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Variance reduction technique in reliability evaluation for distribution system by using sequential Monte Carlo simulation

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ABSTRACT

This paper discusses the need for variance reduction in simulations in order to reduce the time required to compute a simulation. The large and complex network is commonly evaluated using a large-scale Monte Carlo simulation. Unfortunately, due to the different sizes of the network, it takes some time to complete a simulation. However, variance reduction techniques (VRT) can help to solve the issues. The effect of VRT changes the behaviors of a simulation, particularly the time required to run the simulation. To evaluate the reliability indices, two sequential Monte Carlo (SMC) methods are used. SMC with VRT and SMC without VRT are the two options. The presence of VRT in the simulation distinguishes the two simulations. Finally, reliability indices: system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), and customer average interruption duration index (CAIDI) will be calculated at the end of the simulation to determine the efficiency for the SMC with and without VRT. Overall, the SMC with VRT is more efficient because it is more convenient and saves time than the SMC without VRT.

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1. INTRODUCTION

One of the most important evaluations in today's network systems is reliability evaluation. The increase in population size causes the system to increase the size of the system [1] to meet the power demand. The reliability analysis is a tool used to assess the possibility of component failure in the presence of randomness [2]. Analytical and Monte Carlo simulation (MCS) [3], [4] are the two methods for determining reliability. MCS will be used to assess its reliability in this paper. MCS is frequently used to validate reliability analyses [2], [5]. It is a probabilistic process based on statistical theory [6]. Furthermore, MCS is used to simulate complex networks [7], [8].

It frequently takes a longer time to obtain the reliability indexes. To enhance the time, there are two methods to enhance the sequential Monte Carlo (SMC): improve the sequential convergence rate and choose a small network size to perform the simulation [9]. Variance reduction technique (VRT) [10], [11] is used to improve convergence time and speed [12]. VRT is one of the most important steps in obtaining reliable simulation results. VRT is used to improve the performance of MCS methods. With increasing percentage error, the accuracy of fault rates and repair times decreases. As a result, it will improve accuracy [13] for the time-to-fail (TTF) and time-to-repair (TTR) [14] based on their calculated mean, as well as the MCS's efficiency [15] antithetic variables [13], stratified sampling, importance sampling, and normal variance reduction are the variance reduction methods.

In order to use the stratified sampling technique, the population must be divided into discrete subgroups, or strata, from which the sample is drawn at random [9]. However, due to the complexity of this method, a suitable computation strategy is required [16]. Antithetic variables are another method of reducing variance. A pair of random variates and their modified random variate are considered to be synthetic variates if their correlation coefficient is negative [17]. The normal VRT technique is the fundamental VRT to be implemented in MCS for this simulation. The computation of the mean and variance for each year is a necessary step in VRT [18]. As long as the coefficient is below the intended tolerance, the simulation continues [18].

Figure 1 is the network used for the simulation, which is the IEEE-14 bus. This network consists of 17 overhead lines, three transformers, two generators, and three synchronous compensators. The IEEE-14 represents the networks to evaluate the reliability indices using simulation with VRT and without VRT. In this network, G1 refer as the slack bus, and the other generator is the generation bus. In addition, three synchronous compensators supply only reactive power, Q. The main reason for the chosen 14-buses network is because this network represents a distribution network. It is not the distribution network; it is close to the characteristic of the distribution network.

The input data used in the simulation are listed in Table 1. The component's expected interruption will be determined by the fault rates. The interrupted overhead line or transformer was factored into the repair times. The fault rates for the overhead lines were calculated per kilometer (km). Therefore, based on the length of the overhead line, the fault rates must be increased. Additionally, the length of the overhead line affects the fault rate for the line. Longer-distance overhead lines consequently have a higher likelihood of experiencing frequent outages.

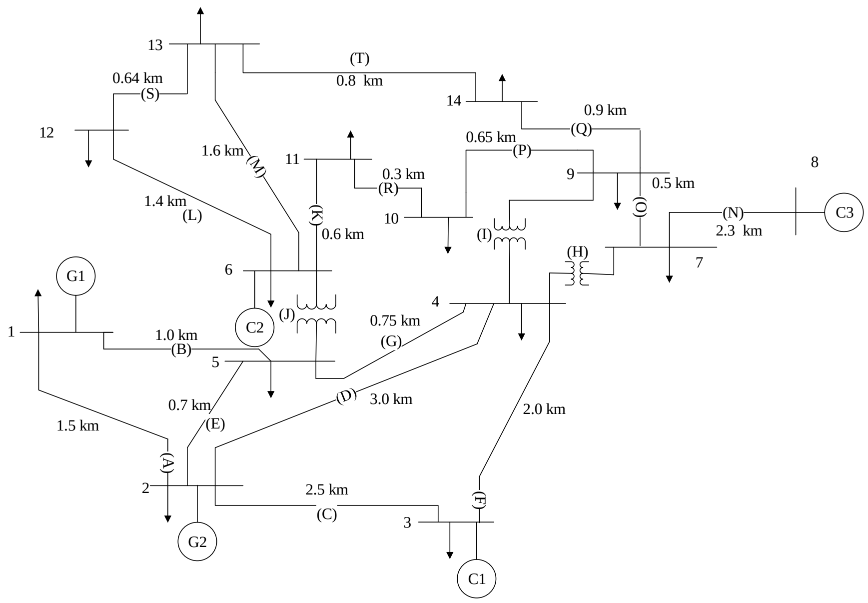

Figure 1. Detailed IEEE-14 bus

Table 1. Data for the input

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

2. METHOD

There are two Monte Carlo methods for evaluating reliability: SMC and nonsequential Monte Carlo (NSMC) [19]. This study focuses solely on SMC methods. SMC is a simulation method that counts the time sequence of the system and generates various scenarios in the distribution system while it is operating normally [4].

State sampling is another name for NSMC. This method only uses two states: on-state and off-state [20]. It is a distribution sequence for SMC. It necessitates a set of simulation-based methods that offer a beneficial and appealing approach to enumerating the posterior distributions.

The two main components in SMC simulation were TTF and TTR [21]. TTF was used to determine the time for the component to fault. TTR used to extend the time required to repair the fault at the TTF location. SMC simulates the state of the components as they change in chronological order [22].

2.1. SMC without VRT

Figure 2 is the flowchart for the SMC without VRT. Referring to the figure, the first step for this simulation is generating fault rates. The fault rates will act as an indicator to estimate the probability of the interruption that should be occurred at the component. The number of fault rates is proportional to the number of network components. In this simulation, the fault rate is denoted as lambda (λ). After that, the overhead lines and transformers will represent by a uniform distribution random number between [0, 1] [23], [24]. Calculation of TTF will take place after that. TTF will be used to calculate the time it will take for the component interruption to occur.

After the calculation of the TTF, include the TTR in the next step. TTR will be used to calculate the required time to repair the created interruption at TTF. TTR only exists when the components have interruptions. After that, based on the calculation of TTF and TTR, the network of 14-buses will be interrupted. Then, the simulation will run power flow after the force fault to observe which buses/loads were affected by the interruptions at components. Lastly, the affected bus will be classified to calculate the reliability indices.

A 4-bus network would explain the interruption occurring on the bus if the components connected to the bus are at fault. Figure 3 illustrates a 4-bus network with two fault components. Component 2 and component 4 (C2 and C4) in the figure were force faults based on the TTF calculation. Because of the interruption, load 3 (L3) failed to receive power; when the components fail, they fail to supply in any direction. Fortunately, it remains uninterrupted for L4 even if it connects with the fault components thanks to C3, which backs up the demand at L4.

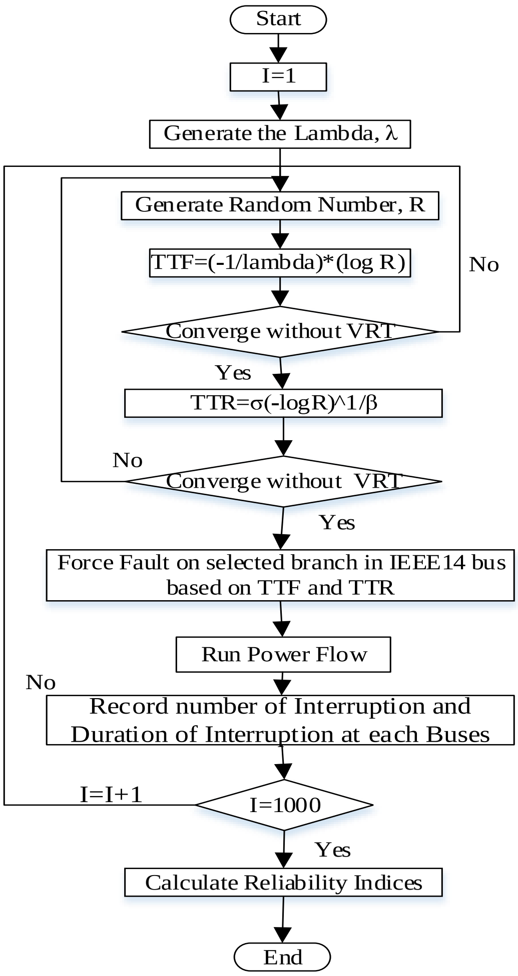

Figure 2. Simulation without VRT

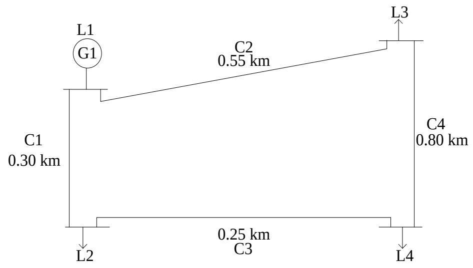

Figure 3. IEEE 4-bus

2.2. SMC with VRT

Figure 4 depicts the steps involved in simulating the SMC when the VRT is present. The VRT in this simulation focuses on the input data, which are TTF and TTR. However, VRT can also be performed at the simulation's output. When the VRT is present, the simulation will converge based on the chosen variance. The number of years should be 1,000 years to achieve the smallest difference between the current and previous values, and VRT is in the simulation. When the simulation has converged, it will come to an end.

Presents above are the basic steps to converge in a simulation. These are the needed step in VRT. The difference between each VRT is the sampling method and the formula to calculate the variance. As mentioned before, the stratified sampling needs to be divided into a small group from a population, while antithetic variates need to generate another sample to make a negative correlation. The variance will indicate when the simulation should stop or converge.

$$Mean, \bar{x} = \frac{1}{N} * (\sum_{i=1}^{N} x(ui) \tag{1}$$

$$Variance, var = \frac{1}{N-1} * \sum_{i=1}^{N} (x(ui) - \bar{x})^2 \tag{2}$$

Where N is the number of years and Ui is the vector for random numbers generated for sample i for each year I.

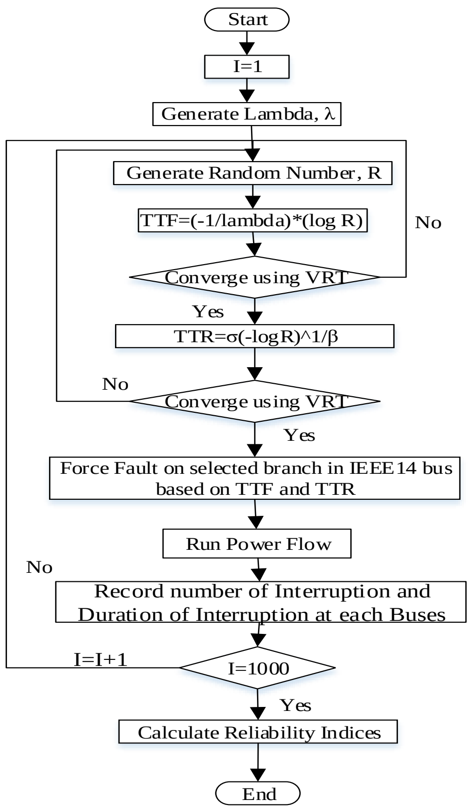

Figure 4. Simulation with VRT

3. RESULTS AND DISCUSSION

3.1. Reliability indices

The probability density function (PDF) for two cases, SMC without VRT and SMC with VRT, is represented by the system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), and customer average interruption duration index (CAIDI) [25]. According to the simulation, the SMC with VRT recorded only 4621.484436 seconds (recorded by MATLAB), whereas the SMC without VRT recorded 4718.735568 seconds (recorded by MATLAB). The SMC with VRT converges faster than the SMC without VRT due to improved simulation convergence. Aside from that, the simulation for SMC with VRT convergence at 205 years from the designed 1,000 years, according to Table 2. However, for SMC without VRT, this simulation starts at 205 years and ends at 205 years, indicating that no convergence occurred. Even though the number of years for SMC without VRT is similar to SMC without VRT, it still took a long time to finish a simulation. Besides that, even the number of years is the same for both cases. SMC without VRT created a lot of interruptions, in Figure 5.

Table 2. Time taken to complete a simulation

	SMC without VRT	SMC with VRT
Number of years	205	205 from 1000 years
Elapse time (s)	4718.736	4621.484

3.2. SAIFI PDF

Figure 5 depicts the PDF for the SAIFI. According to the graph, the SMC with VRT has fewer interruptions than the SMC without VRT. Aside from that, the SMC with VRT has the highest uninterrupted components. The number of interruptions would be reduced if the simulation reduced the number of years. As a result, SMC experiences this with VRT. SMC with VRT has 205 years while SMC without VRT has 1000 years. As a result, it tends to cause more interruptions.

According to the diagram, the SMC using VRT can cause less disruption and resulting high number of uninterrupted. Thus, the benefit of combining SMC and VRT is that it able to reduce the number of interruptions. Because of the VRT, the time required to evaluate the network has been reduced. While for SMC without VRT, the number of years that failed to suppress and resulted in the interruption is high. Lastly, referring to the overall average for both cases. SMC with VRT has the lowest occurrence compared to SMC without VRT. Thus, the VRT is compulsory in simulation. With VRT in the simulation, the time to complete a simulation reduces with the number of years. Along with that, the number of interruptions also will be reduced.

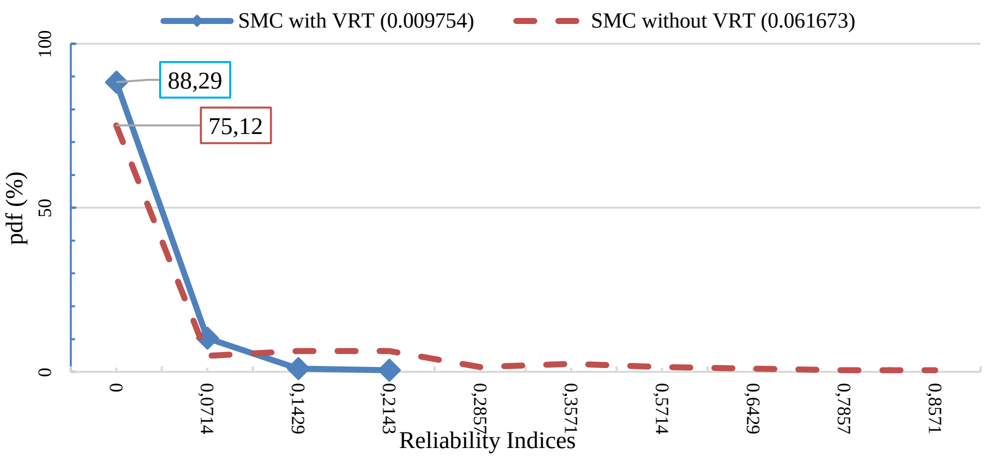

Figure 5. SAIFI PDF

3.3. SAIDI PDF

Figure 6 illustrates the SAIDI for every case. Usually, SAIDI reflects the previous figure. SAIDI is the total duration needed to repair all interruptions. For example, within a week, four interruptions were recorded. The time needs to fix those interruptions is 12 hours. Hence, from the figure, SMC without VRT has several total durations compared to SMC with VRT. That is due to the number of interruptions for SMC without VRT being more than for SMC with VRT.

Each total interruption has a different total duration. However, there are some cases where the time overlaps even though the interruptions are not similar. Thus, that explains the small bumps for SMC without VRT since it recorded a few similar duration times. For the uninterrupted buses, time is does not exist since no interruption occurs. Repair time only appears when there are interruptions at the components. The overall average for the total duration needed shows SMC without VRT is the highest since high interruptions were from this case.

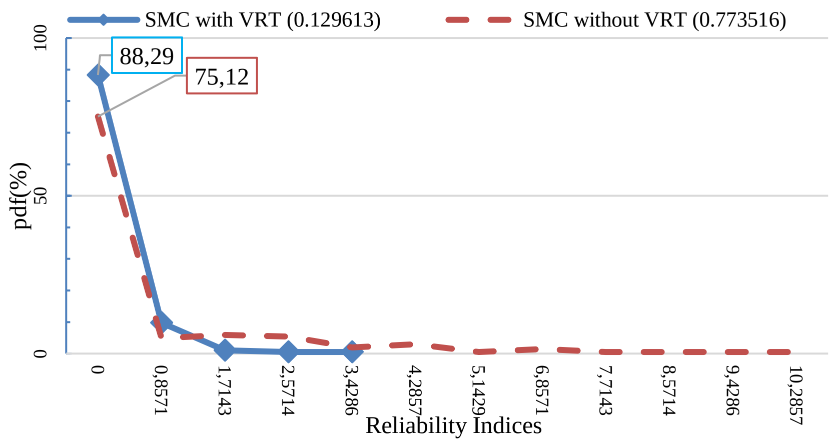

Figure 6. SAIDI PDF

3.4. CAIDI PDF

Figure 7 depicts the PDF for CAIDI when VRT is included in the simulation. According to the data, 88.29% of the years were uninterrupted (zero interruption). As a result, from 88.29% equal to 181 years did not require time to repair because no fault detected. However, only a few years with interruptions, and each year has its own TTR. For this case, it takes 12 hours to repair 23 interruptions. One interruption requires only 48.02 hours.

Also shown in Figure 7 is the PDF for CAIDI for SMC without VRT. From the figure, 154 uninterrupted years (75.12%) do not need repair time since interruptions at the component are zero. However, 51 years are interrupted, 45 of which require 12 hours of repair time, and the remaining years require varying amounts of time. For a brief explanation of CAIDI, a simple table will show how CAIDI is measured. Refer to Table 3, two components with different total interruptions SAIFI and duration SAIDI for both components are 12 hours. Only a few customers were affected by the bus interruptions. Hence due to the interruption, every one interruption, the customer at C1 will be affected for 12 hours/interruption for the customer at C2 interrupt for 4 hours/interruption. To obtain the time needed for CAIDI, divide SAIDI with SAIFI as shown in (3).

$$CAIDI = \frac{SAIDI}{SAIFI} \tag{3}$$

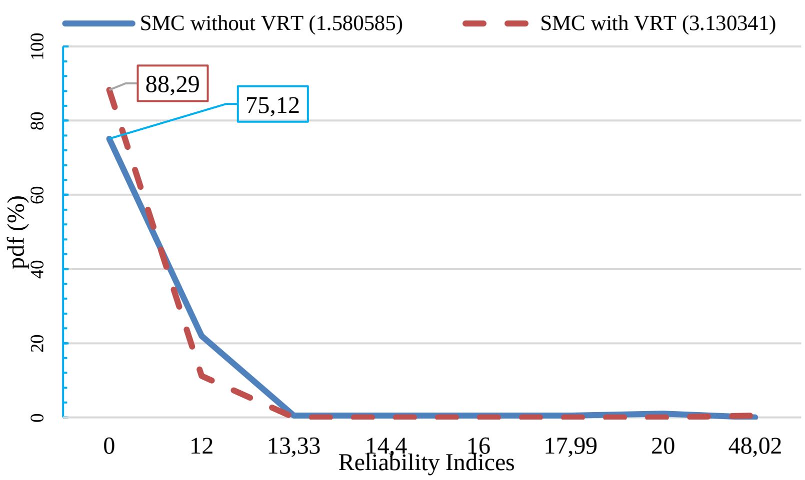

Figure 7. CAIDI PDF

Table 3. Example of CAIDI

Component	SAIFI	SAIDI (hours)	CAIDI (hours/fault)
1	1	12	12
2	3	12	4

4. CONCLUSION

According to the discussion, the SMC with VRT reduces the number of years and the number of interruptions. The simulation cannot reduce the number of years resulting in an increasing number of interruptions when compared to SMC without VRT. The SMC with VRT is expected to operate for 1,000 years. However, with VRT in the simulation, the number of years can be reduced to 205 years. For SMC without VRT the simulates year is similar as the decided years due to VRT is not present in the simulation. As a result of the large time difference between the two simulations, the number of interruptions will be higher in SMC with VRT.

In this simulation, the SMC without VRT design is expected to last for 205 years. As previously stated, the simulation was terminated after 205 years. If SMC with VRT is run until 205 years, the simulation will stop before it reached 205 years. As a result, the number of interruptions and the time required to repair the disruption at the component can be reduced. In conclusion, the SMC with VRT is able reduce simulation time compared with SMC without VRT because the time required for SMC with VRT is longer and it is more efficient for SMC with VRT.

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