Reliability Assessment of Distribution System with the Integration of Distributed Energy Resources and Electric Vehicle Charging Stations

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Abstract: - Renewable energy sources play an important role in the future of electrical energy generation due to the reduction in existing fossil fuels. Solar energy and wind energy are renowned and easily accessible renewable energy sources. Connecting these sources to distribution system impacts reliability due to the unpredictable nature of the atmosphere. This paper presents a reliability assessment of distribution systems with renewable distributed energy resources (DER) units like wind turbine generators (WTG), electric storage systems (ESS), photovoltaic (PV) panels, and electric vehicle charging stations (EVCS). The stochastic characteristics of the DER sources and EVCS are analyzed by using the Markov model and the impact of the integration of DER sources into the distribution system is evaluated. The effects of DER and EVCS on the distribution system's overall reliability and economy are assessed by using indices like System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI). Various scenarios are considered to evaluate the benefits of integrating WTG, ESS, PV, and EVCS into the distribution system in terms of reliability and stability. The results presented illustrate that the addition of DERs and EVCS into the distribution system improves its reliability and enhances resiliency.

Key-Words: - Distributed Energy Resources, Electric Vehicle Charging Stations, Reliability Assessment, Wind Turbine Generators, Photovoltaic Panels, Electric storage systems, SAIFI, SAIDI, Expected Interruption Cost.

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1 Introduction

Wind and solar generation systems are emerging as important alternatives to conventional power generation by using fossil fuels to protect the environment from pollution. This awareness of the atmosphere and advanced technologies in mobility increases the adoption of electric vehicles (EVs) in transport which raises the requirement for electric vehicle charging stations (EVCS). Incorporating distributed energy resources (DERs) and EVCS into the distribution system introduces unique challenges by affecting the reliability of power supply, [1], [2], [3], [4].

Wind and PV generation systems are in the lead in offering clean energy. With feasible atmospheric conditions, there is a huge possibility that these two-generation systems generate a significant amount of electrical energy, [5]. When integrating novel technologies like DERs and EVCS, the performance and dependability of the distribution system can be evaluated using reliability assessment. A power system that offers electrical energy to consumers with few interruptions is defined as a reliable power system. Fluctuations in wind speed and irradiance are the main factors that decide the possible generation of power from wind and PV systems. These factors create significant challenges to the operator of the distribution system in providing a stable and reliable power supply, [6], [7], [8], [9].

Markov model which uses stochastic characteristics of the components in the distribution system is the efficient approach in evaluating the reliability. These models represent the probabilistic behavior and state transition of the components in the distribution system. This behavior of Markov models is suited to evaluating the reliability of distribution system, [10], [11].

To enhance the generation capacity and to reduce the burden on the grid wind and solar generations are placed in radial distribution systems. Fluctuations in generation with these renewable sources due to their dependency on atmospheric conditions can be defended by integrating energy storage systems with the distribution system. Surplus energy due to low demand and excessive generation can be stored in the storage system and this saved energy can be utilized during high demand and low energy generation, [12], [13]. Optimal placement of DER units in the distribution system using Montecarlo simulations by modelling the stochastic nature of solar and wind energy can enhance the reliability of the system thereby reducing power interruptions and improving voltage stability, [14].

A framework to assess the reliability of a distribution system by considering the generation and load conditions with integrated DER units is studied in detail in literature by researchers. The outcome of this research the indicates that integrating DERs into the distribution system can improve reliability. This improvement in reliability depends on generation and characteristics of the network. For enhancement in reliability and to achieve maximum benefits from renewable energy it is very necessary to choose the best position and size of DER in the distribution system, [15], [16], [17], [18], [19].

In the case of integrating EV charging stations into distribution systems, the operator must face challenges in terms of load management and maintaining reliability. These charging stations enhance mobility and reduce emissions. Placing EVCS at an optimized place with optimized capacity is crucial to providing efficient service to EV users, [20], [21], [22], [23], [24]. Introducing vehicle to grid technology in addition to EVCS can improve the reliability of the distribution system due to the additional storage capacity of energy by EV's battery. Integration of both DERs and EVCS creates different challenges and opportunities for the enhancement of reliability in the distribution system. Researchers have explored various topologies in optimizing the integration of DER and EVCS, [25], [26], [27].

This paper presents a reliability assessment of distribution systems integrating both DER and EVCS. The characteristics of the DERs and EVCS are analyzed to identify their effect on the reliability of conventional distribution systems. The study focuses on calculating the effects of integrating DER and EVCS on system reliability and the cost implications of power outages. The research explores the benefits of incorporating wind, solar, and storage solutions with EVCS. Through various case studies, the paper demonstrates these integrations can upgrade reliability indices and enhance the stability of distribution networks.

2 Distribution System

The distribution system is the extreme part of the power system infrastructure, serving as the important connection between consumer load points and the generation and transmission networks. The primary role of the distribution system is to deliver electricity from high-voltage transmission systems to consumers at a lower voltage level which is suitable for consumption. Reliability is a vital point in the operation of distribution systems. Regular assessments are necessary to understand outages, along with the frequency and duration of power interruptions, impact system reliability. Environmental conditions, system configuration (such as radial or mesh networks), and the types and locations of loads installed are the factors affecting the reliability of the system. For the power delivery to be reliable it is essential to avoid the economic and social costs associated with power interruptions.

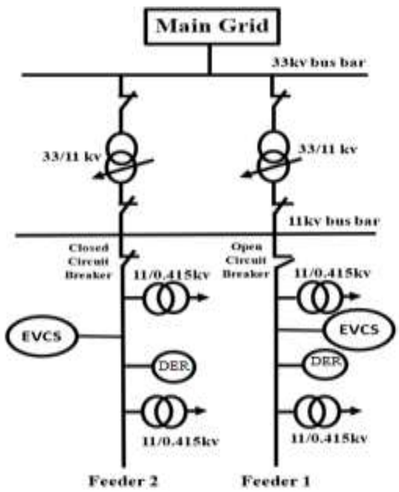


Fig. 1: Distribution system incorporating DER units and EVCS

The modern distribution system is progressing with the integration of DER units, ESS and EVCS. DER units, like wind turbines, photovoltaic (PV) systems, and energy storage systems (ESS), are incorporated to enhance sustainability and resilience in distribution system. And the excess of electric vehicles necessitates the widespread utilization of EVCS to support the growing demand for charging infrastructure.

An illustrative example of a distribution system incorporating DER units and EVCS is illustrated in Figure 1. The main grid and several DER units are integrated into the distribution system through feeders. A balance between consumer requirements and generated power in the system should be maintained for optimal performance of the distribution network. Integrated renewable DER units and utilities are coordinated in terms of available power to achieve required power balance. The complexity of the distribution system further increased by connecting EV charging stations to the distribution network. The impact on the distribution network due to EVCS can be reduced by optimal charging scheduling EV when there is an increased generation from DER units or when the load requirement is low. Adopting vehicle-to-grid technology by sending the stored power in the EV battery back to the grid when there is a high requirement of consumer demand can increase the reliability of the system.

2.1 The Hybrid System

The work presented in this paper adopts a distribution system integrated with a solar generation system, wind generating system, and energy storage system as DER units and EV charging stations. The single-line diagram of the network is illustrated in Figure 2. Enhancement of the reliability of the adopted distribution system with DER units and EVCS is the main objective of the paper. Increased consumer demand and limitations of conventional power infrastructure are the main reasons for poor reliability in the distribution system. Solar and wind generation systems have several advantages including decreased greenhouse gas emissions, minimal operational costs, and improved sustainability.

Power output from solar and wind generation systems depends on the atmospheric conditions. If irradiation fluctuation then the power output from solar generation also fluctuates and if the wind speed oscillates then power output from the wind generation system also oscillates. These fluctuations create challenges while maintaining uninterrupted power supply to sensitive loads and hence requirement of ESS increases in which the surplus energy during high power generation can be stored and this stored energy can be used during increased demand or during reduced power generation. Battery storage systems are adopted as ESS to provide a constant power supply to the consumers even during variable atmospheric conditions.

Charging stations for EVs are important in the distribution system which provides charging requirements for EV users. EVCS plays an important role in the modern distribution network. Integrating charging stations into the distribution system increases load requirements and also there is a change in peak power. By adopting smart and optimized charging schedules the challenges faced by EVCS can be mitigated efficiently. These strategies include time-of-use pricing, which encourages EV owners to charge their vehicles during off-peak hours. Adopting vehicle-to-grid technology by sending the stored power in an EV battery back to the grid when there is a high requirement of consumer demand can increase the reliability of the system.

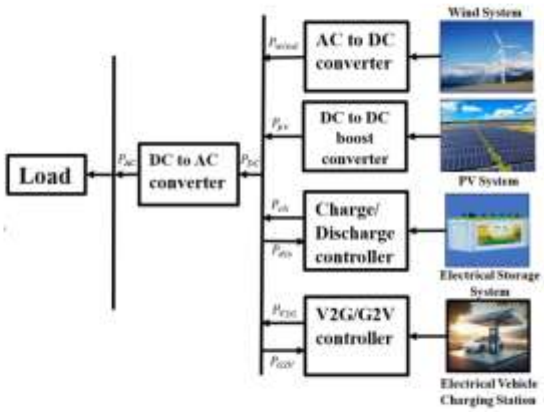


Fig. 2: A hybrid system comprising PV, WTG, ESS, and EVCS systems

2.1.1 PV System

A photovoltaic (PV) system is an advanced technology designed to generate electricity by converting sunlight directly into electrical energy through the photovoltaic effect. This process is facilitated by PV cells, which are semiconductor devices typically made from silicon. The rapid growth and adoption of PV systems can be attributed to several key advantages including low Operating and Maintenance Costs, environmental Friendliness, noise-Free Operation, and fuel cost reduction. The performance of a PV system is influenced by several factors, primarily the operating temperature and solar irradiance at the installation site. This output power of the PV system can be expressed as follows, [28], [29], [30]:

$$P_{pv}(s(t)) = \eta_{cells} * FF * V * I \quad (1)$$

$$T_{ct} = T_{at} + s(t) * \left\{\frac{NOCT-20}{0.8}\right\} \quad (2)$$

$$\mathrm{I} = \mathrm{s(t)} * \{I_{SC} + K_{CT} * (T_{CT} - 25)\} \quad (3)$$
$$\mathrm{V} = \{V_{OC} + K_{VT} * T_{CT}\} \quad (4)$$
$$FF = \frac{V_{mp} * I_{mp}}{V_{oc} * I_{sc}} \quad (5)$$

T_{CT} is the cell temperature in degrees Celsius. $\mathrm{T_{at}}$ represents the ambient temperature in degrees Celsius. $\mathrm{s(t)}$ symbolizes random irradiance. $NOCT$ stands for nominal operating cell temperature in degrees Celsius. I_{SC} denotes short circuit current in Amperes.K_{CT} signifies the current temperature coefficient in milliamperes per degree Celsius. V_{OC} represents the open circuit voltage in Volts. K_{VT} denotes the voltage temperature coefficient in millivolts per degree Celsius. V_{mp} signifies the voltage at maximum power in Volts. I_{mp} represents the current at maximum power in Amperes. FF stands for Fill Factor. V is the output voltage in Volts. I is the output current in Amperes. η_{cells} represents the number of photovoltaic cells. $\mathrm{P_{pv}}(\mathrm{s(t)})$ represents the PV power output in Watts.

2.1.2 Wind System

A wind turbine system uses the kinetic energy present in the wind to generate electrical energy. The output power of WTG depends on several factors, including Wind Speed, Air Density, Rotor Swept Area, Tower Height, Turbine Performance, and Efficiency of the Gearbox and Generator. The relationship between wind turbine power output and wind speed can be described as follows:

$$\mathrm{P_{wtg}}(\mathrm{v(t)}) = \begin{cases} 0 & v(t) < v_{ci} \\ \frac{v(t) - v_d}{v_r - v_d} & v_{ci} \le v(t) \le v_r \\ p_r & v_r \le v(t) \le v_{co} \\ 0 & v(t) < v_{co} \end{cases} \quad (6)$$

where p_r = rated power (kW), v_{ci}= cut-in speed (m/s), v_r= rated speed (m/s), v_{co} = cut-out speed (m/s), and $\mathrm{P_{wtg}}(\mathrm{v(t)})$ = power output of the WTG (kW).

2.1.3 Electric Storage System

Energy Storage Systems (ESS) are employed in power systems to address the inherent variability associated with renewable energy resources. ESS plays a crucial role in enhancing the reliability, stability, and efficiency of power systems, by storing excess energy during periods of high generation and releasing it during times of low generation or high demand,. ESS serves as a buffer, absorbing surplus energy during periods of high renewable generation and supplying it back to the grid when generation levels are insufficient to meet demand. By integrating ESS, the reliability of the distribution systems can be improved. In addition to this efficiency can be enhanced, and stability can be improved. The state of charge of a battery as ESS at time t can be determined using the following expression, [31]:

$$\mathrm{SOC}_{ESS}(\mathrm{t}) = \mathrm{SOC}_{ESS}(0) + \eta_c \sum_{t=1}^{t} P_{ch}(t) - \eta_d \sum_{t=1}^{t} P_{dis}(t) \quad (7)$$

2.1.4 Electric Vehicle Charging Stations

Adding EVCS into the distribution system can restore integral mobility which provides a flexible and dynamic energy storage solution. This stored energy can be used during power interruptions in the distribution system using a vehicle-to-grid technology. Mobilization of these storage units which are an integral part of EVs is simple. These units can be used as an ideal solution for energy supply during power outages. This advantage of EVs improves the flexibility of the power system which is not possible with stationary storage units. The efficacy of EVs as mobile energy storage systems depends on their SOC characteristics and the uncertainty of system failures.

While evaluating the reliability of the distribution system with EVCS, it is considered that mechanical and electrical systems of EVs are 100% reliable to simplify the modelling process of the overall system. The state of charge of EV battery at time t can be determined using the following expression [32]:

$$\mathrm{SOC}_{EV}(\mathrm{t}) = \mathrm{SOC}_{EV}(0) + \eta_{G2V} \sum_{t=1}^{t} P_{G2V}(t) - \eta_{V2G} \sum_{t=1}^{t} P_{V2G}(t) \quad (8)$$

3 Cost Minimization

The main objective of this work is to reduce the costs related to the power outages in the distribution system while all necessary requirements of the system are achieved. This work concentrates on evaluating the effects of DER units, EVCS units, and ESS on the reliability and economy related to power outages. To minimize the cost of power outages two objective functions related are framed: Minimization of Expected Energy Not Supplied (EENS) and Reduction of Expected Interruption Cost Index (ECOST).

EENS is calculated using the amount of energy that is not supplied to consumers due to power outages. Reduction of this EENS is the first objective. Lowering the value of EENS improves the reliability of the system and hence during outages more consumer demands are met. ECOST is the financial losses due to power outages which includes costs borne by consumers and utilities.

ECOST includes damaged equipment and lost productivity due to power outages. The second objective is the reduction of ECOST after integrating DERs, EVCS, and ESS.

$$C_{net} = \max\left(C_{con} - C_{pro}\right) \quad (9)$$

$$C_{con} = \sum_{i=1}^{n_{lp}} \left(t_e EENS_{con} + ECOST_{con}\right) \quad (10)$$

$$C_{pro} = \sum_{i=1}^{n_{lp}} \left(t_e EENS_{pro} + ECOST_{pro}\right) \quad (11)$$

C_{con} sum of EENS and ECOST due to the power outage in cthe onventional distribution system, C_{pro} sum od EENS and ECOST due to the power outage in distribution system with DER units, ESS and EVCS units.

Power demand and supply constraints:

$$P_{wind} + P_{pv} + P_{ESS} + P_{V2G} + P_{grid} = P_{Load} \quad (12)$$

3.1 Distribution System Reliability Indices

A distribution system is the combination of primary or main feeders and lateral distributions. It's important to interpret these components thoroughly while designing and operating a distribution system. The primary feeder is the main section of the distribution circuit, commencing from a substation and crossing through major load centers. Various reliability indices should be considered to evaluate and improve the performance and reliability of distribution systems. These indices are mostly grouped into two categories: Load Point Reliability Indices and System Reliability Indices. Load point reliability indices concentrate on the reliability of individual load points within the distribution network. Key indices include:

Failure Rate (λ): average value of the number of failures per year at a particular load point.

Average Outage Duration (r): average time duration for which a load point faces an outage.

Annual Unavailability (U): The total duration in hours per year that a load point is facing power outage.

Average failure rate (λ_{Lp}) of a load point (Lp) is given as

$$\lambda_{Lp} = \sum_{i=1}^{m} \lambda_i \quad (13)$$

Annual unavailability (U_{Lp}) of a load point (Lp) is given as

$$U_{Lp} = \sum_{i=1}^{m} \lambda_i r_i \quad (14)$$

Average outage duration (r_{Lp}) of a load point (Lp) is given as

$$r_{Lp} = \frac{U_{Lp}}{\lambda_{Lp}} = \frac{\sum_{i=1}^{m} \lambda_i r_i}{\sum_{i=1}^{m} \lambda_i} \quad (15)$$

m is the number of outages which are affecting load point Lp, λ_i and r_i are failure rate and repair rate of component of i respectively. System Reliability indices accumulate data from all load points to provide a comprehensive measure of system performance. Using the three basic load point indices—failure rate, average outage duration, and annual unavailability—as well as energy consumption at load points, various reliability indices can be calculated.

1. **System Average Interruption Frequency Index (SAIFI)**: average number of interruptions a customer experiences in a year. It is calculated by adding the failure rates of all load points and dividing that value with the total number of customers supplied by the system.

$$SAIFI = \frac{\sum_{j=1}^{n_{Lp}} \lambda_j N_j}{\sum_{j=1}^{n_{Lp}} N_j} \quad (16)$$

2. **System Average Interruption Duration Index (SAIDI)**: The total duration of interruptions experienced by an average customer in a year, stated in hours. It is achieved by dividing the total customer interruption duration with the total number of customers.

$$SAIDI = \frac{\sum_{j=1}^{n_{Lp}} U_j N_j}{\sum_{j=1}^{n_{Lp}} N_j} \quad (17)$$

3. **Average Service Availability Index (ASAI)**: Represents the proportion of time that the system is available to supply power. It is calculated by subtracting the total outage time from the total time period considered (typically one year) and then dividing by the total time period.

$$ASAI = \frac{\sum_{j=1}^{n_{Lp}} N_j \times 8760 - \sum_{j=1}^{n_{Lp}} U_j N_j}{\sum_{j=1}^{n_{Lp}} N_j \times 8760} \quad (18)$$

4. **Average Service Unavailability Index (ASUI)**: Complements ASAI by indicating the proportion of time that the system is unavailable to supply power. It is calculated by dividing the total outage time by the total time period considered.

$$ASUI = 1 - ASAI \quad (19)$$

5. **Energy Not Supplied (ENS)**: Quantifies the total amount of energy not delivered to customers due to interruptions. It is calculated by summing the products of the outage duration and the load demand at each affected load point.

$$ENS = \sum_{j=1}^{n_{Lp}} L_{a(j)} U_j \quad (20)$$

6. **Average Energy Not Supplied (AENS)**: Measures the average amount of energy not supplied per customer. It is obtained by dividing the ENS by the total number of customers.

$$AENS = \frac{ENS}{\sum_{j=1}^{n_{Lp}} N_j} \quad (21)$$

n_{Lp} is number of load points, N_j number of customers connected at load point j. λ_j failure rate of load point j in failure/yr. U_j unavailability of load point j in hr/yr. $L_{a(j)}$ average connected load at load point j in kW.

3.2 Expected Interruption Cost (ECOST)

Reliability worth in the context of power distribution systems can be quantified by evaluating customer interruption costs. These costs provide an indirect measure of the monetary losses that customers incur due to power failures. The SCDF is a critical tool for estimating the monetary loss incurred by customers due to power failures. It is a function that varies based on customer class (e.g., residential, commercial, industrial) and the duration of the outage. Figure 2 (hypothetical) graphically represents the SCDF, plotting outage costs against outage durations for different customer sectors.

$$ECOST_{Lp} = \sum_{j=1}^{n_c} C_{j,Lp}(r_j) L_{av,p} \lambda_j \quad (22)$$

$ECOST_{Lp}$ expected interruption cost of load point Lp, $L_{av,p}$ average connected load at load point Lp, $C_{j,Lp}(r_j)$ contingency cost of load point Lp with an outage duration of r_j, λ_k failure rate of contingency, n_c number of contingencies that isolate load point Lp.

4 Distribution System

This section details the implementation of a modified Roy Billinton Test System (RBTS) shown in Figure 3 (Appendix) which incorporates Distributed generation (DERs) and Electric Vehicle Charging Stations (EVCS). The integrated DERs include:

1. DER 1: Photovoltaic (PV) system coupled with a boost converter and inverter.
2. DER 2: Wind Turbine Generator (WTG) paired with a converter and inverter.
3. DER 3: Battery Energy Storage System (BESS) equipped with a controller and inverter.
4. Electric Vehicle Charging Station (EVCS) with a DC-DC converter and inverter.

These DERs are strategically placed in various sections of the distribution system to enhance its reliability and efficiency. The primary objective of this paper is to validate the effectiveness of the modified RBTS by demonstrating the improved reliability and cost savings achieved through the integration of these DER units and EVCS. The modified RBTS bus distribution test system, as illustrated in Figure 8, serves as the testbed for this validation. The ratings and specifications of the DER units and EVCS are detailed in Table 1 (Appendix). Additionally, the customer and feeder data employed are sourced from the references, [33], [34].

To ensure a comprehensive analysis, several key assumptions have been made in this study:

1. Overhead Lines: Only overhead lines operating at 11 kV from the supply point bus to the load points, including both lateral and main feeders, are considered.
2. Component Failure and Repair Rates: The supply point, main feeder bus bars, and circuit breakers are assumed to have specific failure and repair rates as documented in the references, [33], [34].
3. Automatic Load Transfer: In the event of any fault, the loads on the transformer connected to each DER will be automatically transferred to a standby transformer rather than repairing the faulty transformer immediately. This automatic load transfer mechanism is designed to significantly reduce power outage durations and enhance overall system reliability. The integration of DER units (PV, WTG, BESS) and EVCS at various points in the distribution system aims to leverage their benefits for enhanced reliability and operational efficiency. Each DER unit and the EVCS are paired with appropriate power electronics (boost converters, inverters, controllers, and DC-DC converters) to ensure seamless integration and optimal performance.

1. PV System with Boost Converter and Inverter (DER 1)
2. WTG with converter and inverter (DER 2)
3. Battery Energy Storage System with Controller and Inverter (DER 3)
4. EVCS with DC-DC Converter and Inverter (DER 4)

By integrating these DER units and EVCS into the RBTS, the study aims to demonstrate significant improvements in system reliability and cost efficiency. The modified RBTS test system, supported by strong data and realistic assumptions, serves as an effective platform for validating the benefits of integrating renewable energy sources, energy storage solutions, and EV charging infrastructure in modern distribution networks.

The study evaluates the distribution system's reliability across six different scenarios, each featuring different combinations of DER units. The cases are designed to provide a comprehensive understanding of configurations of DER units and EVCS that impact the distribution system's performance. The specific scenarios considered are as follows:

1. Conventional Distribution System without DER Unit
2. Conventional Distribution System with DER 1 Unit and EVCS 1 Unit
3. Conventional Distribution System with DER 2 Unit and EVCS 2 Unit
4. Conventional Distribution System with DER 2, DER 3 Units and EVCS 2, EVCS 3 Units
5. Conventional Distribution System with DER 1, DER 3 Units and EVCS 1, EVCS 3 Units
6. Conventional Distribution System with DER 1, DER 2, DER 3 Units and EVCS 1, EVCS 2, EVCS 3 Units:

Table 1 (Appendix) illustrates the DER, EVCS unit Ratings, and Location for 6 scenarios.

5 Results and Discussion

The reliability assessment technique applied in this paper is a key performance indicator used to evaluate the impact of incorporating Wind Turbine Generators (WTG), Photovoltaic (PV) systems, Electric Vehicle charging stations (EVCS), and Energy Storage Systems (ESS) into conventional distribution systems. Table 2 illustrates various configurations of the renewable Distributed Energy Resource (DER) units and EVs, utilizing Markov models to analyze the stochastic characteristics of these components. The study employs six distinct case studies to estimate the reliability indices of the DER units under different configurations.

5.1 Scenario 1

In this case study, the reliability assessment is conducted on the RBTS bus distribution system, specifically excluding the application of Distributed Energy Resource (DER) units and Electric Vehicle (EV) charging stations. The findings, detailed in Table 3, indicate that relying solely on the conventional distribution power system without incorporating DER units results in an increase in both the frequency and duration of power outages experienced by consumers at the load points.

Table 2. Failure rate and repair rate of DER units and EVCS units, [35]

Description	Failure Rate	Repair rate
Wind turbine and generator	0.05	20
PV Panels	0.04	18.25
Battery	0.0312	51.9571
Battery Bidirectional converter	0.125	45.213
EV battery	0.0454	51.9
EV battery Bidirectional converter	0.0492	46.2
EVCS Inverter	0.11	55.1
Boost converter	0.0657	62.5
Inverter	0.143	52.143
Rectifier	0.152	55.232

Table 3. Simulation results of reliability evaluation without DER units and EV charging stations

Indices	**Conventional RBTS**
SAIFI (f/customer yr)	0.1368
SAIDI (h/customer yr)	0.7726
CAIDI (f/customer Interruption	5.6469
AENS (MW h/customer yr)	0.0048
IEAR (D/kW h)	4.5440
Total EENS (MW h/yr)	9.1087
Total ECOST ($/yr)	41389.7445
Total Cost of EENS ($/yr)	50097.6503
Total Outage Cost ($/yr)	91487.3948

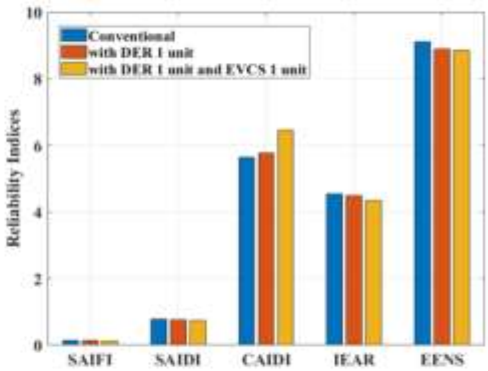
5.2 Scenario 2

The second case study examines a conventional distribution system integrated with a Distributed Generation (DER) unit, referred to as DER 1, and Electric Vehicle (EV) charging stations (EVCS). The incorporation of the DER 1 unit and EVCS into the conventional distribution system significantly enhances the values of various reliability indices and cost-saving parameters, as detailed in Table 4.

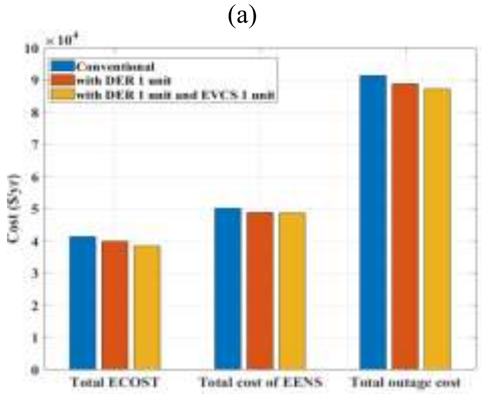
The integration of EVCS results in substantial improvements across various reliability metrics compared to a system that incorporates only Distributed Generation (DER) Unit 1. Table 2 presents a detailed comparison of the reliability and cost indices for a system with only DER Unit 1 and a system equipped with both DER Unit 1 and EVCS. Figure 4 graphically compares the reliability and cost indices for the conventional RBTS, a system with DER Unit 1, and a system with both DER Unit 1 and EVCS 1 unit.

Table 4. Simulation results of reliability evaluation with DER 1 unit and EVCS 1 unit

Indices	With DER 1 unit	With DER 1 unit and EVCS 1 unit
SAIFI (f/customer yr)	0.1311	0.1149
SAIDI (h/customer yr)	0.7552	0.7425
CAIDI (f/customer Interruption	5.7602	6.4642
AENS (MW h/customer yr)	0.0048	0.0046
IEAR (D/kW h)	4.4854	4.3496
Total EENS (MW h/yr)	8.8945	8.8611
Total ECOST ($/yr)	39895.4800	38542.4100
Total Cost of EENS ($/yr)	48919.7214	48735.9547
Total Outage Cost ($/yr)	88815.2014	87278.3647
Total cost saving of EENS ($/yr)	1177.9289	1361.6956
Total cost saving of ECOST($/yr)	1494.2645	2847.3345
Total cost saving ($/yr)	2672.1934	4209.0301
Total improved cost saving (%)	2.9208	4.6007



(a)



(b)

Fig. 4: Reliability Indices and Cost indices for a conventional system, with DER 1 unit and with DER 1 unit and EVCS 1 unit

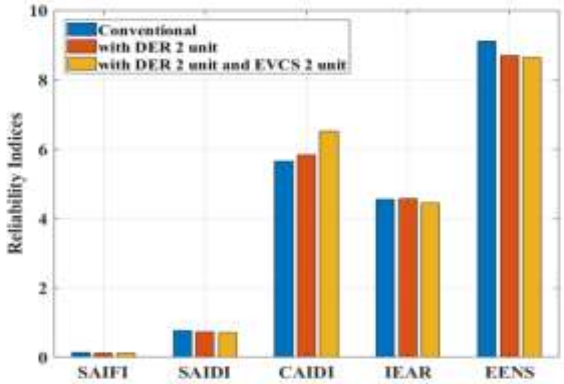
5.3 Scenario 3

The third case study evaluates a conventional distribution system integrated with a Distributed Generation (DER) unit, specifically DER 2, and compares it with the system including an Electric Vehicle Charging Station (EVCS)-2 unit. The reliability indices and cost-saving parameters for this case study, both with DER 2 alone and with DER 2 plus EVCS, are presented in Table 5. The total cost savings for the system are further increased by 6.11% due to the vehicle-to-grid (V2G) integration behavior facilitated by the EVCS.

This case study demonstrates that while the integration of DER 2 significantly enhances the reliability and cost-effectiveness of the conventional distribution system, the additional inclusion of EVCS offers further improvements in these metrics. Figure 5 graphically compares the reliability and cost indices for the conventional RBTS, a system with a DER 2 unit, and a system with both a DER 2 unit and an EVCS 2 unit.

Table 5. Simulation results of reliability evaluation with DER 2 unit and EVCS 2 unit

Indices	With DER 2 unit	With DER 2 unit and EVCS 2 unit
SAIFI (f/customer yr)	0.1255	0.1098
SAIDI (h/customer yr)	0.7320	0.7148
CAIDI (f/customer Interruption	5.8327	6.5076
AENS (MW h/customer yr)	0.0046	0.0045
IEAR (D/kW h)	4.5703	4.4416
Total EENS (MW h/yr)	8.6985	8.6399
Total ECOST ($/yr)	39754.5935	38375.0612
Total Cost of EENS ($/yr)	47841.5563	47519.4453
Total Outage Cost ($/yr)	87596.1497	85894.5065
Total cost saving of EENS ($/yr)	2256.0940	2578.2050
Total cost saving of ECOST($/yr)	1635.1510	3014.6833
Total cost saving ($/yr)	3891.2450	5592.8883
Total improved cost saving (%)	4.2533	6.1133



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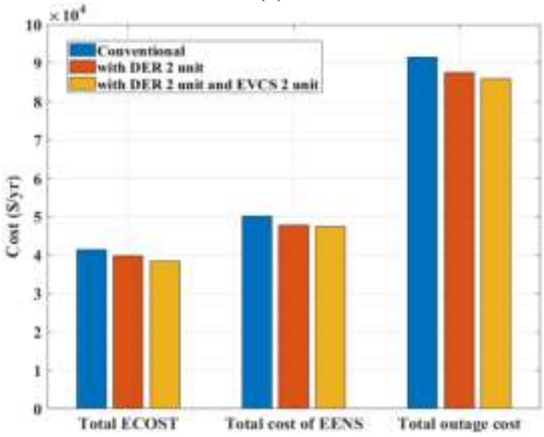

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Fig. 5: Reliability Indices and Cost indices for conventional system, with DER 2 unit and with DER 2 unit and EVCS 2 unit

5.4 Scenario 4

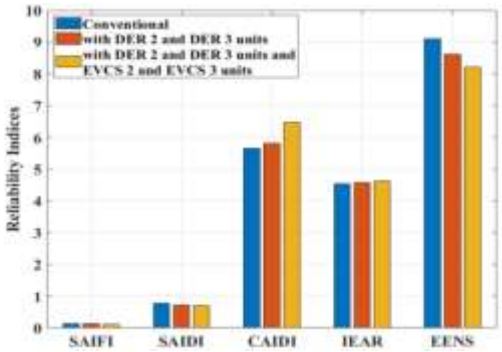
The fourth case study studies the integration of DER1, DER2, and DER3 into a conventional distribution system and examines the effects of adding EVCS2 and EVCS3 units to this configuration. The values of key reliability indices and cost-saving parameters for the system with DER2 and DER3 are presented in Table 6. These results highlight that incorporating EVCS further optimizes the distribution system, particularly in terms of reducing interruption durations and enhancing overall reliability. The total cost savings for the system increased by an additional 9.06% due to the integration of EVCS, compared to the system with only DER2 and DER3 units. Figure 6 graphically compares the reliability and cost indices for the conventional RBTS, a system with DER 2 unit and DER 3 unit, and a system with both DER 2 and 3 unit and EVCS 2 and 3 unit.

Table 6. Simulation results of reliability evaluation with DER 2 and DER 3 units and with DER 2, DER 3, and EVCS 2 and EVCS 3 units

Indices	**With DER2 and DER3 units**	**With DER2, DER3, and EVCS 2, EVCS 3 units**
SAIFI (f/customer yr)	0.1241	0.1087
SAIDI (h/customer yr)	0.7198	0.7030
CAIDI (f/customer Interruption	5.8014	6.4665
AENS (MW h/customer yr)	0.0045	0.0043
IEAR (D/kW h)	4.5748	4.6337
Total EENS (MW h/yr)	8.6130	8.2097
Total ECOST ($/yr)	39402.3967	38041.5396
Total Cost of EENS ($/yr)	47371.2292	45153.1631
Total Outage Cost ($/yr)	86773.6259	83194.7028
Total cost saving of EENS ($/yr)	2726.4211	4944.4872
Total cost saving of ECOST($/yr)	1981.3478	3348.2048
Total cost savi 2ng ($/yr)	4713.7689	8292.6920
Total improved cost saving (%)	5.1524	9.0643

5.5 Scenario 5

The fifth case study examines the integration of Distributed Generation (DER) units DER1 and DER3, along with EVCS 1 and EVCS 3 units into a conventional RBTS. The specific improvements in reliability indices and cost-saving parameters with the integration of DER1 and DER3 units are detailed in Table 7. The enhanced reliability results in substantial cost savings, with the total improved cost savings for the system increasing by 9.52% compared to the baseline conventional system. EVCS plays a crucial role in supporting the increased demand for electric vehicle charging and offers additional benefits through vehicle-to-grid (V2G) technologies. These technologies enable electric vehicles to feed stored energy back into the grid during peak demand periods, further enhancing grid reliability and stability. Figure 7 graphically compares the reliability and cost indices for the conventional RBTS, a system with DER 1 unit and DER 3 unit, and a system with both DER 1 and 3 unit and EVCS 1 and 3 unit.



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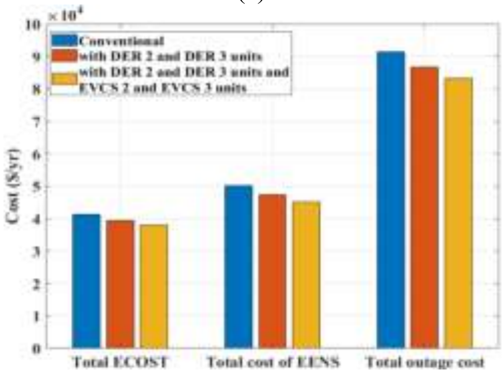

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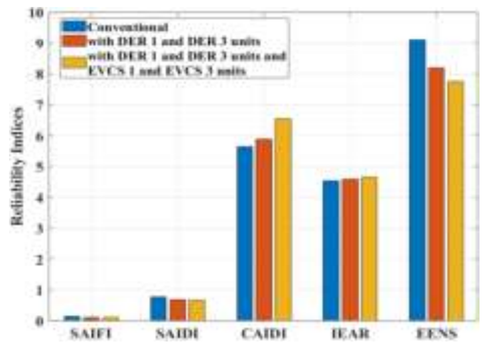
Fig. 6: Reliability Indices and Cost indices for conventional system, with DER 2 and with DER 3 units and with DER 2, DER 3 units and EVCS 2, EVCS 3 units



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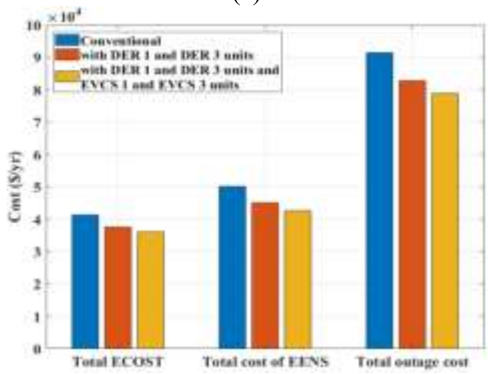

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Fig. 7: Reliability Indices and Cost indices for conventional system, with DER 1 and with DER 3 units and with DER 1, DER 3 units and EVCS 1, EVCS 3 units

Table 7. Simulation results of reliability evaluation with DER1, DER3 units and EVCS 1, EVCS 3 units

Indices	**With DER1 and DER3 units**	**With DER1, DER3, and EVCS 1, EVCS 3 units**
SAIFI (f/customer yr)	0.1186	0.1039
SAIDI (h/customer yr)	0.6931	0.6812
CAIDI (f/customer Interruption	5.88445	6.5557
AENS (MW h/customer yr)	0.0043	0.0041
IEAR (D/kW h)	4.5896	4.6530
Total EENS (MW h/yr)	8.2045	7.7683
Total ECOST ($/yr)	37654.9342	36146.5046
Total Cost of EENS ($/yr)	45124.6613	42725.9149
Total Outage Cost ($/yr)	82779.5955	78872.4195
Total cost saving of EENS ($/yr)	4972.9890	7371.7354
Total cost saving of ECOST($/yr)	3734.8103	5243.2399
Total cost saving ($/yr)	8707.7993	12614.9753
Total improved cost saving (%)	9.51802	13.7888

5.6 Scenario 6

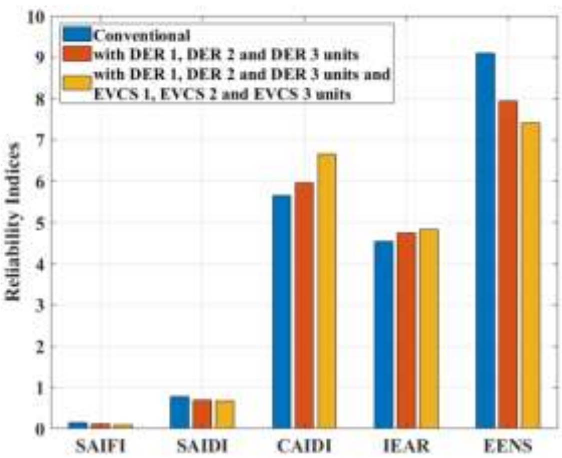
This scenario examines the impact of integrating DER units DER1, DER2, and DER3, along with EVCS1, EVCS2, and EVCS3 units into a conventional RBTS system. Resulting of the improvements brought by DER1, DER2, and DER3 units, the addition of EVCS units is analyzed to calculate its impact on the system's performance. EVCS supports the risen demand for electric vehicle charging and proposes additional benefits through vehicle-to-grid (V2G) technologies.

These technologies let electric vehicles feed stored energy back into the grid during peak demand periods, enhancing grid reliability and stability. The values of reliability indices for the system with DER1, DER2, DER3, and EVCS are listed in Table 8.

Figure 8 compares the reliability and cost indices for the conventional RBTS, system with DER 1, DER 2, and 3 units and EVCS 1, 2, and 3 units.

Table 8. Simulation results of reliability evaluation with DER1, DER2, and DER3 units and with DER 1, DER 2, DER 3 units and EVCS 1, EVCS 2, EVCS 3 units

Indices	**With DER1, DER2 and DER3 units**	**With DER1, DER2, DER3 and EVCS 1, EVCS 2, EVCS 3 units**
SAIFI (f/customer yr)	0.1151	0.1008
SAIDI (h/customer yr)	0.6856	0.6704
CAIDI (f/customer Interruption	5.9569	6.6535
AENS (MW h/customer yr)	0.0042	0.0039
IEAR (D/kW h)	4.7401	4.8358
Total EENS (MW h/yr)	7.9359	7.4131
Total ECOST ($/yr)	37616.9522	35848.4388
Total Cost of EENS ($/yr)	43647.6464	40772.1678
Total Outage Cost ($/yr)	81264.5986	76620.6066
Total cost saving of EENS ($/yr)	6450.0038	9325.4825
Total cost saving of ECOST($/yr)	3772.7923	5541.3057
Total cost saving ($/yr)	10222.7961	14866.7881
Total improved cost saving(%)	11.1740	16.2501



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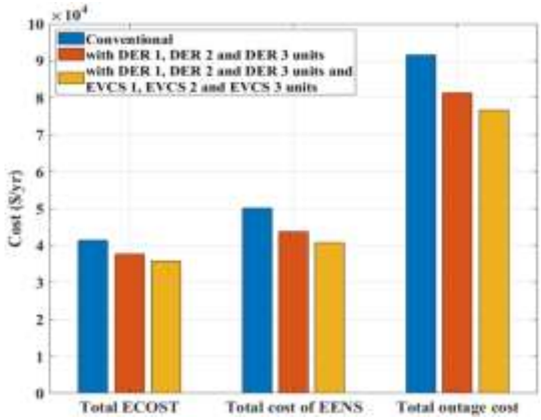

(b)

Fig. 8: Reliability Indices and Cost indices for a conventional system, with DER 1, DER 2, and with DER 3 units and with DER 1, DER 2 and DER 3 units and EVCS 1, EVCS 2 and EVCS 3 units

6 Conclusion

This study highlights the critical importance of integrating renewable distributed generation (DER) units—specifically wind turbine generators (WTG), electric storage systems (ESS), and photovoltaic (PV) panels—alongside electric vehicle charging stations (EVCS) into modern distribution systems. The comprehensive reliability assessment conducted through the Markov model reveals that the strategic incorporation of these renewable energy sources significantly enhances the reliability and stability of distribution networks. Key reliability indices such as SAIFI, SAIDI, CAIDI, AENS, IEAR, EENS, and ECOST present significant improvements, indicating a more resilient and efficient grid infrastructure. The findings highlight the benefits of DER integration. The study highlights the potential of DER units to support distribution systems against interruptions, thereby contributing to a more sustainable and reliable energy future. Equally, the results concern the haphazard placement of EVCS, which can impose additional stress on the distribution network and potentially compromise system reliability. The analysis demonstrates that while EVCS are essential for supporting the growing adoption of electric vehicles, their integration must be planned and managed to avoid adverse impacts on the distribution system. This research provides valuable insights for utilities and policymakers on optimal integration strategies for renewable energy and EV infrastructure.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work the authors used ChatGPT in order to proofread the paper. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- P. Sangeetha carried out the conceptualiza-tion, Data curation, Investigation, Methodology, Formal analysis, Software and Writing-Original draft.
- G. Suresh Babu carried out the Project administration, Supervision and validation.
- E. Vidyasagar carried out the Supervision, Validation and Writing - review & editing.

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Conflict of Interest

The authors have no conflicts of interest to declare.

APPENDIX

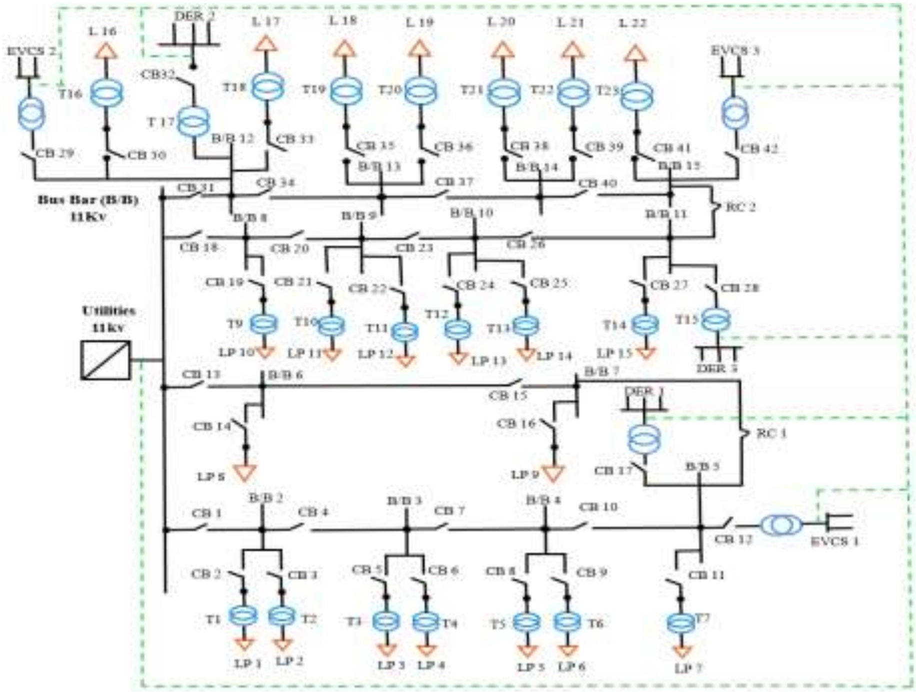

Fig. 3: Modified RBTS distribution system

Table 1. DER, EVCS unit Ratings and Location for 6 scenarios

Scenario	DER Location (Bus Number)			DER Capacity (MW)			EVCS Location (Bus Number)			EVCS Capacity (MW)		
1	-	-	-	-	-	-	-	-	-	-	-	-
2	5	-	-	2	-	-	5	-	-	1.5	-	-
3	12	-	-	3	-	-	15	-	-	1.5	-	-
4	11	12	-	0.5	3	-	5	12	-	1.5	1.5	-
5	5	11	-	2	0.5	-	15	12	-	1.5	1.5	-
6	5	11	12	2	0.5	3	5	15	12	1.5	1.5	1.5