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Monte Carlo simulation convergences' percentage and position in future reliability evaluation

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ABSTRACT

Reliability assessment is a needed assessment in today's world. It is required not only for system design but also to ensure the power delivered reaches the consumer. It is usual for fault to occur, but it is best if the fault can be predicted and the way to overcome it can be prepared in advance. Monte Carlo simulation is a standard method of assessing reliability since it is a time-based evaluation that nearly represents the actual situation. However, sequential Monte Carlo (SMC) typically took long-time simulation. A convergence element can be implemented into the simulation to ensure that the time taken to compute the simulation can be reduced. The SMC can be done with and without convergence. SMC with convergence has high accuracy compared to the SMC without convergence, as it takes a long time and has a high possibility of not getting accurate output. In this research, the SMC is subjected to five different convergence items to determine which converge simulation is the fastest while providing better performance for reliability evaluation. There are two types of convergence positions, namely input convergence and output convergence. Overall, output convergence shows the best result compared to input convergence.

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1. INTRODUCTION

Reliability assessment is a must in today society. The development of the world is becoming more and more complex, and this is also true for the power system network. The increase in the number of people in the society and the need for more houses, and buildings. This leads to the need for a sufficient power supply to provide enough power supply to the user [1]. However, a system is not enough if it is not interrupted because interruption will always occur in the network [2] and fully reliable system is not exist because of few factors [3]. Monte Carlo simulation (MCS) is one of the preferred methods for reliability assessment [4], [5]. The purpose of reliability assessment is to ensure that the end user receives sufficient supply from the network [6]. The distribution system must supply power without interruption. Since reliability needs to be assessed, an assessment method is mandatory. There are two types of methods that can be used to evaluate reliability, enumeration and simulation. As for enumeration, the analytical method is one of the types. It use analytical model to represent the network and used mathematical solution to evaluate reliability for the network [3]. It is very time consuming and is suitable only for the simplest networks, as it requires a large number of calculations. Since the network used in this research is quite large and complex, an accurate method is needed to analyze the network in a very short time. Therefore, MCS is the answer when the analytical calculation are not adaptable [7]. In MCS, there are two methods that are commonly used for evaluation: sequential Monte Carlo (SMC) and nonsequential Monte Carlo (NSMC) [4]-[8]. MCS usually apply for complex and large network [9]-[10] and it also generates the system through random sampling [11]. Complex networks means all the needed component in the power system networks is present [12]. Thus, the common steps in evaluating reliability are 1. Generates the distribution system in random states, 2. Minimize the number of faults in random states and lastly 3. Calculate reliability indices [5].

The difference between SMC and NSMC is that SMC is a time-based simulation, which means that it evaluate the system in time sequence [13]. Other than that, SMC also arranged the sample in chronologically states, and the frequency of the interruption and the duration for the interruption can be calculated [14]. In terms of this analysis, time to failure (TTF) and time to repair (TTR) [15] are used to evaluate the reliability for the network. They are two types of TTF which are for non-repairable system, and for repairable system [16]. Basically, TTF is the expected time from the repair time to the next break down. While for TTR, it can be defined as the total time need to perform maintenance for the faulty system divided by the total number of fault [16]. SMC creates an interruption based on the calculated TTF, while NSMC is based on random interruption solely. For the SMC, the computation of TTF and TTR is a must, since it has to decide which time to disrupt. Since the interruptions caused by TTF, the force fault system needs TTR to repair the system. After all the necessary steps in the simulation have been performed, a stopper is needed to ensure that the simulation converges. Variance reduction technique (VRT) [17] in the simulation is needed to reduce the time simulation to achieve fast convergence [17]. In addition to reducing the time required, it can also increase the speed of computer, since in the research, there are certain small probabilities of fault which it may take a longer time to execute a simulation even though the computer is a modern computer [18]. There are a few VRTs that are commonly used in MCS. Which are, Antithetic variates that introduce negative correlation between two samples [19] to evaluate the reliability in the system, importance sampling [20] that operates by changing the probability distribution of the sample by keeping the expectation of reliability indices stable [21], stratified sampling that operates by dividing the sample into a small region [22], and a few more.

There are a few parts that convergence can be added, overall, it can be grouped into two types which are convergence at the input and convergence at the output. For the convergence at input, there are three types of convergence at input which are TTF, TTR, and both of TTF and TTR. To determine the convergence in TTF and TTR, the accuracy limit is used, which is the percentage of the acceptance range for the simulation. The percentage determines the range of accepted intermittency that is close to the expected one. The smaller the accuracy limit, the longer it takes to reach convergence. Finally, for output convergence, there are two elements that make the simulation converge, namely the system indices and the customer indices. For output convergence, the variance calculates the difference between the current value and the previous value. When the difference becomes smaller a few times, the system starts to become stable, and then convergence is achieved. At the end of the simulation, reliability indices: system average interruption frequency index (SAIFI), system average interruption duration index (SADI), and customer average interruption duration index (CAIDI) [23] will be calculated to observe which methods is accurate based on time and percentage accuracy. SAIFI is system average interruption frequency index, SAIDI is system average interruption duration index, and lastly CAIDI is customer average interruption duration index [24].

Table 1 shows the input data used to run the simulation. The fault rate is used to determine the expected interruption at the component. The repair time is only used if a fault occurs on the component. The fault rate for the overhead line was expressed in kilometers (km). Therefore, to use it in the simulation, the fault rate must be expanded based on the length of the overhead line. The longer the overhead line, the greater the fault rate. This means that overhead lines with a greater length have a higher tendency to interrupt. The display in Figure 1 is IEEE-14 buses. This network contains 20 components consisting of 17 overhead lines and 3 transformers. Each overhead line represents with different length. The greater the length, the higher the fault susceptibility of the lines.

In output convergence, convergence occurs at the end of the simulation, either in the system indices (SAIFIs, SAIDIs, CAIDIs) or in the customer indices (SAIFIc, SAIDIc, and CAIDIc). Convergence at the output is different from convergence at the input. Input convergence focuses on the mean of the outcome, which should converge to the expected mean, while output convergence focuses on the calculation of the variance between the current value and the previous value. The calculation of the variance decreases until it reaches a steady state, which means that convergence has been achieved.

Table 1. Exact input data

Component	kV	Fault rate (Fault/km)	Repair time (hours/fault)
Overhead line (per km)	0.4	0.168	5.7
Transformer	0.4	0.002	5

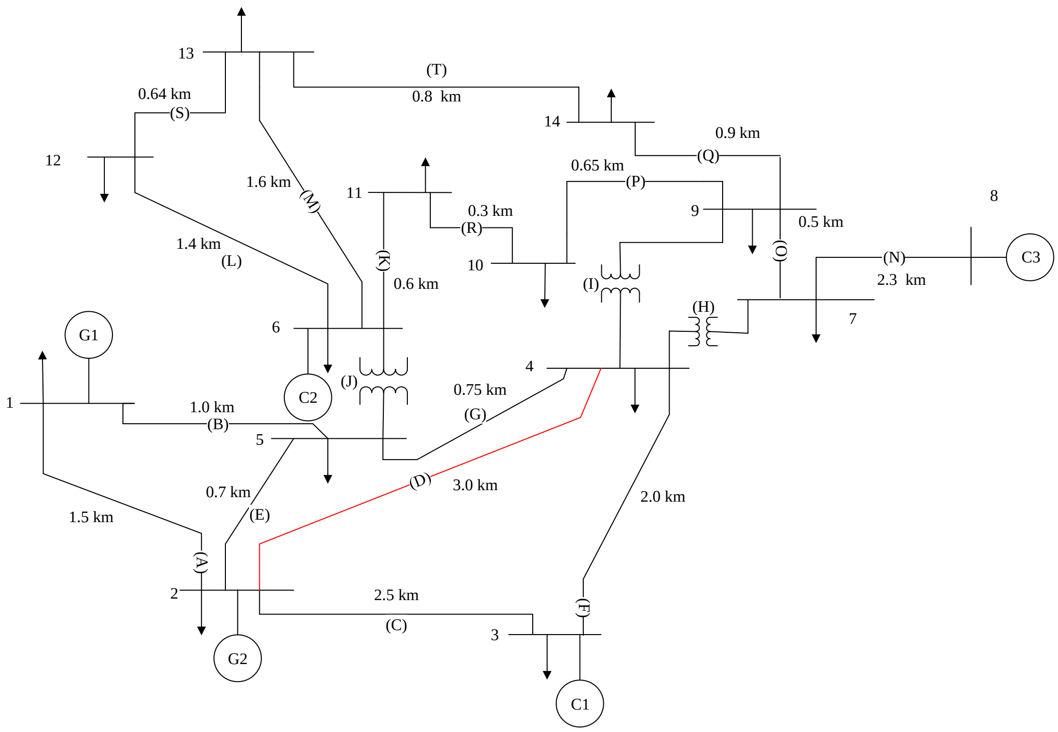

Figure 1. IEEE 14-bus

2. RESEARCH METHOD

In the Figure 2, shows the flow chart for each positioning is shown. The figure lists some positioning for convergence that can be performed. Five positioning have been listed, namely convergence at TTF and TTR, convergence at TTF or TTR only. Basically, there are three convergence positions at the input of the simulation. While the remaining two convergences are at the output of the simulation. Which of the output convergences, occur at system indices and customer indices. In general, the convergences were dependent on the variance calculated. The first step for reliability assessment simulation is to generate fault rates (denoted as lambda) and repair times. These fault rates represent the probability of fault for each component. They are used to estimate the expected interruptions that should occur on the representative components. Then, uniformly distributed random numbers in the range between 0 and 1 are generated then incorporated with CDF. The TTF (1) is used to determine the time in which the component would fail. Later, the calculation of TTR (2) is performed after the generation of random number for TTR based on the created interruption in TTF.

$$F^{-1}(t) = \frac{-\log(R)}{\lambda} \tag{1}$$

$$F^{-1}(t) = \sigma(-\ln(R))^{\frac{1}{\beta}} \tag{2}$$

After the calculation of TTF and TTR is completed, the power flow, which consists of 20 components and 14 buses, is force fault based on the calculated TTF and TTR. Finally, after running the network with faulty components, an observation of the buses is performed. It is determined which buses are affected by the interruption at the components. The number of interruptions and the duration of interruptions at each bus are recorded to calculate reliability indices for the buses. Normal variance reduction is the common method that being use by the researcher to converge simulations. Usually in normal variance reduction convergence can be obtained by calculating the expected value and the variance of the estimate function by using stated formula. After obtained the expected and variance of the estimate function, then, the coefficient of variation needs to obtain make sure that the chosen reliability index is less than the tolerance level. If it is exceeded the tolerance level, then the simulation needs to repeat again from the beginning.

$$E(F) = (\tfrac{1}{N})\sum_{i=1}^{N} F(Ui) \tag{3}$$

Where, *E* (*F*) is estimate of the expected value [25], *N* is number of simulations, and *F* (*Ui*) is test result for the i^{th} sampled value:

$$V(F) = \left(\frac{1}{N-1}\right)\sum_{i=1}^{N}\left(F(Ui) - E(F)\right)^2 \tag{4}$$

where, *V* (*F*) is variance of the estimate function F.

$$\varepsilon = \frac{\sqrt{V(F)}}{\sqrt{N}.E(F)} \tag{5}$$

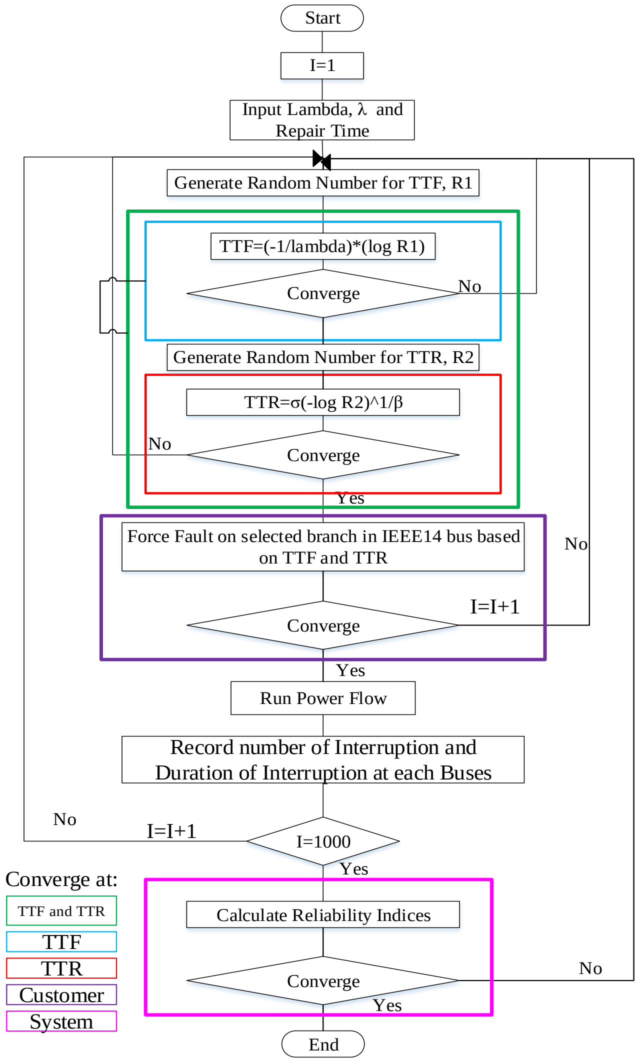

Figure 2. Convergence flowchart for different positioning for convergence

2.1. Convergence at input

Input convergence focus on the input data of fault rates and repair time as the expected values. In addition, percentage limits have been added to the simulation. The function of the percentage limit is to extend the range of the expected value. If the expected TTF is set to 0.25 faults/years. This means that the expected interruptions would be 250 interruptions in 1,000 years. However, it is somewhat difficult to determine the exact number of 250. Therefore, the interruptions that are around 250 should be accepted based on the percentage limit. As shown in Figure 2, the green box shows convergence on two input data, namely TTF and TTR as example. The blue and red boxes show that convergence occurs on one of the input data. It depends on the researcher himself which part he allows to converge. Almost the same process for convergence on the output.

2.2. Convergence at output

From the Table 2, E1 shows the smallest percentage limit compared to E20. For E1, due to the smaller percentage accuracy, hence it took long time to complete a simulation, as the range for the percentage limit (positive limit and negative limit) for this case is smaller. Thus, it is difficult to complete a simulation when the range of the percentage limit small, compare to E20, the number of years for this case is only 9 years, and referring to the negative and positive limit, the range for this case is wider. It can be concluded that, the larger the percentage accuracy the shortest the time taken for the simulation to complete, as the range for the percentage limit is wider, thus it easy to achieve convergence.

The percentage accuracy for E1 is 1%, so the simulation took 62 years to converge the simulation. While for E20, the simulation used larger percentage accuracy which are 20% and it took only a moment to converge, which 9 years. From the figure itself, it can be seen that if the percentage accuracy small, it took longer time to complete a simulation and vice versa.

Table 2. Limit for each percentage accuracy for case E

Case	Percentage Accuracy	Number of Years	Positive Limit	Negative limit
E1	1%	62	62.62	61.38
E5	5%	13	13.65	12.35
E10	10%	11	12.1	9.9
E15	15%	10	11.5	8.5
E20	20%	9	10.8	7.2

3. RESULTS AND DISCUSSION

3.1. Interruptions at component

Figure 3 shows the interruption at component D see Figure 1. The reason for choosing component D is that component D has the longer length in the network of IEEE -14 buses. Thus, it also has a higher failure rate since the failure rate for overhead lines depends on the length of the overhead line. The figure therefore shows the number of interruptions for component D for each case. The number of interruptions for case A, case B and case C are almost the same, since the convergence were occurred at the input of the simulation. However, convergence at TTR shows better performance as it reduced the time required to compute a simulation.

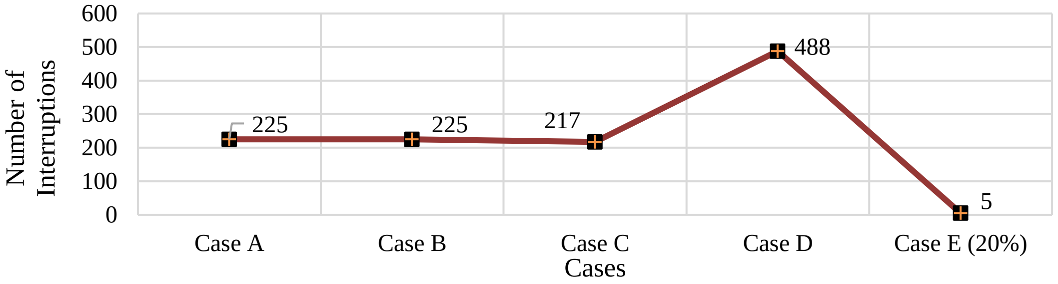

Figure 3. Number of interruptions at component D

In output convergence, convergence on system indices shows better performance because it able to converge. Compared to convergence at customers, convergence does not occur even though the number of years has already been extended to 4,000 years. It seems that the simulation cannot calculate the variance because it cannot converge. Therefore, convergence should be applied in the system when convergence is at the output. Roughly, the number of interruptions for case A, case B, case C and case D are almost the same. If referring to the Figure 3, case D shows the highest number of interruptions due to the non-convergence simulation. However, if the number of interruptions being divided into 500 years (limit number of years for case A to C) then the number of interruptions for case D would be 244 interruptions (488 interruptions divided half of the years).

3.2. Interruptions at bus 8

Figure 4 shows the average interruption that occurs at bus 8. Out of all 14 buses in the network, only bus 8 was affected by component interruption. Basically, bus 8 is the only bus that connected with one overhead line. Figure 1 for bus 13 shows that the bus is connected to 3 overhead lines. When one of the overhead lines is broken, the other two overhead lines back up the broken line. Basically, SMC tends not to interrupt the buses at the same time compared to NSMC because it randomly interrupts the component one at a time (in sequences), so the interruptions do not occur at the same time. Figure 4 shows that cases A to D are similar in terms of the average of interruptions that occur.

Case E, however, shows a low average. This is because the years converge only up to 9 years. Moreover, the accuracy limit for E20 is also very high. When the accuracy limit is large, it is easy to achieve convergence. Therefore, for E20, the percentage accuracy needs to be adjusted to obtain an average similar to the other cases. The smaller the percentage accuracy, the longer of time (years of simulation) to achieve accuracy.

Present in Figure 5 is the average interruptions and duration for case E when using different percentage accuracy. As stated before, E20 produce lowest number of years as shown in Table 2. However, due to the huge different between the other cases, another simulation was being done to check which accuracy that has the same accuracy as the other cases. If referring to Table 2, the reading for E20 is the lowest, and it seem that case E not suitable with 20% of accuracy. With that, four more simulations were done with different accuracy (1%, 5%, 10% and 15%).

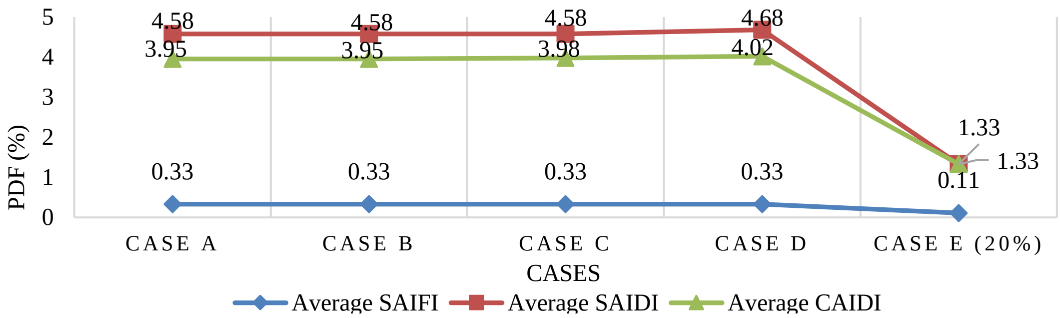

Figure 4. Average SAIFI, SAIDI and CAIDI at bus 8

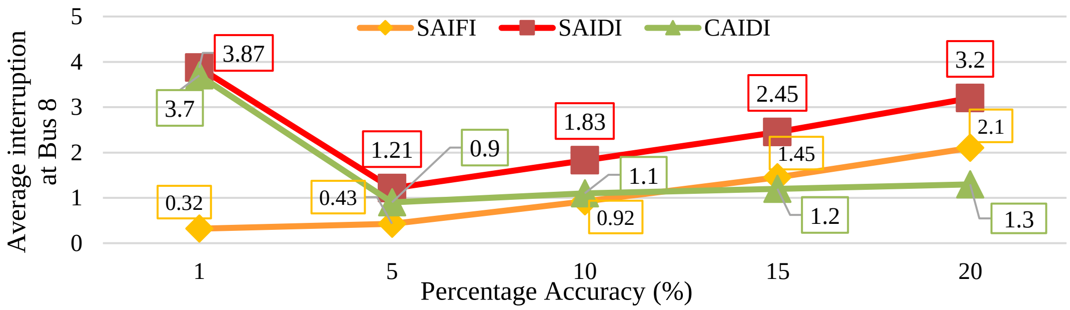

Figure 5. Different percentage accuracy for case E

As shown in Figure 5, it shows the average interruptions and duration for bus 8. From the figure, if comparing with other cases in Figure 4, only 1% of accuracy that almost has the same reading as other cases. If focusing on 1% of percentage accuracy, the SAIFI for 1% is 0.32, and is almost the same as the rest of the cases in Figure 4. However, for average SAIDI, the reading for 1% of accuracy is slightly lowest from the other cases. It could be because the number of interruptions for E1 is lowest compared to other cases, which result in less time needed to repair the interruption. For CAIDI PDF, the average durations for customer in E1 is in the range with other cases.

Present in Figure 6 is the average interruptions and duration for case D (4,000 years). Among all cases, only case D fail to converge, as it stops at the decided years (1,000 years). According to Monte Carlo, the more the number of iterations, it is easy for the simulation to meet the expected input data. Thus, in order to analyze whether the simulation converge when the number of years were extend for another 3,000 years, which include the current years, the simulation was done for 4000 years. However, the simulation still fails to converge. Apart from that, the shocking result shows that the recorded value for case D is almost the same as the other cases. Focusing on Figure 6, the average SAIFI for case D (4,000 years) are 0.33, and it just the same as the rest cases which are also 0.33 as shown in Figure 4. The same goes for average SAIDI and CAIDI where the recorded values are similar with average SAIDI and CAIDI in Figure 4.

Figure 7 shows the system average interruption frequency index (SAIFI) PDF for case A through E. From the figure, E20 has the highest percentage for uninterrupted buses, while the other cases have similar values. If comparing with case D, case E has highest uninterrupted because of the lowest number of years, hence result in small interruptions in the system. However, after reducing the percentage accuracy for E20, the uninterrupted bus was recorded at 70.97% (refer Table 3) almost the same as other cases.

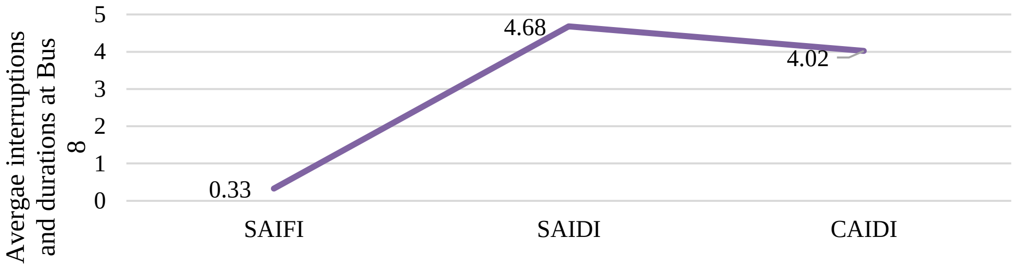

Figure 6. Average interruption and duration for case D (4,000 years)

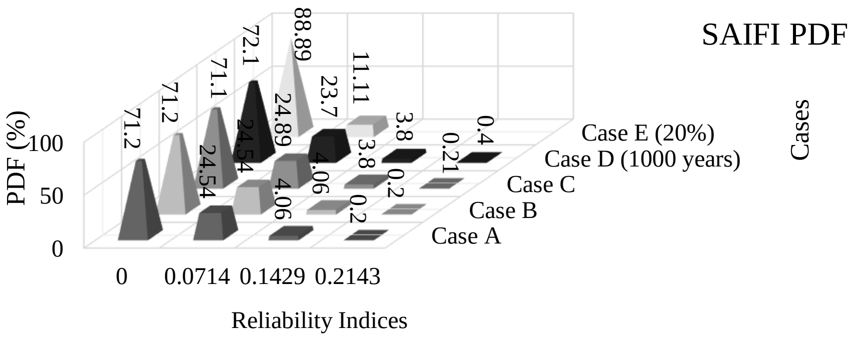

Figure 7. SAIFI PDF

Since a large accuracy bound was used in case E, it is easy to achieve convergence. In the opposite case, the simulation would take longer to complete. To achieve a similar percentage in E20 as in the other cases, the accuracy must be reduced to 1% of the accuracy limit, as shown in Table 2. It may not be the main intention of this research to obtain a similar percentage of reliability indices, as at the beginning of the research the accuracy limit was standardized to 20% of accuracy. However, since E20 has an irregular reading, another research see in Table 2 was conducted to observe which accuracy has a similar value to the other cases. Refer to the Figure 7, E20 has less interruptions compared to other cases. It stated that, the 0.0714 for E20 is 11.11% which is totally different from the 0.0714 of other cases with the range of 20% of occurrence. Due to the high percentage accuracy, the PDF tends to get small values since the percentage limit affected the simulation by decreasing the size of the sample drastically. However, if the percentage accuracy got smaller, the size of the sample will be increased see in Table 2. Thus, when case E using 1% of percentage accuracy, the reading for 0.0714 is 27.42%. The reading might be slightly higher compared to the other cases, however it still in the range of 20% of occurrence.

For the SAIDI PDF, it was calculated based on the time taken to repair the interruption created at SAIFI PDF. For the uninterrupted system, repair time is not needed since the system remain on state. For the rest of the interrupted systems, there will be its own time to repair, and it is not the same for each interruption. From the Figure 8, in E20, low number of repair time is taken. As mentioned earlier, the reason for less repair time is that the number of years for E20 was drastically reduced from 1,000 years, and this happened because the percentage of accuracy for E20 is too large. Among the convergence items, E20 converges faster and reduces drastically as it reaches a convergence of less than 1,000 years. Table 2 shows that at 1% accuracy, E1 took 62 years to converge, while at 20% accuracy, it took only 9 years to converge. It can be seen by referring to the Table 3. For the 0.8571, for E20, the probability of occurrence for this reliability indices are 11.11%, however, when the case E used 1% of percentage accuracy, the 0.8571 reliability indices have 25.81% of occurrence. Which is E1 has almost the same reading as case A, case B, case C and case D.

Table 3. PDF for E1

SAIFI		SAIDI		CAIDI	
Reliability Indices	PDF (%)	Reliability Indices	PDF (%)	Reliability Indices	PDF (%)
0	70.97	0	70.97	0	70.97
0.0714	27.42	0.8571	25.81	12	27.42
0.1429	1.61	1.7143	3.23	24	1.61

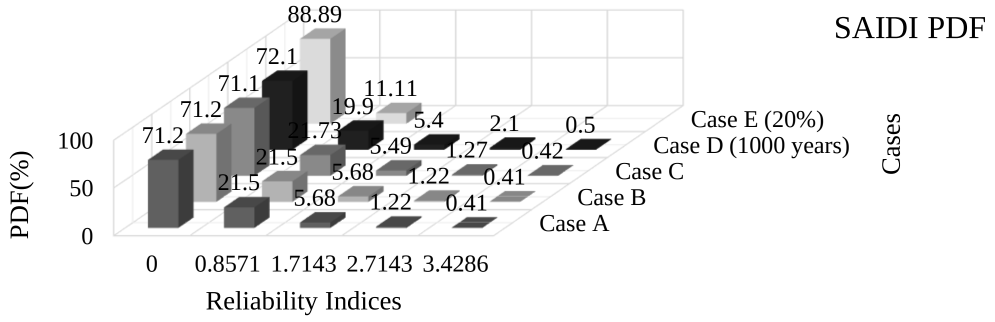

Figure 8. SAIDI PDF

For the Figure 9, CAIDI PDF it just basically the same as the previous average CAIDI PDF at bus 8. Where CAIDI used to measure time taken for the customer will experience for one interruption. CAIDI is differ from SAIDI, as SAIDI used to measure the time taken for all interruptions occurred. From the figure, case D has the longer hours for one interruption, which is 48 hours/interruption. If referring to Figure 3, case D has the highest interruptions at component thus for the interruptions at Bus 8 it is quite severe, as there is interruption that required 48 hours to repair. The most common time needed to repair for one interruption are 12 hours/interruption for every cases. For E20, it shows that only two repair times experience by the customer. That is because, the number of years for E20 is only 9 years. Hence, due to low number of years, less interruptions were created in the system. Thus, that is explains why only two repair times were recorded in E20, compared to other cases. For case E, by using 1% of percentage accuracy, the number of repair times that being recorded for this simulation are three see in Table 3, CAIDI. Since the percentage accuracy being reduced, the number or years will be increased as it is difficult to converge when the percentage accuracy small. Due to the increase of number of years, the interruptions created in the system also will be increased along with the number of years. Referring to the 12 hours reliability indices in Figure 9, the E20 recorded 11.11% of occurrence, however, when the limit accuracy being decreased to 1%, the occurrence for 12 hours reliability indices increased to 27.42% possibility.

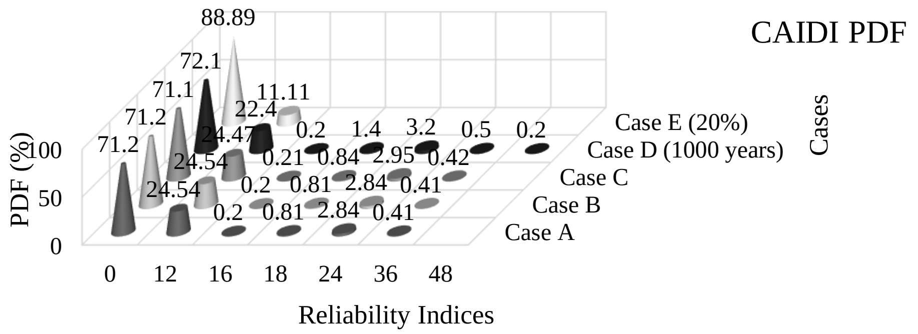

Figure 9. CAIDI PDF

4. CONCLUSION

In conclusion, from the overall results, it can be stated that the value of the convergence plays their own parts very well. However, to get the precise result as the expected, the percentage of accuracy also need to be considered at the first place. As for E20, the accuracy limit for case E need to be small in order to get the similar result as the other cases. Since, due to the large percentage accuracy, the simulation converged faster and reduced the number of years drastically comparing to the other cases. Based on the new simulation for case E, by using 1% of percentage accuracy, the accuracy for the case E is almost similar as the other cases which is, to converge a system indices, the researcher needs to used small percentage accuracy in order to get high accuracy. For other cases, the number of years being reduced around 450 to 500 years. Except for case D, where it failed to converge even though the simulation were being extend to 4,000 years. However, it can be stated that, even though the number of years being extend, the accuracy for case D (4,000 years) is remained the same as case D (1,000 years). Even the simulation failed to converge, the result from case D can be classified as reliable because the recorded value for this case it similar as the cases that manage to converge. As for the input convergence, it can be seen that, the convergence only occurs for the input data that were set to converge. If the simulation were set to converge at TTF and TTR than both of the input data will converge. However, if the convergence were set at one of the input data, example TTR, then only TTR will converge, and the TTF will be ignored since the convergence were set at TTR only. The same goes for the convergence at TTF only. Lastly, it is important for the researcher to know what kind of result that they want at the end of their research. Because each convergence shows different output with different characteristic of the simulation.

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