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Reliability Study on the Placement of Electric Vehicle Charging Stations in the Distribution Network of Cambodia

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Abstract: *The growing number of battery technologies and increasing environmental concerns have accelerated the transition to electric vehicles. As internal combustion engine vehicles are replaced by EVs, the impact of EV charging loads on power system operations has become a significant concern. However, the growing adoption of electric vehicles (EVs) presents a challenge for power grids that cannot be neglected. The high charging loads, particularly from fast charging stations, can negatively impact key distribution network parameters such as voltage stability, reliability, power loss, and harmonics. Ensuring the reliability of distribution networks is paramount for maintaining customer satisfaction in the power system. The charging station is integrated into the grid via a common DC bus, allowing multiple EVs to connect. Each EV is controlled locally, with independent management provided for the power exchange between the AC grid and the DC bus. This study investigates the impact of EV charging on the reliability of the bus distribution system. The analysis is conducted on the IEEE 33 bus test system, which represents a standard radial distribution network, across five different cases of EV charging station placement. It is observed that the system can withstand the placement of DC fast charging stations at strong buses up to a certain level, but placing fast charging stations at weak buses disrupts the smooth operation of the power system. Furthermore, these test results confirm the effectiveness of the reliability index-based approach for the allocation of EV charging stations within a distribution system.*

Keywords: Impact, Reliability, Electric Vehicle, Charging Station Placement, Distribution network.

1. INTRODUCTION

The government of Cambodia is currently working on implementing various policies, action plans, and specific measures to encourage the growth of a vibrant electric vehicle (EV) market. In 2016 [1], the Ministry of Environment introduced regulations for battery reprocessing and recycling, setting the stage for this sector's development. More recently, import duties on four-wheeled electric vehicles have been reduced to 50% of those on internal combustion engines. The number of eco-friendly electric vehicles (EVs) is rising due to the environmental damage caused by internal combustion Engines. This heightened interest is partly driven by the need for clean energy sources, sparked by the global warming debate. Environmentalists in Cambodia are deeply concerned about climate change, environmental pollution, and the energy crisis. The transportation sector, which is a major source of CO2 emissions, contributes significantly to global warming and climate change [2]. Additionally, as urbanization progresses, city traffic is increasing at an alarming rate. To reduce the carbon footprint, the government has issued a notification emphasizing the need for transportation electrification. Factors such as the Cambodia Agreement and poor air quality are driving forces behind this initiative. According to the Ministry of Public Works and Transport (MPWT), Cambodia aims to have over 1 million electric two- and three-wheelers in the country between 2030 and 2040. These vehicles are expected to generate between 0.7% and 2.8% of Cambodia's national electric consumption, reaching between 2.1 and 7.3 million units by 2050. Additionally, around 100,000 electric cars are projected to be on the road between 2035 and 2042 [1]. Currently, there are over 270 million light electric vehicles on the road, including 18 million cars, 685,000 buses, and 613,000 vans and trucks. In Cambodia, 14 Electric Vehicle.

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Charging Stations (EVCS) have been installed, 8 in Phnom Penh, 1 in Sihanoukville, 1 in Siem Reap, 1 in Battambang, and 3 in Mondulkiri. And by 2030, between 25 and 100 strategically located DC fast charging station will be needed to fully connect Cambodia's provinces; by 2050, this requirement is expected to rise to between 1,700 and 5,900 locations. Notably, electric car sales are expected to surpass those of internal combustion engine vehicles (ICEVs) in most markets between 2025 and 2040. Researchers are advocating for the replacement of Internal Combustion Engine (ICE) vehicles with Electric Vehicles (EVs). In [3], the authors used a probabilistic Monte Carlo approach to simulate the harmonics generated by PHEV chargers, considering all uncertainties, and concluded that residential Level 1 chargers significantly affect power quality. The impact of non-linear EV charging loads on the distribution system's power quality was examined in [3], where it was noted that the harmonic distortion from EV loads shortened the lifecycle of distribution network assets. It has been reported that EV battery charging loads can cause harmonic distortion of extreme cases. According to [4], the optimal placement of EV charging stations is determined using voltage sensitivity indices, and the proper placement also enables the system to alleviate the voltage problems at various buses with smaller current flow from the storage element.

In recent years, researchers have focused on measuring the changes in peak load demand following the installation of EV charging stations in the distribution network. In [5], the results indicate that the voltage profile decreases and harmonics increases with 25% of EV penetration. The increasing number of EVs has led to the development of sustainable charging infrastructure. However, the charging load from fast EV charging stations poses an additional burden on the power grid, potentially degrading the operating parameters of the distribution network, including voltage stability, reliability, power loss, and harmonics. The analyzed that effect of EV charging load on voltage stability of IEEE 14 bus test system [6]. In [7], the authors investigated the effects of EV charging loads on a standard 14 bus distribution network. They found that the transient voltage stability index deteriorated with higher levels of EV penetration. The increased load demand from EV charging can strain service transformers, reducing their lifespan and increasing system losses [8]. Additionally, EV charging may create new load peaks that exceed the service transformer's rated capacity, accelerating the aging of equipment [9]-[10]. In [11], the authors examined the impact of uncontrolled EV charging on the daily load profile and demonstrated how coordinated charging can improve the load profile. A comprehensive analysis of the impact of EV charging loads, including both slow and fast charging, on various distribution network parameters was conducted in [15]. The different adverse effects of EV charging station loads, such as voltage instability, harmonic distortion, and power losses on the distribution network, were examined in [3]-[11]. However, there is a lack of literature reporting on the impact of EV charging station loads on various reliability indices of the distribution network. This work is studies of the impact of DC fast charging stations on customer oriented as well as energy-oriented reliability indices of IEEE 33 bus system which is a standard radial distribution network analyzed for different scenarios.

The rest of the paper is constructed as follows: Section 2 provides a detailed analysis of distribution system reliability indices and different test case scenarios, and outlines the proposed methodology for assessing reliability, including mathematical formulation. Then Section 3 presents the case studies and results for determining the reliability indices of the impact of charging station in the IEEE 33 bus test system. Finally, Section 4 concludes the paper.

2. METHODO LOGY

In this section, present the overall flowchart for proposed method, and workflow of distribution of Distribution Network Reliability Indices. Also present to identify the bus reliability which both of strong and weak bus, based on failure rate, outage time as present on Table. 2, we consider selecting appropriate reliability indices of Customer-Oriented Reliability Indices (SAIFI, SAIDI, CAIDI) and compute the Energy Oriented Reliability Indices (ASAI) to measure the impact on various aspects of reliability. The power flow of analysis is used to calculate the reliability scenarios and the base case. On the other hand, the collected data will be analyzed to identify the relationship between charging station placement/size and the various reliability indices, as shown in the method flowchart Fig. 1, this study proposes examining the placement of DC fast charging stations on the IEEE 33 bus test network system, with test scenarios that involve increasing the load at the i^{th} bus points. We will then compute the values of the customer reliability indices after the load increase (SAIFIl, SAIDIl, CAIDIl, AENSl) and finally, to present the results.

2.1. Reliability Analysis of Distribution network System

Ther reliability analysis of the distribution network has become a challenging area of research. In this study, we focus on the reliability of the distribution network. The reliability indices are evaluated based on statistical data, including failure rate, repair rate, average outage duration, and number of consumers [12]. This section presents a brief overview of the distribution network reliability indices, as shown in Fig. 2. The bus reliability index for the test network was determined using outage data AIT_i and AIT_j, and the reliability indices of distribution network are broadly categorized into customer oriented and energy oriented reliability indices. SAIFI, SAIDI, and CAIDI are the three major classifications of customer oriented reliability indices. The energy oriented reliability indices can be further subdivided into ENS and AENS.

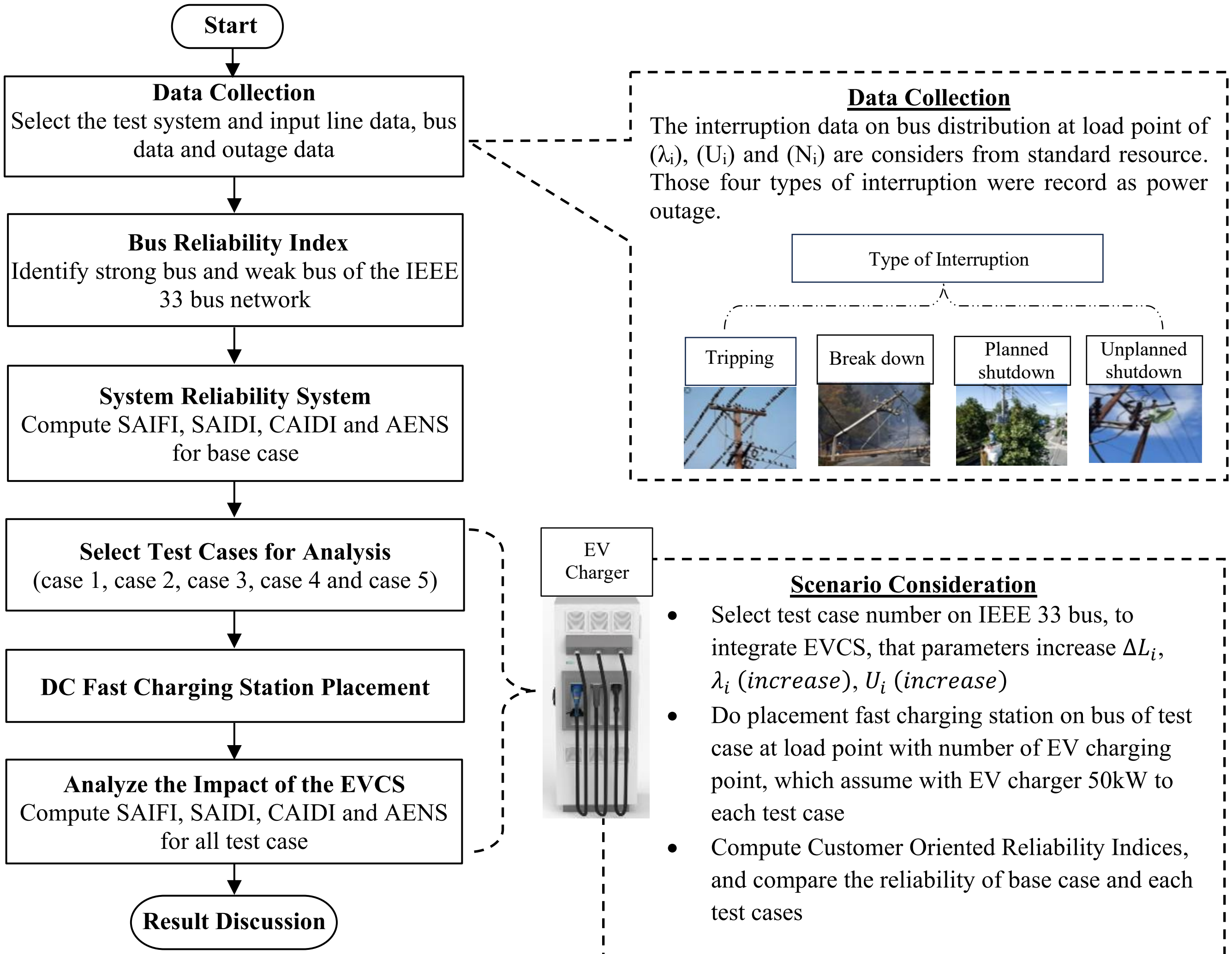

Fig. 1. The overall flowchart for proposed method

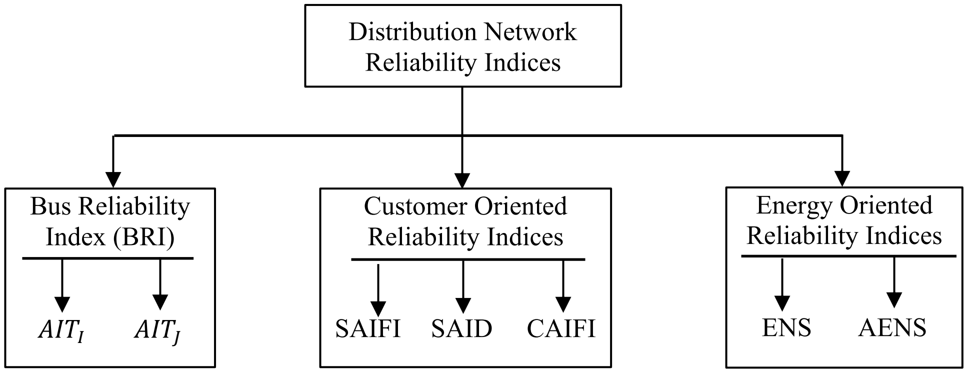

Fig. 2. Distribution Network Reliability Indices.

2.1.1. *Bus Reliability Index (BRI)*

The Bus Reliability Index (BRI) is used to determine the reliability and vulnerability of each bus in the distribution network [13]. BRI is computed as given in Eq. (1).

$$BRI = \frac{AIT_i}{AIT_j} = \frac{\lambda_i U_i}{AIT_j} \qquad \text{(Eq. 1)}$$

Where AIT_i is the Average Interruption Time of the i^{th} bus and, index j is the bus with maximum AIT. The reliability indices of distribution network determine the quality of the power system based on the average data of fail rate (λ_i), average outage duration (U_i).

2.1.2. *Customer Oriented Reliability Indices and Energy Oriented Reliability Indices*

The customer-oriented reliability indices are the System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), and Customer Average Interruption Duration Index (CAIDI). SAIFI is defined as number of times a system customer experiences interruption during a particular time period. The source responsible for interruption can be line outages, equipment failure rate due to fault or increase load demand and scheduled break to maintenance. The increase in the interruptions and the number of customers degrades SAIFI of the system. SAIDI is expressed in hours/ customer year and depends on the duration of interruption as well as the number of consumers. CAIDI is the ratio of SAIDI and SAIFI. CAIDI is expressed in hour/ customer interruption. It depends on the average failure rate, duration of the failure rate, and the number of customers. As the number increases of loads during EV charging, the result can degradation of all indices that lead to customer dissatisfaction. The energy-oriented reliability indices rely on the load demand at the load points of the buses and provides information on the amount of energy not supplied during a particular period. These indices are helpful in determining the weak load points in the buses and the intensity of system failure. It also evaluates the sequential changes affecting the performance of the power system. Energy oriented reliability indices are crucial for assessing system reliability. One such measure is the Average Energy Not Supplied (AENS), which depends on the load demand at the bus load points and indicates the amount of Energy Not Supplied (ENS) during a specific period. These indices are mathematically expressed by all index from These indices are mathematically expressed in all index from [12] and shown in Table 1. These indices are valuable for identifying vulnerable load points within the buses and the severity of system failures. They also assess the sequential changes that impact the power system's performance.

Table 1. Different customer and energy oriented reliability in dices.

Index Formula	Physical Significance
$SAIFI = \frac{\sum \lambda_i N_i}{\sum N_i}$	SAIFI illustrates the condition of the system in term of interruption
$SAIDI = \frac{\sum U_i N_i}{\sum N_i}$	SAIDI illustrate the condition of the system in term of duration of interruption
$CAIDI = \frac{SAIDI}{SAIFI}$	CAIDI gives the average outage duration that any given customer would experience
$ENS = \sum L_i U_i$	ENS is an indicator of energy deficiency of the system
$AENS = \frac{ENS}{\sum N_i}$	AENS is the index giving an idea of how much energy is not served during a particular time period.

2.1.3. *Numerical Analysis of the Bus Test System*

The impact of this work is evaluation of the proposed DC fast charging of EVCS on the distribution network reliability index, using the standard IEEE-33 bus radial distribution network system. A 12.66 kV radial system with 33 nodes with 32 load points, as shown in Fig. 3, was considered. In this scenario, DC fast charging stations are integrated into the grid via a common DC bus.

- Reliability assessment is evaluated for all the load points are considered form [14], which comprise the information on the average failure rate λ_i, average annual outage duration U_i and the number of customer N_i at the load piont as shown in Table. 2.
- The Bus Reliability (BRI) for each load point is computed using the aforementioned reliability assessment table. A higher BRI value signifies a weaker bus, thereby evaluating weak and strong buses. Mathematically it is expressed as in Eq. (1), and report data computations as shown in Table. 2.

2.1.4. Different scenarios considered for analysis

a) Load increasement

For the purpose of evaluating reliability indices, five test cases are considered by placing the DC charging station amid large EV penetration. Due to the EV charging load, average failure rate λ_i and average annual outage duration U_i increases. The new value of $\lambda_i\,(increas)$ and $U_i\,(increas)$ can obtained form respectively [15]. The increase in reliability assessment after the placement of charging stations is calculated as shown in Eq. (2) and Eq (3).

$$\lambda_i\,(increase) = \frac{\lambda_i(L_i + \Delta L_i)}{L_i} \qquad \text{(Eq. 2)}$$

$$U_i\,(increase) = \frac{U_i(L_i + \Delta L_i)}{L_i} \qquad (Eq. 3)$$

Where L_i and ΔL_i are actual load and increment in the load at the load point i^{th}.

In this work, each EV charger is considered to consume 50 kW, which is typical for a DC fast charging station, according to the Ministry of Public Works and Transport (MPWT) of Cambodia. EV chargers are categorized into four levels based on power consumption and the range of voltage supported. Level 1 is less than 3.7 kW, Level 2 ranges from 3.7 to 22 kW, Level 3 ranges from 22 to 120 kW, and Level 4 exceeds 120 kW. Levels 1 and 2 are classified as slow charging, while Levels 3 and 4 are considered DC fast charging. A single charging station may potentially have more than one charging point [1].

$$\left.\begin{aligned} N_{charger} &= \left[\frac{N_A W_1(\rho+1)}{t_1 P_1 \eta_3 \eta_4}\right] + 1 \\ N_A &= \sum_{m=1}^{q} n_i \\ n_i &= f_i \eta_1 \eta_2 \\ f_i &= \sum_{m=1}^{j} f_{im} \end{aligned}\right\} \qquad \text{(Eq. 4)}$$

b) Determine number of Charger per charging point

The guideline for determining the number of chargers is to ensure that the peak charging demand within the area served by each charging station is met [16]. The number of chargers in Cambodia was calculated using mathematical Eq. (4).

Where $N_{charger}$ is the number charger with the slots number per charging point (N_{slot}), W_1 is the average capacity of electric vehicle batteries, ρ is the charging capacity margin of the charging station, t_1 is the operation time of charging station, P_1 is the quick charging power of the charger, η_3 is the charging efficiency of the charger, η_4 is the simultaneous rate of the charger, N_A is the number of electric cars that the charging station needs to meet per unit time, n_i is the number of electric vehicles that need to be charged in unit time at intersection node i, q is the number intersection node of charging station serves, η_1 is the proportion of electric vehicles in the total vehicle flow, n_2 is the proportion of electric vehicles that need to be charged in electric vehicles flow, and f_i is the vehicle flow per unit time at the intersection node i, f_i is the vehicle flow at each intersection node, f_{im} is traffic flow per unit time in the m-th road section connected with intersection node i.

In this study, we propose several scenarios involving an increase in the number of EV chargers. We tested 5 cases by placing DC fast charging stations, each with a power consumption of 50 kW. As the compute the number of chargers from using mathematical Eq. (4), So the result consists of $N_{charger}$ being 11 chargers and N_{slot} being 3, with a total of 33 charging points.

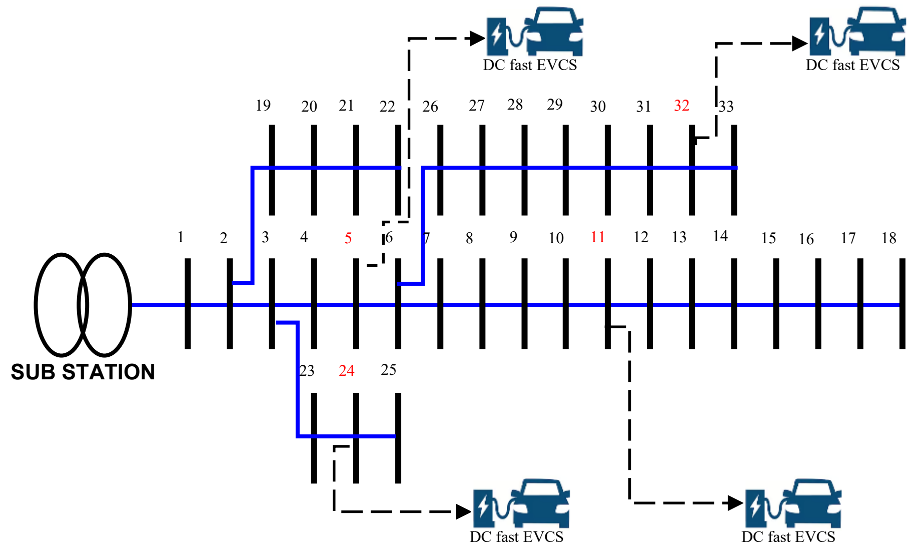

Fig. 3. IEEE 33 Bus Test Network Standard with Electric Vehicle Charging Station (EVCS) at different bus locations.

Table 2. Different scenario analysis of test cases

Case No	Case Description	Average of EV No. Charging point	Charger type (kW)	Load increasement (kW)
1	DC fast charging station is placed at bus 11	33	50	1650
2	DC fast charging station is placed at bus 5	33		1650
3	DC fast charging station is placed at bus 32	33		1650
4	2 DC fast charging station is placed at bus 24	66		3300
5	DC fast charging station is placed at bus 24 and bus 32	66		3300 (1650 each)

Table 3. Reliability and Bus Reliability Index of IEEE 33 bus test System

Bus No.	h (f/yr)	U (hr/yr)	N_i ($No. customer$)	L_i (kW)	AIT	Bus Reliability Index	Bus Evaluation
2	0.05	0.3	26	100	0.02	0.07	Strong
3	0.04	0.3	23	90	0.01	0.06	Strong
4	0.06	0.3	31	120	0.02	0.09	Strong
5	0.03	0.2	16	60	0.01	0.03	Strong
6	0.03	0.2	16	200	0.01	0.03	Strong
7	0.09	0.6	52	200	0.05	0.26	Weak
8	0.03	0.6	52	60	0.02	0.09	Strong
9	0.03	0.2	15	60	0.01	0.03	Strong
10	0.02	0.2	15	45	0.00	0.02	Strong
11	0.03	0.1	12	60	0.00	0.01	Strongest
12	0.03	0.2	16	60	0.01	0.03	Strong
13	0.06	0.2	16	120	0.01	0.06	Strong
14	0.03	0.3	31	60	0.01	0.04	Strong
15	0.03	0.2	16	60	0.01	0.03	Strong
16	0.03	0.2	16	60	0.01	0.03	Strong
17	0.03	0.2	16	60	0.01	0.03	Strong
18	0.04	0.2	23	90	0.01	0.04	Strong
19	0.04	0.2	23	90	0.01	0.04	Strong
20	0.04	0.2	23	90	0.01	0.04	Strong
21	0.04	0.2	23	90	0.01	0.04	Strong
22	0.04	0.2	23	90	0.01	0.04	Strong
23	0.04	0.2	23	90	0.01	0.04	Strong
24	0.19	1.1	109	420	0.21	1.00	Weakest
25	0.19	1.1	109	420	0.21	1.00	Weakest
26	0.03	0.2	16	60	0.01	0.03	Strong
27	0.03	0.2	16	60	0.01	0.03	Strong
28	0.03	0.2	16	60	0.01	0.03	Strong
29	0.54	0.3	31	120	0.16	0.78	Weak
30	0.09	0.5	25	120	0.05	0.22	Weak
31	0.07	0.4	39	150	0.03	0.13	Weak
32	0.10	0.6	35	210	0.06	0.29	Weak
33	0.03	0.2	16	60	0.01	0.03	Strong

3. RESULTS AND DISCUSSION

The impact of EV charging station, present to compare of the value reliability index placement fast charging station and without placement fast charging station on IEEE 33 bus test system.

3.1. Reliability Indices of base case

The reliability indices are evaluated for all index of base case on IEEE 33 bus test network, without placing EVCS. The results of this analysis are reported in Table 4 which indicates that both the customer and energy-oriented, SAIFI, SAIDI, CAIDI, and AENS.

3.2. Reliability Indices of case testing

The impact of reliability indices is evaluated for all 5 cases as mentioned in Table 2 with placing the DC fast EVCS. The results of this analysis are reported in Table 5 which indicates that both the customer and energy-oriented indices are downgraded by the placement of EV charging loads. A reduction in the values of SAIFI and SAIDI indicates an enhancement in the progression of supply whereas CAIDI remains as a useful index, but not suitable for comparison or analysis. The most commonly used system-level indices include SAIFI, SAIDI, CAIDI, and AENS.

Table 4. Evaluation of Reliability Indices on Based case

Reliability Index	Units	Value
SAIFI	interruptions/ year	0.0982
SAIDI	hr/ year	0.5048
CAIDI	hr/ interruption	5.1385
AENS	kWh/ year	1.9369

Table 5. Evaluation of Reliability Indices each test cases of scenario.

Reliability Index	Units	Case 1	Case 2	Case 3	Case 4	Case 5
SAIFI	interruptions/ year	0.1090	0.1126	0.2778	0.2753	0.2167
SAIDI	hr/ year	0.5407	0.6005	1.5820	1.5299	1.1969
CAIDI	hr/ interruption	4.9601	5.3334	5.6953	5.5572	5.5234
AENS	kWh/ year	7.2334	12.5299	60.2627	40.8721	24.2643

3.3. Discussion

Based on the result comparation of each case as Fig. 4, 5, 6 and 7, the value of SAIFI in the base case is 0.0982 interruption/yr. After the placement DC fast charging station with 33 charging points at bus 11 which is the strongest bus of the system SAIFI increases to 0.1090 interruption/yr. SAIDI CAIDI and AENS value for case 1 also increase to 0.5407hr/yr, and decrease 4.9601 hr/interruption and increase 7.2334 kW/yr respectively but less critical than case 2. Similar degradation in case 1 and case 2 are also observed degradation referred to base case value. For case 3 where fast charging station is placed at the weakest bus the value of AENS is as high as 60.2627 kWh/yr. This signifies that placement of fast charging stations at the weakest bus are detrimental to the security of the system. However, slow charging stations of 3.7 and 3.7 to 22 kW can be placed even in the weak buses. For case 4 and case 5 the degradation of reliability indices is even more prominent. However, the reliability indices of case 5 where charging station load is distributed between two buses is better than case 4 where two charging stations are concentrated at a single weak bus. Case 1 is the most reliable position for placing EVCS. From the above result, it is clear that the placement of fast DC EVCS at weak buses degrades the reliability indices to a value that cannot be accepted. Thus, for the reliability operation of the distribution network, appropriate locations for placing EVCS must be established to improve customer satisfaction.

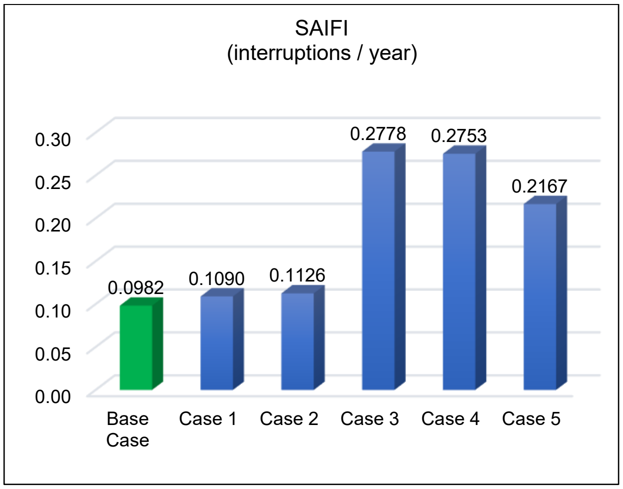

Fig. 4. Impact of DC charging station on SAIFI

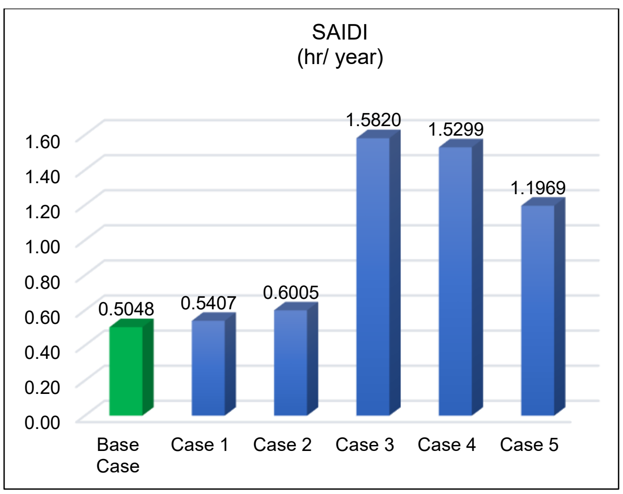

Fig. 5. Impact of DC charging station on SAIDI.

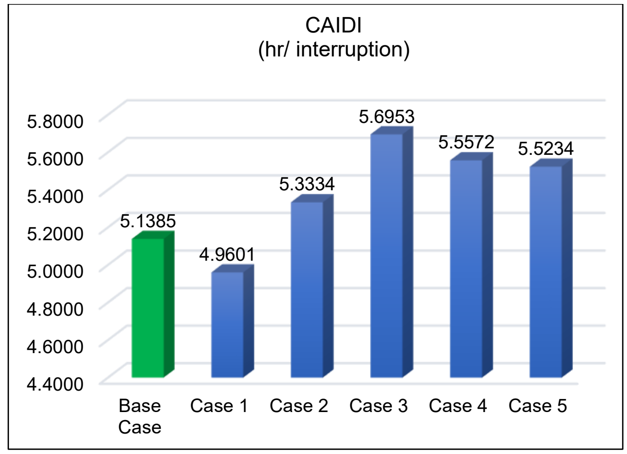

Fig. 6. Impact of DC charging station on CAIDI.

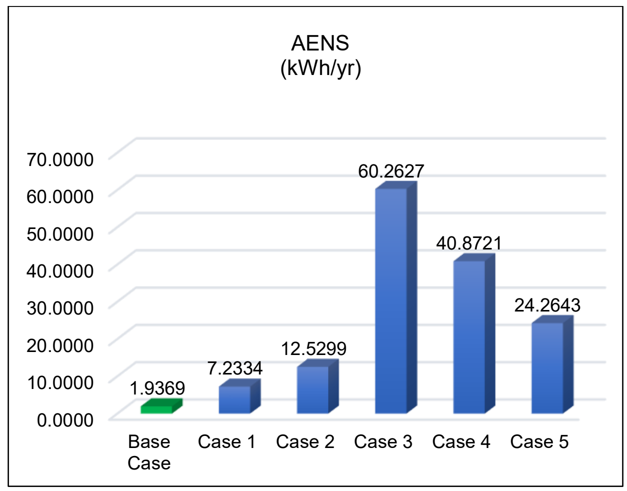

Fig. 7. Impact of DC charging station on AENS.

4. CONCLUSIONS

This paper proposes a study of the impact of placing fast DC charging station in the IEEE-33 bus radial distribution system, analyzed in the context of Cambodia over 25 years. It also presents a strategy for allocating charging stations in a distribution system without compromising power reliability and quality. The result of case study, as shown in Table 3 and Fig. 3, show that reliability indices were obtained for five test cases, and it is observed that the system is robust enough to withstand the placement of EVCSs at strong buses, but limits the smooth operation of the system at weak buses. Thus, the placement of fast charging stations at weak buses is critical. The increased load demand due to EV charging increases the failure rate and duration of failure rate per customer thereby degrading the reliability indices which leads to customer dissatisfaction. However, keeping in mind the ever increasing popularity of EVs, the future placement of slow charging stations (level 1 and level

2), even at the weak buses, may be required as seen in case 4 and case 5. To improve the reliability indices, it is better to distribute the charging stations across multiple strong buses rather than placing them in a single weak bus. Therefore, for Case 1 and Case 2, it is better to recommend the use of DC fast charging stations (Level 3 and Level 4) for smooth operation.

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