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Sensitivity Reliability Analysis of Power Distribution Networks Using Fuzzy Logic

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***Abstract*—This paper proposes a combined method utilizing both the reliability block diagram analytical technique and the Monte Carlo simulation method to estimate the reliability of power systems. Since the reliability of collected data is associated with noise and erroneous data, performing the sensitivity analysis is indispensable. Sensitivity analysis utilizing fuzzy logic specifies these uncertainties and their effects on the reliability calculations. The proposed method is applied to the Roy Billiton Test System Bus-2 to confirm its applicability. The obtained results have verified the sensitivity analysis's importance in drawing an accurate picture of reliability evaluation and a crucial tool for distribution power utilities to identify the susceptible parameters that seriously erode the system's complete reliability.**

***Index Terms*—Power distribution networks, Monte Carlo simulation, reliability, reliability block diagram, sensitivity analysis, fuzzy logic, Roy Billiton test system.**

I. INTRODUCTION

The power system can be divided into three major areas of operation: generation, transmission, and distribution. The primary duty of the distribution system is to deliver electricity to the customers as reliable and cost-effective as possible. However, it has been found that more than 80% - 90% of failures occur in the distribution system [1] [2] [3] [4]. This pushed to improve the quality of the overall power system and, particularly, the distribution system. The quality of any system can be divided into two levels: power quality and power reliability [5] [6]. Although reliability and power quality are partially related, they are two independent problems, as illustrated in Figure 1. Reliability indicates the capability of a system to achieve the role it is planned for, considering all the operational constraints undergone through its expected lifetime [7]. Therefore, the reliability belongs to total electric interruptions such as the number of customers, the connected load, the interruption duration, the amount of interrupted power, and the frequency of interruptions [7]. In other words, improving reliability can be accomplished by reducing one or both factors: frequency of interruptions (number of failures) and outage time of power supply (duration of failures). Reliability evaluation can be categorized into historical and predictive evaluations. The historical evaluation mainly depends on the historical data collection, analyzing the cause and the duration of system components failures, system outages, and customer interruptions. Predictive reliability evaluation combines historical interruption data and mathematical models to approximate the system's reliability. Reliability evaluation mainly depends on the reliability of system parts [8].

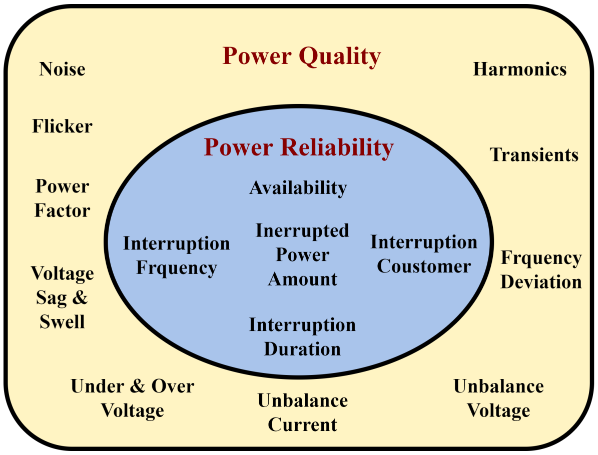


Fig. 1: Power quality and reliability relation.

Wadi and Baysal [9] developed an analytical Reliability Block Diagram (RBD) approach to evaluate the radial networks reliability by integrating the Failure Mode and Effect

Analysis (FMEA) technique. The developed approach showed more simplicity than the Markov and fault tree analysis. The reliability of the closed-loop distribution networks was assessed using the Total Loss Of Continuity (TLOC) technique. The results were compared to open ring power systems, and dramatic improvement in reliability of the closed-loop was shown [10] [11]. Wadi et al. [12] presented a practical approach to evaluating the reliability of closed-loop power distribution networks utilizing the combination of TLOC and MCS techniques yielding a new approach called Modified MCS (MMCS). Bus-2 and Bus-4 were utilized to conduct the study that verified the suitability of the presented method. The combination of the MMCS method and sensitivity analysis was appeared in the literature to estimate the closed-loop distribution power networks [13]. The study was verified based on three different systems and scenarios. Wang [14] presented an analytical method that considers the stochastic Load Points (LPs) interruption duration and network reconfiguration to evaluate the reliability of complex grids. It was examined on Bus-2 and Bus-4.

The following sections are organized, as The reliability indices are explained in Section II. The reliability estimation in power distribution networks utilizing Reliability Block Diagram (RBD) and MCS is given in Section III. Section IV presents the sensitivity analysis based-fuzzy. Section V demonstrates the results. Sections VI concludes the paper.

II. RELIABILITY INDICES

The reliability estimation for any power system is divided into three phases. The LP indices such as the failure rate (λ), repair rate (μ), repair time per failure (r), and annual failure duration (U) are calculated in the first phase. In the second phase, for each LP, Time-To-Failure (TTF) and Time-To-Repair (TTR) are computed [12] [15] [16]. Finally, the whole system reliability indices are computed in the third phase.

$$\lambda_{sys} = \sum_{i} \lambda_i \tag{1}$$

$$U_{sys} = \sum_{i} \lambda_i \ \ r_i \tag{2}$$

$$r_{sys} = \frac{U_{sys}}{\lambda_{sys}} = \frac{\sum_i \lambda_i \ \ r_i}{\sum_i \lambda_i} \tag{3}$$

Where

$$\lambda = \frac{Number\ of\ Failures}{Total\ Operation\ Time} \tag{4}$$

$$\mu = \frac{Number\ of\ Repairs}{Total\ Maintenance\ Time} \tag{5}$$

TTF and TTR using exponential distribution can be calculated [17]:

$$TTF = -\frac{1}{\lambda} \ln{(r_n)}, \quad TTR = -\frac{1}{\mu} \ln{(r_n)} \tag{6}$$

where r_n takes values within [0, 1].

Depending on LP index values and TTF and TTR parameters, the overall system indices (SAIFI, SAIDI, CAIDI, and ASAI) can be calculated.

$$SAIFI = \frac{\sum_i \lambda_i \ N_i}{\sum_i N_i} \tag{7}$$

$$SAIDI = \frac{\sum_i U_i \ N_i}{\sum_i N_i} \tag{8}$$

$$CAIDI = \frac{\sum_i U_i \ N_i}{\sum_i \lambda_i \ N_i} \tag{9}$$

$$ASAI = \frac{\sum_i \ \ N_i \times AH - \sum_i U_i \ N_i}{\sum_i \ \ N_i \times AH} \tag{10}$$

where, N_i: is the number of customers of LP_i and AH is the annul hours ($\cong 8760$).

III. RELIABILITY ASSESSMENT IN POWER SYSTEMS

The following sections illustrate the most utilized reliability methods, the analytical RBD and the simulation Monte Carlo methods.

A. Reliability Block Diagram in Power Distribution System

RBD is a method to represent the system components into blocks logically. Each block symbolizes a single component. Besides, RBD is the foundation for the latest reliability estimation methods. In general, the power system includes series, parallel, and mixed series and parallel components. The block diagram technique can be applied to the power system considering a single input and a single output. In order to transfer energy from the input to the output, at least one active path is required [9] [18] [19]. Therefore, two formulas are used to calculate the reliability of series and parallel systems. For mixed series and parallel, firstly, the reliability of series is calculated, then the reliability of parallel. The formula of the series reliability $R_s\,(t)$ for m components is computed as follows.

$$R_s\,(t) = \ R_1\,(t) \times R_2\,(t) \times \ldots \times R_m\,(t) = \prod_{i=1}^{m} R_i\ (t) \tag{11}$$

Most components' life cycles generally follow the exponential distribution. If $\lambda_i\,(t)$ is the failure rate per a particular component, $R_s\,(t)$ can be calculated as follows.

$$R_s\,(t) = \ exp\left[-\sum_{i=1}^{n} \lambda_i \ t\right] \tag{12}$$

Mean-Time-To-Failure (MTTF), and probability of failure $Q\,(t)$ of a serial system can be calculated by equations 13 and 14.

$$MTTF = \frac{1}{\sum_{i=1}^{n} \lambda_i} \tag{13}$$

$$Q\,(t) = 1 - R_s\,(t) = 1 - \ exp\left[-\sum_{i=1}^{n} \lambda_i \ t\right] \tag{14}$$

If $R_i(t)$ is the reliability per component. Then, the parallel reliability of the system $R_p(t)$ with m components is computed using the probability of failure $Q(t)$ by equation 15.

$$R_p(t) = 1 - \prod_{i=1}^{n} Q_i(t) \tag{15}$$

Similarly, as for series components, the reliability of the parallel system based on the exponential probability density function is as follow:

$$R_p(t) = 1 - \prod_{i=1}^{n} \left(1 - exp\left[-\sum_{i=1}^{n} \lambda_i \, t\right]\right) \tag{16}$$

Generally, for n identical parallel blocks, MTTF can be calculated as follow:

$$MTTF = \frac{1}{\lambda} + \frac{1}{2\lambda} + \frac{1}{3\lambda} + \ldots + \frac{1}{n\lambda} \tag{17}$$

B. Monte Carlo Simulation for Power networks

Many methods have appeared in the literature to assess the reliability of power systems. However, MCS is the prevalent one. The main advantage of MCS is that it can imitate the random behavior of the components. Consequently, MCS can yield arbitrary values of λ and μ per component like relays, circuit breakers, transformers, generators, and lines. As mentioned before, both TTF and TTR are calculated by calculating λ and μ. Afterward, the whole system indices can be calculated, and the distribution per component can be established. The established distributions can be utilized to predict any component reliability. Figure 2 shows the flowchart of the MCS for reliability estimation. In brief words, MCS can construct an artificial history of the component's failure by employing its ability to generate random values for LP index values.

IV. SENSITIVITY ANALYSIS

Reliability evaluations commonly depend on historically recorded data gathered by the site workers, simulation, or statistical analysis, that in most cases, leads to an inaccurate assessment of reliability because of shortage or error of the gathered data. Sensitivity Analysis (SA) is required to get rid of this dilemma. The SA offers a tool for investigating and verifying the obtained results by considering all the uncertainties combined in reliability data to get accurate results. In addition, it is crucial when considering renewable energies such as solar and wind [20] [21] [22] [23]. Fuzzy logic [24] [25] is an effective technique to treat the uncertainties associated with collected data for reliability [26] [27] [28]. Thus, this study utilizes fuzzy logic to characterize the uncertainties of reliability data of the distribution lines and transformers. Four fuzzy inputs are utilized for each component, age, risk, weather conditions, and maintenance. Two fuzzy outputs are used for each component, λ and r, as displayed in Figures 5 and 6.

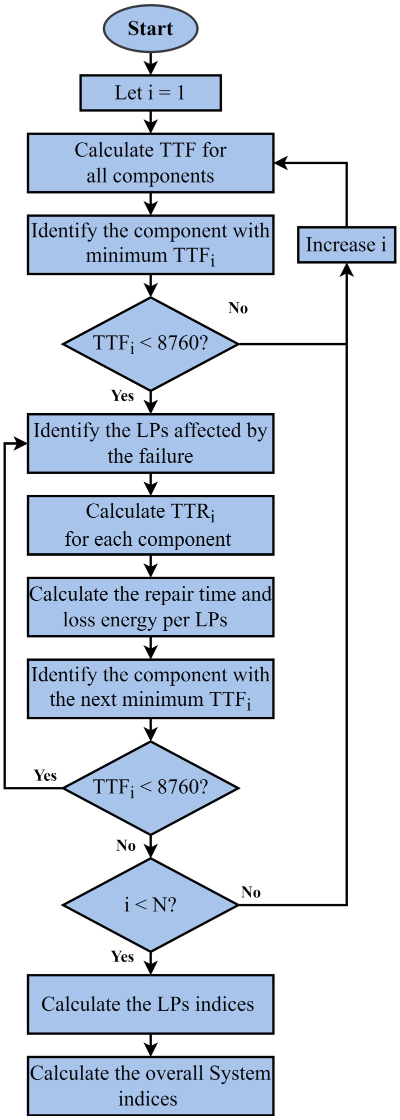
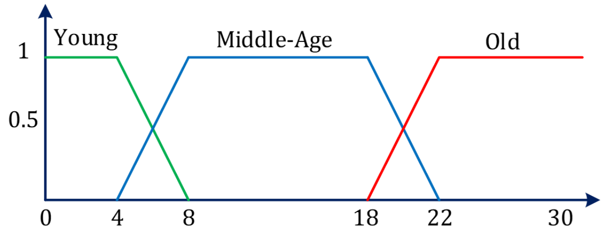


Fig. 2: Flowchart of the MSC for reliability evaluation distribution power system

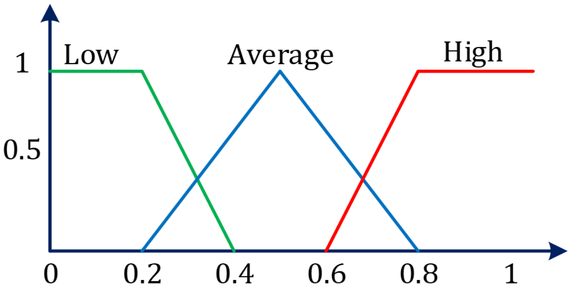
V. RESULTS AND DISCUSSION

The presented combined RBD and MCS approach is tested on Bus-2 to verify its accuracy. The reliability data and calculations of this bus were designed for educational objectives. This test bus consists of four main feeders (F1, F2, F3, and F4) and 22 LPs. Figure 5 The needed data to execute the reliability study are available in [29]. This system was solved analytically by hand [30] to present a complete summary of reliability estimation. The reference case is also solved utilizing the simulation program, DigSILENT [31]. This study solved the reference case [31] by the combined RBD and MCS and compared to [30] and [29] [32], as shown in Table I. The results matching in Table I prove the suitability of the proposed reliability estimation approach.

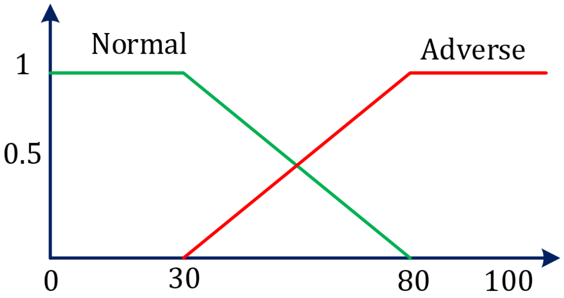
In general, the most performed reliability assessments depends on the average values of λ, μ, and r of each component



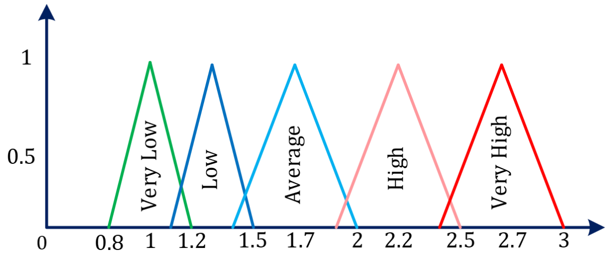
(a) Input Membership Function (MF) of line age



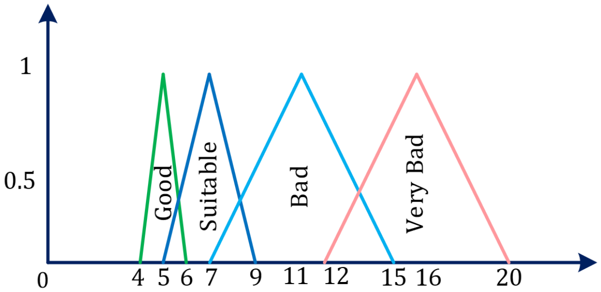
(b) Input MF of Line risk



(c) Input MF of line weather

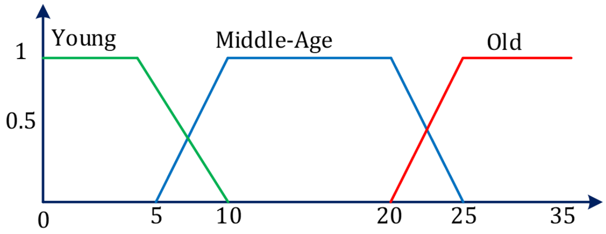


(d) Output MF of line failure rate

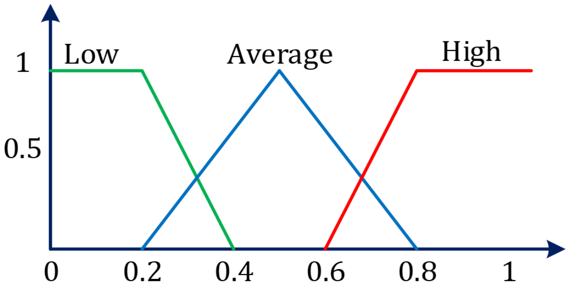


(e) Output MF of line average outage time

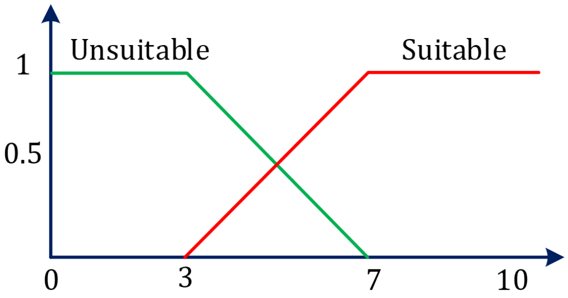
Fig. 3: Fuzzy MFs of the line.



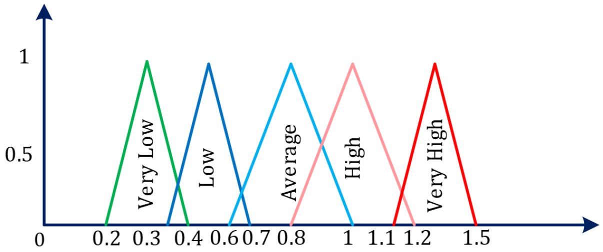
(a) Input MF of transformer age



(b) Input MF of transformer exposure risk



(c) Input MF of transformer operation conditions



(d) Output MF of transformer failure rate

Fig. 4: Fuzzy MFs of the transformer.

TABLE I: Bus-2 system reliability indices.

System Indices	**Index Value [30]**		**Index Value [31]**	**Index Value [*This Study*]**	
	1^{st} Case	2^{nd} Case	1^{st} Case	1^{st} Case	2^{nd} Case
SAIFI	0.16	0.41	0.159	0.15923	0.412
SAIDI	5.03	29.3	5.02	5.01721	29.364
CAIDI	31.75	71.55	31.65	31.5125	71.583
ASAI	0.99943	0.99667	0.99911	0.99944	0.99667
ASUI	0.00057	0.00333	0.00089	0.00056	0.00333
ENS	54656	305625	-	54662.75	305630.45
AENS	28.75	160	-	28.64921	160.20112

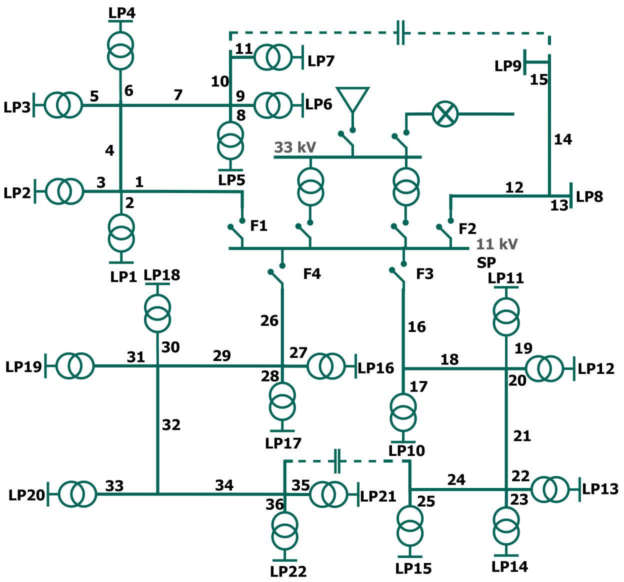


Fig. 5: RBTS Bus-2.

within the power system. The importance of SA originates from its ability to detect the uncertainties within these average values. Uncertainties are attributed to technical, operational, maintenance, and environmental factors. This study performs the SA considering the distribution transformers and lines since these two ingredients are the most susceptible to failure. Figures 3 and 4 depict the fuzzy MFs for transformers and lines. Table II displays nine cases in comparison to the reference case. The (age, risk, weather) are initialized as (20 years, 75%, 60 km/h) for the base case of the line, whereas the (age, risk, maintenance) are initialized as (20 years, 60%, three inspections) for the base case of the transformer. The last column in Table II displays the modifications obtained by the SA compared to the base case.

TABLE II: Fuzzy MFs input parameters.

Case No.	Line (Age, Risk, Weather)	Transformer (Age, Exposure, Maintenance)	Modifications
1^{st}	(20, 0.75, 60)	(20, 0.6, 3)	Reference Case
2^{nd}	(20, 0.75, 25)	(20, 0.6, 3)	Weather Condition
3^{rd}	(10, 0.75, 60)	(20, 0.6, 3)	Age of Line
4^{th}	(20, 0.4, 60)	(20, 0.6, 3)	Exposure Risk of Line
5^{th}	(20, 0.75, 60)	(10, 0.6, 3)	Age of Transformer
6^{th}	(20, 0.75, 60)	(20, 0.6, 6)	Maintenance of Transformer
7^{th}	(20, 0.75, 60)	(20, 0.3, 3)	Exposure Risk of Transformer
8^{th}	(20, 0.75, 25)	(10, 0.6, 3)	Cases 2 & 5
9^{th}	(10, 0.75, 60)	(20, 0.6, 6)	Cases 3 & 6
10^{th}	(20, 0.4, 60)	(20, 0.3, 6)	Cases 4 & 6 & 7

Table III presents the reliability results, taking account of the uncertainties of distribution lines and transformers parameters. The outcomes demonstrate that operating new lines and transformers, reducing the vulnerability risks, and performing regular maintenance of transformers dramatically enhance the system's reliability. In the third case, new distribution lines (for instance: ten years) improve the SAIFI index by 6.3% compared to the base case. The fifth case shows that utilizing new transformers like (ten years) instead of old ones (25 years) enhances the SAIDI index from 5.017 to 3.785. In the sixth case, raising the inspections of transformers, like embracing six inspections instead of three, enhances the SAIFI from 0.159 to 0.122.

TABLE III: Reliability analysis based on SA.

Case No	Line (λ,r)	Transformer (λ,, r)	$SAIFI$ int/cust.yr	$SAIDI$ hr/cust.yr	ENS kWh
1^{st}	(2.70, 13.5)	(1.0, 200)	0.159	5.017	54662.75
2^{nd}	(2.69, 11.0)	(1.0, 200)	0.153	5.011	54655.25
3^{rd}	(2.20, 13.5)	(1.0, 200)	0.149	5.011	54654.65
4^{th}	(1.96, 9.67)	(1.0, 200)	0.145	5.001	54650.22
5^{th}	(2.70, 13.5)	(0.8, 200)	0.143	3.785	47657.23
6^{th}	(2.70, 13.5)	(0.5, 200)	0.122	2.563	36558.86
7^{th}	(2.70, 13.5)	(0.8, 200)	0.143	3.766	47645.71
8^{th}	(2.69, 11.0)	(0.80, 200)	0.135	3.788	47668.45
9^{th}	(2.20, 13.5)	(0.5, 200)	0.112	2.668	31623.26
10^{th}	(1.96, 9.67)	(0.5, 200)	0.0986	2.466	29687.56

Combining the third and sixth cases as in the ninth case demonstrates considerable enhancements in reliability index values. For instance, the SAIFI, SAIDI, and ENS indices are improved by 29.56%, 46.82%, and 42.15%, respectively. As in the tenth case, the combination of fourth, sixth, and seventh cases depicts enhancements in SAIFI, SAIDI, and ENS indices reach 38%, 50.85%, and 45.69%, respectively. The ENS was also enhanced by 42% in the ninth and tenth cases when operating new lines and performing regular supervision for the transformers. Figure 6 and Figure 7 display the SAIFI and ENS improvement percents.

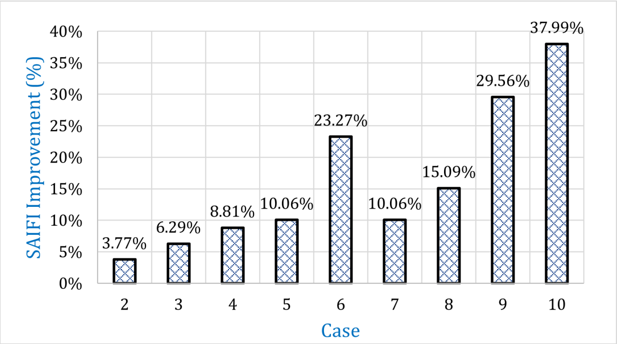


Fig. 6: SAIFI enhancement percents considering the reference case.

VI. CONCLUSION

Numerous approaches and methods have appeared to estimate power systems' reliability. MCS is the most prevalent method. This study integrates the RBD and MCS techniques to estimate the reliability of the power systems. The reliability of Bus-2 is utilized to verify the correctness of the suggested method, and the obtained outcomes prove its effectiveness. Besides, SA utilizing fuzzy logic to eliminate the uncertainty data overlapped with the reliability data is utilized to assess the Bus-2 reliability. The SA can accurately characterize the reliability index values compared to the reliability calculations depending on the average values. All the reliability indices are improved as the conditions of the power lines and transformers

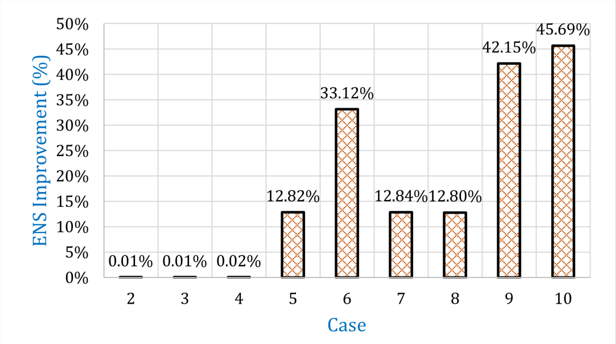


Fig. 7: ENS enhancement percents considering the reference case.

improve. For example, SAIFI, SAIDI, and ENS are enhanced by (29.56%, 46.82%, 42.15%) and (38%, 50.85%, 45.69%) in the ninth and tenth cases, respectively.

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