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Reliability Evaluation of Radial Distribution System with different locations and ratings of Photovoltaic

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Abstract: - The primary objective of this work is to examine how strategically positioning Photovoltaic (PV) units can have effect on reliability of a distribution system. Feeder-1 of RBTS BUS2 system is used for the reliability evaluation. The study utilizes FMEA technique to evaluate the reliability indices, System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Energy Not Supplied (ENS) and Average Service Availability (ASAI) linked to electrical interruptions in two different situations such as no PV unit and PV units are placed at different locations with different ratings along the feeder. The outcomes of installing PV units at different points along the distribution feeder are examined and compared. The prime focus lies in identifying the reliability based optimal placement of the PV unit, a determination made based on the reliability indices. By systematically analyzing and comparing the reliability indices under varying conditions, the research aims to provide insights into how the strategic positioning of PV units can lead to a substantial enhancement in the overall reliability of the distribution system. The findings contribute to the broader understanding of integrating renewable energy sources for reliability improvement within distribution systems and offer practical guidance for decision-makers in the field of energy distribution and planning.

Keywords: Distribution system, Power outage, Radial networks, Reliability assessment, Photovoltaic (PV), Environmental sustainability, Optimal location.

I. INTRODUCTION

The growing demand for electricity, coupled with the escalating environmental concerns associated with conventional power generation, has encouraged a paradigm shift towards integrating renewable energy sources into the electricity grid [1]. Among these sources, photovoltaic (PV) technology has gained substantial traction due to its sustainability and potential to reduce greenhouse gas emissions. In addition to environmental benefits, the incorporation of PV units into distribution systems presents opportunities to enhance system reliability, a critical aspect of ensuring uninterrupted and high-quality power supply to consumers [2]. Reliability of power supply is a fundamental requirement for modern societies, as it supports the smooth functioning of various sectors ranging from residential to industrial. The ability of a distribution system to deliver electricity consistently and with minimal interruptions significantly impacts economic productivity, public welfare, and overall quality of life [3-4].

Many studies have consistently emphasized that power outages at user load points are largely caused by the distribution system's radial structure, as pointed out in various sources [5-6]. As a result, there has been significant research attention towards evaluating the reliability of distribution systems, especially when incorporating Wind Turbine Generators (WTG), Energy Storage Systems (ESS), and Photovoltaic (PV) technologies. Previous studies have investigated how renewable Distributed Generation and battery storage units impact the reliability of standard distribution systems [7]. In [8], explored the features of ESS for fine-tuning power system factors like losses, efficiency, reliability, and energy expenses. In [9], suggested cost-effective hybrid approaches to assess how PV, wind, and micro hydro units influence environmental sustainability.

In [10], presented the use of a Genetic Algorithm (GA) to optimize the performance of PV-wind diesel-battery hybrid energy systems. The presented method aims to improve system efficiency by reducing wasted energy, overall costs, and CO_2 releases. They've undertaken a thorough analysis of renewable energy resource attributes to streamline the proposed system's performance. In [11] introduced a new approach for effectively combining different renewable energy sources in standalone systems. Their main goal is to reduce the total system

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expenses. Together, these studies highlight the diverse research efforts aimed at strengthening the reliability of distribution systems and utilizing the possibilities of renewable energy sources.

The strategic positioning of PV units within a distribution system has the potential to exert varying impacts on system reliability [12]. Placing PV units at optimal locations can potentially alleviate stress on the grid during peak demand periods, reducing the likelihood of overloads and consequent interruptions. Moreover, localized power generation can offset the effects of grid-wide disturbances, such as equipment failures or weather-related events. However, suboptimal placement could lead to inefficiencies, where the benefits of PV generation are not fully realized or where the grid's stability is compromised [13].

The research investigates the effects of PV unit placement on reliability worth in distribution systems. The paper analyses two distinct scenarios: one where no PV unit is present and the other where PV units are strategically positioned along the distribution feeder. The assessment of system reliability is accomplished through a range of well-established indices, including SAIFI, SAIDI, ENS and ASAI. The SAIDI plays a pivotal role in determining the optimal location of PV units, as it quantifies the reliability associated with power outages [14].

The motivation for this study lies in addressing the existing gaps in the understanding of how PV unit placement can influence distribution system reliability. The research methodology adopted in the study involves a comprehensive analysis of reliability indices under different scenarios. By evaluating the system's performance with and without PV units at varying locations, the researchers gain insights into the tangible benefits offered by PV integration.

II. Distribution System

The distribution system connects user load points with the generation and transmission systems [15]. Regular assessments are essential to prevent intermittent power interruptions within the distribution network, making sure that the effects of power system failures and how often/long power interruptions happen are considered when assessing system reliability [16].

The dependability of the distribution system relies on elements such as the system's setup (whether it's radial or mesh), environmental conditions, types of loads, and load placement [17]. An illustration of a distribution system is depicted in Figure 3. When the main feeder's circuit breaker stays open due to electrical issues, the system gets disconnected from the main grid and operates in an islanded mode. In this a PV unit supplies power to all possible feeder loads based on the capacity of PV.

The best performance at the designed capacity happens when a connection between power supply and demand is formed, considering the available output from utilities and PV units.

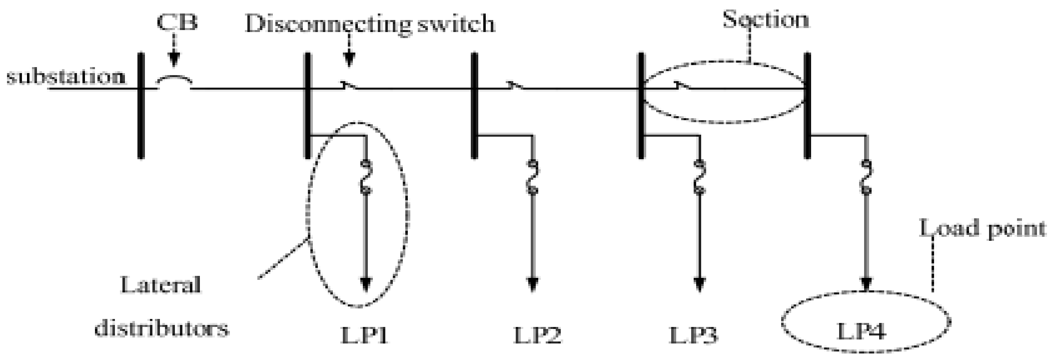

Fig. 1. Distribution system with sections and laterals

The reliability of the distribution system is influenced by factors like the surroundings, system setup (whether it's radial or mesh), load locations, and the types of loads. To strengthen the reliability of conventional distribution systems, a hybrid arrangement involving Photovoltaic (PV) systems is proposed in this study. In response to challenges faced by utilities in meeting consumer demand due to technical and financial limitations, the integration of renewable energy sources has emerged as a viable solution. The choice of Photovoltaic (PV) systems is based on their technical viability, environmental benefits, and economic advantages [18].

A. PV System

A photovoltaic (PV) system is designed to produce electrical power by transforming sunlight directly into usable electricity. Solar PV setup comprises an assemblage of numerous PV modules interconnected in both series and parallel configurations, arranging the production of the essential power output, adjusted to match the voltage and current requirements set by the manufacturer. These PV systems can be utilized to produce power in different setups, including grid-connected systems and standalone setups. A diverse array of applications can be energized by PV systems, encompassing solar street lighting, they find applications in telecommunication exchanges, solar-powered vehicles, radio and TV broadcasting, solar pumps, and even spacecraft.

The electrical output of a PV system is naturally influenced by the temperature and sunlight levels at the specific installation sites.

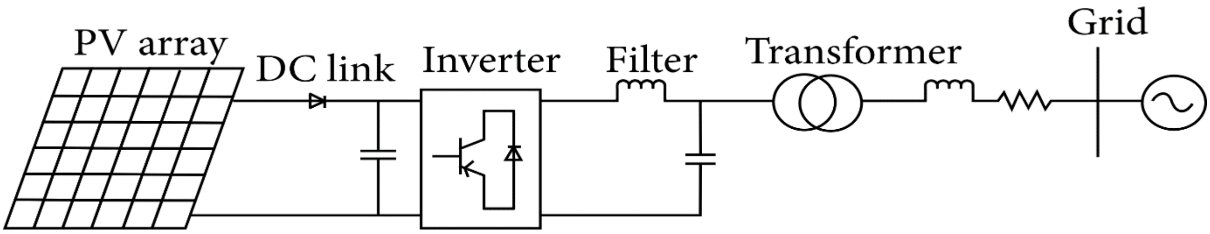

Figure. 2. PV system

B. Reliability Evaluation

Reliability assessment in distribution systems means examining how well the network can provide electricity to consumers without frequent interruptions or failures. This evaluation is essential to ensure the system's effectiveness, performance, and overall quality of service. The main aim is to measure the distribution network's reliability and pinpoint places where enhancements can be made to uphold or boost the system's effectiveness.

Different indices for reliability are employed using FEMA technique [19] measure how well the system performs. These consist of load point indices and System performance indices such as SAIFI (System Average Interruption Frequency Index), SAIDI (System Average Interruption Duration Index), ENS (Energy Not Supplied) and ASAI (Average Service Availability Index). To perform a comprehensive consistency assessment, data related to power interruptions, outages, and equipment failures are taken [20]. This data provides details about how often and how long interruptions occur, as well as where failures happen.

C. Load point Indices

These indices provide valuable insights into the reliability and performance of electricity delivery to specific locations. Load point indices focus on quantifying the frequency, duration, and severity of power interruptions or disturbances that consumers may encounter. Load point indices are employed to gauge how reliable each load point is. These indices are figured out using average failure rate (λ_s), average outage time (r_s), average annual outage time (U_s) at any specific load point (s) and ‘i’ is the component which is responsible for power outage.

$$\lambda_s = \sum_i \lambda_i \; (failures/year) \tag{1}$$

$$U_s = \sum_i \lambda_i r_i \; (hours/year) \tag{2}$$

$$r_s = \frac{U_s}{\lambda_s} (hours/interruption) \tag{3}$$

Customer load point indices are applied to assess how dependable the system is. These indices consist of SAIFI, SAIDI, ENS and ASAI.

D. Performance Indices

1. *SAIFI (System Average Interruption Frequency Index):* SAIFI helps gauge the frequency of power outages or interruptions affecting a specific load point.

$$SAIFI = \frac{\sum_s \lambda_s N_s}{\sum_s N_s} (interruptions/customer\ year) \tag{4}$$

2. SAIDI (System Average Interruption Duration Index): SAIDI measures the typical time of interruptions that a single customer faces within a certain timeframe, typically a year.

$$SAIDI = \frac{\sum_s U_s N_s}{\sum_s N_s} (hours/customer\ year) \qquad (5)$$

3. ASAI (Average Service Availability Index): ASAI representing the customer-weighted availability of the system, conveys equivalent information to SAIDI.

$$\text{ASAI} = 100 * \left(\frac{\sum_s N_s \times 8760 - \sum_s U_s N_s}{\sum_s N_s \times 8760}\right) \qquad (6)$$

4. ENS (Energy Not Supplied): ENS denotes the energy shortage of a distribution network due to faults occurred in the system.

$$ENS = \sum LsUs \quad \text{(kWh/year)} \qquad (7)$$

III. Case Study

A. *Case 1: The Distribution systems reliability evaluation without PV*

The test system used for the reliability assessment is feeder 1 in the RBTS Bus2 shown in Figure 3. In this, the radial feeder has a combined load of 3.715 MW. Table 1-3 [20] provides the customer and feeder information for the given feeder.

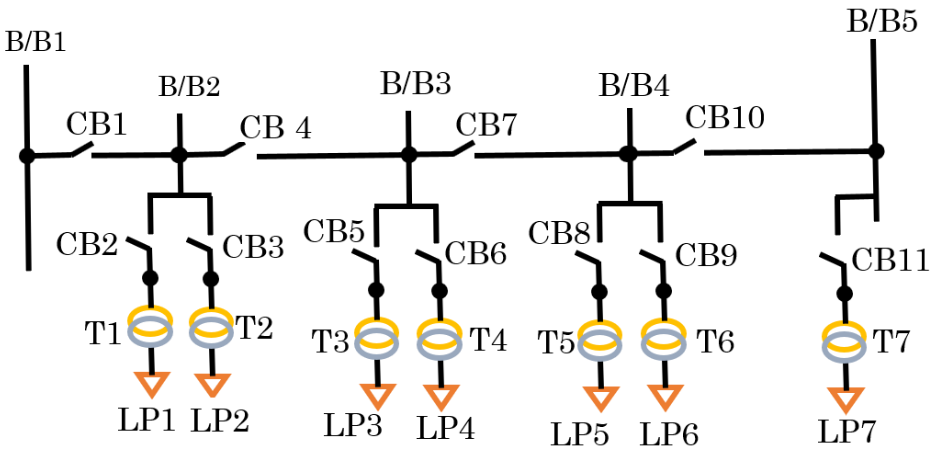

Fig. 3. Feeder-1 of RBTS BUS2 System

The customer and feeder data used for this work is shown in Table 1 and Table 2 respectively. The System data is shown in Table 3.

Table 1. Customer data

Load points	Customer Type	Average load/ each load point (MW)	Peak load/ each load point (MW)	Number of customers/each load point
1,2,3	Residential	0.535	0.8668	210
4,5	Gov/inst.	0.566	0.9167	1
6.7	Commercial	0.4540	0.7500	10

Table 2. Feeder data

Feeder section numbers	Length in km
2,6,10	0.60
1,4,7,9	0.75
3,5,8,11	0.80

Table 3. System data

Component	Failure rate λ (f/yr)	Repair time (hr)	Replacement time (hr)
Transformer (11/0.415 kV)	0.0150	200.00	10.00

Lines (11 kV)	0.0650	5.00	-

Load point indices and system performance indices are calculated using equations (eq.1 to eq.7) which are shown in Table 4 and Table 5 respectively.

Table 4 Load point indices of Test system

Load Point	Failure rate $(\lambda)\ f/yr$	Restoration time $(r)\ hr$	Unavailability $(U)\ hr/yr$
LP1	0.234	17.226	4.121
LP2	0.252	16.596	4.186
LP3	0.252	16.596	4.186
LP4	0.239	17.226	4.121
LP5	0.249	16.747	4.170
LP6	0.252	16.596	4.186
LP7	0.252	16.596	4.186

Table 5. System performance indices of test system

	SAIFI (interruption/ customer yr)	SAIDI (hr/customer yr)	ENS (kWh/yr)	ASAI (%)
Feeder-1	0.2480	4.1652	15.1781	99.952452

B. Case 2: The Distribution systems reliability evaluation with PV

The test system used for the reliability assessment is RBTS Bus2 feeder-1 with PV at B/B5 as shown in Figure 4. PV system is modelled as active power P and capacity of the PV system is equal to the total load of the feeder. In this the radial feeder has a combined load of 3.715 MW.

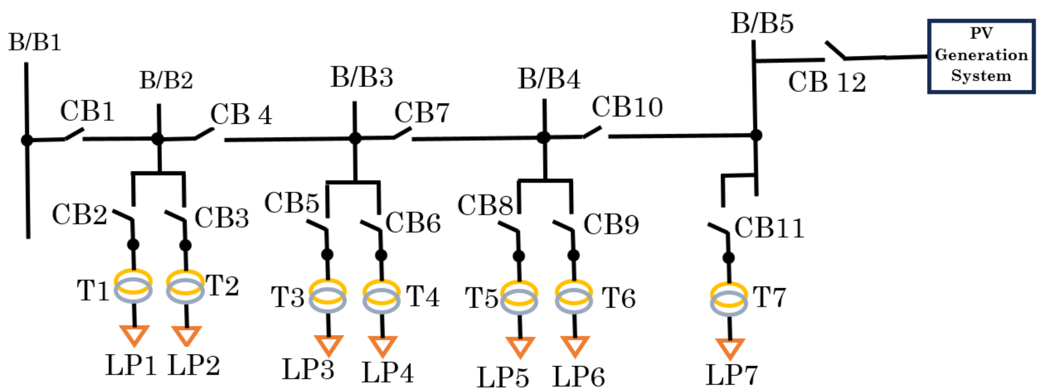

Figure 4. RBTS Bus2 Feeder-1 with PV

Feeder 1 in the RBTS at Bus2 with PV system consists of 12 feeder sections, 12 circuit breakers PV generation system, 7 Distribution Transformers (DTR) and seven load points. In this PV generation system is 100% reliable.

For the analysis, the following assumptions are made.

• This study focuses solely on the 11kV feeders, with a single PV unit serving as a backup generator operating at full availability.

• If a fault occurs, the loads connected to the PV unit's transformer will be shifted to a standby transformer instead of undergoing repairs.

To evaluate the impact of PV units in the distribution system, System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI), Energy Not Supplied (ENS) and Average Service Availability Index (ASAI) are selected. These metrics provide a means to quantify the effects of PV integration. By examining four different scenarios, PV unit at different busbars(B/Bs), the distribution system's reliability is assessed. This comprehensive assessment offers valuable insights into the potential impact of PV units on system reliability, contributing to informed decision-making for optimal integration and enhanced power supply quality. The distribution system's reliability is evaluated using the four given Scenarios.

i. Distribution system with PV unit at B/B2
ii. Distribution system with PV unit at B/B3
iii. Distribution system with PV unit at B/B4
iv. Distribution system with PV unit at B/B5

The values of system performance indices like SAIFI, SAIDI, ENS and ASAI, for four different scenarios are obtained in Table 6 using Eq. (4) to (7).

Table 6. System performance indices

PV location at B/B	Load Points (LP) Considered	SAIFI	SAIDI	ENS	ASAI (%)
2	1-7	0.2480	4.1651	15.1590	99.952453
3	1-7	0.2480	4.1648	15.1582	99.952457
4	1-7	0.2480	4.1645	15.1576	99.952460
5	1-7	0.2480	4.1641	15.1571	99.952465

From the results in Table 6, it is observed that SAIDI and ENS are decreased from scenario 1 to scenario 4. So that considered radial distribution network is reliable when PV located at busbar 5. Figure 5 presents a comparison of the percentage reduction in SAIDI based on the location of PV systems.

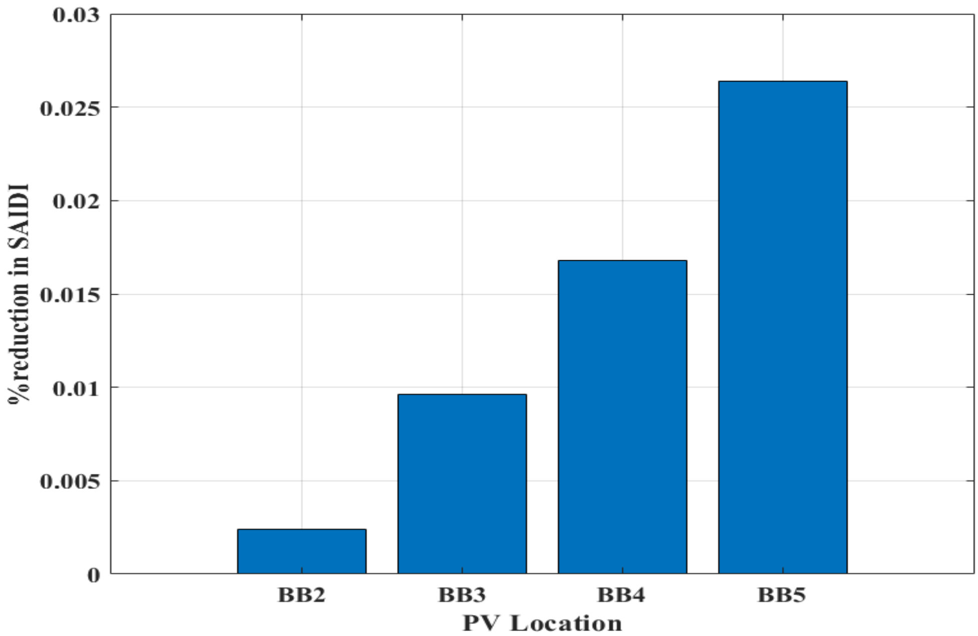

Figure 5. Percentage of reduction in SAIDI

C. Case 3: The Distribution systems reliability evaluation using different Configurations.

1) Distribution system with PV unit with the capacity of 1.5 MW (40% of the total load)

When PV is placed at B/B2, the load points LP1 and LP2 are considered which are near to the B/B2. In similar way nearest load points to that busbar are considered when PV with different capacities located at different busbars according to its Capacity. When PV unit is installed at different busbars (B/Bs) within a distribution system, the choice of load points for analysis typically considers the proximity of the load points to the respective busbars.

In this load points are considered in relation to the PV capacity. PV with capacity 1.5 MW can serve only two load points.

Table 7. Reliability indices with PV (1.5 MW)

PV location with Capacity 1.5 MW at B/B	Load Points (LP) Considered	SAIFI	SAIDI	ENS	ASAI (%)
2	1, 2	0.2480	4.1648	13.8798	99.952457
3	3, 4	0.2480	4.1638	13.7237	99.952468
4	5,6	0.2480	4.1588	13.7047	99.952525
5	6, 7	0.2480	4.1528	13.6317	99.952594

From the results in Table 7, it is observed that SAIDI and ENS are decreased when PV is located at B/B5. So that distribution network is reliable when PV located at busbar 5. Figure 6, presents a comparison of the percentage reduction in SAIDI based on the location of PV systems.

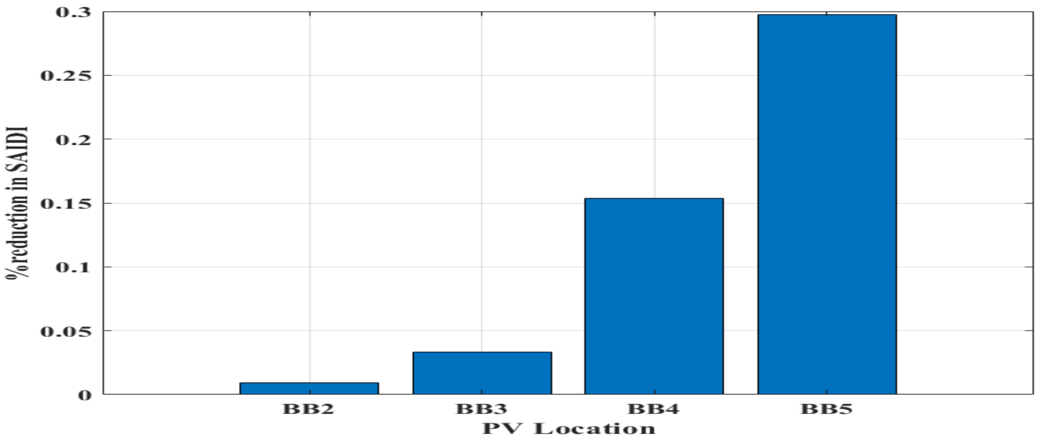

Figure 6. Percentage of reduction in SAIDI when PV unit capacity is 1.5 MW

2) Distribution system with PV unit with the capacity of 1.85 MW (50% of total load)

PV with capacity 1.85 MW can serve only three load points. Load points are considered in relation to the PV capacity and near to the PV location.

Table 8. Reliability indices with PV (1.85 MW)

PV with Capacity 1.85MW at B/B	Load Points (LP) Considered	SAIFI	SAIDI	ENS	ASAI (%)
2	1, 2, 3	0.2480	4.1651	14.5126	99.952453
3	3, 4, 5	0.2480	4.1649	14.5011	99.952455
4	5, 6, 7	0.2480	4.1644	14.5003	99.952461
5	5, 6, 7	0.2480	4.1642	14.4998	99.952463

From the results in Table 8, it is observed that SAIDI and ENS decrease when PV is located at B/B5. So that considered radial distribution network is reliable when PV is located at busbar 5. Figure 7 presents a comparison of the percentage reduction in SAIDI based on the location of PV systems.

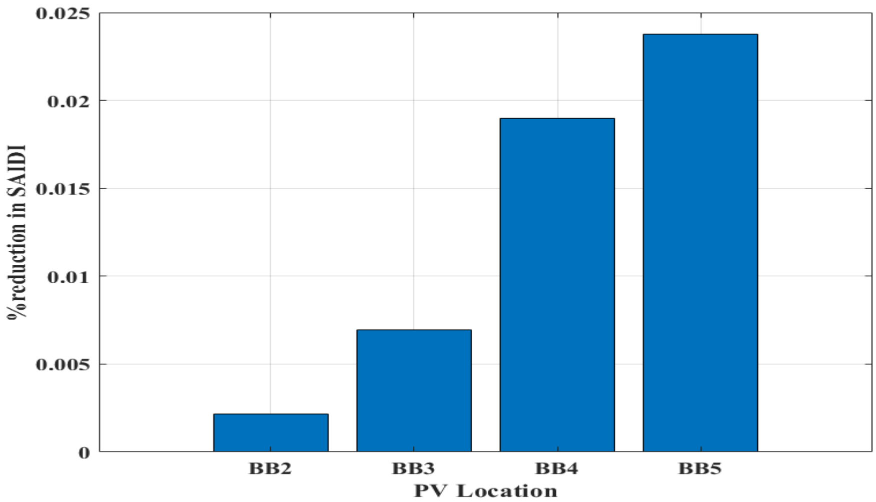

Figure 7. Percentage of reduction in SAIDI when PV unit capacity is 1.85 MW

3) Distribution system with PV unit with the capacity of 2.97MW (80% of total load)

In this also load points are considered in relation to the PV capacity. PV with capacity 1.5 MW can serve five load points which are near to the PV location.

Table 9. Reliability indices with PV (2.97 MW)

PV with Capacity 2.97 MW at B/B	Load Points (LP) Considered	SAIFI	SAIDI	ENS	ASAI (%)
2	1, 2, 3, 4, 5	0.2480	4.1650	15.1735	99.952454
3	2, 3, 4, 5, 6	0.2480	4.1644	15.1720	99.952461
4	3, 4, 5, 6, 7	0.2480	4.1638	15.1701	99.952468
5	3, 4, 5, 6, 7	0.2480	4.1630	15.1698	99.952477

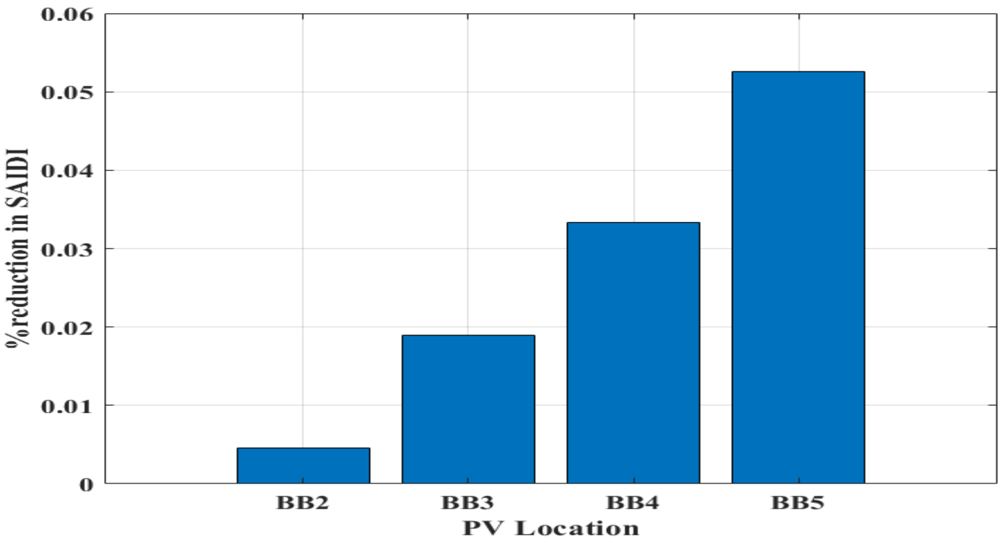

Figure 8. Percentage of reduction in SAIDI when PV unit capacity is 2.97 MW.

For the capacity of 1.5 MW,1.85 MW,2.97 MW of PV and for different location of PV, system reliability indices are calculated using Eq. from (4) to (7) and radial distribution network is reliable when PV located at busbar 5. This comparison highlights how the placement of PV systems affects the SAIDI and ENS under these specific conditions. In Figure 6, Figure 7 and Figure 8, comparisons are provided for scenarios where the PV size is 40%, 50% and 80% of the total load, respectively. These figures illustrate the impact of varying PV sizes on the percentage reduction in SAIDI across different locations.

The reliability evaluation, performed under various cases, provides a comprehensive overview of the distribution system's performance with the inclusion of PV units. The results highlight scenarios in which PV integration effectively reduces both System Average Interruption Duration Index (SAIDI) and Energies not Supplied (ENS).

IV. Conclusion

This study presents the strategic deployment of photovoltaic (PV) units to enhance the reliability of distribution systems. Through a comprehensive analysis of various reliability indices associated with electrical interruptions across different scenarios, the research identifies optimal locations for integrating PV units along distribution feeders. The findings emphasize the critical importance reliability in decision-making processes concerning the integration of renewable energy sources into distribution systems. By strategically positioning PV units, significant improvements in system reliability are demonstrated, as evidenced by enhancements in reliability indices such as System Average Interruption Duration Index (SAIDI), Energy Not Supplied (ENS) and Average Service Availability Index (ASAI). For practical and bigger networks the change of ENS may be large. These insights contribute to understanding of the potential advantages of incorporating renewable energy sources into distribution systems reliability.

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