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Impact of Automatic Circuit Reclosers and Distributed Generators on the Reliability Indices of Electrical Distribution Systems

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Abstract

Reliability is the ability of power system to perform its intended function as at when due. Parameters used to assess the level at which this is done are called reliability indices. Previous researches have not focused deeply on the effect of installing automatic circuit reclosers ACRs and distributed generators (DGs) on the assessment of reliability indices of electrical power distribution system, hence, the drive towards this research paper. Monte Carlo Simulation (MCS) was performed in MATLAB on the IEEE 34 test feeder. Under three different case studies- when one ACF was installed on the test system, when two ACRs were installed on the test system and when 1MW DG unit was installed on the test system. Real system data were used as input parameters for the simulation. The overall distribution system reliability was evaluated using the load point and the system reliability indices such as System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI) and Customer Average Interruption Duration Index (CAIDI). (CAIDI), Average Service Availability Index (ASAI) and EUE.The results obtained with the MCS were compared with the results obtained previously for the same test system using analytical approach and was found to be in agreement. The results of the research paper showed that the installation of an automatic circuit recloser gave a reduction in SAIFI value from 17.33hours/year to 14.93 hours/year with the installation of ACR between nodes (800-802). The best improvement was noticed when ACR was installed between nodes (834-842) in the electrical feeder. The value of SAIDI obtained also decreased from 8.90hom/year to 7.99 hours/year with the installation ACR between nodes (800-802). When two ACR were installed in the test system between nodes (828-824) and (824-826), the values obtained for SAIFI were 10.74 hours/year and 11.20 hours/year respectively representing a level of improvement in the SAIFI index. Between these nodes, values of SAIFI were also 4.211 hours/year and 4.423 hours/year which also represents an improvement in SAIDI values.Installation of 1MW Distributed generator (DG) unit in the test system gave SAIFI and SAIDI values of 14.23 hours/year and 5.80 hours/year respectively representing an improvement in there two indices compared to when ACRs were installed at anywhere in the test system. The values obtained for ASAI for different locations of the 1MW DG unit fluctuate throughout the case descriptions. With the installation of the 1MW DG unit between nodes 834-842, 844-846, 834-860, 836-840, and 862-838, the values obtained for ASAI were 5.196, 5.101, 5.012, 6.141 and 6.128 respectively which represent appreciable level of improvement as compared to the base case. With the installation of one DG in the test system, the value obtained for the EUE was 17709kw. With the additional installation of ACR between nodes (846-848), (862-832), (888-890) and (854-856), the values obtained for EUE were 1152 kW, 11926 kW, 13146 kW and 14191 kW respectively indicating a level of reductions in the values of EUE. The ACRs, once installed optimally on the test system improves the reliability of the distribution system by isolating the healthy parts of the system automatically, which maintains the service to a substantial number of customers and reduce the repair time. The integration of DGs into the distribution test system provides the opportunity of operating the distribution system as a microgrid, allowing continuity of service in the network. It also forms a useful basis for evaluating the reliability of distribution feeders.

Keywords: Automate circuit reclosers (ACRs), Distributed generators (DG), Reliability indices, Monte Carlo Simulation Power Distribution systems, SAIFI, SAIDI, CAIDI, ASAI.

I. Introduction

Reliability is the degree to which the performance of the elements in a bulk system results in electricity being delivered to customers within acceptable standards and in the amount desired. The degree of reliability may be measured by the frequency, duration and magnitude of adverse effects on the electric supply. Reliability deals with total elective interruption such as complete loss of voltage as well as the deformations of the electric sine wave. Reliability indices are parameters used for the assessments of performance levels of electrical distribution systems (Billinton and Li, 1994; Billinton and Allan (1996).

The aspects covered and considered include: the number of customers, the connected loads, the duration of the interruption measured in seconds, minutes, hours or days, the amount of power interrupted and the frequency of interruptions. Indices are used to measure, report and track sustained outage and priorities system improvements. Sustained interruptions are classified as outage within the duration of five minutes or more. Some common reliability indices of electrical power distribution systems are System Average Interruptions Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI) and Customer Average Interruption Duration Index (CAIDI), ASAI etc (Chowdhury and Koval, 2009; Goel and Billinton, 1994).

SAIFI in the average frequency of sustained interruptions per customer over a predefined area. It is the total number of customer interruptions divided by the total number of customers served. SAIDI is commonly called customer minutes of interruption or customer hours and is designed to provide information about the average time the customers are interrupted. It is in the sum of the restoration time for each interruption event times the number of interrupted customers for each interruption event divided by the total number of customers (Brown, 2009).

CAIDI is the average time needed to restore service to the average customer per sustained interruption. It is the sum of customer interruption durations divided by the total number of customer interruptions (Lawrence Berkeley National Laboratory Division, 2003; Li and Sabir, 2008).

Two lesser-used indices are Average Service Availability Index (ASAI) and Customers Experiencing Multiple Interruption (CEMI) [4]. Average Service Availability Index (ASAI) is the percentage of time service that was available to customers. It is calculated by using 8.760 hours in a year (8784 hours in a leap year). Thus, utilities with a SAIDI of 110 minutes (1.83 hours) during the year have an ASAI of 99.98 percent.

$$ASAI = \frac{8760-\text{SAIDI}}{8760} x\ 100\% \qquad 1$$

CEMI measures the percentage of overall customers that have experienced more than a specific number of interruptions. Decreasing this index has the tendency of decreasing the number of customers' complaints. Three interruptions during a six-month period doubles the number of complaints that utility will receive for three outages during a full year. Complaints increase more when customers experience more than three service interruptions within six months. Outage interval is also important. Rural customers accept outages better than urban ones (Brown, 2009).

A reliability index that considers momentary interruptions is called Momentary Average Interruption Frequency Index (MAIFI). MAIFI is the total number of customers' momentary interruptions divided by the total number of customers served. Momentary interruptions are those interruptions that result from each single operation of an interrupting device such as a recloser.

DG is an electrical energy that is distributed to the grid from many decentralized locations, such as from wind, farms and solar panel installations.

Monte Carlo Principle

Monte Carlo methods represent a broad class of computational algorithm that relies on repeated random sampling to obtain numerical results. The main idea is the use of randomness to solve problems that might be deterministic in nature. They can be applied in physical and mathematical problems and are most useful when it is difficult to apply other approaches.

Monte Carlo methods are mainly used in three distinct problem classes: - Optimization, numerical integration and probability distribution.

In physical-related problems, Monte Carlo methods are used to simulate systems with many degrees of freedom, such as fluids, disordered materials, strongly coupled solids and cellular structures. The method can be used to solve any problem having a probabilistic interpretation.

Applications of Monte Carlo Methods

Monte Carlo methods are useful for simulation of phenomena with significant uncertainty in systems with a large number of coupled degrees of freedom. The application areas include (Billinton and Li, 1994):

a. Physical Services: Monte Carlo methods are useful in computational physics, physical chemistry and related applied fields.
b. Engineering: They are useful in engineering for sensitivity analysis and quantitative probability analysis in process design. The method also finds useful applications in the following fields of engineering:
   i. Microelectronics engineering.
   ii. Geostatistics and geometallurgy
   iii. Wind energy
   iv. Fluid dynamics
   v. Autonomous robotics
   vi. Telecommunications
   vii. Reliability engineering
   viii. Signal processing and Bayesian inference
c. Computational biology: The method is useful in various fields of computational biology. For example, for Bayesian inference in phylogeny or for studying biological systems such as genomes, proteins or

membranes.

Other areas of applications include: -
Computer graphics.
Applied statistics
Artificial intelligence for games
Designs and visuals.
Search and rescue.
Finance and business
Law
Mathematics
Integration
Animation and optimization
Solution of inverse problems

The Monte Carlo Simulation (MCS)

The MCS accurately evaluates the reliability of electrical grid.

Division of MCS

MCS can be divided into two main types (Li and Sabir, 2008):

i. Sequential MCS
ii. Non-Sequential MCS

Sequential MCS:

The sequential MCS simulates the system operation as an up-and-down system where a system operating cycle is obtained by combining all the cycles of the system components in chronological order

Non-sequential MCS:

The non-sequential MCS simulates the system with a higher efficiency by choosing intervals at random, even though, it cannot simulate the chronological aspect of the system behavior. The MCS is also useful in the stochastic simulation using random variables to simulate electrical components by considering the behavior of the grid in order to evaluate the expected reliability parameters as well as providing useful information for the load point indices, system indices and the energy not served cost.

II. Materials and Methods

The IEEE 34 test system shown in Figure 1 was simulated using the two-state Markov model shown in Figure 2.

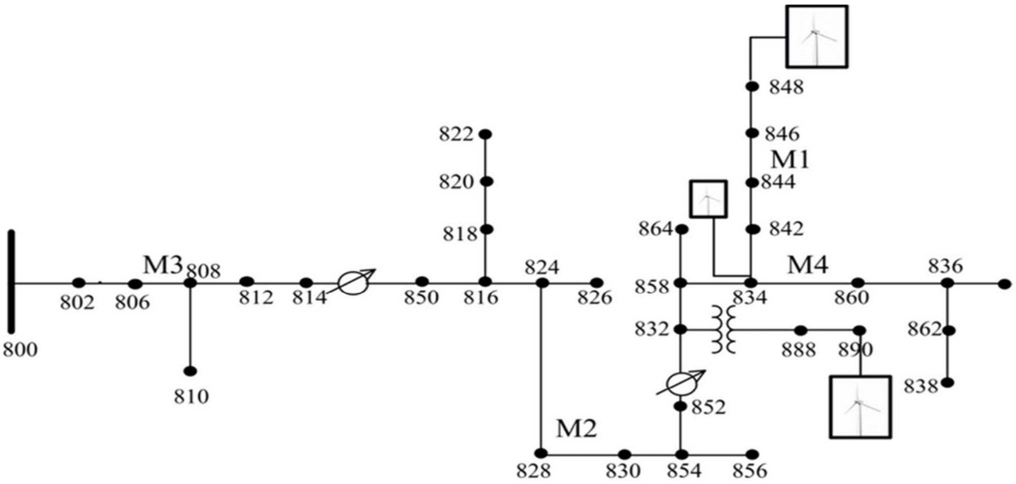

Figure 1: The IEEE 34-node test feeder.

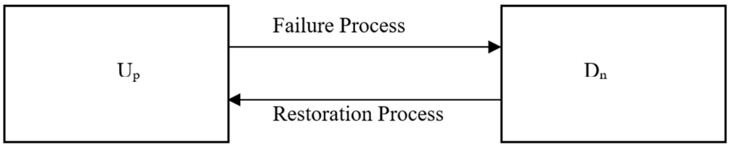

Figure: 2: The two-state model of a component.

The process is random since it is not sure, where, when and which component in the system will fail first considering the fact that the behaviour will be different from one component to another including the type and number of failures and the time between a failure and component restoration.

The Markov model consists of two-states: up and down states. The "up-state" is for the operating condition of the components.

The down-state is for the failing state. The up-state is called time-to-fail (TTF) while the down state is the time-to-repair replace (TTR)

$$TTF = -\frac{\text{Ln(Ui)}}{\lambda i} X8760\ hours \qquad 2$$

$$TTF_i = -Ln(Ui) \times MTTR_i\ hours \qquad 3$$

Both TTR and TTF are random.

The process from up to down is called failure process for a component as a result of contingency event that will take it out of operation.

Simulation Process of the MCS

The process involved in simulating the IEEE 34 test feeder using the MCS approach is as follows:

i. A random value for each of the component using the random number generator was generated. The variables obtained foreach component have equal likelihood with values between 0 and 1.
ii. The component in the system with the minimum TTF was determined.
iii. The outage duration for each failed load point indices were determined after converting the generated values into TTF, TTR for each component in the system.
iv. A near random number for the failed component was generated. This was converted into a new TTF. If the simulation time is less than a year, then return to step (ii) otherwise, go to step (vii).
v. The number and duration of failures for each load point per year was calculated.
vi. The average value of the load point failure rate and duration for the sample year was calculated.
vii. SAIDI, SAIFI, CAIDI, and system indices were calculated and the average values of the results were also recorded.
viii. If the simulation time is less than the specified total simulation years, return to step (ii), otherwise, record the results as final outcomes and end the simulation.

III. Discussion of Results

Case 1: Installation of one AR in the test system.

The results of SAIFI with the installation of one automatic circuit recloser is shown in Figure 1. In the absence of ACR, the SAIFI obtained was 17.33 while the installation of ACRs between nodes 800-802, 802-806,806-808, 808-812, 812-814 gave SAIFI values of 14.93 hours/year, 15.22 hours/year, 15.10 hours/year, 15.04 hours/year and 16.12 hours/year respectively.

SAIFI values of 16.31 hours/year, 14.00 hours/year, 15.11 hours/year, 11.99 hours/year and 13.20 hours/year were also recorded when the ACR was installed between nodes 850-816, 820-822, 824-826, 854-856 and 858-834 respectively. The installation of an ACR gave a reduction in SAIFI. The best improvement was noticed when ACR was installed between nodes 824-842 in the electrical feeder. This improvement is as a result of the part that the ACR has the ability to isolate the fault and restore the service to the healthy parts of the feeder, which also contribute to identification of the faulted area which reduces the repair hours. This improves the overall reliability indices and save much of energy, money and efforts to the utilities.

Figure 2 illustrates the results of SAIDI indices with the installation of one ACR. In the absence of ACR, the SAIDI value was 8.90 hours/year. The values of SAIDI indices reduced from 8.90 hours/year to 7.99 hours/ year, 7.49 hours/year and 8.60 hours/year with the installation of one ACR between nodes 800-802, 802-806 and 912-814 respectively.

When one ACR was also installed between nodes 820-822, 816-824, 824-826, 824-828 and 828-830, the values obtained for SAIDI reduced as well to 7.34 hours/year, 7.19 hours/year, 7.59 hours/year, 6.88 hours/year and 5.97 hours/year respectively. The best improvement for SAIDI was obtained when the ACR was installed between nodes 842-844.

The result of CAIDI with the installation of one AR is also depicted in Figure 3. In the absence of ACR in the test system, CAIDI value obtained was 2.5660. When ACR was installed between nodes 800-802, 802-806, 806-808, 808-812 and 812-816, the CAIDI values reduced to 2.5595, 2.5523, 2.5846, 2.5791 and 2.5639 respectively.

Figure 4 illustrates the ASAI index when one ACR was installed in the test system. In the absence of ACR, the ASAI value obtained was 1.1920. With the installation of one AR into nodes 800-816, 816-818, 818-820, 820-822 and 818-824, the ASAI values obtained were 2.2011, 4.1911, 4.1901, 4.1911 and 4.1991 respectively which marked an improvement in the ASAI values.

The result of the EUE with the installation of one ACR in the test system is shown in figure 5. When there was no AR, the values obtained for EUE was 12,809 KW/year. Installation of ACR between nodes 800-802, 802-806, 806-808, 808-812 and 812-814 gave EUE values of 11348 kw/year, 11365 kw/year, 11945 kw/year, 11863 kw/year and 12324 kw/year respectively which indicated a decrease in EUE with the installation of ACR in the test system.

Case 2: Installation of two ACRs in the test system.

Figure 6 shows the SAIFI results with the installation of two ACRs. In this case, the test system was modified to include an ACR in between nodes 818-824 with the highest SAIFI value of 12.65 hours/year in order to model the modified system to discover any further improvements in the reliability indices so as to add another ACR in the test system.

Figure 7 illustrates the results of SAIDI with the installation of two ACRs in the test system. The SAIDI values obtained with the installation of two Ars between nodes 828-824, 820-822, 852-854, 828-830 and 838-890 are 4.211 hours/year, 4.526 hours/year, 4.326 hours/year, 4.019 hours/year and 4.314 hours/year respectively, showing a fluctuation in the SAIDI trend. ACRs the best option, the second ACR was installed in between nodes 854-856 with SAIDI least value of 3.981 hour/year. This contributed to the system's ability to isolate the faulted area of the feeder once an outage occurs, and be able to restore service and maintain it for the healthy part of the feeder.

The results of CAIDI with the installation of two ACRs is shown in Figure 8. The CAIDI values fluctuates, along the test system as two ACRs were installed there.

Figure 9 illustrates ASAI values of the test system immediately two ACRs were installed. With the installation of two ACRs in the test system, the ASAI values fluctuate accordingly. When two ACRs were installed in between nodes 828-824, 830-854 and 854-852, the values obtained for ASAI values were 2.191, 4.1911, and 3.912 respectively.

Figure 10 shows the results of the EUE when two ACRs were installed in the test system. These values also fluctuate accordingly with the least EUE value as 8097 and the highest value being 8846 which were obtained when additional ACR was installed in between nodes 832-858 and 818-820 respectively.

Case 3: Installation of 1MW DG unit in the test system.

DGs are powerful tools in the enhancement of reliability of electrical power distribution system. It provides energy to the distribution feeder during the occurrence of a major outage on the electrical network. 1MW DG was modelled and connected to node 888 where about 38% of the customers were connected. The demand at this load point was 1.9MW, hence a 1 MW DG was installed along with the ACRs since the 1MW DG units provides the same benefits that could be offered by installation of a higher DG rating, otherwise, the DG unit on the test system would have been sized.

Figure 11 illustrates the results of the SAIFI index with the installation of 1MW DG unit in the test system. Observation shows the need for the ACR/CBs with the installation of a 1MW DG on the distribution system, otherwise there would be no benefit because any fault on that distribution feeder will block the connection of the DG unit when outages occur.

The values obtained for SAIFI with the base case with one DG was 14.23 hours/year while with the installation of ACR between nodes 834-842, 842-844, 844-846, 836-840 and 832-88, SAIFI values obtained were 5.07 hours/year, 5.81 hours/year, 6.60 hours/year, 6.17hours/year and 7.27 hours/year respectively. SAIFI in this case experienced a great reduction from 14.23 hour/year for the base case with one DG installed.

Figure 12 shows the results of SAIDI when 1MW DG was installed in the test system. The value obtained for SAIDI with the base case with one 1MW DG was 5.80 hour/year. When SR was installed along with 1MW DG on the nodes between 860-836, 836-840, 836-862,862-838 and 832-858, the values obtained for SAIDI were 8.80 hours/year, 3.62 hours/year, 3.58 hours/year, 4.21 hours/year and 4.15 hours/year respectively indicating a drastic

The results of CAIDI when 1MW DG unit was installed in the test system is illustrated in Figure 13.

Figure 14 shows the results of ASAI with the installation of 1MW DG unit in the test system. 3.191 was obtained for ASAI with the base case and one DG installed in the test system. The values obtained for ASAI for different locations of the 1MW DG unit fluctuate throughout the case descriptions. Thus, with the installation of the 1MW DG unit between nodes 834-842, 844-846, 834-860, 836-840, and 862-838, the values obtained for ASAI were 5.196, 5.101, 5.012, 6.141 and 6.128 respectively which represent appreciable level of improvement as compared to the base case.

Figure 15 shows the results of the EUE with the installation of 1MW DG unit in the test system. The values obtained for EUE fluctuate throughout the case descriptions. Thus, with the installation of one DG in the test system, the value obtained for the EUE was 17709kw. With the additional installation of ACR between nodes (846-848), (862-832), (888-890) and (854-856), the values obtained for EUE were 1152 kW, 11926 kW, 13146 kW and 14191 kW respectively indicating a level of reductions in the values of EUE.

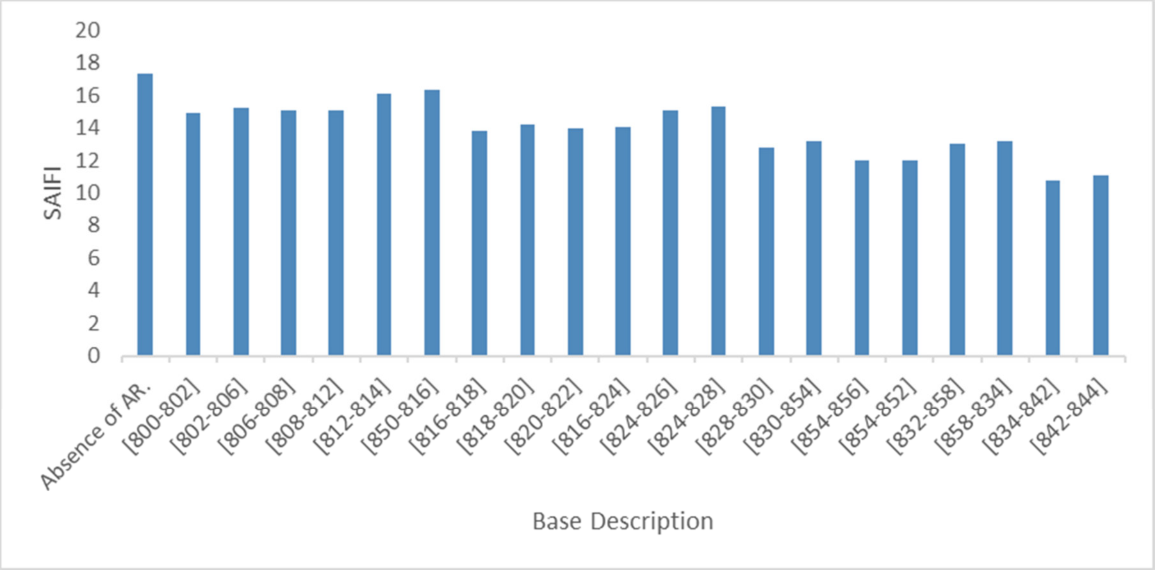

Figure 1: Results of SAIFI with one ACR installed

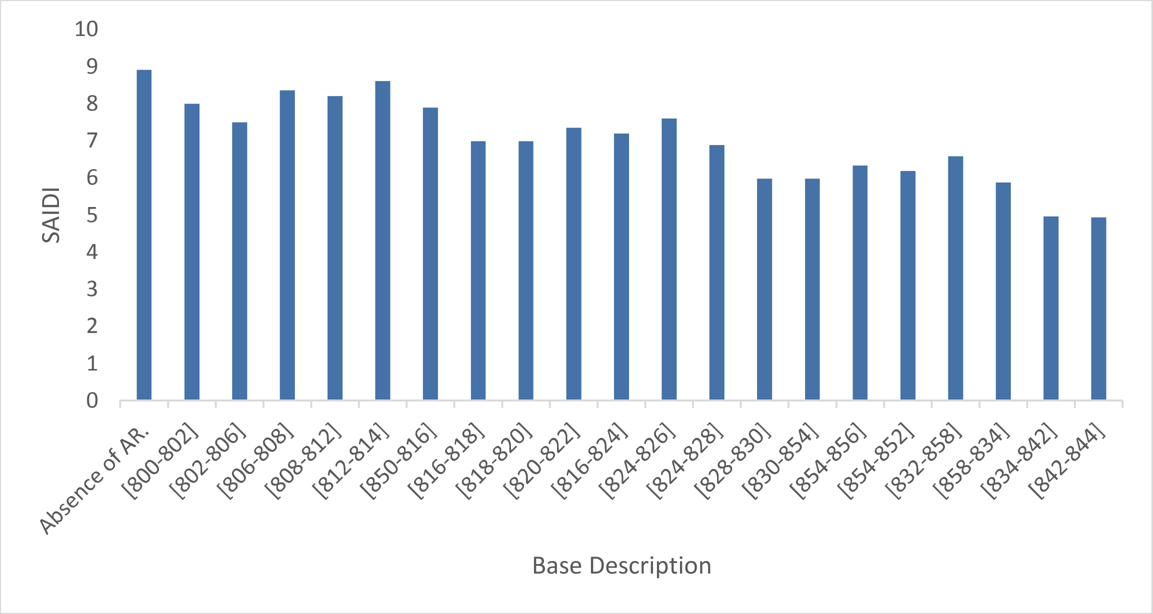

Figure 2: Result of SAIDI with one ACR installed.

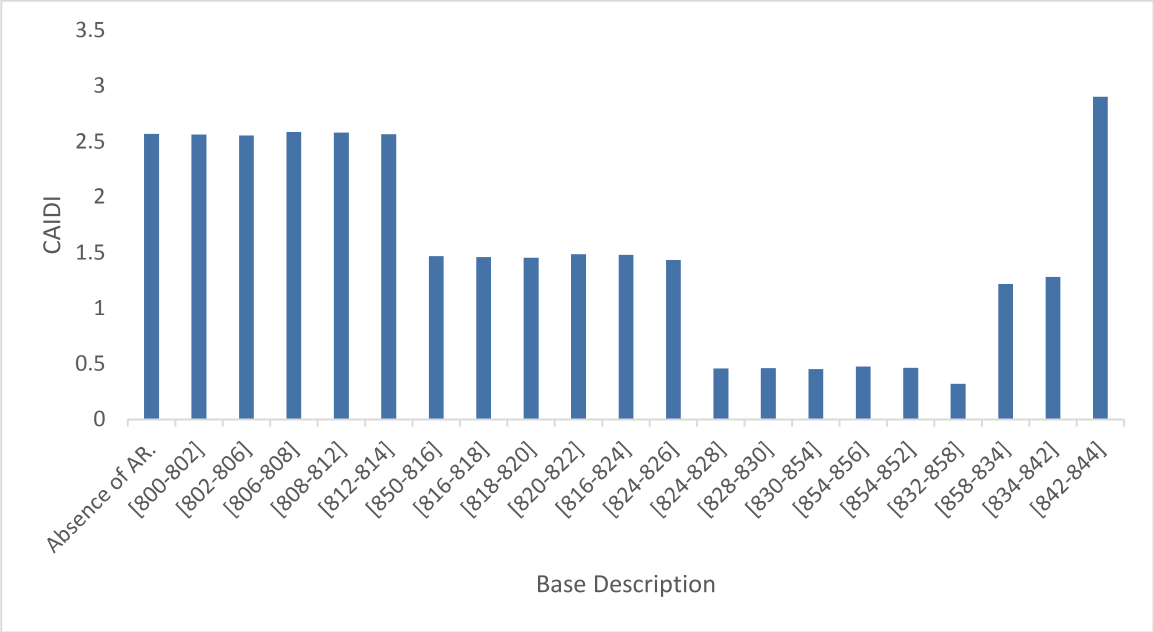

Figure 3: Result of CAIDI with one ACR installed.

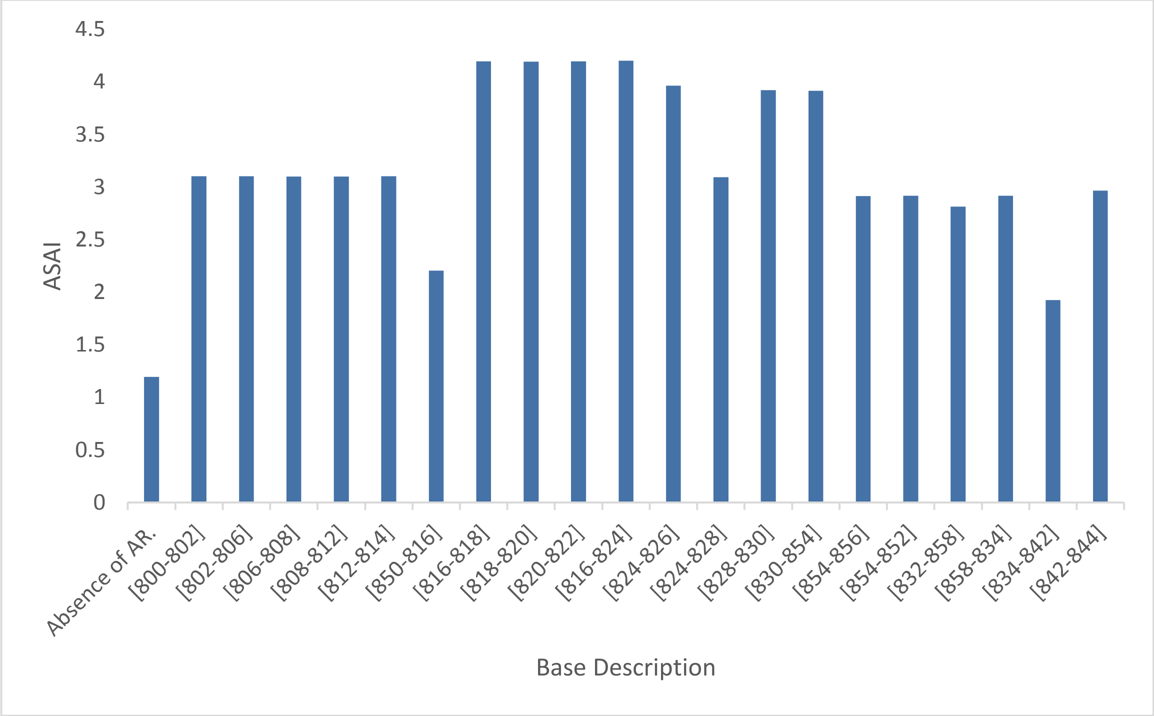

Figure 4: Results of ASAI with one ACR installed.

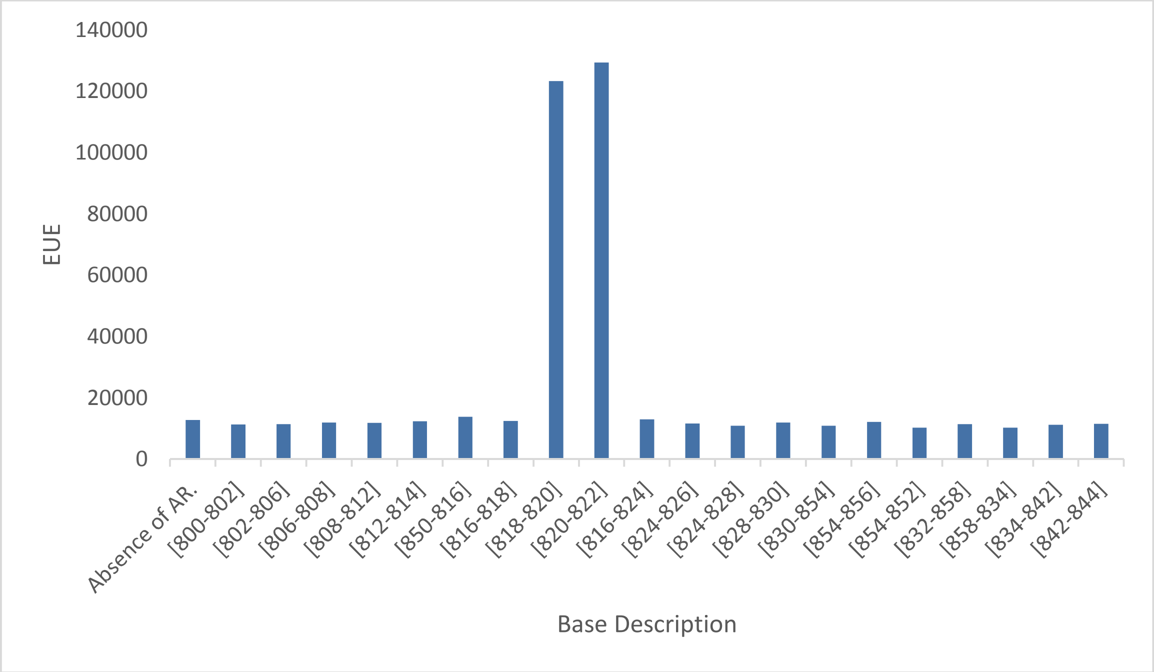

Figure 5: Result of EUE with one ACR installed

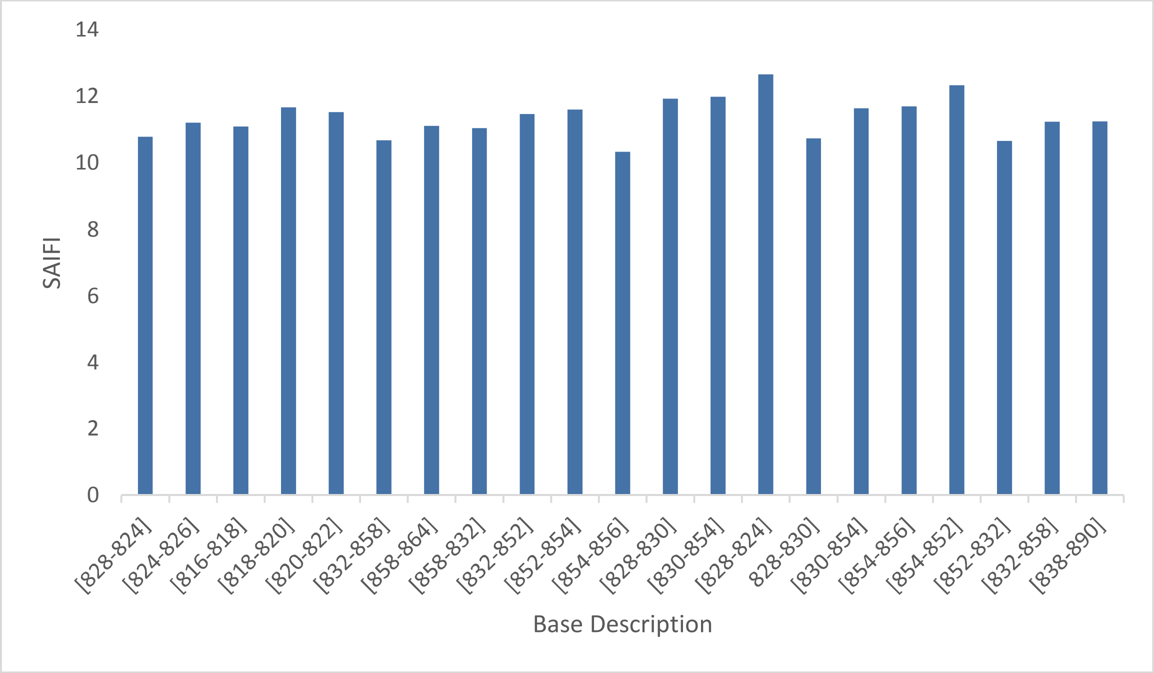

Figure 6: Results of SAIFI with two ACRs installed

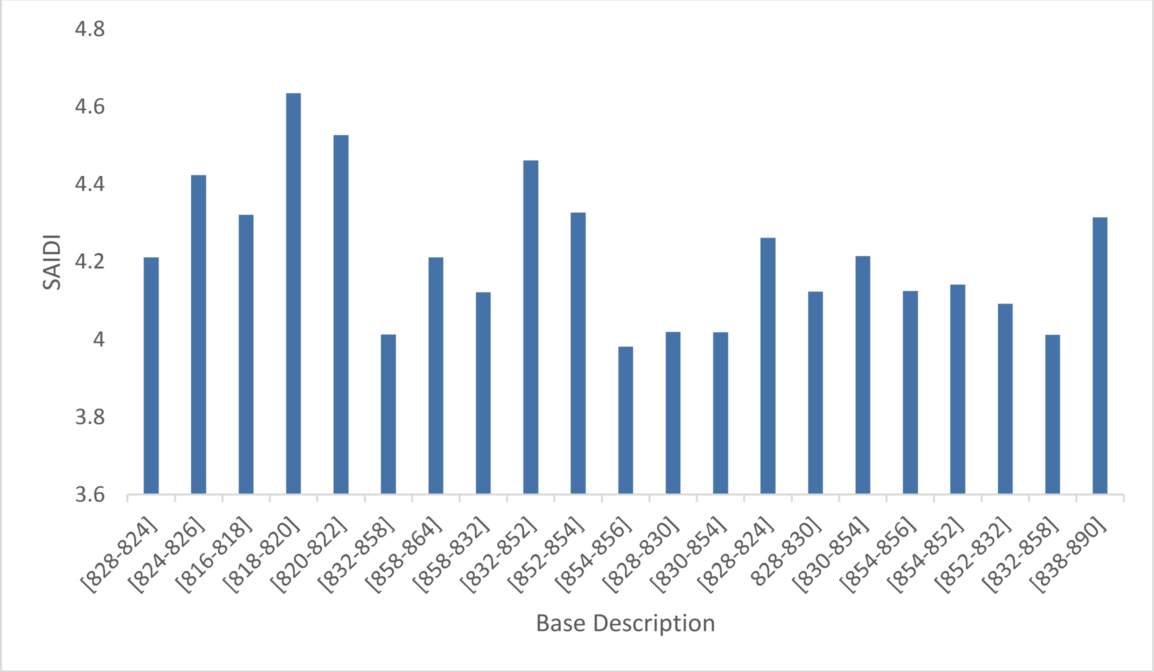

Figure 7: Result of SAIDI with two ACRs installed

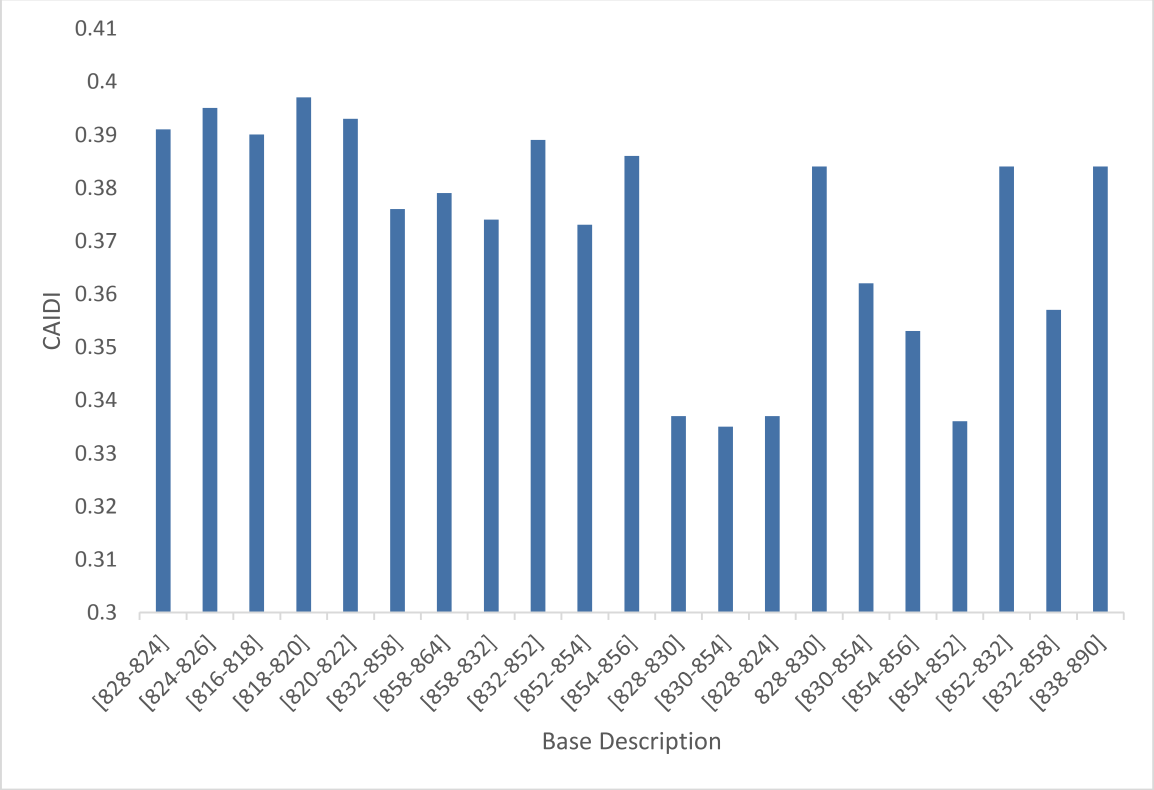

Figure 8: Result of CAIDI with two ACRs installed

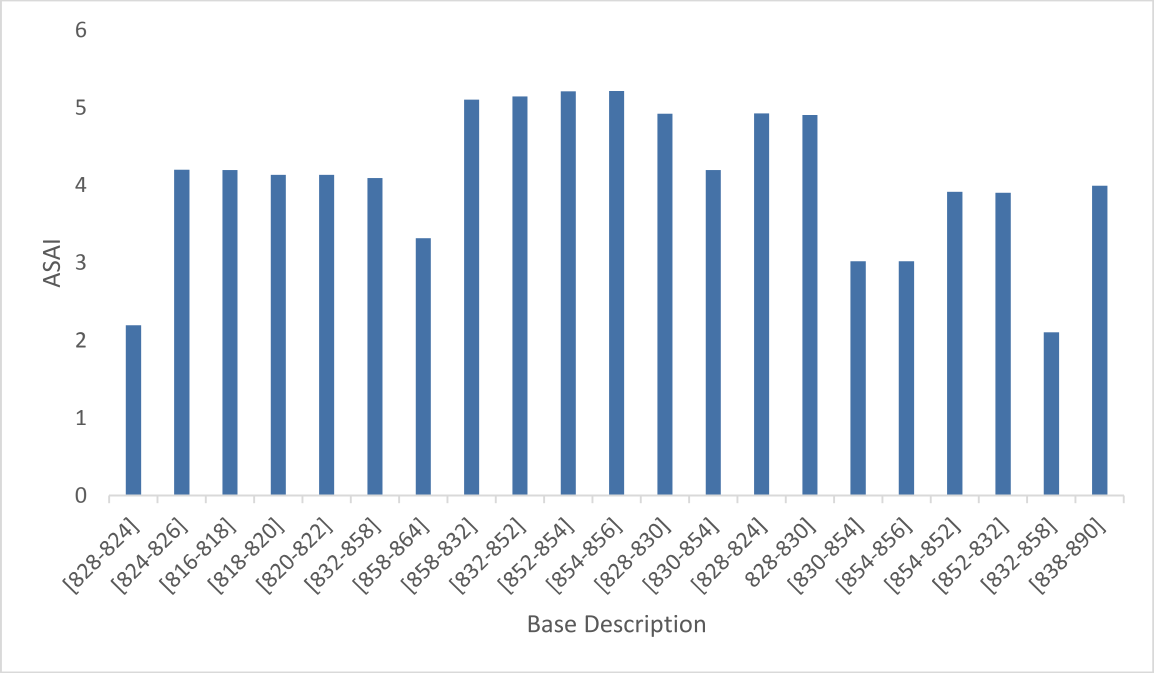

Figure 9: Result of ASAI with the ACRs installed

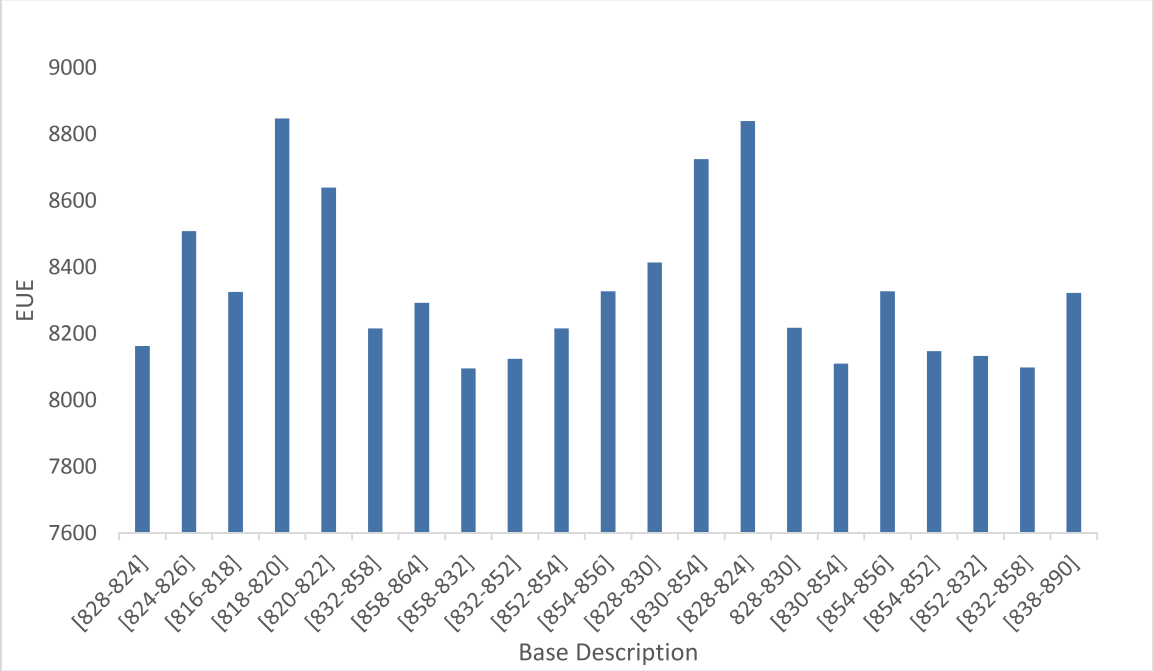

Figure 10: Result of EUE with two ACRs installed.

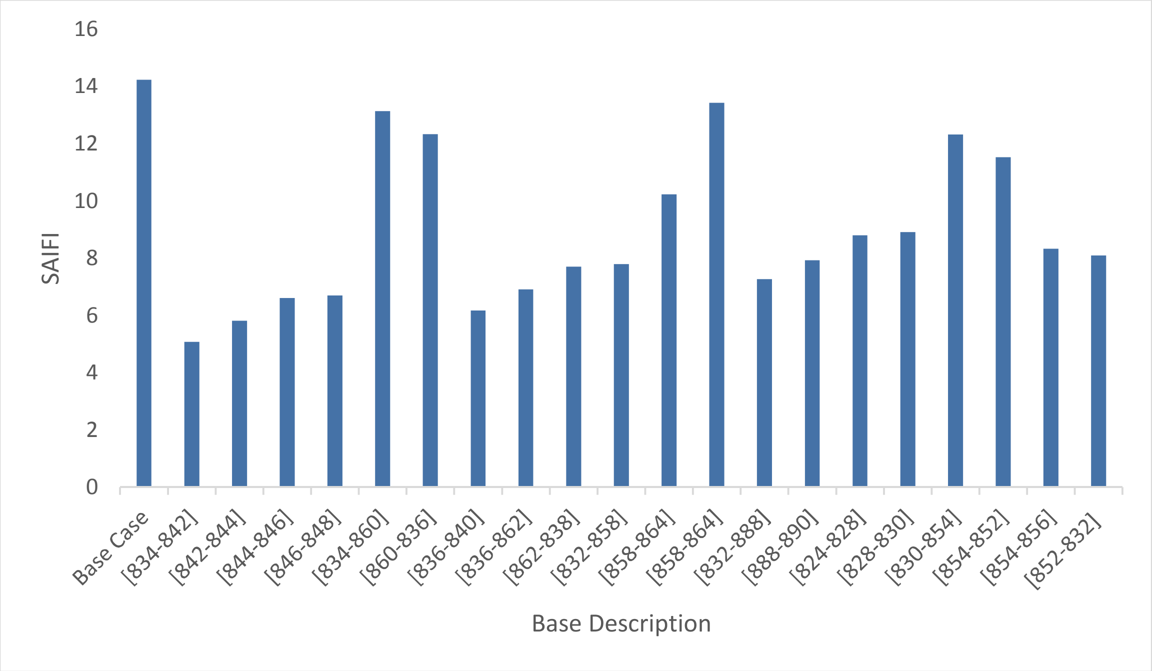

Figure 11: Result of SAIFI with one DG installed

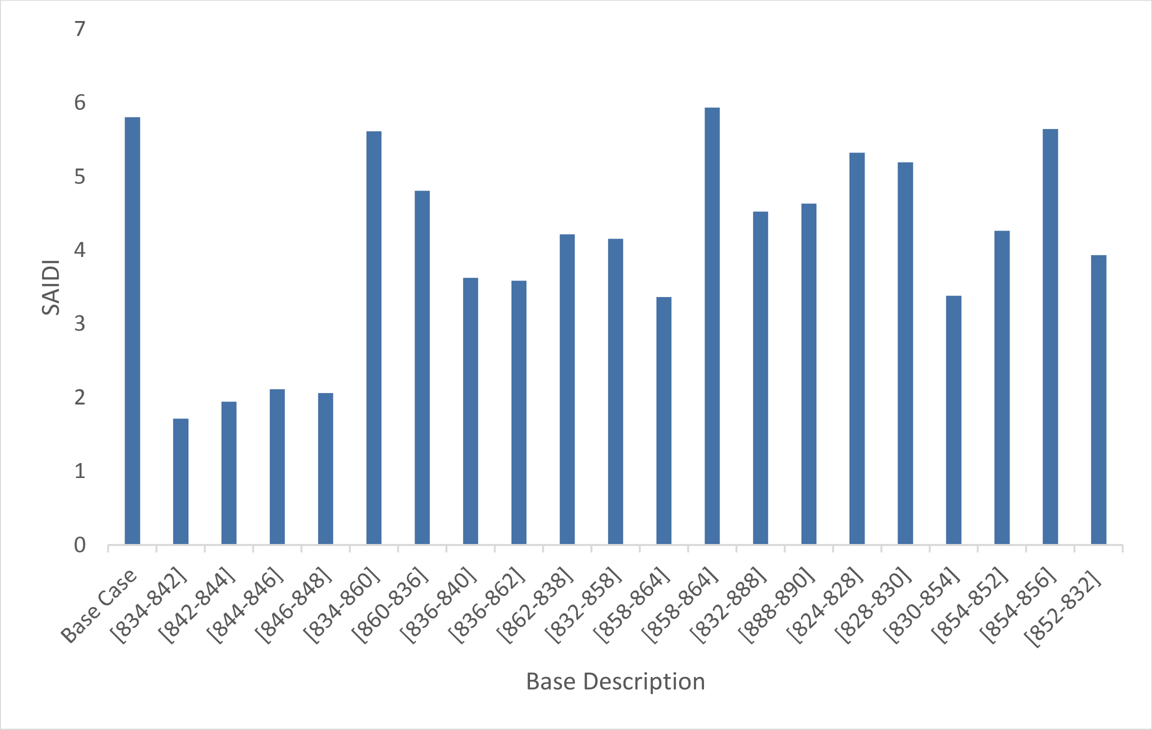

Figure 12: Result of SAIDI with one DG installed

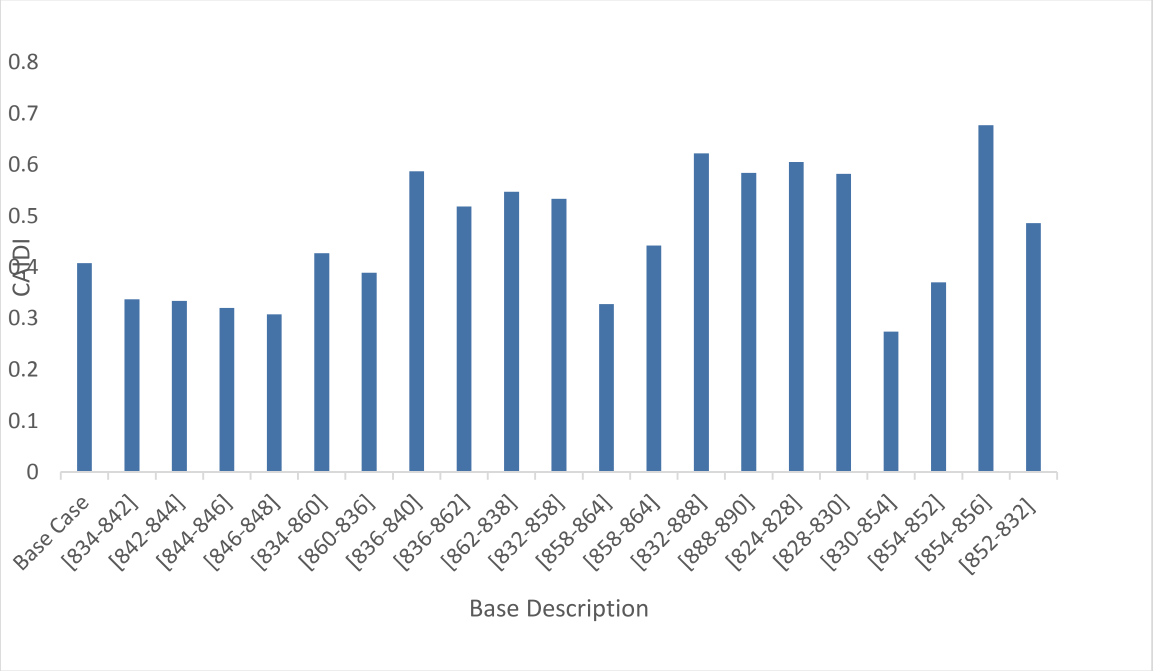

Figure 13: Result of CAIDI with one DG installed

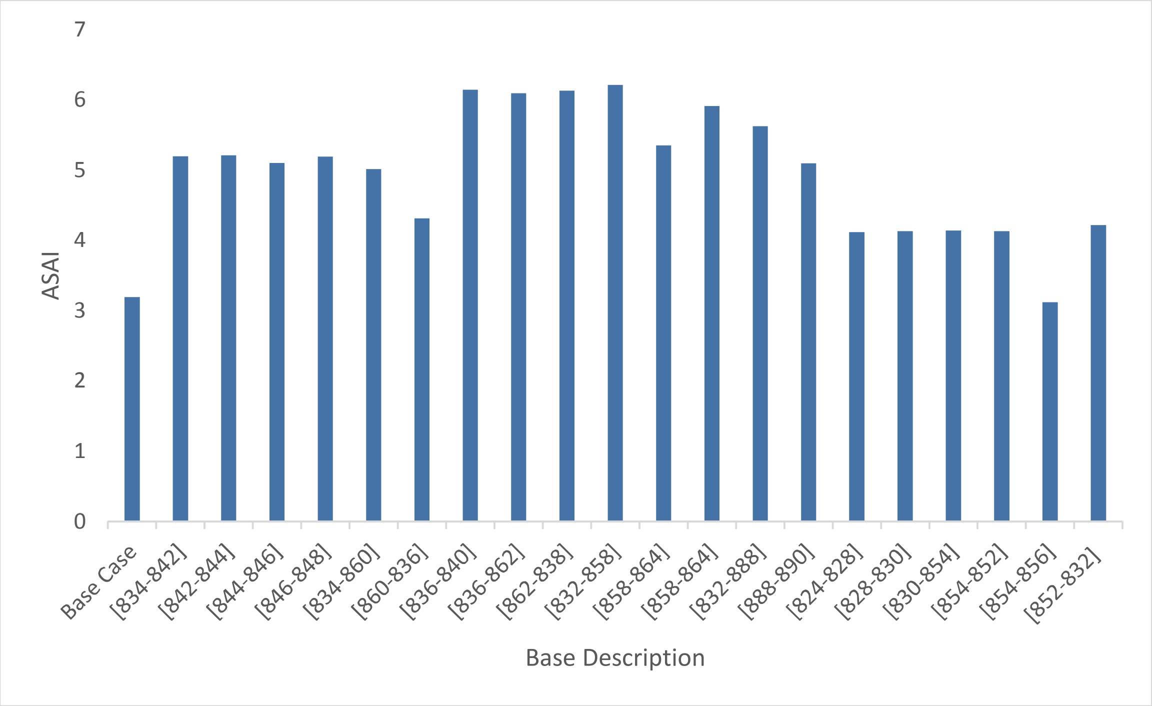

Figure 14: Result of ASAI with one DG installed

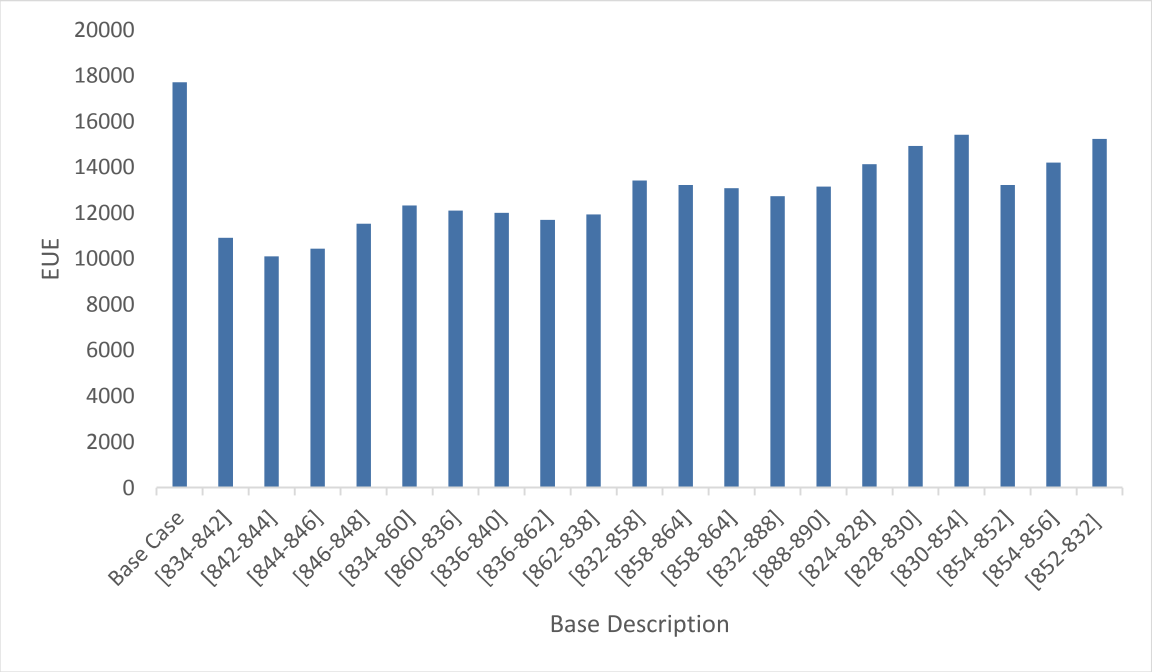

Figure 15: Result of EUE with one DG installed.

IV. Conclusion

Load point and system reliability indices such as SAIFI, SAIDI, CAIDI, ASAI and EUE were used to evaluate the overall reliability of the distribution system using appropriate mathematics notation.

The impact of ACRs and DGs on the reliability indices of electrical power distribution system has been presented. Load point and system reliability indices such as SAIFI, SAIDI, CAIDI, ASAI and EUE were used to evaluate the overall reliability of the distribution system using appropriate mathematics notation. Monte Carlo simulation was performed in MATLAB on the IEEE 34 test feeder under three scenarios- with the installation of one ACR on the test system, with the installation of two ACRs on the test system and with the installation of 1MW DG on the test system.

The results of the research paper indicate appreciable level of improvement in the system reliability indices. It shows that installation of an automatic circuit recloser yielded a reduction in both SAIFI and SAIDI as to the scenario of having a regular system. The best improvement was noticed when ACR was installed between nodes (834-842) in the test system. SAIDI value at this instance also decreased from 8.90 hours/year to 7.99 hours/year. With the installation of two ACRs in the test system between nodes (828-824) and (824-826), SAIFI values of 10.74 hours/year and 11.20 hours/year were obtained. This represents an improvement in this index.

When 1MW DG unit was installed in the test system, values of 14.23 hours/year and 5.80 ours/year were obtained for SAIFI respectively.

The results from this research paper were in close agreement with the results obtained for the same test system using analytical method.

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