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Reliability Evaluation of Radial Distribution Feeder Considering Two Load Modelling of Forecasted Electric Vehicle Load

V. Swarna Rekha, G. Kirankumar, E. Vidya Sagar

***Abstract**: The use of an electric vehicle (EV) in place of an internal combustion engine reduces pollution and produces zero emissions. EVs need considerable electrical energy from the grid, and therefore, it is necessary to evaluate the performance of the radial distribution system, including the Electric Vehicle Charging Station (EVCS) load. The future EVCS load is forecasted using Holt's model, and then it is applied uniformly to the distribution system. This increases the magnitudes of currents, which are calculated using the backwards and forward sweep method of load flow analysis. The increased magnitude of the current moderates the operating temperature of the components, increasing the average failure rate of feeder line sections. The percentage change in the average failure rate is assumed to be directly proportional to the percentage change in current, which in turn affects reliability indices such as SAIDI and ENS. The reliability analysis requires proper modelling of loads on the system, which is categorised into two types: light and heavy loads. The existing load without EVs of the distribution system is taken as a light load, and the future load, including the EV load during the charging period (5hrs) on the distribution system, is taken as a heavy load. In this paper, the reliability indices of a radial distribution feeder are calculated for various cases, including those without EV load, with EV load, and for different percentages of faults during EV load duration. The results are then compared. This work is validated on the IEEE 33 standard distribution system.*

***Keywords**: Electric vehicle (EV), Electric vehicle charging station (EVCS), EV load forecast, Average failure rate.*

I. INTRODUCTION

The automotive industry is expected to undergo significant changes due to the depletion of fossil fuels. A decrease in dependence on fossil fuels will lead to the development of numerous alternative forms of vehicle propulsion.

The electric vehicle (EV) industry is one such booming sector that will serve as an ideal replacement for current motor vehicles. The National Electric Mobility Mission Plan 2020 [1] was unveiled by the Department of Heavy Industry, Ministry of Heavy Industries and Public Enterprises, Government of India, to address the environmental problems caused by conventional motor vehicles and to increase the production of reliable, affordable, and practical electric cars. The FAME (Faster Adoption and Manufacturing of Hybrid & Electric Vehicles) India Plan [2] is one of several initiatives launched by the Indian government to foster the expansion of the hybrid/electric vehicle industry and manufacturing ecosystem. However, no thorough study has been conducted to determine the impact of substantial EV adoption on the future Indian electric power distribution system (EPDS).

In recent years, the research community has shown an increasing interest in electric vehicle technology. The fields of batteries, charging stations, and planning charging systems within a grid have been the focus of research efforts. When these vehicles take over the highways, they need to charge them. To do so, either a separate charging infrastructure is required, or a domestic power outlet can be used. The system's demand increases as a result of the extra load, which also affects the system's characteristics and reliability. Power system load has high unpredictability, volatility, and temporal characteristics, so different load rates have varied failure probabilities [3]-[4].

Industrial and residential energy consumption has been increasing recently, along with the likelihood that the grid would be overloaded, which has a significant impact on the distribution network's reliability. Since the component failure rate is treated as a constant in the traditional evaluation approach, the evaluation result indicates the average level of system reliability over a long period. Still, it is unable to reflect the component's reliability when the load ratio varies. Therefore, it is challenging to accurately depict the system's absolute reliability while calculating a reliability assessment at a single load level. [5]-[6].

The block diagram (Fig. 1) illustrates the process for determining the reliability of the two-load model by forecasting and applying the load to the IEEE33 standard distribution system.

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*Correspondence Author(s)
V. Swarna Rekha*, Department of Electrical Engineering, University College of Engineering, Osmania University, Hyderabad, Telangana, India. Email: swarna.vaddemoni@gmail.com, ORCID ID: 0000-0001-7936-0954.
G. Kiran Kumar*, Department of Electrical Engineering, University College of Engineering, Osmania University, Hyderabad, Telangana, India. Email: kirankumar.g@uceou.edu, ORCID ID: 0000-0003-2796-5382.
Dr. E. Vidya Sagar, Department of Electrical Engineering, University College of Engineering, Osmania University, Hyderabad, Telangana, India. Email: vidyasagar.e@uceou.edu ORCID ID: 0009-0006-5280-7895.

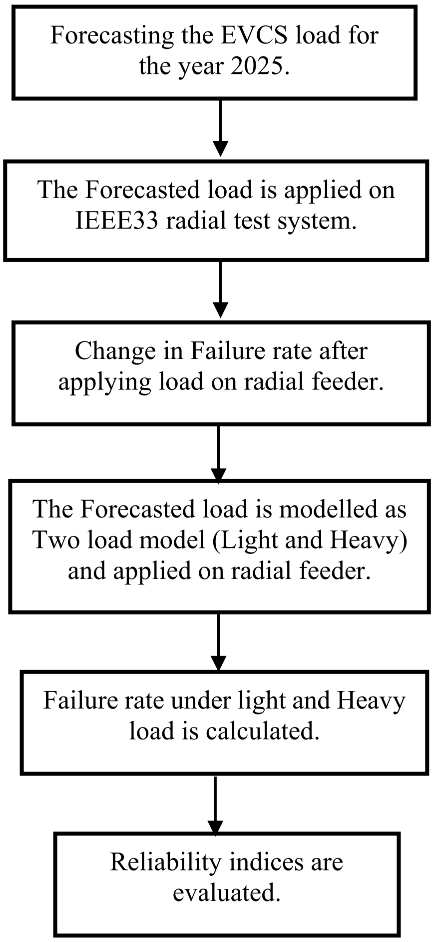

Fig.1 Reliability of the Two-Load Model

Based on the process outlined in Fig. 1, this paper examines the effect of load on reliability, classifying load conditions as either light or heavy. The relationship between the failure rate of feeder sections under two load conditions and the average failure rate is then evaluated. Finally, the relationship between the average failure rate of feeder sections and the load status and its reliability is evaluated.

II. METHODOLOGY

This section explains the method for calculating EV, the load forecast, and the calculation of the new average failure rate for the feeder section, as well as two load models with their corresponding failure rates and reliability indices, considering both load models.

A. Load forecasting techniques

Load forecasting can help an electric utility make informed decisions, such as those concerning electricity production and purchasing, as well as infrastructure development. This enables the precise forecasting of the magnitude of the distribution load. Forecasting the electricity demand is regarded as one of the key elements in determining the distribution system's performance, according to Holt's Model [7] is used. It is a method for analysing data related to trends, known as Holt's linear trend model.

The integration of EV charging load into the power distribution network is expected to occur quickly and significantly in the coming years. With the application of a suitable load forecasting method, the load is forecasted as mentioned here. Accordingly, the impact of EV charging station load on power loss and various operating parameters, such as the voltage profile of the distribution network, was examined for multiple scenarios of installing EV charging stations with a given load assumption. This section provides an overview of the method for calculating load flow analysis in distribution networks.

B. New Average failure rate of feeder sections.

The current in each branch is calculated using load flow analysis [8]. The new average failure rate is calculated using Equation (1), and the computed failure rates for the year 2025 are presented in Table II, along with the base case. The new average failure rate is calculated as

$$\lambda_{avg} = \lambda_{avgold} + \Delta\lambda_{avg} \quad (1)$$

Where $\Delta\lambda_{avg}$ is the increase in average failure rate due to the addition of EV charging stations.

C. Two-load model

The electrical load in the power system varies randomly on an hourly, monthly, and annual basis. Additionally, the load fluctuates throughout the day, week, year, and other periods, exhibiting periodicity. A significant increase or decrease in load demand will impact the anti-disruption capability of the power distribution system, thereby affecting the security of the power system.

This paper classifies burden levels as light load and heavy load. Figure 2 depicts the average failure rate of the load level impact model.

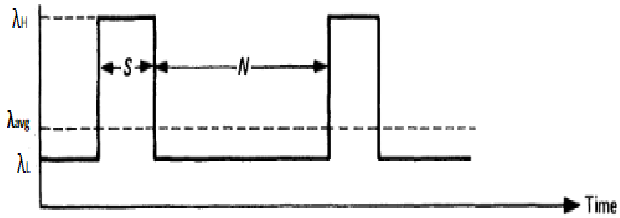

Fig.2 Average load duration profile

λ_{avg} = Average failure rate, λ_L= Average failure rate at light load condition expressed in failures/year; λ_H = Average failure rate at heavy load condition expressed in failures/year

The pattern of durations of load can be viewed as a random process described by expected values, i.e., the expected duration of light load is given by N=$\Sigma_i n_i$/T And the expected duration of the heavy load is given by S = Σi/si/T.

An average value of failure rate expressed in failures per calendar year can be derived from 'λ_L ' λ_H ', N and S using the concept of expectation.

$$\lambda_{avg} = \frac{N}{N+S}\lambda_L + \frac{S}{N+S}\lambda_H \quad (2)$$

The values of λ_L and λ_H can, however, be evaluated from

$$\lambda_L = \lambda_{avg}\frac{N+S}{N}(1-F) \quad (3)$$

$$\lambda_H = \lambda_{avg}\frac{N+S}{S}(F) \quad (4)$$

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Even if the value of F is unknown, a complete reliability analysis can be conducted using $0 < F < 1$ to determine the effect of adverse failures on the system's behaviour.

The relative magnitude of λ_L, λ_H can be illustrated by considering a realistic assumption in which λ_{avg} Is the average failure rate of the sections after application of EVCS load, in failures per year, with n = 19 hours and s = 5 hours. Where F = 0.1, 0.2, 0.3 i.e., 10%, 20%, 30% failures in heavy load condition respectively

D. Reliability Analysis

Distribution network reliability analysis has become an increasingly complex area of research in recent years. Here, the reliability of the distribution network is a concern. Based on statistical information on the failure rate, repair rate, average outage time, and number of consumers. The distribution network's reliability indices are evaluated [9]-[10].

The following section gives a brief overview of the distribution network's reliability indices.

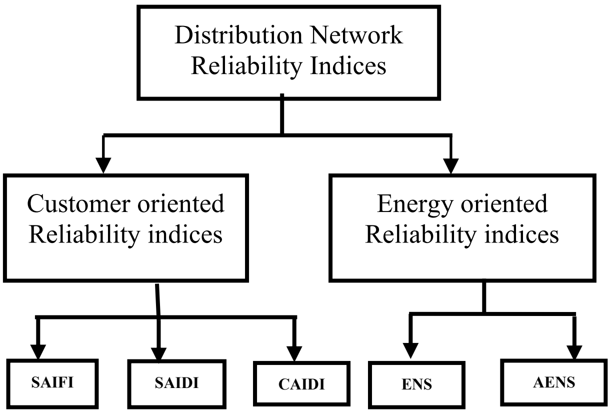

Fig. 3 Distribution Network Reliability Indices

System Reliability Indices represent the overall reliability of the distribution network. As shown in Fig. 3, Customer- and energy-oriented system reliability indices are further divided into categories. Some of the well-known customer-oriented reliability indices include SAIFI, SAIDI, and CAIDI.

A system customer's SAIFI is the number of interruptions that occur over a specific period. Examples of typical reasons for interruption include line outages, equipment failures, severe faults, increased load demand, and scheduled maintenance.

Mathematically,

$$SAIFI = \frac{\sum \lambda_i N_i}{\sum N_i} \tag{5}$$

It is evident from Equation (5) that SAIFI depends on the failure rate. This index will deteriorate when the load points fail more frequently. Increased failure rates can be attributed to various circumstances, including rising load demand, harsh weather conditions, ageing components, and inadequate maintenance practices. An increase in the number of consumers at the load points is a significant element that could lower this index. SAIFI is stated in interruption/customer years.

The average interruption time per serviced customer is known as SAIDI [9]. Mathematically,

$$SAIDI = \frac{\sum U_i N_i}{\sum N_i} \tag{6}$$

SAIDI is measured in customer years and hours. It is evident from (6) that SAIDI depends on both the duration of the interruption and the number of customers. Depending on the severity of the reason for the interruption, the duration of the interruption can vary from a few minutes to a few hours.

The average duration of an interruption for all customers over a year is known as the CAIDI [10]. Mathematically,

$$CAIDI = \frac{\sum U_i N_i}{\sum \lambda_i N_i} = \frac{SAIDI}{SAIFI} \tag{7}$$

CAIDI, thus, is the ratio of SAIDI and SAIFI.CAIDI is measured in customer interruptions per hour.

Equation (7) shows that CAIDI is dependent on the rate of failure, the duration of repair, and the total number of consumers. The load requirement of the buses or load points determines the energy or load-focused indices. The two most important Energy Oriented Reliability Indices used to assess distribution network performance are ENS and AENS [9]-[10]. The complete energy not supplied by the system is provided by ENS. It is denoted mathematically as in (8).

$$ENS = \sum L_i U_i \tag{8}$$

The average system curtailment index, or AENS, is given as in (9).

$$AENS = \frac{\sum L_i U_i}{\sum N_i} \tag{9}$$

The mathematical equations representing various customer- and energy-oriented reliability indicators of the distribution network are presented in Equations (5) to (9). All the reliability indices are used to forecast future system performance trends and the severity of system failures [9]. Power system engineers use these as a parameter in the development and growth of the distribution network. They demonstrate how the system's performance has changed over time and aid in locating the system's load areas [9].

While SAIDI depicts the system's status in terms of the duration of interruptions, SAIFI shows the system's state in terms of the frequency of interruptions. The AENS index provides information on the amount of energy not used during a specific period.

III. CASE STUDIES

The EV forecast is calculated using Holt's model, and the forecast load is applied to Fig. 4 of IEEE33. The distribution network's working parameters deteriorate due to the widespread adoption of EVs, which increases load demand. It shows that the network is radial, with 33 buses and 32 sections, each with 32 load points. Loads are represented by the same number displayed for sections, while a number with a rounded circle indicates the number of sections.

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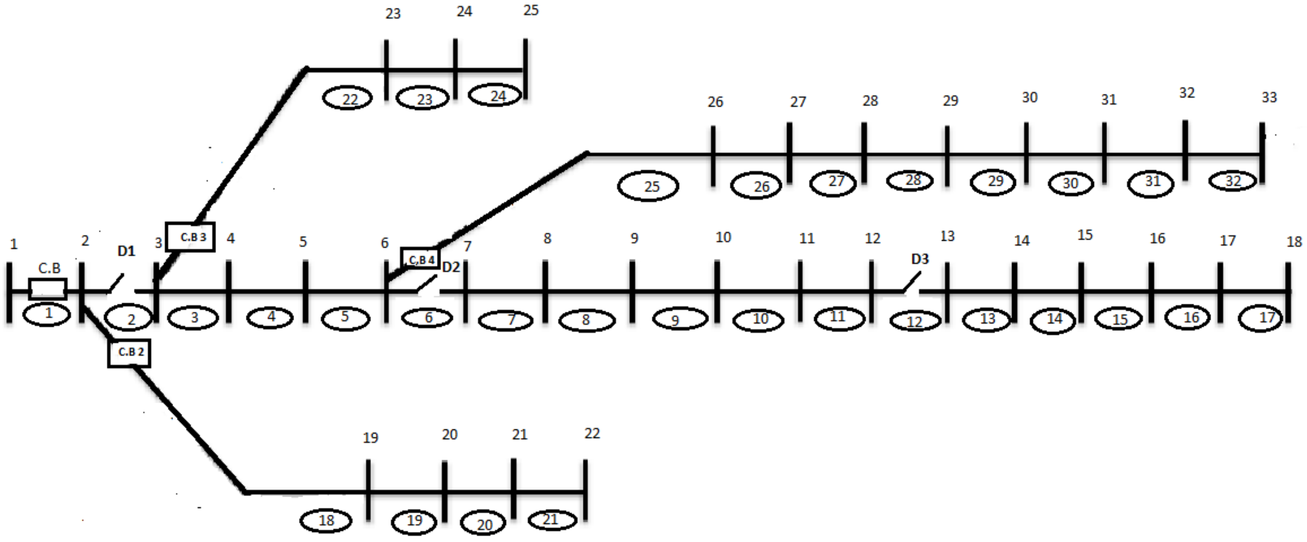

Fig 4. IEEE33 Standard test Radial distribution system

The Holt's Model is used for forecasting the loads from the data obtained by 1. Assuming Alpha(α)=0.2 and Beta (β)=0.3 [7]. The results of the EV forecast up to 2025, using Holt's model, are presented. The forecasted EV adoption rate for 2025 is applied uniformly to the distribution system across all buses, assuming that all customers are adopting EVs, as shown in Table I.

Table-I. Forecasted EV charging station load and locations for the uniform distribution case.

Case	Type	Load (kW) (2025)
1	Base case	-
2	Uniformly Distributed (For Buses 2-33)	62 (At each bus)

B. New Average failure rate of feeder sections.

The radial feeder section average failure rates for the base case [11] were considered. The current in each branch is calculated using load flow analysis. The new average failure rate is calculated using Equation (1), and the computed failure rates for the year 2025 are presented in Table II, along with the base case. Similarly, Table III presents the average failure rate of the radial distribution feeder under both light and heavy loads. With the help of Table III, the reliability indices are calculated and presented in Table IV.

Table II Average failure rate (failures/year) of feeder sections for the base case and with increasing EV load for the year 2025 for uniform distribution of Load.

Feeder Section	λ (failures/year)		Feeder Section	λ (failures/year)	
	Base Case	for 2025		Base Case	for 2025
1	0.05	0.0790	17	0.45	0.4509
2	0.3	0.3006	18	0.1	0.1156
3	0.22	0.2204	19	0.93	0.9330
4	0.23	0.2305	20	0.25	0.2508
5	0.51	0.5110	21	0.44	0.4414
6	0.11	0.1102	22	0.28	0.2805
7	0.44	0.4409	23	0.56	0.5610
8	0.64	0.6413	24	0.55	0.5510
9	0.65	0.6513	25	0.12	0.1202
10	0.12	0.1202	26	0.17	0.1703
11	0.23	0.2305	27	0.66	0.6613
12	0.91	0.9119	28	0.5	0.5010
13	0.33	0.3307	29	0.31	0.3106
14	0.36	0.3607	30	0.6	0.6012
15	0.46	0.4610	31	0.19	0.1904
16	0.8	0.8017	32	0.21	0.2104

Table III below presents the results for the change in average failure rate of feeder sections under two load conditions (Light and heavy loads) for the year 2025.

Table III Average failure rate of feeder sections assuming the percentage of failures under heavy load from 10-30%.

Sections	10%		20%		30%	
	λ_L	λ_H	λ_L	λ_H	λ_L	λ_H
1	0.095	0.040	0.084	0.080	0.074	0.120
2	0.558	0.236	0.496	0.471	0.434	0.707
3	0.439	0.185	0.390	0.371	0.342	0.556
4	0.461	0.195	0.410	0.390	0.359	0.584
5	1.015	0.428	0.902	0.857	0.789	1.285
6	0.254	0.107	0.226	0.215	0.198	0.322
7	1.085	0.458	0.964	0.916	0.844	1.374
8	1.732	0.731	1.539	1.462	1.347	2.193
9	1.744	0.736	1.550	1.473	1.357	2.209
10	0.318	0.134	0.283	0.269	0.248	0.403
11	0.598	0.253	0.532	0.505	0.465	0.758
12	2.346	0.991	2.085	1.981	1.825	2.972
13	0.839	0.354	0.746	0.709	0.653	1.063
14	1.018	0.430	0.905	0.860	0.792	1.289
15	1.261	0.532	1.121	1.065	0.981	1.597
16	2.104	0.888	1.870	1.776	1.636	2.664
17	1.066	0.450	0.948	0.900	0.829	1.351
18	0.219	0.092	0.195	0.185	0.170	0.277
19	2.011	0.849	1.787	1.698	1.564	2.547
20	0.541	0.228	0.481	0.457	0.421	0.685
21	0.952	0.402	0.846	0.804	0.740	1.206
22	0.402	0.170	0.357	0.339	0.312	0.509
23	0.762	0.322	0.678	0.644	0.593	0.965
24	0.749	0.316	0.666	0.632	0.582	0.949
25	0.197	0.083	0.175	0.166	0.153	0.249
26	0.270	0.114	0.240	0.228	0.210	0.342
27	1.009	0.426	0.897	0.852	0.785	1.278
28	0.732	0.309	0.651	0.618	0.569	0.927
29	0.437	0.184	0.388	0.369	0.340	0.553
30	0.966	0.408	0.859	0.816	0.751	1.224
31	0.285	0.120	0.253	0.240	0.221	0.360
32	0.548	0.231	0.487	0.463	0.426	0.694

The IV represents the Reliability indices [12]–[14] of the two-load model for failure rates under heavy load conditions of F = 10 to 30, as well as the overall percentage for each percentage of failure rate.

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Table IV Reliability indices for failure rates under Heavy load conditions for F=10 to 30%

F (%)	Case	SAIFI (Interruptions/ customer year)	SAIDI (Hours/ customer year)	ASAI	ENS (kWh/ customer year)
	Base	16.1612	2.7137	0.99969	9591.4
10	Light load	18.7449	6.4275	0.99926	23894.1
	Heavy load	7.91452	2.7346	0.99968	10191.6
	Overall	16.4885	5.6581	0.99935	21039.4
20	Light load	18.6342	5.7133	0.99934	21239.2
	Heavy load	15.8290	5.4277	0.99938	20177.2
	Overall	18.0498	5.6538	0.99936	21045.9
30	Light load	17.0808	5.7133	0.99934	21239.2
	Heavy load	23.7435	8.1415	0.99941	30265.8
	Overall	18.4689	6.2192	0.99939	23119.7

IV. CONCLUSION

Due to the increased forecasted EV loads for 2025, as shown in Table II, the percentage change in failure rate is 58% when the load is modelled as two-load. The average failure rate of each section in the radial distribution feeder changes and is presented in Table III. By considering the calculated values from Table III, the reliability indices are evaluated and shown in Table IV. According to the analysis in Table IV, it is verified that the percentage change in SAIDI and ENS increased from F = 10% to 30%. At F = 30%, the percentage change with respect to the base case increased by 129% and 141%, respectively. It is observed that the number of failures occurring during heavy loading conditions dominates at F = 30%, whereas at other percentages (10% and 20%), it is less dominant compared to F = 30%. Thus, this study can be implemented for real-time power infrastructure or used as a reference when the electric vehicle sector expands. It can also help determine essential parameters, such as the system failure rate and reliability.

DECLARATION

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Availability of Data and Material/ Data Access Statement	Not relevant.
Authors Contributions	All authors have equal participation in this article

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AUTHOR PROFILE

V. Swarna Rekha Research Scholar in Electrical & Electronics Engineering Department, University college of engineering, Osmania University, Hyderabad. She has done B.Tech. in Electrical Engineering from DVR College of Engineering and Technology, Affiliated to JNTU(H), and M.E. from University College of Engineering, Osmania University. Her research includes Power Quality, Distribution System Reliability, Distribution Automation, and Smart Grid.

G. Kirankumar is currently working as an Assistant Professor in the Department of Electrical and Electronics Engineering at the University College of Engineering, Osmania University, Hyderabad. He has completed his bachelor's degree from Vaagdevi College of Engineering, affiliated with JNTU (H), and his M.Tech from JNTU (H). He has 13 years of experience in teaching. His research areas include Smart Grid, Distribution Automation, and Power System Reliability.

Dr. E. Vidya Sagar is currently working as a Professor in the Electrical & Electronics Engineering Department at the University College of Engineering, Osmania University, Hyderabad. He has earned his Bachelor's, Master's, and Doctorate Degrees in Electrical Engineering from JNTU (H) College of Engineering, Hyderabad. His main research areas include distribution reliability, Power Quality, Deregulated Power Systems, Smart Grid, and Distribution Systems.