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4 authors:

Mohammed Wadi
Istanbul Sabahattin Zaim University

Mustafa Baysal
Yildiz Technical University

Abdulfetah Abdela Shobole
Istanbul Sabahattin Zaim University

Mehmet Rıda Tur
Batman Üniversitesi

Reliability Evaluation in Smart Grids via Modified Monte Carlo Simulation Method

Mohammed Wadi[1], Mustafa Baysal[2]
[1, 3]EEE Dept., Istanbul Sabahattin Zaim University, Istanbul, Turkey, mohammed.wadi@izu.edu.tr
[2]Electrical Engineering Dept., Yildiz Technical University, Esenler, Davutpasa, Istanbul, Turkey, baysal@yildiz.edu.tr

Abdulfetah Shobole[3], Mehmet Rida Tur[4]
[4]Electrical and Energy Department, Mardin Artuklu University, Mardin, Turkey
[3]Abdulfetah.Shobole@izu.edu.tr
[4]mehmetridatur@artuklu.edu.tr

***Abstract*—Operation of closed-ring power distribution systems has various advantages over both meshed-operated and radially-operated systems. Closed-ring system unlike to radial system, the voltage drop is less, achieves high reliability of power on demand since the power is supplied from both ends, and reduces the voltage fluctuation in high loaded areas by using a tie power line. However, the reliability assessment of closed-ring power grids is not a trivial task. Monte Carlo Simulation (MCS) is one of the most famous methods to assess the availability of any power system. However, the most proposed methods are able to evaluate the reliability of radial and open-ring grids. This paper developed the best known MCS method to assess the reliability of closed-ring grids by integrating the total loss of continuity (TLOC) definition into the MCS. The developed method is called modified Monte Carlo Simulation (MMCS) method. The MMCS is tested by using Roy Billinton Test System (RBTS) buses 2 and 4. The obtained results confirm the correctness of the proposed method. Therefore, MMCS method is appropriate to assess the reliability of both simple and complicated closed-ring systems.**

Keywords— Power system reliability; smart power grids reliability; total loss of continuity (TLOC); modified Monte Carlo simulation method (MMCS)

I. Introduction

The improvement of the reliability of electricity distribution systems is currently a subject of increasing interest and importance; since power outage due to any fault affects both of the power utilities and the end users. Closed-ring operation mode provides high reliability by reducing the duration and frequency of faults. Furthermore, it has various advantages over other all operation topologies. Closed-ring operation topology unlike to radial operation topology, it reduces the voltage drop, achieves high reliability of power on demand since the power is supplied from both ends, reduces the voltage fluctuation in high loaded areas by using a tie power line as well as it increases the adoption of distributed generations (DGs) and achieves availability of power on demand with an acceptable level of reliability [1]. These features are among the most remarkable goals of smart grids. In other respect, the closed-ring system leads to initial high costs of construction since it requires more and complex materials, unlike the radial system. It requires for speedy and efficient equipment to distinguish and determine the faults accurately, smart protection and control methodologies, and advanced communication infrastructure to deal with huge data flow [2], [3]. From the utility viewpoint, reliability studies are so paramount since it enables the operators to predetermine the frequent causes of faults, the areas of ultimate amount of energy not supplied and the fragile areas of protection system [4]. There are two main assessment reliability methods, the historical assessment, and predictive assessment. The predictive reliability assessment of power systems also can be divided into two categories namely, the simulation method and the analytical method [5]. Analytical methods based on mathematical models that are used to assess the system reliability indices using direct mathematical solutions. The main analytical methods are the block diagram, the fault tree, and the Markov model methods; while the simulation methods can be divided into the subset and the line sampling methods. Analytical methods are suitable for simple systems, however, it is a nontrivial task to assess the reliability of complex systems. Generally, the core of analytical methods in calculation both load points (LPs) and the overall system-reliability indices based on computing the average values of these indices. On the other hand, simulation methods, approximate the overall system-reliability indices by emulating the system real process and random behavior. One of the most widely-used simulation methods is the Monte Carlo method. MCS can be divided into two methods, the sequential simulation method, and the random sampling method. The MCS sequential simulation can be performed by creating a string of events using random numbers and their probability distribution variables characterize the duration of each component state. The sequential simulation also can be divided into two categories, fixed interval (synchronous timing) technique, and the next event (asynchronous timing) technique. MCS random sampling depends on random numbers and probability distributions of each component state. In general, the sampling method is rapid than the sequential method and is appropriate when the component failure states and repair states are independent [6]. In this paper, the proposed MMCS method is developed to easily evaluate the reliability assessment based on the integration of the TLOC into the MCS. To show the applicability and to verify the correctness of the proposed method, MMCS is tested by using Roy Billinton Test System (RBTS) Buses 2 and 4[7].

II. Reliability Indices

To execute the reliability analysis for any system, firstly the basic three LP reliability parameters, λ, r, and U respectively need to be determined [8].

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$$\lambda_{sys} = \sum_i \lambda_i \quad (1)$$

$$U_{sys} = \sum_i \lambda_i \ r_i \quad (2)$$

$$r_{sys} = \frac{U_{sys}}{\lambda_{sys}} = \frac{\sum_i \lambda_i \ r_i}{\sum_i \lambda_i} \quad (3)$$

Depending on these parameters, many system indices can be computed such as SAIFI, SAIDI, CAIDI and ASAI which can be calculated by the formulas (4), (5), (6) and (7) [9]:

$$SAIFI = \frac{Total\ Number\ of\ Customer\ Interruptions}{Total\ Number\ of\ Customers\ Served} = \frac{\sum_i \lambda_i \ N_i}{\sum_i N_i} \quad (4)$$

$$SAIDI = \frac{Sum\ of\ Customer\ Interruption\ Durations}{Total\ Number\ of\ Customers\ Served} = \frac{\sum_i U_i \ N_i}{\sum_i N_i} \quad (5)$$

$$CAIDI = \frac{Sum\ of\ Customer\ Interruption\ Durations}{Total\ Number\ of\ Customer\ Interruptions} = \frac{\sum_i U_i \ N_i}{\sum_i \lambda_i \ N_i} \quad (6)$$

$$ASAI = \frac{Customer\ Hours\ of\ Available\ Service}{Customer\ Hours\ Demanded} = \frac{\sum_i \ N_i \times 8760 - \sum_i U_i \ N_i}{\sum_i \ N_i \times 8760} \quad (7)$$

where N_i is the number of served customers of LP_i, 8760: is the yearly total number of hours

In some cases, it is important to evaluate load-energy-orientated indices to compute the energy not supplied (ENS) at each LP. ENS index and average Energy not supplied index (AENS) are the widely-used indices and can be calculated by equations (8) and (9) respectively. The advantages of these two indices that can be used to differentiate between the interruption of large and small loads; determine whether there is growth in customers or add new loads, and to compare the costs benefits between alternative reinforcement.

$$ENS = \sum_i L_i \, U_i \quad (8)$$

where L_i is the mean load connected to LP_i

$$AENS = \frac{\text{Total ENS}}{Total\ Number\ of\ Customers\ Served} = \frac{\sum_i L_i \, U_i}{\sum_i N_i} \quad (9)$$

III. Reliability Evaluation In Distribution Systems Based On MCS

A. MCS

MCS uses mathematics and statistics to model real-time systems and then expect the future values of these systems. MCS introduces a powerful technique to estimate the reliability of a system. The results accuracy of MCS technique is based on the number of iterations of the sampling process. As the number of iterations increases as the accuracy is [10]; therefore, MCS can be considered computationally-expensive. MCS technique is mainly based on two techniques, namely, subset simulation and line sampling. The subset simulation technique based on the concept that the probability of a small fail can be defined as a multiplication of larger conditional probabilities of some intermediate events (IEs): with a convenient selection of the IEs, to provide precise approximation with a little number of samples, the conditional probabilities can be formed to be efficiently large. The line sampling method utilizes lines instead of random points to implement the failure domain of interest (DOI) by determining an important direction. Important direction indicates towards the failure DOI, and it solves the high-dimensional reliability problem by converting them into a number of low-dimensional conditional problems [10]. Mathematically, the probability of unavailability P(Q) is defined as a multidimensional integral by the following formula:

$$P(Q) = P(x \in Q_n) = \int I_Q(x) \, q(x) dx \quad (10)$$

where, $\boldsymbol{x} = \{x_1, x_2, x_3, \dots, x_j, \dots, x_n\} \in \boldsymbol{\Re^n}$ is the vector of the uncertain input parameters of the system model, with high-dimensional PDF $q: \boldsymbol{\Re^n} \rightarrow [0, \infty), Q \subset \boldsymbol{\Re^n}$ is the failure region and $I_Q: \boldsymbol{\Re^n} \rightarrow \{0, 1\}$ is an indicator function i.e. $I_Q(x) = 1$, if $x \in Q$ and $I_Q(x) = 0$, otherwise.

B. Modified Monte Carlo Simulation Method (MMCS)

The failure mode and effect analysis (FMEA) method [12, 13] mainly based on minimal cut sets of equations for computing the reliability indices of series, parallel as depicted in Table I and series-parallel networks. It is a powerful tool to assess and estimate the various fails and their influence on the allover reliability of the system. FMEA is grouped into two methods, total loss of continuity (TLOC) and partial loss of continuity (PLOC). TLOC is defined as an LP fails if all the paths between the LP and all the sources are faulted, while PLOC defined as all possible outage combinations without paths that are lead to a TLOC event [11]. In addition, it is found that classical MCS can assess the availability of radial and open-ring networks, while it needs for modifications in order to be suitable for reliability assessment of closed-ring networks. The original idea of this paper is to integrate the concept of TLOC [14] definition into MCS method to assess and analyze the reliability of closed-ring distribution networks which we called "Modified Monte Carlo Simulation (MMCS)" method. Fig. 1 describes the proposed flowchart of MMCS. Further, MATLAB is used to develop the algorithm of MMCS.

TABLE I. LP RELIABILITY INDICES FOR PARALLEL SYSTEMS

# Parallel Component	λ_p [failure/yr]	r_p [hr]	$U_p = \lambda_P r_P$ [hr/yr]
Two Component	$\frac{\lambda_1\lambda_2(r_1+r_2)}{1+\lambda_1 r_1+\lambda_2 r_2}$ $\lambda_1\lambda_2(r_1+r_2)\ if\ \lambda_i r_i \ll 1$	$\frac{r_1 r_2}{r_1+r_2}$	$\lambda_1\lambda_2 r_1 r_2$
Three Component	$\lambda_1\lambda_2\lambda_3(r_1r_2+r_2r_3+r_3r_1)$	$\frac{r_1r_2r_3}{(r_1r_2+r_2r_3+r_3r_1)}$	$\lambda_1\lambda_2\lambda_3 r_1r_2r_3$

$$TTF = -\frac{1}{\lambda}\ln(r_n), \qquad TTR = -\frac{1}{\mu}\ln(r_n) \tag{11}$$

where TTF: Time-to-failure, r_n: a random number, TTR: Time-to-repair, λ: Failure rate and μ: Repair rate

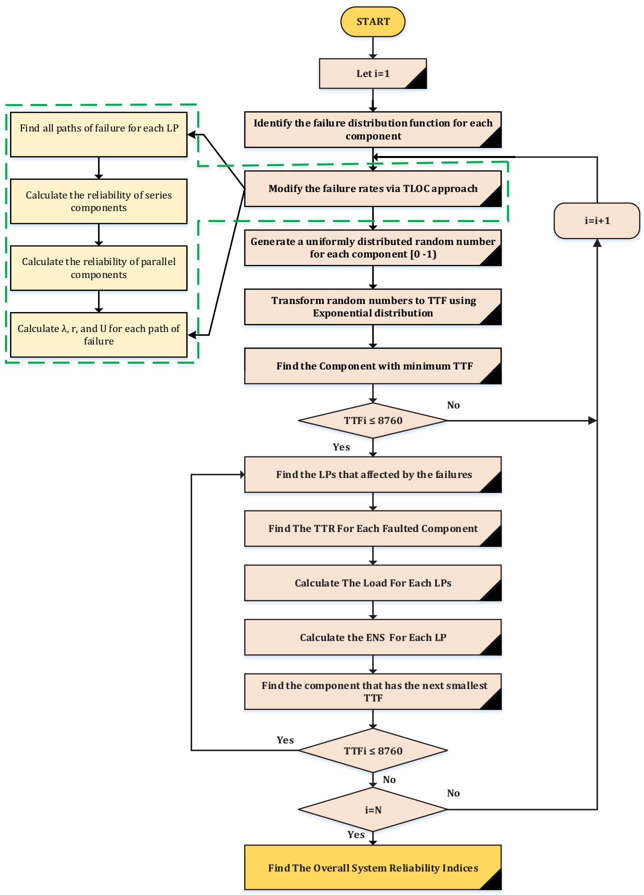

Fig. 1. *The proposed flowchart of MMCS*

IV. CASE STUDY AND RESULTS

A. RBTS Bus-2

To verify the correctness of the developed MMCS method, it is tested by using RBTS Bus-2 that developed at the University of Saskatchewan [7] as the case study A. RBTS Bus-2 distribution test system consists of four feeders (F1, F2, F3, and F4), twenty-two load points (LP1~ LP22), and the other details are as given in [7]. Fig. 2 describes the RBTS Bus-2 test system. The system is solved in [7] using hand calculations in order to provide the full understanding of evaluation techniques, and the results as given in Table II. The same system also, solved by developing a tool based on DigSILENT programing language [15], and the results as given in Table III.

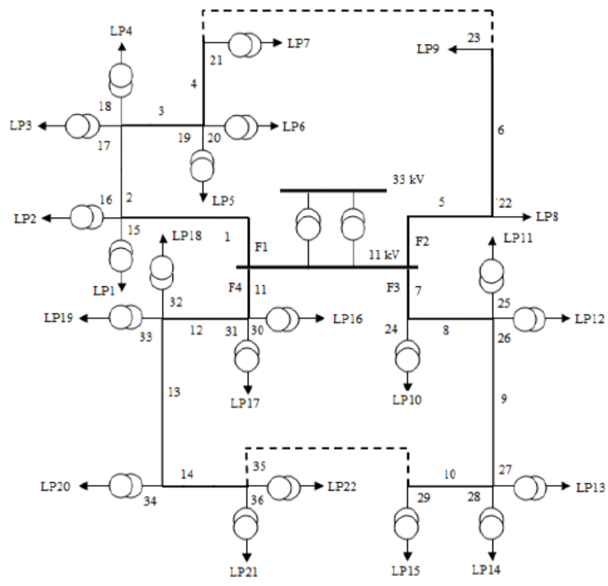

Fig. 1. *Distribution test system for RBTS Bus 2*

In this paper, to confirm the rightness of the proposed method, MMCS is tested by using RBTS Bus-2, cable type and the base case (A) as a case study, and the results are given in Table IV. The test results by using the MMCS reliability assessment method are compared with the reference results from [7] and [15]. The matching of the obtained results in this paper with both results obtained in [7] and [15] confirm the rightness of the MMCS reliability evaluation method.

TABLE II. SYSTEM INDICES FOR RBTS BUS 2 (CABLES TYPE) [7]
BASE CASE (A): DISCONNECTS-FUSES-ALTERNATIVE SUPPLY-REPAIR OF TRANSFORMERS

Feeders/Indices	SAIFI	SAIDI	CAIDI	ASAI	ASUI	ENS	AENS
F_1	0.158	5.03	31.77	0.999426	0.000574	18268	28.02
F_2	0.086	1.85	21.52	0.999789	0.000211	3968	1984
F_3	0.160	5.05	31.65	0.999424	0.000576	15463	24.47
F_4	0.158	4.98	31.54	0.999432	0.000568	16956	27.26
System	**0.159**	**5.02**	**31.65**	**0.999427**	**0.000573**	**54655**	**28.65**

TABLE III. SYSTEM INDICES FOR RBTS BUS 2 (CABLES TYPE) [15]

System Indices	Index value	Measurement Unit
SAIFI	0.1590	Int/cus.yr
SAIDI	5.0161	hr/ cus.yr
CAIDI	31.647	hr/cus.int
ASAI	0.9990	
ASUI	0.0010	

Int: Interruption, cus: Customer, hr: Hour, and yr: Year

TABLE IV. SYSTEM INDICES FOR RBTS BUS 2 (CABLES TYPE) BASED ON THE MMCS METHOD

System Indices	Index value	Measurement Unit
SAIFI	0.159211	Int/cus.yr
SAIDI	5.017231	hr/cus.yr
CAIDI	31.64213	hr/cus.int
ASAI	0.999436	
ASUI	0.000564	
ENS	54662.65	kWh/yr
AENS	28.64918	kWh/cus.yr

B. *RBTS Bus-4*

In this case study, Bus-4 also is used to test the correctness of the proposed method, MMCS. Distribution test system for RBTS Bus 4 consists of seven feeders (F1~F7), thirty-eight load points (LP1~ LP38), and the other details are as given in [7]. Fig. 3 describes the distribution test system for RBTS Bus-4.

As shown in Fig. 3 there are some modifications to the Bus 4, but these modifications did not consider in reliability evaluation in the scope of this paper.

The system is solved in [7] using hand calculations and the results as given in Table V. The same system also, solved by developing a tool based on DigSILENT programing language [15], and the results as given in Table VI. In this paper, to confirm the correctness of the proposed method again, the developed MMCS is tested by using RBTS Bus-4, cable type and the base case (A) as a case study, and the results are given in Table VII. The test results by using the MMCS reliability evaluation method are compared with the reference results in Tables V and VI. The obtained results show a significant matching with both results obtained in [7] and [15] and manifest the correctness of the proposed MMCS reliability assessment method.

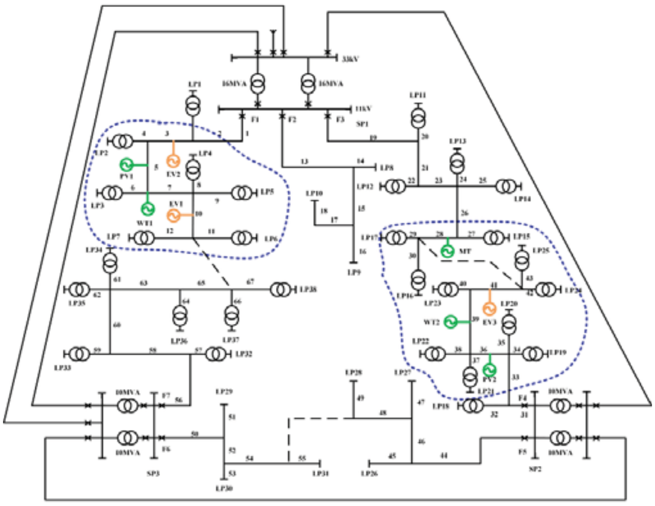

Fig. 3. *RBTS Bus-4 distribution test system*

TABLE V. SYSTEM INDICES FOR RBTS BUS 4 (CABLES TYPE) [7]
BASE CASE (A): DISCONNECTS-FUSES-ALTERNATIVE SUPPLY-REPAIR OF TRANSFORMERS

Feeders/Indices	SAIFI	SAIDI	CAIDI	ASAI	ASUI	ENS	AENS
F_1	0.191	4.29	22.43	0.999511	0.000489	15109	13.74
F_2	0.117	1.12	09.63	0.999872	0.000128	3954	1318
F_3	0.186	4.30	23.11	0.999509	0.000491	14858	13.76
F_4	0.195	4.30	22.03	0.999510	0.000490	17205	13.23
F_5	0.115	1.12	09.75	0.999872	0.000128	3354	1118
F_6	0.120	1.06	08.85	0.999879	0.000121	3687	1229
F_7	0.188	4.31	22.90	0.999508	0.000492	15439	11.97
System	**0.190**	**4.29**	**22.58**	**0.999510**	**0.000490**	**73605**	**15.40**

TABLE VI. SYSTEM INDICES FOR RBTS BUS 4 (CABLES TYPE) [15]

System Indices	Index value	Measurement Unit
SAIFI	0.190	Int/cus.yr
SAIDI	4.290	hr/ cus.yr
CAIDI	22.556	hr/cus.int
ASAI	1.0000	
ASUI	0.0000	

TABLE VII. SYSTEM INDICES FOR RBTS BUS 4 (CABLES TYPE) BASED ON THE MMCS METHOD

System Indices	Index value	Measurement Unit
SAIFI	0.190451	Int/cus.yr
SAIDI	4.296624	hr/cus.yr
CAIDI	22.56026	hr/cus.int
ASAI	0.9999367	
ASUI	0.0000633	
ENS	73685	kWh/yr
AENS	15.415	kWh/cus.yr

V. CONCLUSION

It is found that classical MCS is able to assess the reliability of radial and open-ring networks and cannot assess the reliability of closed-ring ones. In this paper, MMCS is modified by integration of TLOC definition into the classical MCS technique. In this paper, the reliability of RBTS Bus-2 and Bus-4 are assessed in order to verify the correctness of the proposed MMCS method. The matching of both results show the rightness of MMCS method as given in Case Studies A and B. In addition, MMCS method is suitable for complex closed ring networks as well as for smart grids. Furthermore, the importance of simulation techniques originates from the fact that it can evaluate the reliability of complex systems, and is able to provide a wide range of system behavior such as probability density functions and then effectively able to expect the future reliability indices.

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