D	23
	E	16,17,18,19,20,21,22
2	A	1, 2, 20
	B	12,13,14,15
	C	3,4,5,6,7,8,9,10,11
	D	21,22,23,24
	E	16,17,18,19
3	A	1, 2, 7
	B	12,13,14,15
	C	16,17,18,19,20,21,22,23,24
	D	8,9,10,11
	E	3,4,5,6
4	A	1, 2,10
	B	12,13,14,15
	C	16,17,18,19,20,21,22,23,24
	D	11
	E	3,4,5,6,7,8,9

Table 3. system data related to overloading.

Distribution segment	Failure/year (λ)	Average repair time , hour (r)
1	0.200002	0.438
2	0.2	0.25
3	0.05000005	0.175
4	0.04	0.219
5	0.100005	4.38
6	0.075	6.09399
7	0.025	8
8	0	0
9	0.075	6.09399
10	0.0025	80
11	0.0375	18.0290029
12	0.025	16
13	0	0
14	0	0
15	0.05	0.1752
16	0.05	0.1752
17	0.04	0.219
18	0.01	4.38
19	0	0
20	0	0
21	0	0
22	0	0
23	0.0375	18.0290029
24	0.025	18.2819
25	0.075	2.666

4.3. Circuit breaker model

In the modeling of circuit breaker, it is assumed that 20% of fault on breaker is associated with the inadvertent opening, 40% is related to bus side and 40% related to line side. Reliability parameters of circuit breakers and related segments are modified. It should be noted that the breaker model is considered for two states of faulted segments consist of overloading and fault in operation. These states are series with each other. For instance, circuit breakers 9, 11 and bus 10 in Fig. 2. Then, failure rate and repair time of respected components due to operation failure of breakers are modified as below:

$$breaker9 \quad \lambda = (20\% \times 0.005) + (40\% \times 0.005) = 0.003 f \ / \ yr$$
$$r = 13.86320032 \ hour$$
$$breaker11 \quad \lambda = (20\% \times 0.05) + (40\% \times 0.05) = 0.03 f \ / \ yr$$
$$r = 13.19600012 \ hour$$
$$busbar10 \quad \lambda = (40\% \times 0.005) + (40\% \times 0.05) + (0.00346) = 0.02546 f \ / \ yr$$
$$u = (40\% \times 0.005 \times 13.86) + (40\% \times 0.05 \times 13.196) + (0.00346 \times 5.78) = 0.311646 \ hour \ / \ yr \quad r = \frac{u}{\lambda} = 12.24 \ hour$$

Moreover, failure rate and repair time for respected components due to overloading failure are modified as below:

$$breaker9 \quad \lambda = (20\% \times 0.075) + (40\% \times 0.075) = 0.045 f \ / \ yr$$
$$r = 6.09399 \ hour$$
$$breaker11 \lambda = (20\% \times 0.375) + (40\% \times 0.375) = 0.0225 f \ / \ yr$$
$$r = 18.029 \ hour$$
$$busbar10 \quad \lambda = (40\% \times 0.075) + (40\% \times 0.375) + (0.0025) = 0.07 f \ / \ yr$$
$$u = (40\% \times 0.075 \times 6.09399) + (40\% \times 0.375 \times 18.029) + (0.0025 \times 80) = 0.6532 \ hour \ / \ yr \quad r = \frac{u}{\lambda} = 9.3322 hour$$

Tables 4 and 5 show the modified reliability parameters of segments, taking into account the breaker model, in states of overloading and operation failures. It can be seen from Table 1 and Table 4 that failure rate and repair time of breakers and bus are changed, when breakers are modeled. Comparing Table 3 with Table 5 show that the results are the same. Therefore, inserting the breaker model is important in reliability assessment, since reliability indices are affected by breaker failures.

4.4. Simulation results

Monte Carlo simulation is used for assessing the system reliability. In order to generate sustainable repair time for customer (T), two normal distribution functions with different means and standard deviations are considered for two sets of segments. Table 6 shows parameters of two normal distribution function as well as segments.

Table 4. Modified parameters accounting of breaker model and failure due to fault in operation.

Distribution segment	Failure/year (λ)	Average repair time , hour (r)
1	0.18624	10.28041
2	0.39936	8.983983
3	0.07656	5.010658
4	0.07	33.98571
5	0.01352	14.3355
6	0.03	13.8632
7	0.0546	8.741099
8	0.01764	13.5551
9	0.003	13.8632
10	0.02546	12.24063
11	0.03	13.196
12	0.056	7.142857
13	0.0846	15.8
14	0.069	27.56522
15	0.09312	6.865979
16	0.09312	6.865979
17	0.07	33.98571
18	0.01352	14.3355
19	0.03	13.42368
20	0.0966	9.032497
21	0.03	13.42368
22	0.01764	13.5551
23	0.03	13.196
24	0.0746	9.756568
25	0.03	13.8632

Table 5. Modified parameters accounting of breaker model and failure due to overloading.

Distribution segment	Failure/year (λ)	Average repair time , hour (r)
1	0.120001	0.438
2	0.340001	0.281036
3	0.03	0.175
4	0.04	0.219
5	0.100005	4.38
6	0.045	6.09399
7	0.055	6.960358
8	0	0
9	0.045	6.09399
10	0.07	9.332211
11	0.0225	18.029
12	0.025	16
13	0	0
14	0	0
15	0.03	0.1752
16	0.03	0.1752
17	0.04	0.219
18	0.100005	4.38
19	0	0
20	0	0
21	0	0
22	0	0
23	0.0225	18.029
24	0.07	11.53549
25	0.045	2.66667

As mentioned by (9), if the failed segment is located in the first row of table6, then random number T is generated out of the respected probability distribution function. In addition, if the failed segment is located in the second row of Table 6, then the random number T is generated out of the respected probability distribution. If TTF is less than T, repair time is removed and the fault is neglected; otherwise, the repair time remains without change in the simulation procedure. Convergence criterion is based on error tolerance for average mean down time and average mean up time; defined by Eqs. (13) and (14).

Table 6. Normal distribution specification.

Normal distribution function	Segments
$\mu = 4.8125$, $\sigma = 1.8697$	1- 3, 5- 7, 9- 10, 15- 16, 18- 21, 24- 25
$\mu = 12.44$, $\sigma = 3.53$	4, 8, 11- 14, 17, 22- 23

$$\sigma_u^2 = \frac{1}{N}\sum_{i=1}^{N}(TTF_i - MUT)^2 \tag{13}$$

$$\sigma_d^2 = \frac{1}{N}\sum_{i=1}^{N}(TTR_i - MDT)^2 \tag{14}$$

where, N is the number of samples, TTF_i and TTR_i is time to failure and time to repair of load point in each sample. MUT and MDT are the average up and down times of load point for all samples, defined by (15) and (16).

$$MUT = \frac{1}{failure\ rate} = \frac{1}{N}\sum_{i=1}^{N} TTF_i \tag{15}$$

$$MDT = repair\ time = \frac{1}{N}\sum_{i=1}^{N} TTR_i \tag{16}$$

Standard deviation of MUT (s_u) and MDT (s_d) are then calculated :

$$s_u = \frac{\sigma_u}{N} \tag{17}$$

$$s_d = \frac{\sigma_d}{N} \tag{18}$$

Variation coefficient for convergence of the simulation is defined by:

$$\beta_u = \frac{S_u}{MUT} \tag{19}$$

$$\beta_d = \frac{S_d}{MDT} \tag{20}$$

where, β_u and β_d are variation coefficients for assessing the convergence and stopping the simulation. In the simulation procedure if β_u and β_d become less than 0.005, then simulation algorithm will be stopped and reliability indices are converged.

In order to validate simulation results of this paper, the main test system has been simulated and then the results (analytical and simulations) have been compared with each other. Simulation results for the main system consisting 18 segments and ignoring the overloading, breaker model and repair time omission are presented in Table 7.

Table 7. Simulation results for main test system.

Load point	Analytical results			Simulation results		
	MUT (year)	MDT (hour)	U (hour/year)	MUT (year)	MDT (hour)	U (hour/year)
1	2.53	10.3	4.08	2.5	10.2	4.05
2	2.14	10.4	4.86	2.12	10.3	4.83
3	2.53	10.3	4.08	2.51	10.2	4.07
4	3.13	10.2	3.28	3.13	10.3	3.31

It can be seen from Table 7 that the simulation and analytical results have few difference with each other, which show the accuracy of simulation method. Table 8 shows simulation results. Simulation convergence is obtained with 50000 samples of simulation with respect to the convergence criteria. Graphical representations are shown in Fig. 4.

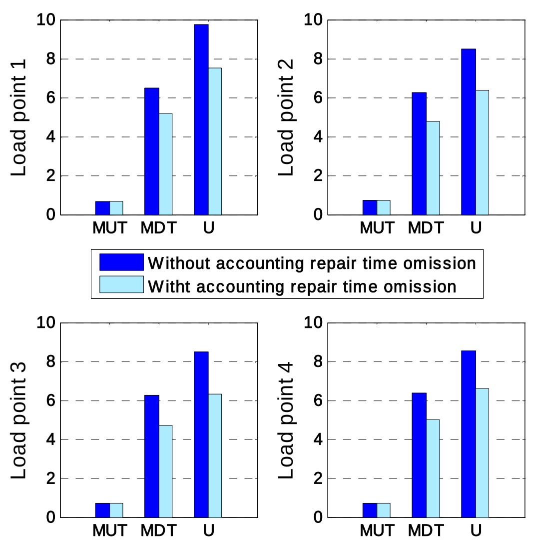

Fig. 4. Simulation results.

It can be seen from Table 8 and Fig. 4 that omitting the repair time of load point reduces unavailability of load points. Furthermore, MUT of load point has small variation and almost is constant because failure rate of load point is small. In addition, effect of omitting the repair time is mostly on the MDT and unavailability of the load points. Unavailability of the load points 1-4 has been decreased by 23%, 24.4%, 25/4%, 22.7%, respectively. Therefore, repair time omission results in better choices for improving reliability indices. Furthermore, more attentions can be paid on the load points having lower tolerable time and high unavailability. It is shown that including the tolerable repair time can lead us the lower value of unavailability. This is consistent with the real system and actual situations. In this way, unnecessary budgeting for system with lower requirements for reliability improvement is addressed.

Table 8. Simulation results.

	Without repair time omission			With repair time omission		
Load point	MUT (year)	MDT (hour)	U (hour/year)	MUT (year)	MDT (hour)	U (hour/year)
1	0.68	6.46	9.74	0.68	5.16	7.5
2	0.74	6.27	8.46	0.74	4.8	6.4
3	0.73	6.24	8.50	0.73	4.7	6.3
4	0.74	6.34	8.54	0.74	5	6.6

On the other hand, tolerable repair time is considered to be different for two sets of segments. Accurate results are therefore obtained, because large tolerable repair time is not reasonable for a segment comprising low repair time. Furthermore, this is consistent with the fact that segments consisting of large repair time have larger tolerable repair time than the others. As it Table 8 shows, the biggest of mean down time is related to the load point 1. However, the biggest of mean down time is obtained for the load point 2, where constant tolerable repair time is considered for segments. It can be concluded that different tolerable time consideration, can lead us different and then realistic results. Moreover, more precise results are obtained when breakers are modeled as independent components. Simulation results confirmed that considering the breaker model as well as other components is not accurate, since it does not model switching function of breaker. As a future research, more details on breaker can be included for calculating reliability of the meshed distribution network.

5. CONCLUSIONS

In this paper, impacts of customer tolerable repair time omission on electric distribution system reliability have been studied. System components are considered as a segment with two states of operation (up) or failure (down). Failure states for segments consist of operation failure or overloading failure. Then, based on the series components reliability equations, the modified reliability indices have been calculated. Circuit breaker has been separately modeled accounting some assumptions. Some repair times are sustainable in view of customer. Such repair times can be eliminated in reliability evaluation. The following conclusions can be drawn from the developed model of the paper:

1) Unavailability of load points has been decreased by omitting sustainable repair time. Therefore, sustainable repair time omission has economically advantage, such as preventing extra and unnecessary budgets for improving system reliability. In addition, more accurate maintenance scheduling and system design can be conducted.

2) Inclusion of the breaker model shows considerable difference with respect to the case where breaker model is not considered. It is required to include breaker model in the meshed distribution networks reliability evaluation; especially for studies that are based on repair time of components.

3) Monte Carlo simulation shows that removing sustainable repair time from reliability assessment process gives more accurate results. Thus, this model can be applied in practical systems.

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