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Research Article

HISTORICAL AND MONTE CARLO SIMULATION-BASED RELIABILITY ASSESSMENT OF POWER DISTRIBUTION SYSTEMS

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ABSTRACT

Historical reliability assessment, which is based on past real data, is vital for utilities since it reflects the system's operational behavior best. Therefore, most utilities prefer historical reliability assessment rather than a predictive assessment. This paper includes two major parts; the first part analyses the historical data for four feeders sector of the Bosporus Electricity Distribution Incorporated distribution grid based on their historical collected data, while, the second part of the paper uses the analyzed historical data as a reference input for the Monte Carlo simulation method to assess the future reliability analysis. The results show that the proposed reliability assessment methodology is a powerful tool for the future reliability assessment of power distribution grids.
Keywords: Power system reliability, historical assessment, Monte Carlo Method, Istanbul.

1. INTRODUCTION

It is crucial to assess and evaluate the reliability of power systems to get the most accurate and appropriate decision in planning, operation, and maintenance. Historical assessment and predictive assessment are widely used methods to evaluate the reliability of a distribution network. Analytical and simulation are the two basic methods of predictive reliability assessment. Moreover, analytical methods can be categorized into two groups, network modeling and Markov modeling [1].

On the other hand, simulation is the most flexible method, but it is computationally-extensive. However, most utilities prefer historical assessment rather than a predictive assessment. This is because of the historical assessment based on real data, which is very vital in reliability analysis and can be a reference for comparison with other reliability assessment techniques [2]. Therefore, the utilities need to maintain and update the data recording systems for plans and analysis. The collected real data would improve the system studies in the future and the overall reliability of the system. The importance of reliability studies for utility operators is vital for determining the most

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frequent ca use of failures, such as areas of the highest amount of energy not supplied as well as the weaker areas of protection system which contribute to interruptions and failures [3]. In [4], extensive historical reliability analysis of thirteen utilities that participate in the Canadian Electrical Association (CEA) is done to determine the historical performance and assess the financial risk for them.

Further, it is established the regulations that are needed to specify the reward/penalty levels. In [5], Swedish historical data for one distribution utility from 2004 to 2006 is used to assess customer outage compensation. The result showed that the annual outage cost was more than 500 Euro per customer. In [6], actual data for two different Canadian utilities are presented to enhance performance-based regulation in a deregulated environment to ensure an acceptable level of service reliability to customers. In [7], Monte Carlo Simulation (MCS) is used to assess the reliability of distribution systems due to severe weather. In [8], MCS is also used to assess the impact of distributed generation on system reliability. In [9], MCS, as well as is used to assess the reliability of complex structural power systems. The principal objective of this paper is to evaluate the reliability of distribution networks for the four-feeders sector of the BEDAS network and to determine the system reliability indices using historical, and MCS approaches. Results from these approaches and some changes in the study of philosophy are analyzed and compared.

In this paper, the following significant issues shall be discussed: (1) showing the importance of reliability assessment studies in planning, design, and maintenance of power systems; (2) assessing the existing reliability indices of the distribution network system of four-feeder related to BEDAS network in Istanbul via historical assessment; (3) determining the reliability indices using MCS method; and (4) comparing the results for further recommendation and improvement in decision making of planning, design, and maintenance based on MCS method and some changes in the operating philosophy.

2. DISTRIBUTION NETWORK STRUCTURE IN TURKEY

Like most countries, in Turkey, the structure of electric distribution networks is a radial-operated configuration or meshed designed radial-operated such as the Bayazit-Beyoglu distribution section in the old city of Istanbul Figure 1. Besides, a substantial part of the BEDAS network is ring designed and radial-operated, e.g., the considered network in this paper, as shown in Figure 2. Many distribution utilities have been trying to improve their grids by converting them into closed rings instead of radial ones based on innovative bidirectional protection devices and modern control equipment [12], [13]. Also, power electronic converter switches in place of manual-operated ones play a vital role in such grids [14]. In Turkey, there are many trials from the Scientific and Technological Research Council of Turkey (TUBITAK) to develop the distribution system's automation and structure. TUBITAK-UZAY [11] proposed new functions for fault detection and service restoration for BEDAS in Istanbul, known as the TUBITAK Distribution Automation System (TUDOSIS). In [15], an algorithm is proposed based on TUDOSIS for fault detection and system restoration in medium voltage distribution systems. The system has been operated successfully for more than ten years in Istanbul. Nevertheless, this period has expanded the distribution system without the application of automation technology due to lack of funds; thus, impeding TUDOSIS to work correctly.

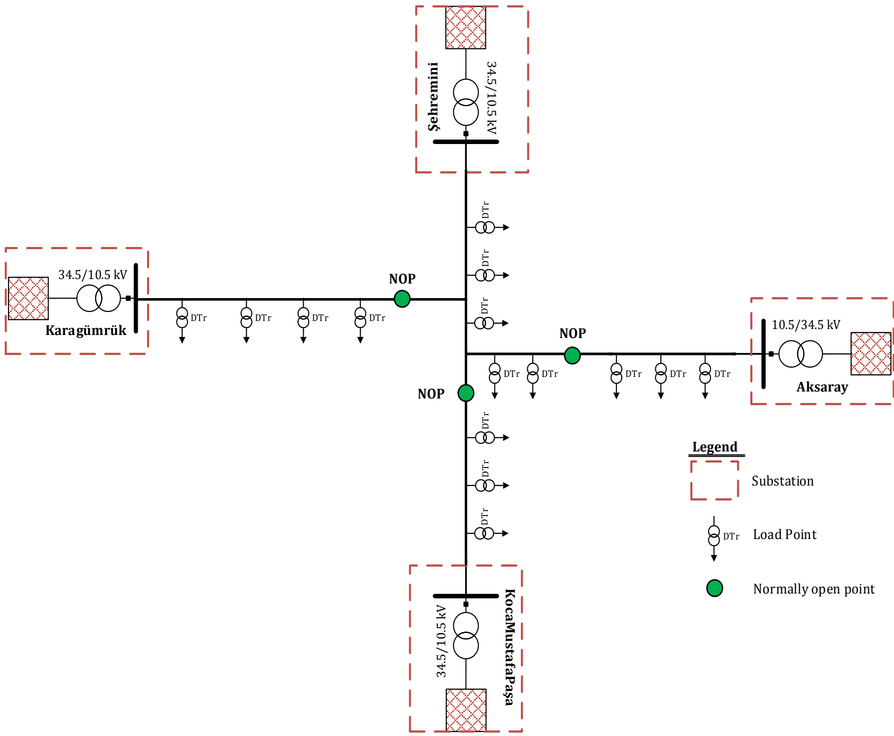

Figure 1. Bayazit-Beyoglu distribution section mes hed designed radial-operated

3. DESCRIPTION OF SYSTEM CONFIGURATION

The historical data for the four-feeders sector of the BEDAS grid in Istanbul, which is considered as the largest distribution company in Turkey serving about 5 million customers, are used to assess the reliability of the electric distribution grid. The understudy sector comprises four 34.5 kV distribution feeders between the Levent and Cendere central transformers (CT), as shown in Figure 2.

To evaluate the historical assessment reliability for the system given in Figure 2, it is needed to collect the following data [16]:

- The failure data of the components.
- The outage and the switching time data for each component.
- Average load and peak load at each load point.
- The number of customers connected at each load point.
- The length of the feeder's sections and laterals.
- The data mentioned above required for reliability assessment are given in Tables 1-4.

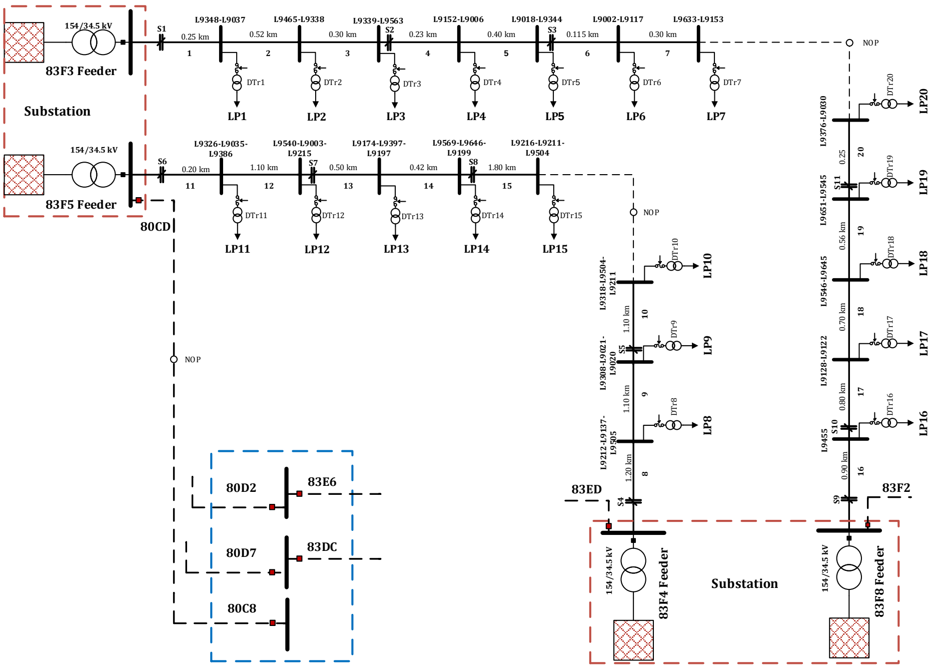

Figure 2. Single line diagram of BEDAS 4-Feeders distribution system

Table 1. Feeder's sections and laterals length data in km

S.N*	F1**: 83F3	S. N	F2: 83F4	S. N	F3: 83F5	S. N	F4: 83F8
1	0.25	8	1.20	11	0.20	16	0.90
2	0.52	9	1.10	12	1.10	17	0.80
3	0.30	10	1.10	13	0.50	18	0.70
4	0.23	28	0.595	14	0.42	19	0.56
5	0.40	29	0.313	15	1.80	20	0.25
6	0.115	30	0.331	31	0.086	36	0.316
7	0.30			32	0.272	37	0.127
21	0.11			33	0.222	38	0.335
22	0.252			34	0.156	39	0.208
23	0.181			35	0.397	40	0.221
24	0.152						
25	0.273						
26	0.10						
27	0.217						

* **S.N:** Section Number, ****F_i:** Feeder Number

Table 2. Feeder load point in kW

Load Point	Average Load/Customer	Peak load/ Customer
1-7, 11-15	2.50	3.125
8-10, 16-20	3.00	3.750

Table 3. Four feeder customer data

Load Point	No. of Customers	Load Point	No. of Customers
1	3305	11	3281
2	1447	12	3571
3	866	13	4742
4	2378	14	6335
5	640	15	8023
6	209	16	2611
7	549	17	2866
8	5439	18	2103
9	5216	19	663
10	7322	20	735

4. HISTORICAL RELIABILITY ASSESSMENT OF BEDAS NETWORK

The reliability indices categorized into two main groups, namely, load point indices (failure rate (λ), repair time (r), and annual outage time (U)) and system indices (SAIFI, SAIDI, CAIDI, ASAI, and ENS) as given in [21]. The historical assessment results from 2012 to 2014, are summarized as given in Tables 5 and 6. Furthermore, the results are depicted in Figures 3, 4, 5, and 6.

Table 4. Feeder switches locations

Feeder	Section No.
F1	S (1,1), S (2,4), S (3,6)
F2	S (4,8), S (5,10)
F3	S (6,11), S (7,13), S (8,15)
F4	S (9,16), S (10,17), S (11,20)

S (x, y): Switch location, where x is number of switches, while y the number of sections

Investigating Figure 3 shows that Feeder 83F8 has the smallest SAIFI, 0.0305, and 0.0611 interruption /customer for the years 2012 and 2013, respectively. Therefore, the customer supplied from this feeder experiences the least occurrence of sustained interruptions between all feeders. On the other hand, the Feeder 83F5 has the highest SAIFI, 0.4679, and 0.2366 for the years 2012 and 2013, respectively.

Based on the historical assessment of the BEDAS system, it is possible to extract the reliability data, which is necessary to predict the system's future reliability using MCS. Table 7 summarizes the reliability data. In this study, it is noticed that the most failures were with the lines such as earth fault and phase-to-ground fault. The only failure with circuit breakers (CB) was registered for one time at 9540 CT related to Feeder 83F3 due to the explosion of CB. Similarly, the failure of transformers occurred for one time at 34.5/0.4 kV 9569 CT related to 83F5 feeder due to a rat's external cause.

Table 5. Feeders and system indices for the period 2012-2013

Feeders/Indices	SAIFI	SAIDI	CAIDI	ASAI	AENS
F1-83F3	0.1825	0.3499	1.9178	0.99996006	0.87
F2-83F4	0.0797	0.0964	1.2105	0.99998899	0.24
F3-83F5	0.4679	0.4952	1.0582	0.99994347	1.24
F4-83F8	0.0305	0.0285	0.9333	0.99999675	0.07
System-Average	0.1901	0.2425	1.2754	0.99988927	0.61
SAIFI- interruptions/customer.year, **SAIDI** hrs/customer.year **CAIDI-** hrs/customer. interruption, **AENS-** kWh/customer. year					

Table 6. Feeders and system indices for the period 2013-2014

Feeders/Indices	SAIFI	SAIDI	CAIDI	ASAI	AENS
F1-83F3	0.1245	0.0692	0.5557	0.99999210	0.17
F2-83F4	0.1408	0.1286	0.9133	0.99998532	0.32
F3-83F5	0.2366	0.1458	0.6162	0.99998336	0.36
F4-83F8	0.0611	0.0326	0.5333	0.99999628	0.08
System-Average	0.1408	0.0940	0.6681	0.99995706	0.24

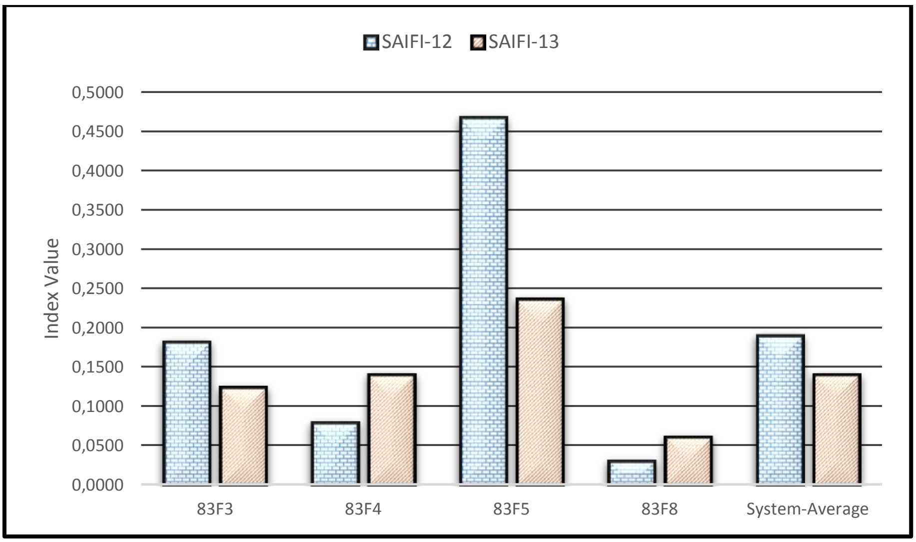

Figure 3. Feeders and system SAIFI index for the period 2012-2014

Similarly, the Feeder 83F8 has the least interruption duration with 0.0285 and 0.0326 *SAIDI* index for the years 2012 and 2013, respectively, as shown in Figure 4. However, Feeder 83F5 has the highest interruption duration with 0.4952 and 0.1458 SAIDI index for the years 2012 and

2013, respectively. Examining Figure 5, it can be noticed that the feeders have, to some extent, a similar amount of reliability with about system reliability of 0.99988927 and 0.99995706 for the years 2012 and 2013, respectively.

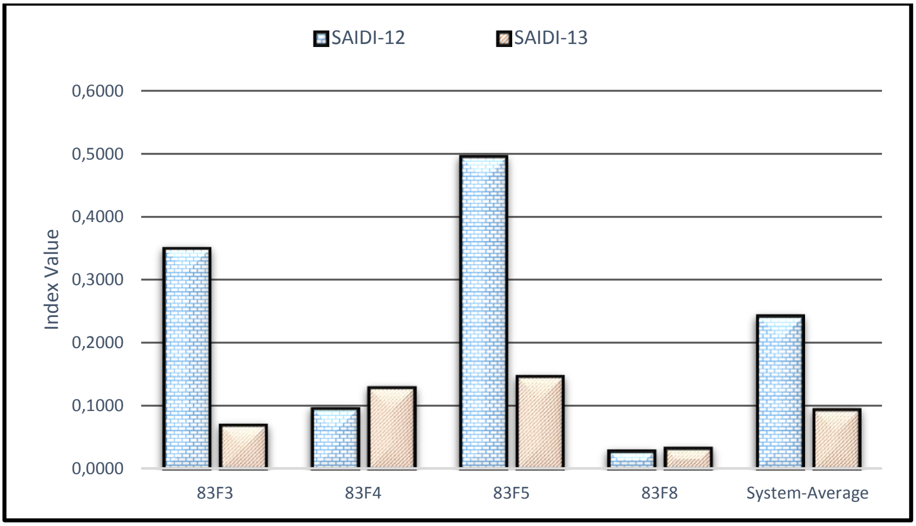

Figure 4. Feeders and system SAIDI index for the period 2012-2014

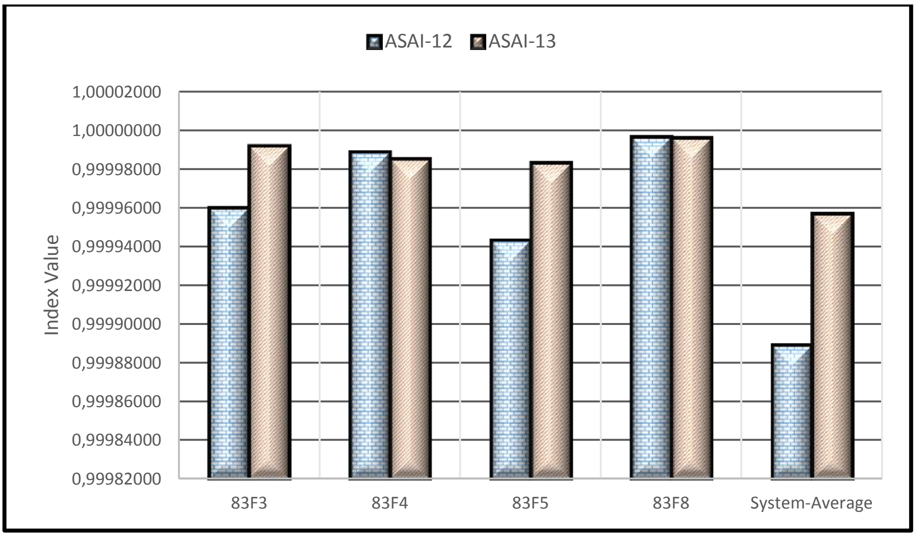

Figure 5. Feeders and system ASAI index for the period 2012-2014

It is essential to measure the average amount of non-supplied energy to the customer since it is a primary index in cost interruption evaluation. Figure 6 shows that the average AENS is found to be 0.61 and 0.24 kWh/year/customer for the years 2012 and 2013, respectively.

Table 7. System reliability data for the period 2013-2014

Component	λ (Failure/Year)	r (hours)
Transformer 34.5/0.40 kV	0.025	3.0
Circuit Breakers 34.5/0.4 kV	0.025	2.0
Lines 34.5 kV	0.05	1.5
Lines 0.4 kV	0.125	1.0

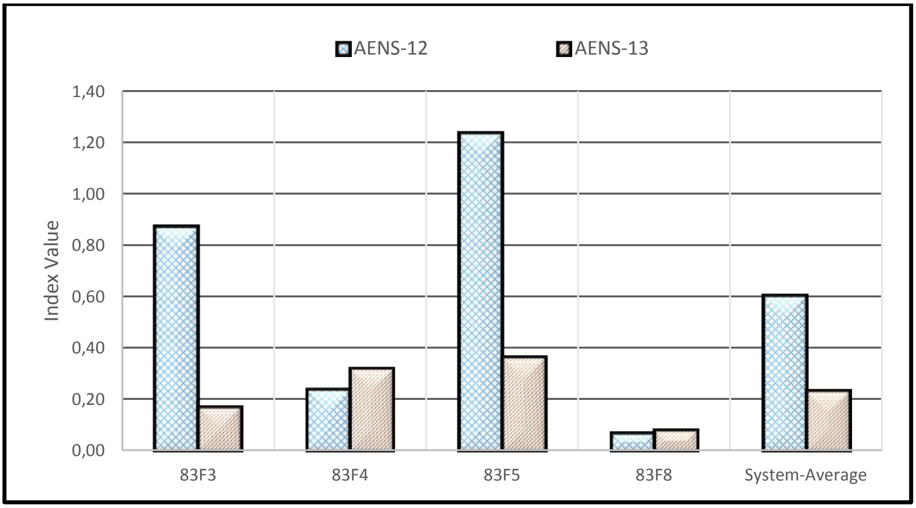

Figure 6. Feeders and system AENS index for the period 2012-2014

5. RELIABILITY ASSESSMENT VIA MONTE CARLO SIMULATION

Monte Carlo simulation uses mathematics and statistics to model real-time systems and then predict future values. Monte Carlo technique occupies a distinctive standing in many fields such as complicated mathematical calculations, stochastic simulation, medical statistics, engineering system analysis, and reliability evaluation [17]. MCS introduces a powerful approach to estimate the reliability of a system [18]. However, to perform MCS, the statistical distributions of time to failure (TTF) and repair to time (TTR) must be determined. The failure process was frequently modeled using Weibull or Exponential distribution, while Lognormal or Exponential distribution for modeling repair process [19]. In this paper, Exponential distribution is used for modeling both TTF and TTR as in equation (1) [20]

$$TTF = -\frac{1}{\lambda}\ln(n)\,, \quad TTR = -\frac{1}{\mu}\ln(n) \tag{1}$$

where: λ, is the failure rate, μ, is repair rate and n, is a random number between 0 and 1

MCS is used to generate the TTF and TTR for each component based on random numbers and usually uniform random numbers [21-23]. To obtain accurate and robust results, it is crucial to expand the simulation time to be tens or hundreds of thousands of years. Figure 7 explains the steps of MCS [24], [25].

In this study, the following operating conditions are taken into account;

- All feeder sections and lateral distributors' failures are included.
- All protection devices and sectionalizers are assumed to be 100% reliable.
- Not all the feeder sections have sectionalizer (see Table 4), while all laterals have fuses at the starting point of lateral.
- All customers are residential.
- All 34.5 kV feeders' sections and 0.4 kV lateral distributors are overhead lines.
- The average time for repair is 2 hours.
- The average failure rate for 34.5 kV lines is 0.05 failure/year, while 0.4 kV lines is 0.125 failure/year.

The results of MCS reliability assessment are given in Table 8 with a comparison with average system reliability indices based on historical assessment. Figure 8 illustrates the difference in system reliability indices between both approaches.

Table 8. Comparison between historical and MCS assessments

Indices	Historical Assessment	MCS Assessment
SAIFI	0.165	0.1163
SAIDI	0.168	0.4382
CAIDI	1.017	3.767
ASAI	0.99992316	0.99956999
AENS	0.42	0.25

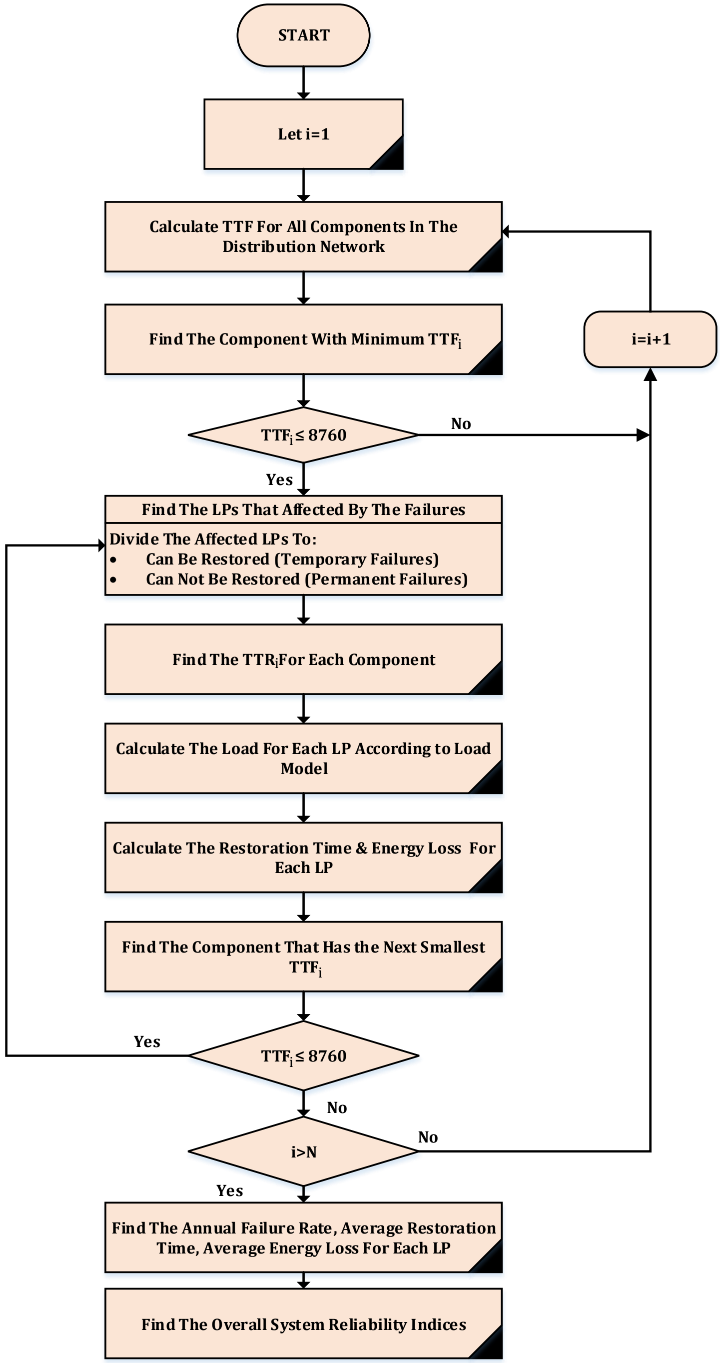

Figure 7. Flowchart for evaluation reliability of distribution system based on MCS

Investigating Table 8 shows that there is, to some extent, a difference between the results of historical reliability analysis and MCS analysis. This difference is because of the historical reliability assessment based only on three years of data. The simulation in this paper based only on these years; since no data were missing within 2012-2014 years compared with the other data collected during 2008-2012. Due to this, the data were insufficient to create the probability distribution function of TTF and TTR [26], [27]. Based on the minimum advised period for proper reliability evaluation is five years of reliability data, while ten years is the best for accurate reliability evaluation and expectation [28-30]. Furthermore, it is necessary to notice that the maximum difference was in CAIDI, which can be explained due to the sensitivity of this index to SAIFI and SAIDI. In other words, any change in SAIFI, SAIDI, or both causes dramatically change in CAIDI.

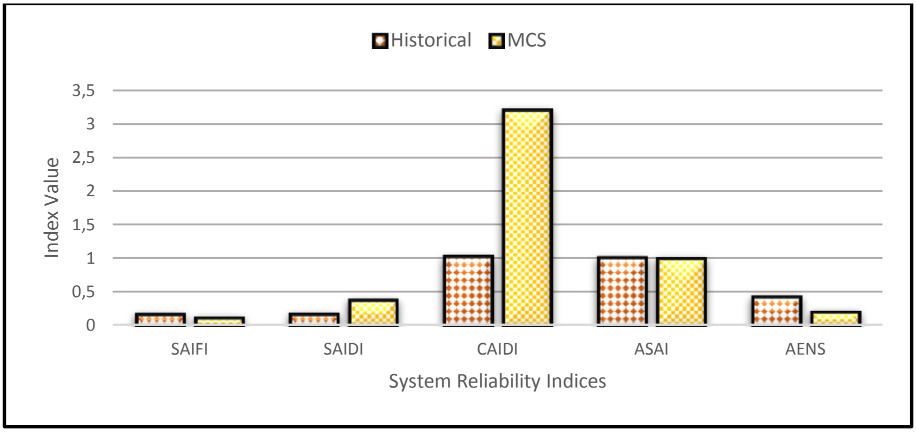

Figure 8. Comparison between historical and MCS reliability assessment

6. CONCLUSION

The distribution system's historical reliability assessment is instrumental in the sense that it can be a reference to other reliability assessment techniques. Moreover, it is an essential tool in planning, design, and maintenance programming of power systems. In this paper, the historical reliability assessment for the four feeders of the BEDAS distribution network is evaluated and compared. Due to the shortage of real historical data, it was challenging to create the probability distributions functions of TTF and TTR, and due to, there were some differences between the historical results and MCS results. Therefore, MCS based on average system values extracted from the historical assessment. MCS introduces a powerful approach to estimate the reliability of power systems. The results of the comparison are given in Table 8 and Figure 8. In this paper, it is found that Feeder3-83F5 experiences the most significant frequency and duration of interruption with 0.4679 and 0.2366 for SAIFI index, and 0.4952 and 0.1458 SAIDI index for the years 2012 and 2013 respectively, while Feeder4-83F8 experiences the least frequency and duration of interruption with 0.0305 and 0.0611 for SAIFI index, and 0.0285 and 0.0326 SAIDI index for the years 2012 and 2013 respectively. Finally, the proposed methodology for reliability evaluation is a powerful tool to determine the network's weakness and then decide the relevant remedial actions required to achieve specified service reliability levels. Power utilities and electric companies in Turkey can consider the following recommendations to improve their systems' reliability;

• Continuous and accurate registration of different failures and interruptions by preparing certain forms, including all data needed for reliability analysis.

• Training the crew of maintenance to take care of filling out the forms of reliability on time and the date of fault, the cause of failure as well as the exact period for repair and restoration.

• Preparing a smart mobile application instead of filling out forms; to increase registration speed and the accuracy of the collected data.

• Organizing the collected data into a database to simplify future reliability studies.

• Increase the number of sectionalizers at feeder sections to reduce the number of customers being interrupted.

• Replacing manual sectionalizers by automated ones to reduce the time of restoration.

• Installing insulators and anti-bird cones on the top of poles impede birds from access to distribution transformers and connections.

• To ward off the rodents, it is essential to use tightly sealed cabinets, poison materials, or ultrasonic devices.

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APPENDIX

$$\mathrm{SAIFI} = \frac{\text{Total Number of Customer Interruptions}}{\text{Total Number of Customers Served}} = \frac{\sum_i \lambda_i \; N_i}{\sum_i N_i}$$

$$\mathrm{SAIDI} = \frac{\text{Sum of Customer Interruption Durations}}{\text{Total Number of Customers Served}} = \frac{\sum_i U_i \; N_i}{\sum_i N_i}$$

$$\mathrm{CAIDI} = \frac{\text{Sum of Customer Interruption Durations}}{\text{Total Number of Customer Interruptions}} = \frac{\sum_i U_i \; N_i}{\sum_i \lambda_i \; N_i}$$

$$\mathrm{ASAI} = \frac{\text{Customer Hours of Available Service}}{\text{Customer Hours Demanded}} = \frac{\sum_i \; N_i \times 8760 - \sum_i U_i \; N_i}{\sum_i \; N_i \times 8760}$$

$$\mathrm{ENS} = \text{Total Energy not Supplied by the System} = \sum_i L_i \, U_i$$

$$\mathrm{AENS} = \frac{\text{Total Energy not Supplied}}{\text{Total Number of Customers Served}} = \frac{\sum_i L_i \, U_i}{\sum_i N_i}$$

where:
N_i: *is the number of customers of load point* i
8760: *is the number of hours in a calendar year*
L_i: *is the average load connected to load point* i

NOMENCLATURE

AENS:	Average Energy Not Supplied (kWh/customer/year)
ASAI:	Average System Availability Index
BEDAS:	Bosporus Electric Distribution LTD Company
CAIDI:	Customer Average Interruption Duration Index (hour/failure)
CEA:	Canadian Electrical Association
CT:	Central Transformer
DTr:	Distribution Transformer
ENS:	Energy Not Supplied (MWh /year)
LP:	Load Point
MC:	Monte Carlo
MCS	Monte Carlo Simulation
S:	Switch
SAIFI:	System Average Interruption Frequency Index (interruption/customer)
SAIDI:	System Average Interruption Duration Index (hour/interruption)
S. N.	Section Number
TTF:	Time to Failure
TTR:	Time to Repair
TUBITAK:	The Scientific and Technological Research Council of Turkey
TUDOSIS:	TUBITAK Distribution Automation System
U:	Average Annual Outage (hour/year)
λ:	Average Failure Rate (failure/year) for lines and cables (failure/year.km)
μ	Average Repair Rate (hour/year)