Reliability performance of distribution network by various probability distribution functions

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ABSTRACT

Electricity is one of the essential sources for the daily basis activities. The continuous electricity supplied to the customers is one of the main goals for electricity provider. Reliability is one of the main aspects that is focused more on the planning of the power system especially in distribution network. The performance of reliability in the system is evaluated with three main reliability indices: system average interruption frequency index, system average interruption duration index, and customer average interruption duration index. These indices will only give information about the overall condition of the power system without showing the details about the specific of the consumers such as the amount interruptions experienced by customer in the system. In this paper, probability distribution function (PDF) observing the behavior of the components in the system is used in the reliability analysis. Weibull distribution, also known as Weibull family, is one of the most common PDF used in reliability analysis. As Weibull distribution is also related to several distributions, such as exponential and Rayleigh, these types of distributions are applied in the output reliability analysis to observe the performance of reliability in the system. IEEE 9-bus is used as distribution network and carried out using Monte-Carlo simulation.

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1. INTRODUCTION

For the past decades, the reliability assessment is focus more on generation compared to distribution as it is known as individually capital intensive. In the other words, any failure in generation will give big impacts to the whole system [1]. But since distribution systems represents up to 90% of all consumers' reliability issues thus it very crucial for electrical provider to enhance the system as it will improve customer reliability. Therefore, the distribution system is expected to have a highest reliability. Reliability in power system is defined as the ability to provide continuous services to the customers [2]. A good reliable system means that the system experienced less interruptions within certain duration and the restoration time to have electricity back is shorter. The quality of the electrical distribution system is accessed by two factors which are the frequency of the occurrence of blackout and outage can be recover as soon as possible [3]–[6]. The power system especially the distribution system has been exponentially developed especially in terms of scale and innovation technology, the electrical provider must make ensure optimal strategic planning and cost-effectiveness is achieved [7]. Reliability is one of the most factors need to consider in designing the system. The reliability indices are used for the calculation of energy clarity by calculating the average system index. The main reliability indices used are system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI) and customer average interruption duration index (CAIDI) [8].

In most research, reliability performance analysis is analyzed based on the average customer interruption indices [9], which is based on the value of reliability indices. System reliability indices can be obtained from customer reliability indices or directly from failure data [8]. However, this system reliability indices performance only provides information about the customers without underlying probability distribution which only show the numerical value of the overall system performance without showing the specific changes of the reliability analysis in the stated duration. The used of the average value will cause misleading as the average value are based on duration stated such as monthly or yearly [10]. Hence, if there are major interruptions in the certain duration, it is difficult to detect and observe if the analysis is only using average value. The extreme occurrence can only be observed through the tails of distribution.

The use of average indices ignores the form of the probability distribution function (PDF) and restricts the consistency of index interpretation. This PDF will give an additional valuable information since the average yearly index does not show how consistent the random behavior of a system will differ from year to year [9]. The level of skewness of the PDF is important to interpret the data. Edimu *et al.* [9] employed PDFs for the assessment of system reliability performance by estimating the probability of networks performing within certain limits. This PDF can be applied in both input and output of reliability analysis in which for input PDF is plotted based on time to failure (TTF) and time to repair (TTR) in, while for output, the PDF is plotted based on reliability indices. Most of the research focus more on the application to the input instead of output of reliability. For example, Sheng *et al.* [11] and Baharum *et al.* [12] uses PDF to describe the TTF of the distribution system. As the output of reliability analysis refers to the reliability indices, hence in this analysis, different PDF which are exponential, Weibull, and Rayleigh distribution are selected to describe the reliability performance of the system.

2. PROBABILITY DISTRIBUTION FUNCTION

Probability distributions are used to model random events where the outcome is uncertain, for example the time a component fails. The time it will fail is unknown before demand for this component is made [13]. In engineering field especially manufacturing, probability distribution is used to model the collected data in which the properties of model are used to determine the product design, manufacture, reliability assessment and logistic supports [14]. In fact, a probability function is a statistical function describing all possible values and probabilities in a specific random variable range. These random variables will be classified into two types which are discrete or continuous. Discrete random number defined as the variable that be countable such as number of demands to failure whereas continuous random number defined as the values are in a given interval of numbers such as time-to-failure [13]. The range of this number will be plotted based on the probability distribution. Accordingly, PDF is actually an integral of the probability density function. This PDFs shows the probability of occurrence of an event using mathematical solutions within the time interval.

In reliability, PDF can be utilized in order to represent or model the failure rate in every stage of the curve. This PDF can be applied for both inputs and outputs of the reliability analysis as stated in. In this reliability analysis, two important input data used are failure rate and repair time. Failure rate refers to units' failure per unit time while repair time refers to the number of repairs per unit time [15]. In most cases, the fault data is obtained from the historical data recorded which then are fitted through the selected distribution functions in order to see the graph pattern of the failure data [8]. Edimu *et al.* [9] stated that the failure data is modelled by empirical models which are by standard PDF for the reliability performance analysis. Thus, the fault data in the reliability performance can be analyzed by plotting the TTF according to the selected PDF. TTF is used to decide on the time allocation for failure. While for the output, the PDF is used to describe the performance in the system based on the reliability indices. As stated above, four types of PDF are used in this analysis which are Weibull, exponential, Rayleigh, and exponential Weibull family.

2.1. Weibull distribution

Weibull distribution is the most common utilized distribution for modelling reliability data. It is highly flexible can handle many types of failure rate behavior with the right choice of parameters and models. This distribution is available with two or three parameters; scale, shape and location [16]. The shape and curve of Weibull distribution is determined by beta (β). The different beta (β) values show the different failure rate state. When $\beta<1$, the failure rate is a decreasing function of time t. In the case where $\beta>1$, failure rate is an increasing function of time t [17]. However, when $\beta=1$, the Weibull distribution becomes the exponential distribution with a constant failure rate which also known as special case of Weibull distribution. The formula of TTF obtained by doing inverse transform of the cumulative distribution functions (CDF) of the distributions. The CDF of the Weibull describe where λ represents the characteristic of life or the age at which 63.2% of units will have failed, while k represents slope of the best-fit line [17]. The distribution of

Weibull with the assumed shape parameter is usually better than the exponential distribution for most products, as pointed out by Nelson [18].

2.2. Exponential distributions

Exponential distribution is known as the most common used distribution compared to others [19]. It has a constant failure rate over time which differs from other probability distribution function. This unique property of exponential distribution makes it is suitable representing the bath curve of the graph. Bath curve represents the failure probability of the products. The tail of exponential distribution is flattened towards the end as the failure probability at the area is low due to the random failure. Exponential distribution is usually used to build lifespan distribution models and stochastic processes in general. Even if the simple mathematical form of distribution does not provide sufficient information about real life complexity, it typically acts as a basis for evaluating the consequences of departure that allow for certain sorts of disturbance. Exponential distribution is actually a special case the random failure. Exponential distribution is actually a special case of Weibull distribution which β=1. The TTF of the exponential distribution is obtained by inverse transform of the CDF.

2.3. Rayleigh distributions

Rayleigh is a continuous probability distribution for random variables with a positive value. In the other words, Rayleigh distribution is a continuous probability distribution that used to model random variables that can only take on values equal to or greater than zero. According to [20], This Rayleigh distribution is often used to the behavior of units that have an increasing failure rate. This Rayleigh distribution is also known as special Weibull distribution which β=2. The key element in Rayleigh distribution is that its failure hazard function is an increasing function of time [21]. As mentioned above, the TTF of the Rayleigh distribution is obtained by inverse transform of the CDF.

3. RESEARCH METHOD

Monte Carlo simulation (MCS) is mostly used in many fields such as engineering, physics and finance which used probability distributions in making selection [22]. One of its main properties, which can be used in the analysis of complex and large networks, makes MCS is the most suitable method for reliability assessment [23]. There are various desirable characteristics in the Monte Carlo system reliability analysis, the most essential being that it is reasonably easy to check the failure criterion, regardless of the system complexity [24]. MCS generates random numbers, which is repeated many times and takes into account the number of occurrences of a particular situation. MCS mimics the component and system fault and repair histories using the probability distributions of component condition [25]. Based on the collected data about the failure rate and the repair time of the component, the reliability of the system can be estimated.

In this analysis, IEEE 9-bus system is used as a distribution network system. The year simulation is set to 1,000 years. In MCS, the higher number of year simulations, the better the output of reliability analysis can be analyzed and observed. Hence, since the network has configured, the value of the basic inputs of the reliability need to assign according to the component. In Figure 1, the MCS approach need to generate random number of every component in the network and integrated with CDF equation (failure rate/repair time) to form TTF and TTR. The formulas for both TTF are based on the type of PDFs, while the formulas for TTR are the same for all PDFs. Basically, TTF decides the time to fault based on the calculated formula while TTR shows repair time allocated for each fault based on created TTF in the system. As the reliability analysis involved the interruption of the system, hence the simulation is simulated to force the fault of the component thus the analysis can be done.

3.1. Network and reliability inputs

IEEE 9-bus system consists of 9 bus, 9 branches, and 3 generators. The main focus in the analysis is to observe the failure on overhead line. The fault rate of overhead line is calculated based on the assigned length of the line by multiplying the fault rate of the component with its length. Figure 2 shows the IEEE 9 bus system. Failure fate and repair time are the basic input of the MCS. The failure rate means the number of equipment failure of a unit per unit time while repair rate is the number of repairs per unit failure [5]. The value of failure rate and repair time are selected based on data obtained from [6] as shown in Table 1. The component is chosen according to 0.4 kV as this analysis focus on low voltage (LV) system.

Table 1. Mean fault rate and repair time

Component	kV	Fault Rate (fault/year)	Repair time
Overhead Line (per km)	0.4	0.0706	6.44

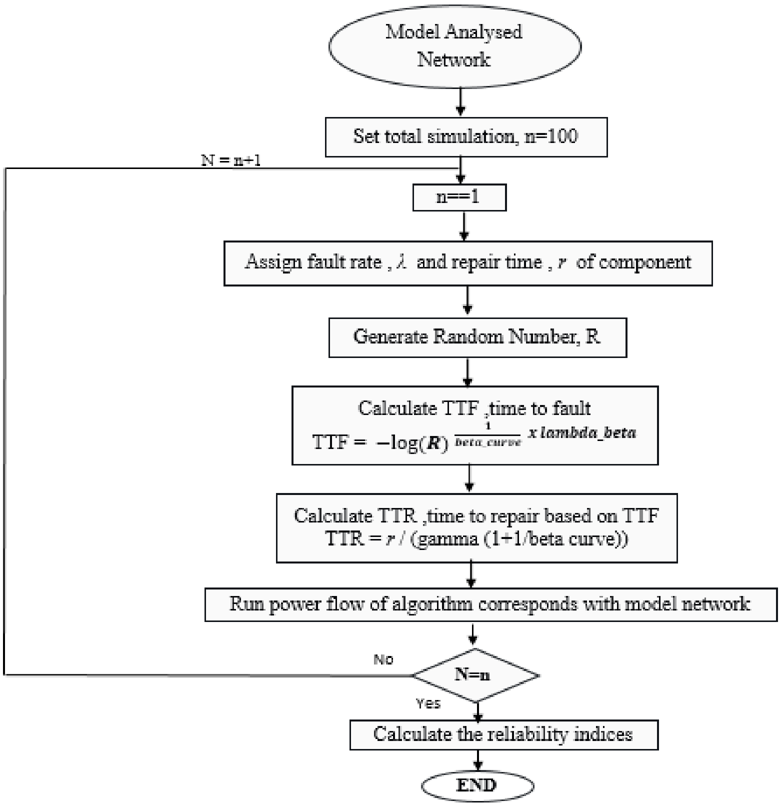

Figure 1. The flowchart of MCS

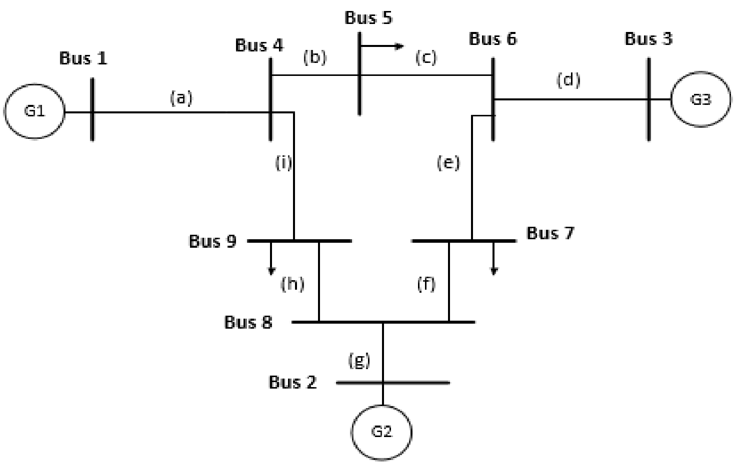

Figure 2. The network of IEEE 9 bus system

4. RESULTS AND DISCUSSION

In reliability analysis, SAIFI, SAIDI, and CAIDI are used to evaluate the performance of reliability in the system. These indices are typically comprised of annual average interruption or duration values. The graph of reliability indices shown are plotted based on four types of PDFs which are exponential, exponential Weibull family, Rayleigh, and Weibull. Each of the graph presented will show different analysis. The value reliability indices only describe the overall performance of the system without showing what is exactly happening to the system. For example, in Figure 3, the value of SAIFI using exponential distribution has the lowest value of SAIFI followed by exponential Weibull family, Weibull and Rayleigh distribution. This value indicates that system using exponential distribution has the lowest interruption occurrence compared to the other. If the result is plotted by curve of PDF, it will show which value has the highest repeated interruptions in the system.

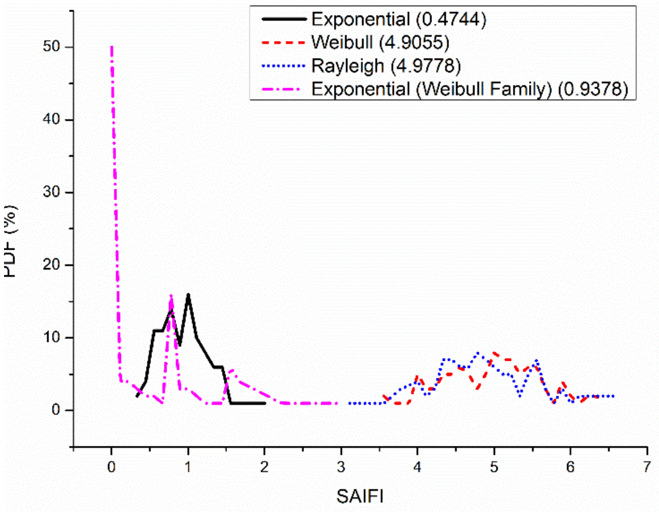

Figure 3. The graph of SAIFI

4.1. System average interruption frequency index

Figure 3 shows the values of SAIFI obtained using four types of PDFs. SAIFI describe how many failures a year affect a customer on average which shown that this. SAIFI is also known as the average of failure which often labelled as λ [26]. Thus, it can be concluded that the higher the customer interruptions, the higher the value of SAIFI and the lower the system reliable. As shown in Figure 3, the graph of exponential is closest to Y-axis, whereas the graph of exponential Weibull family is started near the value of 0 while the graph Weibull and Rayleigh is started in the middle. The beginning curve for Weibull and Rayleigh are close to each other, which the graph of Weibull distribution begins first compared to Rayleigh. In this case, it shows that the network system using Weibull distribution has the lowest amount of interruption compared to Rayleigh. Whereas the exponential and exponential Weibull family are close to the Y-axis due to the amount interruption occurred are smaller compared to Weibull and Rayleigh. As for exponential distribution, about 50% of pdf percentage is repeated for uninterrupted bus, which the value of SAIFI is 0 in 100 years. In Figure 4, although the Weibull and Rayleigh distributions have the same shape of graph, but it differs in the starting point. Both tail graph of Weibull and Rayleigh distributions are started in middle of the graph while the other two distributions started at the beginning. The tail of Weibull distribution is leading Rayleigh's which shows that it interrupts earlier.

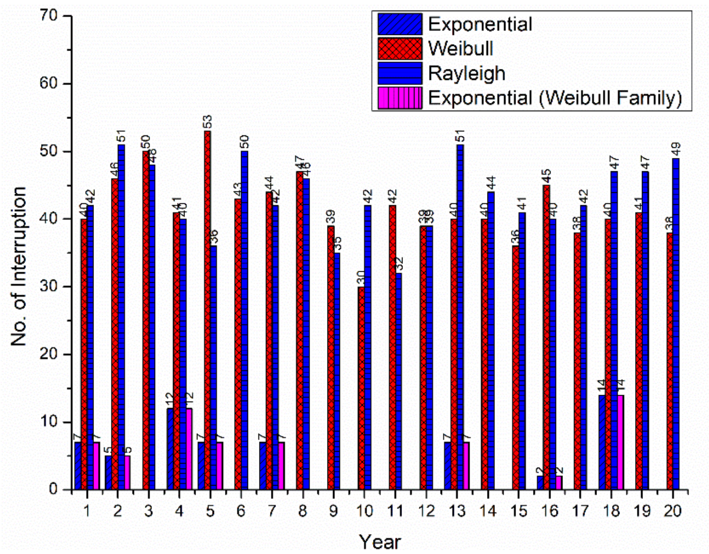

Figure 4. The total interruptions experienced by component

As the graph started in the center it demonstrated that in both distributions' interruptions are occurring in the middle which the majority of interruption faults at the indices range from 3.1 to 6.6. The years of simulation in this reliability analysis is set up to 100 years. The histogram in Figure 5 presents the details of SAIFI indices for both Weibull and Rayleigh distribution in 100-year simulations. It clearly shows the value of SAIFI which are intercept between each other as illustrated in Figure 3. From the histogram, it concludes that both distributions mostly will experience the same number of interruptions without concerning the interrupted years. The difference between these is only the repetition of the interruptions occurred which explains why most of PDF at certain point of SAIFI indices are varies between Weibull and Rayleigh distribution. For example, at the value of SAIFI is 3.5556, both distributions experienced about 32 total interruptions but the component in Weibull distribution only experience it once over 100-year simulations which at 99th year compared to Rayleigh distribution which experience twice at 11th year and 22nd year.

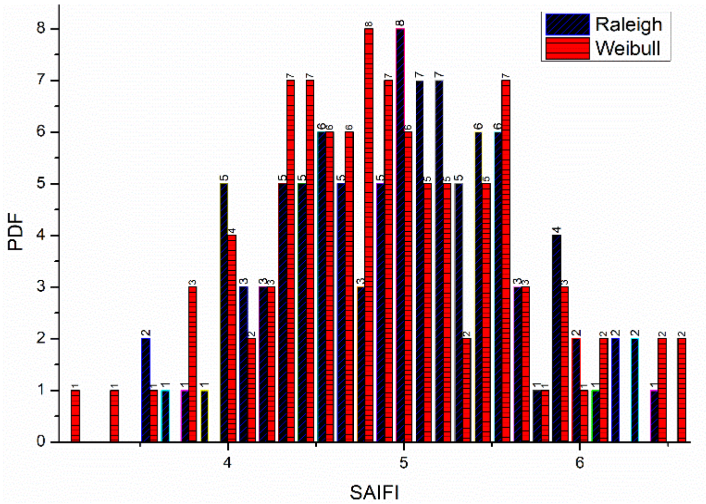

Figure 5. The comparison of SAIFI indices between Weibull and Rayleigh

4.1.1. Interruptions at the component

The interrupted component in the system will affect the supply to the load. In this reliability analysis, only bus 9 is interrupted in the system for both Weibull and Rayleigh distribution. This is due to the interruptions is occurred at the same time which causes no source is applied to bus 9. Basically, the interruption in the system is obtained through TTF. Thus, in order to observe the supply to the bus, each line connected the bus is analyzed. In this case, bus 9 is connected to branch 8 (line 8-9) and branch 9 (line4-9). Figure 6 presents the value of TTF in the first 180 hours. From this figure, both line graphs are parallel to each other which shows that they are interrupt at the same time. As a result, no electricity can supply from the source to the bus 9. Table 2 shows a clear and detailed data of TTF which has illustrated in Figure 6.

Figure 6 and Table 3 presented the amount of TTF for every component in distributions and the total interruptions experienced by the customer respectively. From the figure, it shown that the amount of failure for each branch in Weibull and Rayleigh distributions is higher compared to the other distribution. Hence, it results to the total interruptions experienced by customer shown in Table 3. From the data, Rayleigh distribution has highest total interruptions followed by Weibull, exponential Weibull family and exponential distribution. As Rayleigh, and exponential are related to the Weibull family, thus the formula used to find the value of TTF for interruptions are all the same. As Weibull distribution is a continuous probability distribution, therefore, a range of limit is included in the analysis in order to find the interruption through the value of TTF. The component will interrupt if the value of simulated TTF is within the range. Weibull distribution also related to Rayleigh and exponential which they had known as Weibull family. Thus, these distributions use the same formula in this analysis which only difference is the used of beta curve in the simulation. The value of beta used in exponential, Weibull and Rayleigh is 1, 2, and 6, respectively

Table 2. The TTF in Rayleigh distribution in first 180 hours

Branch	TTF (hours)
8 (Line8-9)	6, 10, 20, 24, 30, 32, 44, 86, 120, 134, 144, 180
9 (Line9-4)	6, 10, 20, 24, 30, 32, 44, 86, 120,1 34, 144, 180

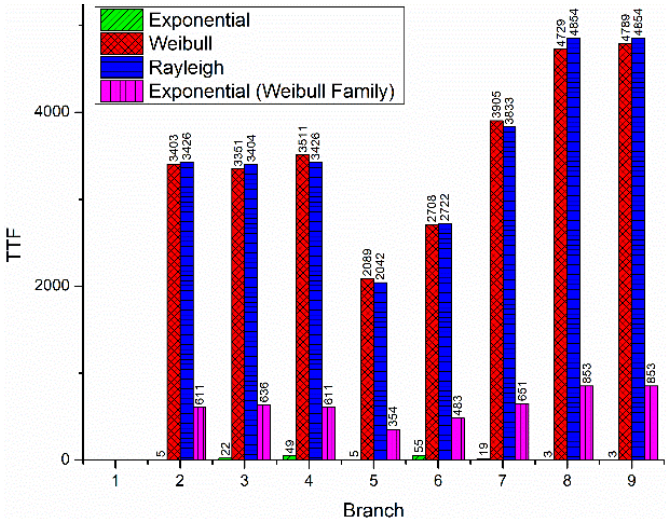

Figure 6. The amount of TTF for every component in distributions

Table 3. The Total Interruptions in 100 years

Distribution	Total Interruptions Experienced by Customer
Exponential	427
Weibull	4480
Rayleigh	4415
Exponential (Weibull Family)	844

4.2. System average interruption duration index

Figure 7 shows the value of SAIDI in different distributions over 100 years. SAIDI can be calculated based on monthly or yearly basis but sometimes daily or at any period of time. In the other words, this graph of SAIDI shows the total duration interruption of experienced by the customers. The graph of SAIDI is the actually the reflection of the SAIFI as they are linearly proportional to each other. From the graph, it seems that the tails of Rayleigh and Weibull for SAIDI begin at the same points, but it is ended a bit longer for Weibull's tails. The end tail of Weibull distribution is a bit longer compared to Rayleigh distribution.

As the longest end point of Weibull distribution is repeated at 1%, it means in 100 years of simulation, there is one year that has the highest interruptions. As SAIDI and SAIFI are related to each other, it can conclude that as higher the interruptions occurred, as higher the total duration of interruption. This is because the repair time for component to recover is set to 6.44 hours/failure.

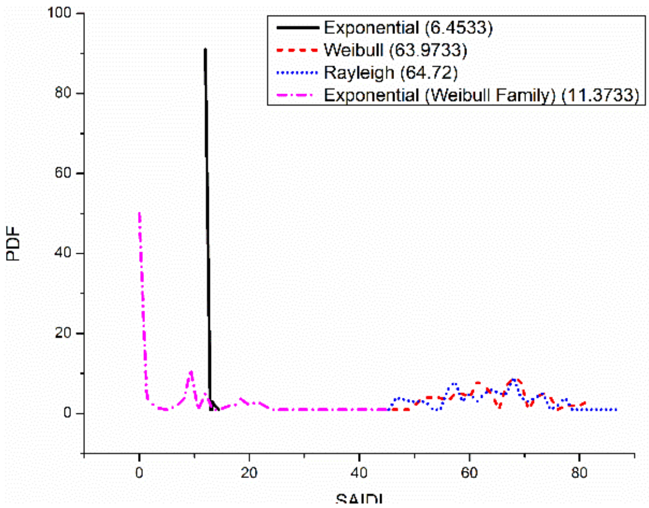

Figure 7. The graph of SAIDI

Figure 8 presented the total duration interruptions in Weibull and Rayleigh distribution. The graph data clearly explains the tails of the distributions as illustrated in Figure 7. The least total duration interruptions in Rayleigh and Weibull distribution are 396 hours and 408 hours which bring about 44 hours/customer and 45.333 hours/customer respectively. The customer only experienced once in 100 years which explain why the tail of Rayleigh's started earlier than Weibull's. The Weibull distribution has the highest duration compared to Rayleigh distribution, which repeated once and three times respectively.

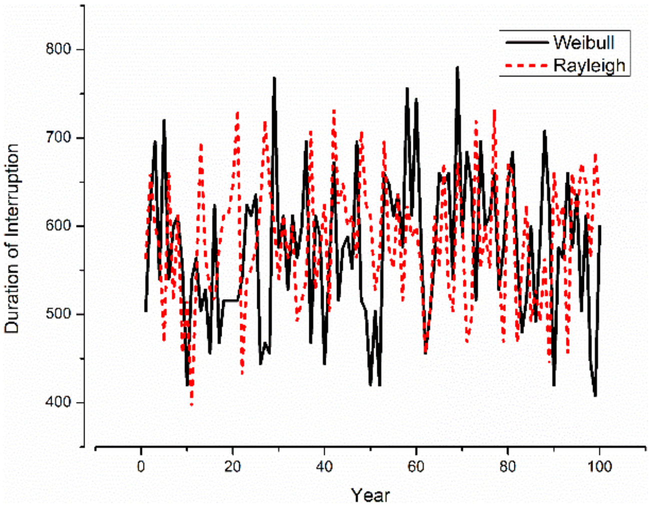

Figure 8. The total duration interruption

4.3. Customer average interruption duration index

The graph of exponential Weibull family based on Figure 9 shows the highest peak within range reliability indices between 12 to 14.4. The graph CAIDI of exponential Weibull family as shown is so different from the others as the graph looks like a straight line. The peak of the graph is at value 12 as it repeats about 91% over 100 years. It means mostly the customer will experience about 12 hours/interruption. The value of CAIDI depends on both value of SAIFI and SAIDI as the formula of CAIDI is SAIDI over SAIFI. Table 4 presents examples of the SAIDI and SAIFI affects to value of CAIDI. As shown in the Table 4, although the value SAIFI are same at certain year, but due to the difference of SAIDI, it results to the different value of CAIDI. Thus, it can interpret why the CAIDI of the most customer is 12 hours/interruption as there is no specific range of indices can determine the value of CAIDI. It proves that value of calculated CAIDI depends on the value of SAIDI and SAIFI.

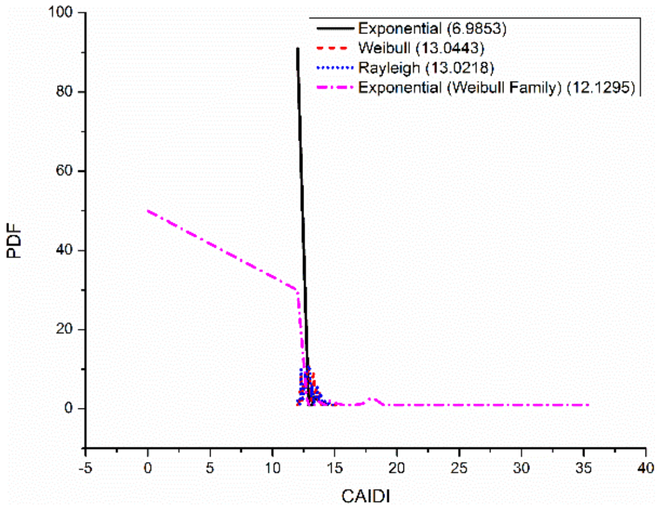

Figure 9. The graph of CAIDI

Table 4. Value of reliability indices at certain years in exponential Weibull family

SAIDI	SAIFI	CAIDI
8	0.55556	14.4
6.666667	0.55556	12
10.66667	0.77778	13.7
10.66667	0.888889	12

5. CONCLUSION

As a conclusion, each probability distribution functions will show different analysis in power system reliability. As Rayleigh distribution is a part of Weibull family hence these distributions have almost the same shape but different in starting and ending points. The starting tail of Weibull distribution as shown in Figure 3 is leading the Rayleigh distribution which means that Weibull distribution interrupt earlier. In this case, different shape value can change the shape of graph. As in Weibull distribution, the shape value is 1 and it is known as the most rapid increase occurring initially. In this analysis, the total interruptions in Rayleigh distribution are higher compared to the Weibull. However, in Weibull, the least and most interruptions recorded are 28 and 59, respectively, while in Rayleigh is 32 and 58. Thus, it justifies the tail graph SAIFI in Weibull is longer than Rayleigh. Whereas for exponential distribution itself, it does not show the worst part in the system as most of the component are not uninterrupted. For exponential Weibull family distribution, the shape of graph follows Weibull and Rayleigh distributions.

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