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Reliability analysis of an automated radial distribution feeder for different configurations and considering the effect of forecasted electrical vehicle charging stations

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ABSTRACT

In the future, the expansion of electrical vehicles is becoming more prevalent, which requires electric vehicle charging stations (EVCS), and at the same time, distribution automation and smart grid technology will be implemented as part of the reforms in the distribution system. This paper reviews the effect of the increased EVCS, which causes an increase in the magnitude of current and moderates the average failure rate of feeder sections. The implementation of distribution automation and a smart grid reduces the average restoration time, thereby increasing the reliability of the distribution system. The number of electrical vehicles (EVs) for the years 2025 and 2030 is forecasted using Holt's model, and the corresponding average failure rate of feeder sections is calculated. The average switching time for adopting distribution automation and smart grid technology is taken as 5 seconds and 20 milliseconds, respectively. The voltages, power losses, and reliability indices are calculated assuming the EV charging points are located with equal capacity at all load buses for different configurations of radial feeders. The results are compared with the reliability indices of the feeder of all the configurations in the absence of EV charging station loads, automation, and smart grid technology. This work is validated on a standard IEEE 33 test bus system.

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1. INTRODUCTION

The ever-increasing demand for energy, as well as the finite nature of the fossil fuel supply, are the primary concerns of environmentalists and scholars in the twenty-first century. Transportation-sector CO2 emissions are one of the primary sources of global warming and climate change [1], [2]. The electric vehicle (EV) industry is one such booming sector that will be the ideal replacement for current motor vehicles due to the depletion of fossil resources. The National Electric Mobility Mission Plan 2020 [3] 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 effective electric vehicles [4], [5]. The faster adoption and manufacturing of hybrid and electric vehicles (FAME) India Plan [6] is one of several initiatives launched by the Indian government to foster the expansion of the hybrid/electric vehicle industry and manufacturing ecosystem.

No thorough study has been carried out to determine the impacts of substantial EV adoption on the future Indian electric power distribution system (EPDS). The degradation of voltage profile [7]–[9] increase in peak load [10], [11], harmonic distortions [12] are some of the consequences of the uncoordinated charging of

Bhadra and Chattopadhyay [13]. addresses the reliability of a distribution system assessed by the performance at the customer load points. The reliability is evaluated [14]–[17] by adding equal increment in load and unequal increment of load on distribution system [18]–[20]. The reliability indices are increasing with addition of load [21]–[23], the problem of increase in reliability indices are reduced through reconfiguring the distribution network explained by Chakraborty [24]. When Electric vehicles take over the highways, they need to charge them. To do so, either a separate charging infrastructure is needed, or a domestic power outlet can be used. The connection of the electric vehicle charging stations (EVCS) to the distribution grid and changes to the voltage profile of the distribution system are addressed in detail by Deb *et al*. [18]. Additionally, this study discusses an approach to calculating reliability indices for the distribution system.

The key contribution of the work is outlined as shown in investigation of forecasted EV charging station load, distribution automation (DA) and smart grid technology (SGT) on the performance of radial distribution network for different configurations. The remaining sections are organized as follows: i) The forecasting of EV load, load flow analysis [25], DA, SGT, and reliability are illustrated in section 2; ii) Section presents the case studies of the EV load forecasting, impact of the charging station loads as well as performance of IEEE 33 bus test network. iii) The work is finally concluded in section 4, which provides an overview of the research findings.

2. METHOD

This section explains the method of forecasting electric vehicle charging station load using Holts model, backward/forward load flow analysis of radial distribution system to calculate voltages at each bus and currents in the feeder section and the power loss of the distribution system. The techniques of automation and smart grid are applied to reduce the system average interruption duration index (SAIDI) and energy not supplied (ENS) of the distribution feeder. The new average failure rate after application of forecasted EVCS load of the feeder sections are calculated and the corresponding reliability indices of a radial distribution feeder.

2.1. Load forecasting techniques

Load forecasting the demand for electricity is regarded as one of the key elements in determining the distribution system's performance, for this Holt's model is used. It is a method to deal with data pertaining to trends which is known as Holt's linear trend model. In this model the seasonality factor γ is neglected. Holt's gave a method to deal with data pertaining trend which is known as Holts linear trend model. It comprises one total forecasted equation (F_{t+1}) and two smoothing equations (a_t, b_t) The total forecasted EV load is given by:

$$F_{t+1} = a_t + b_t \tag{1}$$

Where a_t is the level which represents the smoothened value up to and including the last data and b_t gives the slope of the line representing the data. The values of a_t and b_t are updated using:

$$a_t = \alpha D_t + (1 - \alpha)(a_{t-1} + b_{t-1}) \tag{2}$$

$$b_t = \beta(a_t - a_{t-1}) + (1 - \beta) b_{t-1} \tag{3}$$

In (2) the factor D is the data given.

α and β are smoothing constants for level and trend respectively, whose values lie on the interval between 0 to 1. Using (1)-(3) the EV load forecasted for the year 2025 and 2030. An overview of the method for calculating load flow analysis in the distribution network is presented in this section.

2.2. Load flow analysis

The backward/forward sweep load flow [25], [26] analysis is a classical algorithm that determines the bus voltages and currents passing through each feeder section of the radial distribution system. Backward sweep (BS) is the process of solving for the currents with the provided voltages, while forward sweep (FS) is the process of solving for the voltages with the provided currents of a radial distribution system. The power loss is calculated by using calculated voltages and currents of radial distribution system.

2.3. Power loss

The majority of the power losses present in distribution systems are because of load in the feeder sections of radial distribution feeder. Due to the increase in load the current on the feeder section increases. The I^2R losses referred as power losses of the distribution network.

$$P_k = {I_k}^2 R_k \tag{4}$$

The total power losses of the radial distribution system are (4) is used.

$$P_t = \sum_{k=1}^{n} P_k \quad (5)$$

Where k is the section of radial distribution system. The further section shows the future load forecast of EV's [16], [17], [20], [25] and applied on all possible case studies of IEEE 33 distribution system and the performance is validated.

2.4. Distribution automation

The restoration time is the most important factor in load restoration problem because penalty regimes for network operators are usually based on the capacity and length of load interruption. To restore the fault in distribution network manually, the crew is selected physically and sending the crew to the faulty area, and that results in an increased restoration time depending on the efficiency of the working crew. In the conventional methods, like manual operations, even the easiest step also consumes time in hours because all the actions are performed in series (one after another). In this paper the average repair time and switching time for the feeder section is taken as 1 hour and 30 minutes respectively. Whereas automation is a process of performing a task in an automated manner to achieve a faster rate of power distribution operation, The goal of the automation is to enhance the operating performance of the power distribution system, with the advancement of data acquisition systems, communications technology, and power electronics data analysis tools. In most cases, industrial and commercial distribution systems must be automated. Automation of the distribution system improves reliability by decreasing the duration of interruptions, isolating defective components, maintaining the functionality of system equipment, and automating the required switching processes during system operation.

Distribution automation (DA) is responsible for monitoring, controlling and managing the power distribution grids in the distribution systems. The remote station is interfaced with the measuring instruments (first component) connected to the plant being monitored and controlled. The capabilities of remote stations are.

- Collecting data from the different equipment in the monitored and controlled center.
- Storing the collected data in its memory and awaiting the control center's request to transmit the data.
- Receiving data and control signals from the control center and sending control signals to plant devices.

The remote section is either remote terminal unit (RTU) or programmable logic controller (PLC). The RTU is used effectively in difficult communication. The RTU has digital/analog inputs and outputs with LED indication (per channel selectable), optical isolation for surge protection, and short circuit protection. Distribution automation systems (DAS) are defined by the Institute of Electrical and Electronics Engineers (IEEE) as systems that enable an electric utility to coordinate, monitor, and operate distribution components in real time. If the fault occurs in the system, then it is classified as three sections i.e., upstream, faulty section and downstream. The sections before faulty sections are called upstream, the sections after the faulty sections called downstream. For distribution automation in this paper Figure 1 is considered. The RTU are connected at circuit breaker (CB) and each disconnecting switch. The control center is employed to check the status of RTUs in the network.

For example, if the fault occurs in the 9th section, then sections 1 to 5, 18 to 21, 22 to 24 are upstream, sections 6 to12 are under faulty section and sections 13 to 17 are in downstream. The RTU1 which is placed at CB changes its status after a fault that indicates the fault in the feeder and this information is sent to the control center through communication lines. The control center takes the decision then it opens the disconnecting switches D2 and D3 using remotely operated switches. The faulty section is isolated using a remotely motor operated switch and restores the upstream and downstream network with the main supply and alternate supply located at bus 1 and bus 18, in this process the network takes 5 seconds to restore the upstream and downstream sections in the network.

There are several operational and maintenance advantages to implementing distribution automation strategies: i) Enhanced reliability by decreasing restoration time with an automated restoration strategy; and ii) Decreased man-hours and man-power. By using the above process load lambda is calculated and reliability is evaluated shown in section 3.4.

2.5. Smart grid

"The smartness of the grid is manifested in making better use of technologies and solutions to intelligently control generation, to better plan and run existing electricity grids, and to enable new energy services and energy efficiency improvements". The structure of the distribution system is radial to deliver electricity directly to consumers. A smart grid distribution system (SDSs) combines distributed generation, microgrid, and advanced distribution automation technology. Countries all around the world are increasing distribution system automation by introducing smart grid and intelligent device technologies to benefit from Smart grid systems.

As explained in section 2.5 the process of restoration is same as explained whereas the motor operated disconnecting switches are replaced with high rated power electronic switch like IGBT in smart grid as this switch requires maximum of one-half cycle to trigger or block the circuit, so the restoration time is very less and taken as 20 milliseconds in this evaluation and the reliability is calculated in section 3.4. Following are a smart grid's projected advantages like improving power quality, reducing restoration time of the distribution system and automating maintenance, operation and reduction in greenhouse gas emission.

2.6. Evaluating the new average failure rate

The percentage change in average failure rate (λ_{avg}) of a feeder section is assumed to be directly proportional to the percentage change in current passing through that component due to addition of EV charging stations to meet the future EV demands. The current in each branch is calculated using load flow analysis. The new average failure rate is calculated as:

$$\lambda_{avgnew} = \lambda_{avgold} + \Delta\lambda_{avg} \tag{6}$$

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

2.7. Reliability indices

The distribution network's reliability indices determine the quality of the electricity system. The indices are computed using the average failure rate, average outage duration, and total number of customers. The distribution network reliability indices mentioned in [16], [18]. The following reliability indices are used for the determination of reliability of a distribution system.

$$\text{System average interruption frequency index (SAIFI)} = \frac{\sum \lambda_j N_j}{\sum N_j} \tag{7}$$

$$\text{System average interruption duration index (SAIDI)} = \frac{\sum U_j N_j}{\sum N_j} \tag{8}$$

$$\text{The average service availability (ASAI)} = \frac{\sum N_j X 8760 - \sum U_j N_j}{\sum N_j X 8760} \tag{9}$$

Where 8760 is the number of hours in a calendar year.

$$\text{Energy not supplied (ENS)} = \sum L_j N_j \tag{10}$$

Where λ_j is the average failure rate of load point j in failures/year due to the failure of all the feeder sections responsible for the supplying power to the load point j. This is calculated using failure mode and effect analysis (FMEA) technique; U_j is the annual outage duration of bus j in hours/year; N_j is the number of customers of load point j; and L_j is the average load connected to load point j in kW.

3. RESULTS AND DISCUSSION

EV forecast is calculated by using Holt's model and the forecasted load is applied on IEEE33. The impact of voltage stability and power loss due to EV charging station load examined on Figure 1. It shows the network is a radial network, it has 33 buses, 32 sections with load points 32. For the Con.B the laterals are protected with fuses, for Con.C disconnecting switches are connected at feeder sections 2,6,12 and for Con.D Alternate supply is taken at bus 18. RTU1 to RTU5 are connected at every switch to check the status during fault occurrence using control centre. The switches (D1 to D3) in Con.D are replaced with Power electronic switches for smart grid applications whereas in manual restoration mechanical switches and in automation motor operated switches are used. Loads are taken as the same number displayed for sections, while sections are represented by a number with a rounded circle.

The study, "Status quo analysis of various segments of electric mobility and low carbon passenger road transport in India" up to the year 2020, which was conducted by the German Society for International Cooperation (GIZ) GmbH, the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety, and NITI Ayog, India [4], provided the data on category-wise sales of electric vehicles in India. The percentage of electric station load on the IEEE 33 bus system is calculated and applied using this data to project the future EV load up to the year 2030. The voltage profile, power losses, and reliability are determined after applying the forecasted load for the years 2025 and 2030.

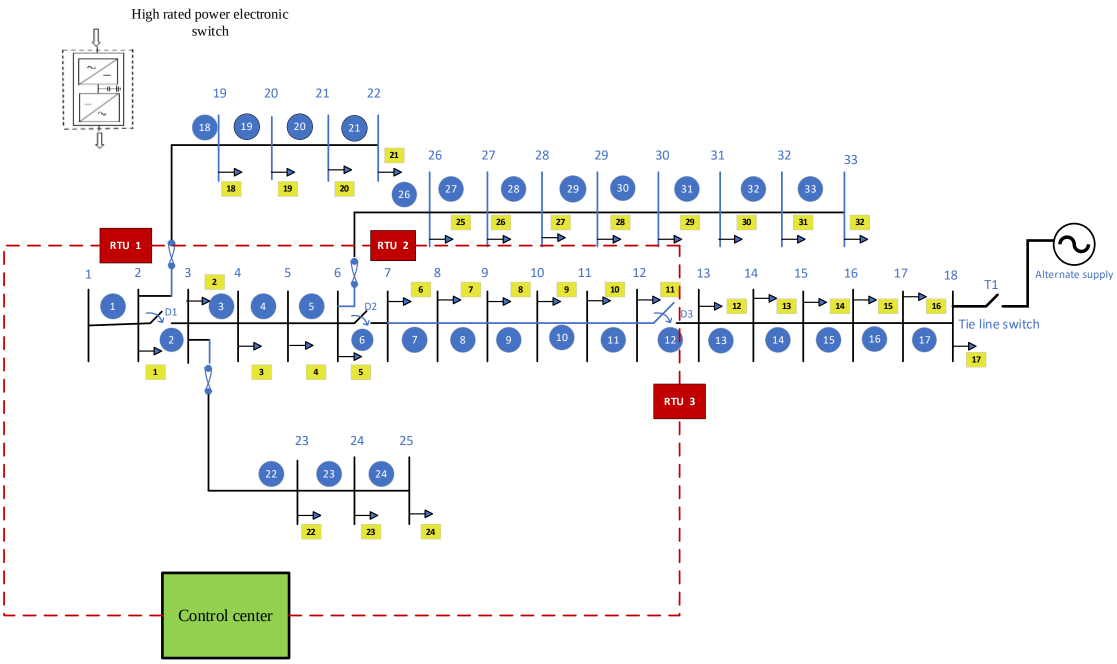

Figure 1. IEEE 33 bus system test network

3.1. Forecasting EV load

The Holt's model is used for forecasting the loads. Assuming Alpha (α) = 0.2 and Beta (β) = 0.3 [3]. The results of EV forecast up to the year 2030 using Holts model explained in section 2.1. The forecasted EV for the years 2025 and 2030 is applied on the distribution system uniformly on all the buses assuming all the customers are adopting EV's is shown in Table 1. From section 2.2 load flow analysis is done on distribution system then the voltage profile of the buses is obtained. The voltages at the buses for case 2 (uniform distribution) for the years 2025 and 2030 are shown in Figure 2.

Table 1. Forecasted EV charging station load and locations for uniform distribution case

Case (C)	Type	EV Load (kW) At each bus 2025	EV Load (kW) (2030)
1	Base case	0	0
2	Uniformly Distributed EVCS	62	81

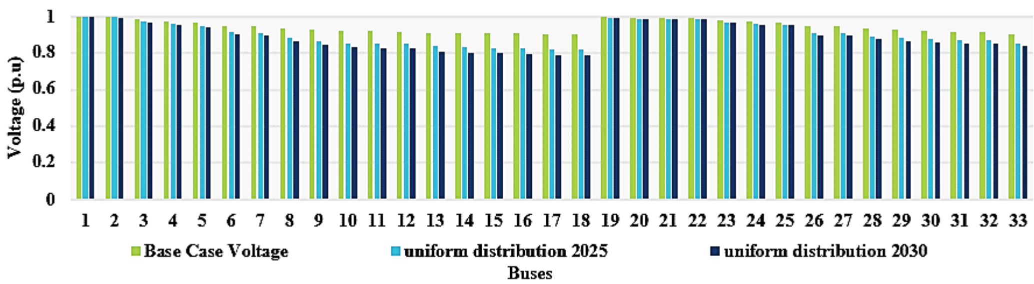

Figure 2. Voltages at each bus after for base case and after applying load for case 2 for the years 2025 and 2030

3.2. Power losses

Using backward/forward load flow analysis, currents in various sections of the system were determined using section 2.2 power losses were computed for the years 2025, 2030. Figure 3 shows the total losses of IEEE33 bus system for the years 2025, 2030. It is shown that the power losses are increasing as the forecasted load is applied in the system.

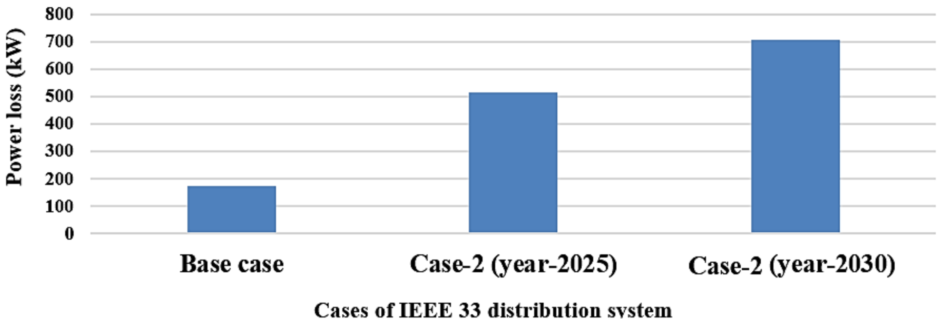

Figure 3. Power loss after applying EV station load for the years 2025 and 2030

3.3. New average failure rate of feeder sections

The current in each branch is calculated using load flow analysis. The new average failure rate is calculated using (6) from section 2.6 and the calculated failure rates for the years 2025, 2030 presented in Table 2 along with base case. Results from Figure 2 shows that the voltages in the year 2030 reduced due to the additional load at load points compared to base case and year 2025.

Table 2. Average failure rate of feeder sections for the base case and with increasing EV load for the year 2025 and 2030 for uniform distribution of load

Section	Base case	failure rate of feeder sections after EV load		Section	Base case	failure rate of feeder sections after EV load		Section	Base case	failure rate of feeder sections after EV load	
		2025	2030			2025	2030			2025	2030
1	0.05	0.083	0.191	12	0.91	2.064	2.013	23	0.56	0.670	1.138
2	0.3	0.491	1.198	13	0.33	0.738	0.730	24	0.55	0.659	1.118
3	0.22	0.386	1.050	14	0.36	0.896	0.797	25	0.12	0.173	0.582
4	0.23	0.406	1.133	15	0.46	1.109	1.018	26	0.17	0.237	0.845
5	0.51	0.892	2.049	16	0.8	1.850	2.071	27	0.66	0.887	1.360
6	0.11	0.224	0.562	17	0.45	0.938	0.996	28	0.5	0.644	1.162
7	0.44	0.954	2.147	18	0.1	0.193	0.200	29	0.31	0.384	0.723
8	0.64	1.523	1.414	19	0.93	1.769	1.864	30	0.6	0.850	1.620
9	0.65	1.534	1.436	20	0.25	0.476	0.501	31	0.19	0.250	0.578
10	0.12	0.280	0.265	21	0.44	0.837	0.882	32	0.21	0.482	0.592
11	0.23	0.526	0.509	22	0.28	0.353	0.569				

3.4. Reliability indices evaluation

Then the EV charging station load is placed uniformly on the system for the year 2025 and 2030, then the failure rate is calculated using (6). From the Table 3, in the configuration A the test distribution system is taken without protection, in configuration B, 3 laterals are protected with 3 Fuses, in configuration C laterals are protected with fuses and disconnecting switches are connected at feeder sections 2, 6, 12 and in configuration D laterals are protected with fuses, disconnecting switches are connected at feeder sections 2, 6, 12 and alternate supply is connected at bus 18 then the load lambda, restoration time, and unavailability are calculated for all the all the configurations and for case 1, case 2 further the reliability is evaluated. Representations for Figure 4*:* manual-M, distribution automation-DA, manual-M, smart grid technology–SGT, Interruption/Customer year-intr/cust-yr, hours/customer year-Hrs/Cust-yr.

A system with configuration A and configuration B the restoration process of power after occurrence of failure is not possible since no switches in the configuration. The adoption of distribution automation and smart grid technology schemes will not have any impact on restoration time thereby reliability. Therefore, distribution automation and smart grid technology are not shown in configurations A and B in Figures 4 and 5.

Table 3. Configuration of IEEE 33 bus for different cases

Configuration	No. of fuses	No. Disconnecting switches	Alternate supply	Configuration	No. of Fuses	No. Disconnecting switches	Alternate supply
A	0	0	0	C	3	3	0
B	3	0	0	D	3	3	1

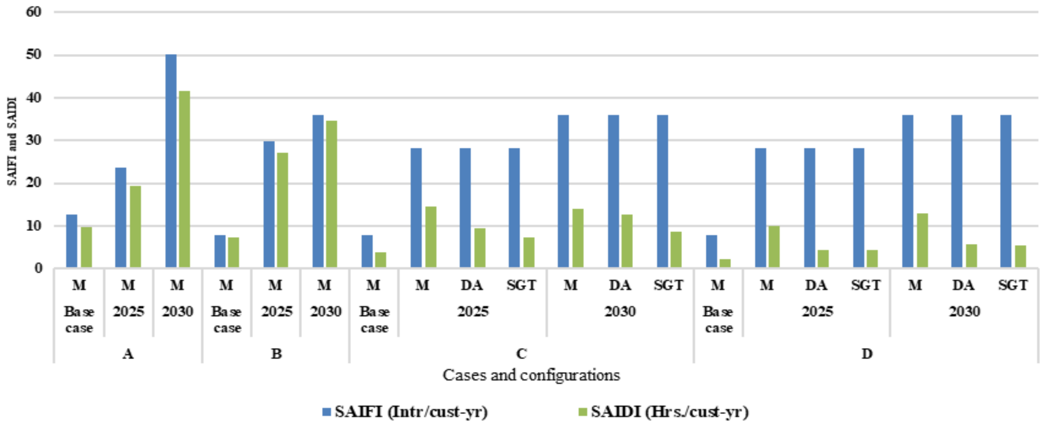

Figure 4. SAIFI and SAIDI with addition of EVCS for the years 2025 and 2030 for different configurations

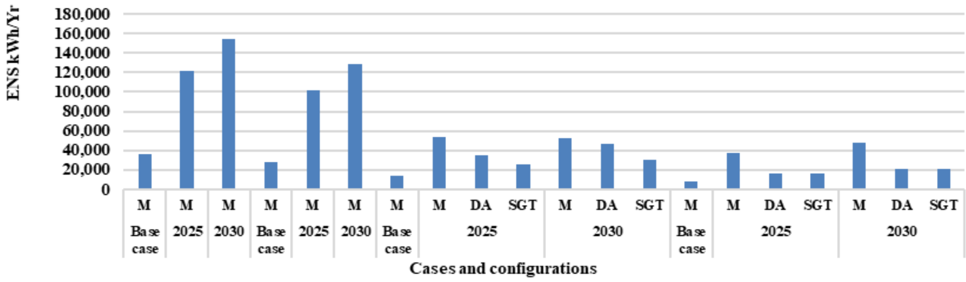

Figure 5. ENS with addition of EVCS load for the years 2025 and 2030 for different configurations

4. CONCLUSION

The reliability indices of the system are calculated using a base case in which there are no EV charging stations on the IEEE 33 test distribution system. According to the analysis done, it is observed that the system's reliability modifies as the additional demand on the EV charging station with adoption of DA and SGT. The percentage change in SAIDI in comparison with base case for configuration A, configuration B, configuration C, configuration D for the year 2025 are 228.16, 264.45, 185.29, 336.46, similarly for the year 2030 are 327.39, 369.60, 272.40, 473.19. From the observation it is concluded that the percentage change for the configuration C is less when compared to other configurations, and for the configuration C the SAIDI for the year 2025 with automation and smart grid are 151.4, 241.2 and for the year 2030 241.23,130.15 the configuration D for the year 2025 with automation, with smart grid are 93.95, 92.59 and for the year 2030 147.61,145.81 respectively. As a result, this study can be applied to real-time power grids or used as a reference when the electric vehicle industry grows. It can also be helpful to calculate important factors like the average duration of system interruptions or the new average failure rate of the distribution system after application of EVCS load. In this paper Holts model is used to forecast the EVCS load by neglecting the seasonality factor γ. For better EVCS load forecast seasonality and cyclicity is considered.

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