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RESEARCH ARTICLE

The Reliability and Economic Evaluation Approach for Various Configurations of EV Charging Stations

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ABSTRACT Electric vehicles (EVs) become more popular as a form of transportation and companies that make useful things are focusing on building charging stations for customers. It is hard to keep charging ports reliable for EVs that are being charged in between, even though charging station companies are building stations according to the distribution system's requirements. To make the charging station of the distribution system more reliable, the 36-ported design has been proposed with the combination of uniform and non-uniform port arrangement. The configurations have been functioned with 50-350 kW distribution system. The failure rate estimation has been implemented with the standards of the MILHDBK217F book. The probability function of the ports has been evaluated in terms of failure rate and reliability as per the standards of the MILHBK-338B book. As per the failure rate of each port, the evaluation process has been introduced to find the success rate of the charging station. The failure rate of the port arrangement of the proposed 36-ported charging station has been evaluated by using the binomial distribution method. Moreover, the cost estimation process has been implemented for the proposed 36-ported charging system in terms of the failure rate and success rate of the individual port maintenance. By the consideration of individual port failure rate and reliability of the 36-ported configuration, the voltage stability of the distribution station has been evaluated. It is inferred that the lesser failure rate and maintenance cost are achieved with better reliability of port arrangement and voltage stability as well.

INDEX TERMS Charging port configurations, electric vehicles, failure rate evaluation, reliability probability of charging port, voltage stability of charging station.

I. INTRODUCTION

In recent times, there has been a growing emphasis on the issue of global warming and climate change, leading to a heightened interest in the adoption of plug-in electric vehicles (PEVs) as a viable alternative to conventional fuel-based vehicles. Two major issues, pollution and the scarcity of fossil fuels-drive the demand for electric automobiles. The governments are providing financial incentives to firms that install charging stations for EVs. Power system engineers are facing considerable challenges due to the growing demand for EV charging. Electric Vehicle Charging Stations (EVCS) need to be strategically distributed to successfully serve users in highly populated areas with high charging demand, but this requires careful planning. It is also crucial to prevent power losses and keep the voltage variation of the power grid within acceptable regulatory parameters. The price of nearby land is also an important consideration when setting up a charging station. Strategically planning the placement of charging stations is complicated by the need to manage the unknowns that come with EVs.

In [1], a thorough methodology to assess the effects of varying degrees of PEVs adoption on distribution network investment and incremental energy losses. The approach utilizes a sophisticated large-scale distribution planning model, which is applied to analyze two actual distribution areas.

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The expenses associated with investment in the distribution network can potentially rise by as much as 15% of the overall real investment expenditures. Additionally, during off-peak hours, energy losses may increase up to 40% in a scenario where 60% of the vehicles in use are PEVs. The investigation of the influence of substantial Plug-in Hybrid Electric Vehicles (PHEVs) charging on the power grid is necessary due to the significant number of these vehicles and their intricate charging characteristics. The charging behavior of PHEVs within a specific regional transmission network or local distribution network is influenced by various uncertain factors. As a result, the overall charging demand for PHEVs is characterized by uncertainty. To assess the effects of PHEVs charging on the power grid under such circumstances, probabilistic power flow (PPF) analysis can be employed. The technique presented in this study introduces a singular model for predicting the charging needs of PHEVs. Subsequently, queuing theory is utilized to elucidate the dynamics exhibited by many PHEVs [2], [3].

This study introduces a multi-objective methodology for determining the ideal location and dimensions of parking lots that serve as vehicle-to-grid (V2G) power sources in distribution systems, thereby functioning as a novel kind of distributed generation (DG). This approach takes into consideration the reliability of the distribution infrastructure, power losses, and investment costs [4], [5]. One significant gap identified in the field of system stability research is the absence of precise load models that adequately represent EV load. Therefore, this paper presents the development of a static load model, which serves as a fundamental foundation for conducting realistic stability analyses. The research findings indicate that the incorporation of EV rapid charging stations can have a notable impact on the steady-state voltage stability of the power grid [6], [7].

The security and reliability of power system operations may be compromised as a result of unregulated EV charging and discharging. Intelligent scheduling for the charging and discharging of EVs is necessary. This research presents a proposed methodology for the intelligent management and scheduling of a substantial quantity of EVs situated within an urban parking facility. The proposed energy management system for the parking lot effectively meets both economic and technological objectives. Furthermore, EV owners have the potential to generate income by discharging their vehicles while ensuring that the state of charge (SOC) meets their desired level at the time of departure [8], [9]. In [10], and [11], the behavior of EVs is modeled using probabilistic methods. Furthermore, a proposed approach for the optimal allocation of parking lots for EVs is presented, taking into consideration reliability constraints.

From [12] and [13], one of the primary solutions to the requirement for charging stations involves the implementation of PEVs parking lots. The objective of this study is to allocate power losses in distribution systems to minimize system costs. These expenses include power loss, network reliability and voltage variation and the framework not only enhances the reduction of distribution network loss but also increases the accessibility of the parking lot from an economic perspective. This study aims to ascertain the most advantageous quantity, placement and capacity of EV parking lots to optimize the profits of electrical distribution firms. Additionally, the anticipated growth rate of EVs in the forthcoming years is considered a probabilistic parameter [14]. In [15] and [16], the numerical findings demonstrate the implementation of the suggested optimization approach in attaining the lowest cost for charging station placements, while simultaneously ensuring charging reliability and desired quality of service. This is achieved by analyzing the behavior of electric vehicle owners and drivers.

To assess the benefits derived from the power exchange between parking lots and distribution networks, as well as EVs, it is imperative to establish an ideal timetable and determine the appropriate time intervals for EV charging and discharging. To address this requirement, a novel approach is introduced for the scheduling of EV charging [17]. One significant challenge arises from the adverse effects on the energy distribution system resulting from the inadequate installation of these charging stations. This pertains to the ideal strategic decision-making process involving the placement and dimensions of charging station infrastructure inside an urban setting. The researchers have employed genetic algorithms and particle swarm optimization techniques to enhance the voltage profile and quality [18]. In [19], [20], and [21], the proposed plan comprises two distinct stages. This is the initial phase of assessing the capacity of distribution networks to meet the charging requirements of PEVs using the current infrastructure. During the second phase, the expansion of public PEV demand is effectively aligned with the installed fuel cell system (FCS) capacity through the utilization of an economically optimized staging plan model.

The global demand for electric vehicles has experienced a significant surge due to its positive impact on both the environment and the economy. Nevertheless, the integration of a significant number of electric vehicles into the distribution system results in voltage instability, heightened maintenance expenses and reduced reliability of the associated charging infrastructure [22], [23]. The aforementioned aspects hold significant importance within the distribution system and warrant focused attention. The unregulated operation of EV charging stations poses challenges to the distribution system. The stochastic charging process of EVs resulting from the presence of an EV fleet poses numerous challenges to the charging infrastructure. The installation of the charging station is contingent upon several factors, including the geographical placement, the concentration of EV users in the vicinity and the financial circumstances of the investors. The evaluation of the parking lot's charging port arrangement will be based on factors such as the overall land size and the capacity of the power supply from the distribution system. Achieving a balanced power load distribution within the system is of utmost importance [24], [25].

Since most power systems are severely loaded and operate closer to their secure operation limitations due to a variety of environmental and economic constraints, voltage stability is a growing global concern. The current body of scholarly work on the planning of EVCS exhibits a notable deficiency in accounting for unpredictable variables within power systems, including demand fluctuations and the ramifications of electric car integration [26], [27], [28]. Hence, the utilization of deterministic power flow (DPF) algorithms in the context of EVCS planning is deemed to be untrustworthy. To tackle this issue, we put forth a probabilistic model for EV charging loads and created a novel index known as dynamic system voltage stability (DSVS) in [29], [30], and [31]. The effectiveness of the suggested methodology was assessed using a case study involving the utilization of the IEEE 33-node distribution network topology diagram and a planning area map.

The test network employed for the study was the IEEE 9-bus radial distribution system. The relevant analysis conducted four scenarios utilizing both deterministic and probabilistic techniques. The findings of the study demonstrated the significant impact of charging strategies on EV charging systems, particularly in terms of mitigating the challenges associated with integrating EV chargers in [32], [33], and [34]. Charging stations are necessary to charge the battery of the vehicle. In response to the heightened power demand associated with EV charging, the distribution system experiences an escalation in power loss and subsequent voltage dips. To maintain a healthy voltage profile and minimize power loss, it is imperative to strategically locate the charging station at the appropriate node. This article presents the allocation of electric vehicle charging stations inside the IEEE 33-node radial distribution network [35], [36], [37]. According to the above statements, the reliability evaluation of the charging stations has been evaluated as per the port arrangements in the next section.

II. METHODOLOGY

Basically, the installation capacity of the charging station is decided by the availability of parking areas for the vehicles. However, the only consideration of parking area is not enough to configure and install the port arrangement to provide the charging services to the customers. Because the installation of the charging station is dependent on the capital investment and expenditure for the maximum charging port capacity in a particular area. Before installing the charging station, the reliability test should be applied to the selected port configuration for budget allocation to procure the required ports [38], [39]. Based on the above statement the reliability estimation has been considered and the reliability estimation methodology introduced as shown in Fig. 1.

To find the reliability of the charging port arrangement the uncertain plug-in condition has been considered as a primary step. The uniform and non-uniformed port designs have been taken into account in order to facilitate the charging

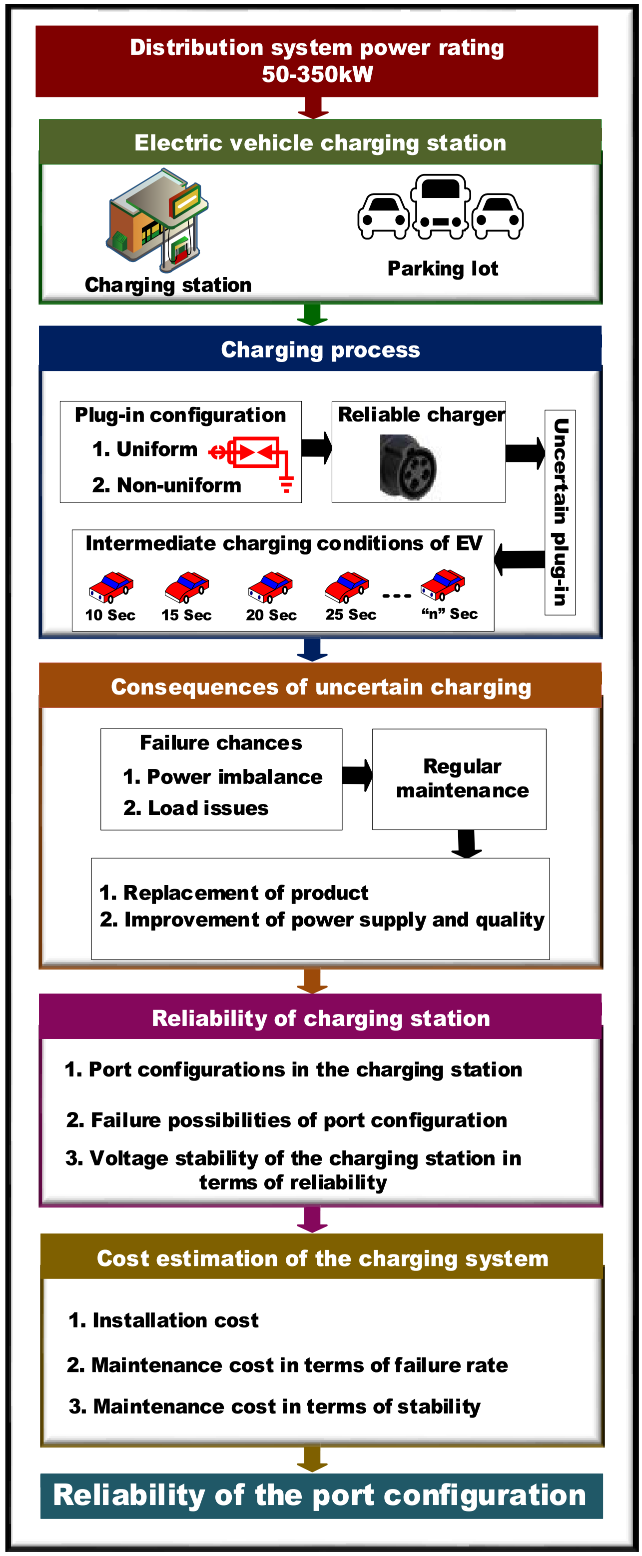

FIGURE 1. The proposed evaluation methodology for the reliability of charging ports in terms of failure rate.

capabilities for the uncertain plug-in system, as depicted in Fig. 1. The intermediate conditions of operation in EVs caution for the higher failure rate in the charging stations due to the load variation on charging ports. The failure occurrence in the charging station is dependent on the customer's demand to charge the vehicle as per the different power ratings. However, the higher port failures will lead to the discontinuation of services, the replacement of the failure port is a solution to maintain the consistency in charging services. The replacement of the failure port is dependent on the quality of the material as per the benchmark of capital investment for the maintenance of charging ports. So, the cost estimation has been considered to allocate the maintenance budget for quality product procurement to replace the failed product to improve the charging facilities. The life of the product has been evaluated for the verification of the quality of the product by following the standards of the (military handbook) MIL-HDBK217F [40]. Based on the proposed methodology the reliability has been estimated in terms of failure rate for each port involved in the charging port arrangement. The capacity and facilities of the charging station are dependent on the port arrangement and configurations. Uniform port layouts are commonly employed for EV charging stations but the installation of uniform configuration requires a higher installation area.

Moreover, equal occupation space for vehicles is a challenging aspect of providing a parking place to charge vehicles. However, the failure diagnosis and maintenance cost of uniform ports are easier and lesser than the non-uniform ports because the non-uniform port structures will operate with a lower to a higher rating of power capability. The non-uniform port configurations are the better option for the minimal area of installations and uniform ports are the better option for the lesser maintenance, long life and reliable operations. From the above statements to achieve better installation features, failure rate, reliability and maintenance costs for both uniform and non-uniform port arrangements have been considered [41]. As per the considerations for the charging station configuration 36-ported charging station structure has been proposed with the port arrangement of uniform and non-uniform configurations. The structure and arrangement of ports of the proposed 36-ported charging station have been discussed in the next section.

A. THE PROPOSED PORT STRUCTURE ARRANGEMENT LOGISTICS FOR COMBINATIONAL UNIFORM AND NON-UNIFORM CONFIGURATION

In this article, a 36-ported combination of uniform and non-uniform port system (CUNPS) arrangement configured charging station structure has been proposed. The proposed charging ports have focused on making it easy to plug in and unplug vehicles while parking, reliability, and lesser maintenance cost. According to that the suitable 36-ported charging station structure has been introduced with categorization of 20-ported uniform and 16-ported non-uniform configurations. The proposed 36-ported uniform and non-uniform port-configured charging station has been pictorially represented as shown in Fig. 2.

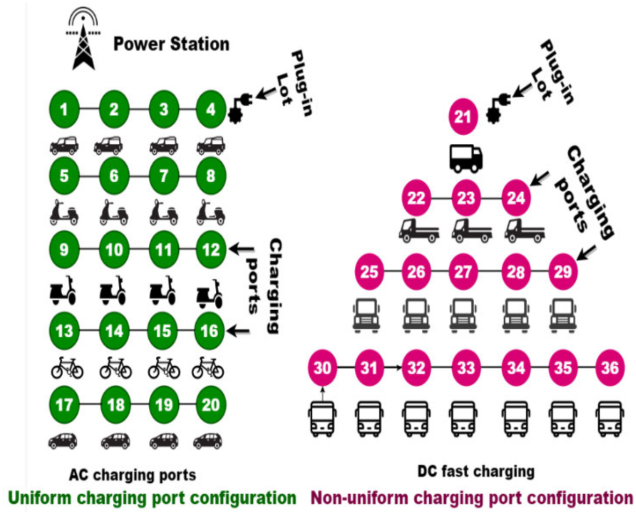

FIGURE 2. Proposed 36-ported charging station configuration (a) 20-ported uniform configuration (b) 16-ported non-uniform configuration.

From Fig. 2 the proposed 36-port charging station has been represented with configuration of different port arrangements as per the maximum port count of 20 and 16. The 20-ported uniform configuration with the uniform arrangement of 4 ports in each batch has been presented as shown in Fig. 2 (a). The 16-ported non-uniform configuration of unequal port arrangements of individual batches has been represented in Fig. 2 (b). The addition of both uniform and non-uniform port arrangements demonstrated that the proposed configuration port population is in the configuration as shown in Fig. 2. Failure rate, reliability and cost function analysis have been carried out to better comprehend uniform and non-uniform system performance. The proposed 36-ported charging station has been operated with a power rating of 50-350 kW to maintain the required voltage and current. The first step in evaluating the charging station's dependability has been taken into account, and the process of doing so in terms of failure rate is depicted in Fig. 3.

B. FOLLOWING METHODOLOGY FOR THE EVALUATION OF EV CHARGING STATION PORT RELIABILITY

For the evaluation of the combinational configuration of uniform and non-uniform charging port arrangements of the proposed 36-port charging station, the stepwise evaluation approach illustrated in Fig. 3. has been proposed. To achieve the desired attributes of a reliable charging station, the selection process for the distribution system for installation area, system configuration and an appropriate probability method was primarily influenced by the reliable charging station. The chosen approach for evaluating the necessary charging station capacity in an area with 36 ports is the binomial distribution. The proposed 36-ported charging station has been configured with the combination of uniform and non-uniform configurations with the allowable population of the ports. To maintain the better charging facilities in the charging station a suitable port pattern has been designed with the parking lot capabilities. Usually, the better charging facilities of the charging station are dependent on the reliability of the charging port in terms of failure rate. The failure chances of the port can be caused by the intermediate charging pattern of the EVs. In this mode of operation, the failure chances of the port will be imaginary to understand the reliability of the product. To realize the failure chances in the port configurations the methodology should be applicable with real and imaginary aspects of statistical validation. To evaluate the imaginary aspects of failure chances the probability statistical methodology is required to find the reliability of the individual port involved in the charging station. According to the intermediate operations of the port configurations reliability estimation has been proposed along with the binomial distribution to find the better probability function of the proposed 36-ported configuration. Here the binomial distribution has been implemented due to the uniform and non-uniform configurations. The reason behind the selection of binomial is that, it can be applicable for two different set of probability evaluations and comparisons are possible at the same time accurate information about the probability as well. These probability evaluation features are related and comfort to find the reliability in terms of the failure rate of the proposed 36-ported uniform and non-uniform configurations of port pattern for charging station. So, that the binomial probability distribution methodology has been implemented to find the reliability of the two different configurations (uniform and non-uniform) of the proposed 36-ported configuration. A charging station with a power source ranging from 50-350 kW has been selected for this purpose [42]. The analysis has been conducted following the workflow of uniform and non-uniform systems, as specified by the standards. As a first step in setting up the system, 36 ports have been considered and the reliability method has been added. Within this particular combinational scheme, the random charging process of the EV has been considered for the evaluation of reliability at different repetitive combinations. The considered parking lot has been facilitated with the dual batched system of charging ports. The uniform system contains 20 individual ports, 2 ports are vulnerable in that and the non-uniform system has 16 individual ports and in this, the repeatability method has been considered to determine the product's reliability. The repeatability will occur whenever a random arrangement configuration is chosen. Therefore, the random and repeatability conclude the configuration. Consequently, the failure rate of the system's interfaces has been evaluated based on MILHBK-338B standards [43]. To initiate the reliability analysis estimation of the proposed port configuration has been evaluated using the equations (1) to (8).

III. PROBLEM FORMULATION

Based on the above evaluation process the reliability probability has been evaluated for charging ports involved in the charging station. The failure rate and reliability have been evaluated by following Eq. (1) to (8).

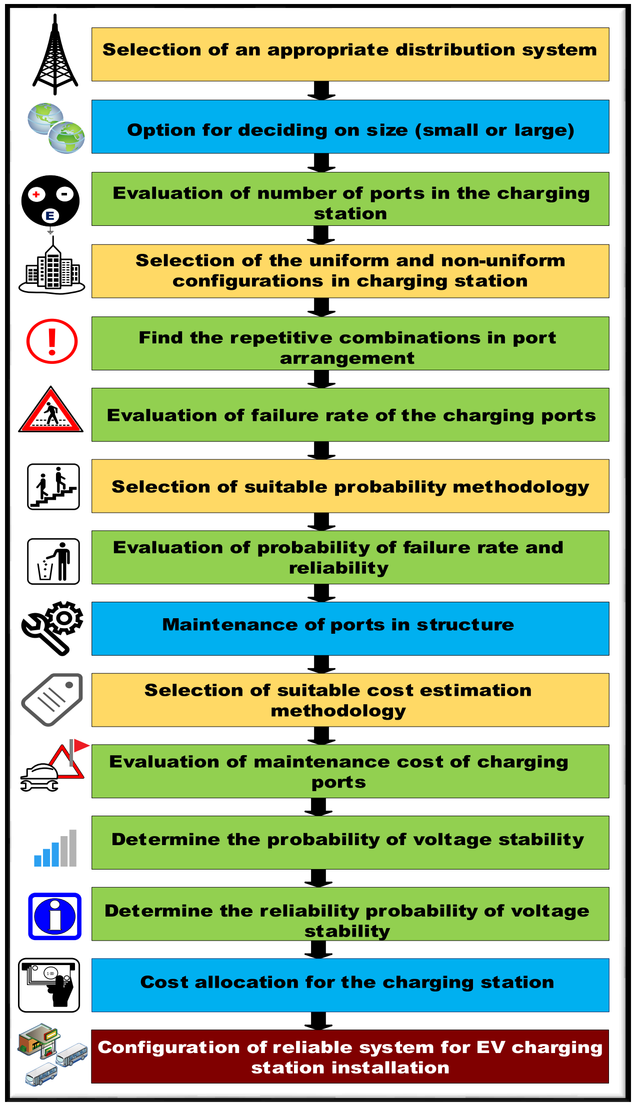

FIGURE 3. Evaluation process for the reliability of charging ports in charging station.

Estimated failure rate (λ_E)

$$\lambda_E = \frac{\lambda_{physical}}{Total\ unit\ operating\ time\ \times\ Annual\ period} \tag{1}$$

Where $\lambda_E = Environmental\ failure\ rate$

$$\lambda_p = \lambda_b \pi_{\mathrm{T}} \pi_{\mathrm{R}} \pi_{\mathrm{S}} \pi_{\mathrm{A}} \pi_{\mathrm{Q}} \pi_{\mathrm{E}}\ Failure/10^6 Hours$$

π_T : *Temperature factor*
π_R : *Current rating factor*
π_S : *Voltage stress factor*
π_A : *Application factor*
π_Q : *Quality factor*
π_E : *Environment factor*

The temperature significantly impacts the lifespan of electrical components. The temperature factor depends upon the current and voltage that are applied to the component. The temperature factor is indicated here.

$$\pi_T = exp\left(-3082\left(\frac{1}{T_j + 273} - \frac{1}{298}\right)\right) \quad (2)$$

where Tj environmental temperature.

0°C is equal to the 273° K.

23°C is considered as the room temperature.

The consideration of both application parameters and environment considerations is important when choosing components. The environment factor's constant value depends upon the product's application. Let's consider the charge application (Ns).

$$Environment\ factor(\pi_E) = N_S = constant\ value.$$

The quality and lifespan of the product are determined by the type of material used in its manufacturing, such as JANTXV, JANTX, or JAN. The component failure rate is directly influenced by quality, making it a significant determinant of product quality. It is represented by the symbol of π_Q.

$$Quality\ factor(\pi_Q) = material = constant \quad (3)$$

The product's operating failure rate depends upon the voltage delivered to the power devices. The failure rates can be maximized by the blocking voltage and peak currents. The two evident factors are the current rating factor and the voltage stress factor π_S.

$$Curren\ trating\ factor(\pi_R) = (I_{rms})^{0.40} \quad (4)$$

where $I_{rms} = current\ rating\ of\ the\ port$

$$Voltage\ stress\ factor \pi_S = (V_s)^{1.9} \quad (5)$$

where $V_s = voltage\ stress$

Actual failure rate of the system (λ)

$$Failure\ rate(\lambda) = \frac{Number\ of\ failures}{Total\ operating\ time\ of\ units} \quad (6)$$

Probability of the system success P(s)

$$P(s) = \sum_{i=x}^{n} \frac{n!}{X!(n-X)!} p^X . q^{n-X} \quad (7)$$

where $n = No.\ of\ plugs$

$r = No.\ of\ allowable\ channel\ failures$

$p = Probability\ of\ individual\ channel\ success$

$q =$ *(1)-p)*

$q = probability\ of\ individual\ channel\ failure$

$X = Number\ of\ success\ channels$

Uncertainty factor (U_λ)

$$U_\lambda = \frac{1}{4r}\left(Z_{0.95} + \sqrt{4r + 3^2}\right) \quad (8)$$

The probability reliability has been assessed for the charging station based on the procedure of reliability evaluation and the combinational batched charging ports with a capacity of a maximum of 36 ports system reliability in terms of failure rate has been estimated as shown in Fig. 4.

IV. THE DISCUSSION ON THE SIMULATION RESULTS OF THE PROPOSED 36-PORTED CONFIGURATION

According to the proposed reliability evaluation methodology, the reliability estimation process has been initiated for the proposed configuration of 36 ported EV charging stations. The constructional structure of the 36-ported charging station has been configured with a categorized combination of 20 uniform and 16 non-uniform port configurations. By following the standards of the evaluation methodology, the failure rate has been implemented as per the consideration of the repetitive possibility of the port structure in the charging lot for both 20 and 16-ported configurations. As per the 20 and 16 ported charging lot uniform and non-uniform configuration, the failure rate and reliability probability have been evaluated as shown in Table 1.

TABLE 1. Failure rate and reliability of combinational uniform and non-uniform oriented porting of charging station.

No. of Charging Ports (n)	Arrangement of Port's Batch Order	Expected Failure Rate	Failure Rate of the System (q)	Probability of System Success P(s)
36	20 (uniform)	2%	2%	0.625
	16 (non-uniform)	2%	4%	0.215
			3%	0.385

From Table 1 it is clear that the evaluation of the failure rate of the proposed 36 ported configuration has been categorized as 20 & 16 ported configuration in terms of uniform and non-uniform port structure. It can be observed that the categorization of the ports has an equal rate of expected failure rate but the repetitive possibility of the port configuration has been differentiated as per the port structure. From Table 1 it can be concluded that the uniform structured 20-ported system is capable of facilitating the charging process for the EV with an acceptable failure rate of **2%** and reliability of **0.625 per 10^6 Hours**. The repetitive combination of the port configurations will lead to the difference in the failure rate of the configuration due to the non-uniform 16 ported configuration has been involved with a failure rate of **3%** and **4%**.

From Table 1 it can be concluded that the 20 ported uniform configuration has been configured with superior functionality with a reliability of **0.625 per 10^6 Hours** in terms of success rate than the 16 ported non-uniform configuration. However, the **0.215 per 10^6 Hours** success rate of the non-uniform system is acceptable for the higher rating of EV for transportation with a maximum failure rate of 4%.

It can be concluded that the uniform configuration is capable of a higher success rate of port operations with a minimal failure rate of **2%** than non-uniform port configurations. As per the expected failure rate of both 20 and 16 ported configurations, the failure rate and reliability of the system have been explained pictorially in the next section as shown in Fig. 4.

A. THE PERFORMANCE EVALUATION OF THE PROPOSED CHARGING PORT CONFIGURATION IN TERMS OF INDIVIDUAL PORT RELIABILITY

According to the proposed structure of the 36-ported configuration, the performance of each port has been evaluated with the different repetitive combinations (R_c) as per the configuration called uniform or non-uniform. The 36-ported system has been designed with two different port arrangements called 20 and 16 ported uniform and non-uniform configurations. As a primary step of the failure rate evaluation process has been initiated with 20 ported uniform configurations. The simulation results have been performed in the environment of Anaconda software dedicated to the Python executions. The 20 ported uniform configuration failure chances in the charging station have been involved with the R_c of 2 ports. Based on the R_c of the system the failure rate, reliability and cumulative comparison have been presented in Fig. 4.

The 20-ported uniform configuration is designed with a uniformly structured 4-port individual batch arrangement for the minimal area of installation. Due to that, the individual port in a 20-ported uniform configuration is involved with a minimal failure rate of **0.0012 per 10^6 Hours** as shown in Fig. 4. The performance of the system has been evaluated in terms of reliability with the concern of failure rate of each port involved in the system. To evaluate the reliability, the failure rate evaluation is required because the reliability is dependent on the life cycle of the product [44]. To make a common platform of statistical analysis, the reliability of each port configuration failure rate has been evaluated with respect to time to simplify the reliability evaluation as shown in Fig. 4 (a) and (b). Based on each port failure rate, the reliability R(x) has been evaluated with respect to time for a better understanding of each port reliability pictorially compared in terms of reliability R(x) versus port as shown in Fig. (b). From Fig. 4 (a) it can be observed that the failure rate of the individual activation of the charging facility is minimal but the simultaneous activation of the charger leads to the higher failure rate of port arrangement in the system. From Fig. 4 (b) it is clear that the failure rate of the individual port in the charging system is affecting the reliability of the system. For a better understanding of the relation between failure rate and reliability, the pictorial representation has been presented in Fig. 4 (c). From Fig. 4 (c) it can be concluded that the 20-ported uniform configuration is capable of a long period of charging with a reliability of **0.19 per 10^6 Hours** at the failure rate of **0.0012 per 10^6 Hours**. The secondary configuration of charging station performance has been evaluated as shown in Fig. 5.

In 36-port configuration, 16 ports are structured with a non-uniform arrangement for EV charging applications. As per the arrangement structure of the 16-ported non-uniform system, the failure rate and reliability of the individual port have been evaluated as shown in Fig. 5. According to the constructional arrangement of the non-uniform system, the port batch configuration has been structured with different repetitive combinations of 3 and 4 ports. Based on the repetitive

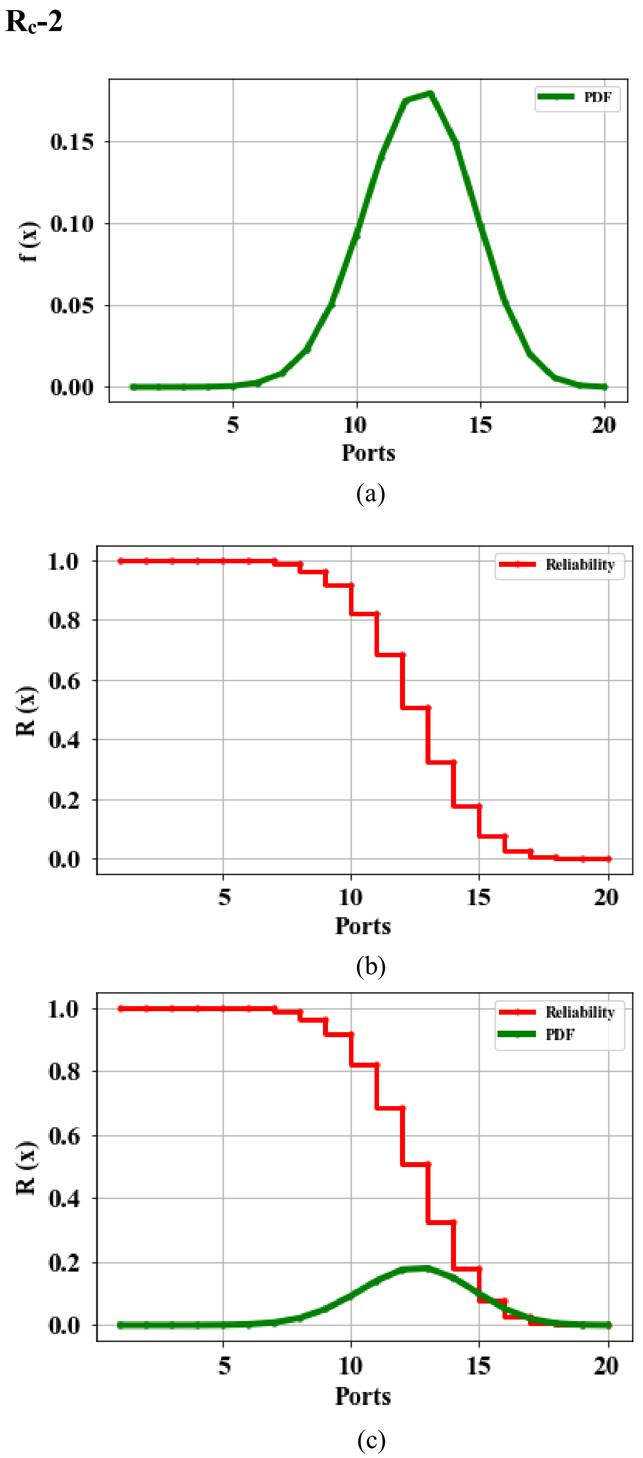

FIGURE 4. 20-ported uniform configuration attributes for EV (a) failure rate probability (b) reliability probability (c) cumulative comparison of the reliability probability.

combinations of 16 ported non-uniform charging stations the failure rate and reliability of each port reliability have been evaluated as shown in Fig. 5. Fig. 5 (a), (b), and (c) represent the failure rate and reliability of the 16-ported charging system for a repetitive combination of 2 ports. From Fig. 5 (a) it can be observed that the failure rate of the 16-ported charging

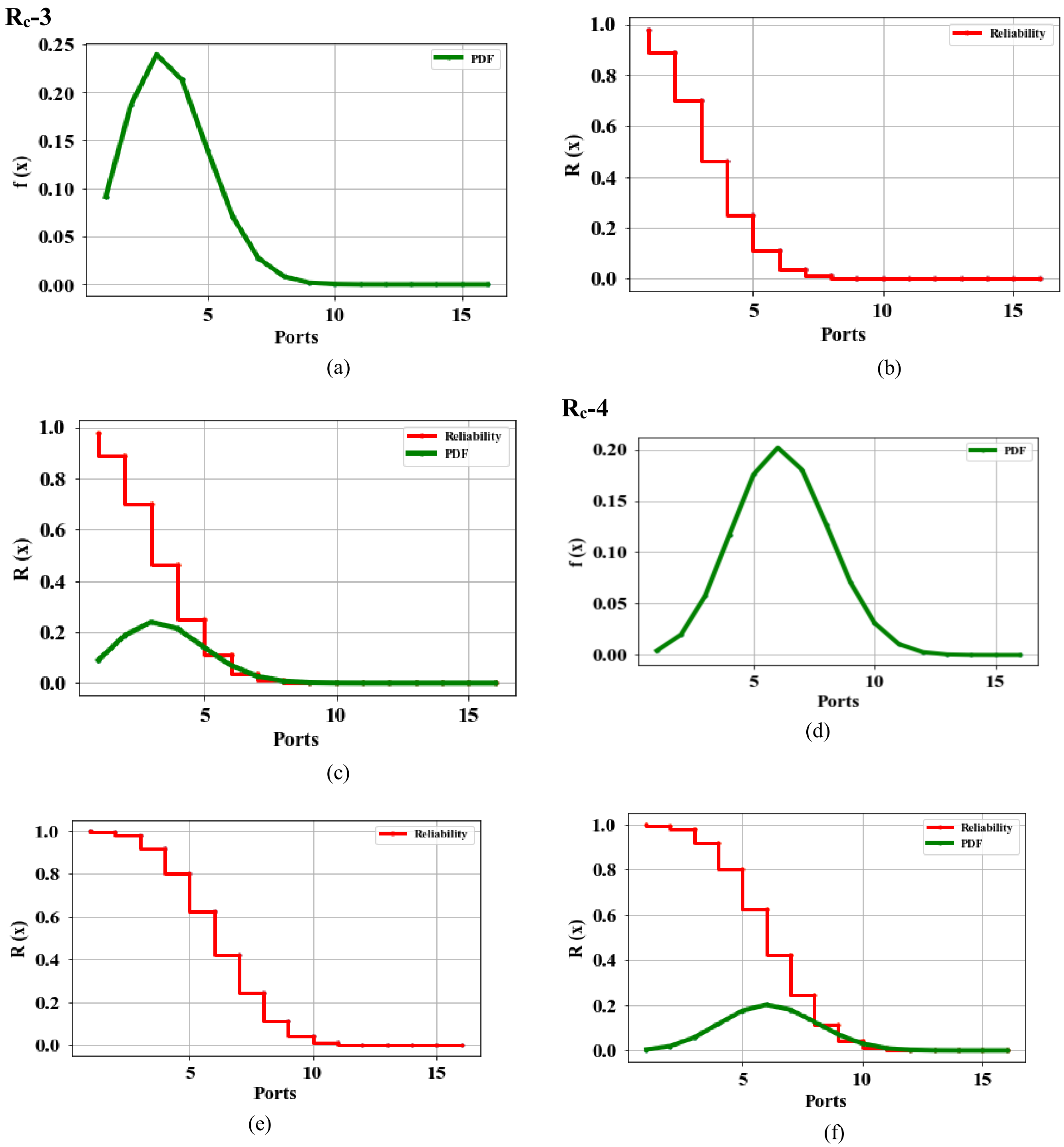

FIGURE 5. 16-ported non-uniform configuration attributes for EV (a) failure rate probability (b) reliability probability (c) cumulative comparison of the reliability probability.

system is capable of providing continuous charging with a maximum failure rate of **0.24 per 10^6 hours**. Moreover, the system failure rate of 16-ported non-uniform charging configurations initially populated with a higher failure rate of **0.09 per 10^6 hours** due to the repetitive combination of port arrangement. Based on the failure rate profile the 16-ported non-uniform configuration provides the charging facilities for EV with a reliability of **1 per 10^6** hours in terms of failure rate. From Fig. 5 (c) it is clear that the 16-ported non-uniform configuration can be functional for charging applications with a failure rate of **0.24 per 10^6 hours** and reliability of **1 per 10^6 hours** at a repetitive combination of 3 ports. Even though the system operates with good reliability of operation the initial higher failure rate possibility made regular maintenance. Due to that, the system has been operated for 4-ports repetitive combination as shown in Fig. 5 (d), (e) and (f).

From Fig. 5 (d) it can be observed that the 4-ports repetitive combination structures repetitive combination is capable of maintaining consistency with a higher failure rate of **0.20 per 10^6 hours**. According to the failure rate of the individual port of the charging station, the 4-ports repetitive combination can function in the charging process with a reliability of **1 per 10^6 hours** as shown in Fig. 5 (e). From the results of failure rate and reliability, it can be concluded that the 4-ports repetitive combination of 16-ported non-uniform charging station configuration is capable of providing better consistency with a lesser failure rate and higher reliability for EV charging as shown in Fig.5. It can be concluded that the proposed 36-ported uniform and non-uniform charging station structure is capable of providing failure rates of **0.17** and **0.20 per 10^6 hours** for EV charging applications as shown in Fig. 5 (f). It can be concluded that in the categorizations in the 36-ported charging station configuration, the 20-ported uniform structure is capable of providing better EV charging facilities with a reliability of **0.24 per 10^6 hours** compared with 16 non-uniform configurations. As per the configuration structure of the 36-ported uniform and non-uniform arrangement of the charging station success rate of each individual batch has been evaluated and tabulated in Table 2.

TABLE 2. Comparison of the success rate of charging ports 36 port batched configuration (uniform and non-uniform.)

Combination of the 36 ported batch system	Batches	No.of Ports/Batch	Healthy Ports	Success Rate
	20-ported batch system			
2	B-1	4	0.0003	8.099
	B-2	4	0.0003	8.099
	B-3	4	0.0003	8.099
	B-4	4	0.0003	8.099
	B-5	**4**	**0.0003**	**8.099**
	16-ported batch system			
3 and 4	B-1	1	0.0086	0.0086
	B-2	3	0.021905	1.510
	B-3	5	0.040572	1.299
	B-4	**7**	**0.061428**	**3.5299**

From Table 2 it can be observed that the proposed 36-ported charging station is capable of providing the maximum 4 port capacity for uniform port arrangement in each batch with a repetitive combination of 2 ports. The non-uniform port combination can be associated with the maximum capacity of 7 switches in any one of the batches and 1 port of minimum capacitance for the EV charging station as per the possible repetitive combination of 3 and 4 ports. From Table 2 it can be concluded that the uniform 20-ported categorization has a similar port success rate of **8.099/10^6 hours** due to the equal rate of healthy port possibility in each batch. However, the 16-ported non-uniform configuration has been structured with different port structures so that the success rate of each batch will vary as per the port count. Based on the constructional structure of each batch it can operate with minimum and maximum success rates of **0.0086** and **3.5299/10^6 hours** for both 3 and 4 ports repetitive combinations as shown in Table 2. From Table 2 it is clear that the uniform 20-ported structure is a superior configuration category in the 36-ported charging station. Even though the non-uniform system provides the allowable rate of success regular maintenance is required to maintain the consistency which will lead to the higher maintenance cost. The maintenance cost of the product is dependent on the quality and reliability of the product. However, the procurement of highly reliable products for installation leads to a higher investment cost. Due to that, the cost of the product has been estimated in terms of maintenance for the proposed configuration of the 36-ported charging station. According to the author in [45], the required parameters to find the maintenance cost of the 36-ported charging station have been discussed in the next section.

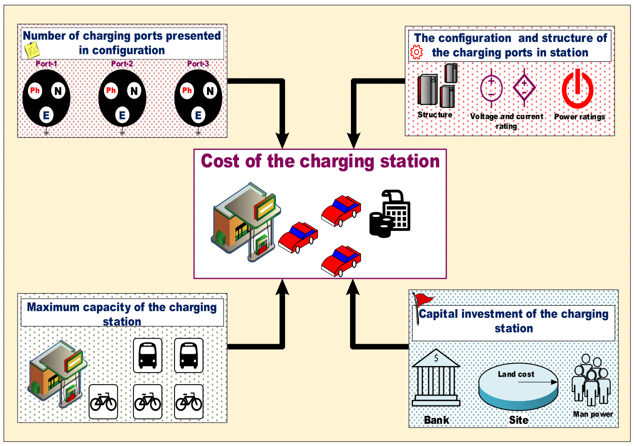

FIGURE 6. Cost-effecting factors of the charging station.

V. COST-EFFECTING FACTORS FOR THE EVALUATION OF MAINTENANCE COST OF 36-PORTED CHARGING STATION CONFIGURATION

The cost-effecting factors of the charging station have been considered to evaluate the cost function of the 36-ported capacitated charging stations as shown in Fig. 6. The 36-ported combination of uniform and non-uniform systems, in which the failure rate of the ports is calculated based on the uniform and non-uniform batch ports and the reliability of the port system is then determined based on the obtained failure rate value. The cost function has been determined for both uniform and non-uniform charging systems, with estimates made for each individual batch through the Eq. (9) to (10).

The individual voltage of each port

$$V_{Loss}^{ind} = \frac{Total\ voltage}{\max\ voltage} \tag{9}$$

The total installation cost of the charging station

$$C.F = N_{port+\alpha}\, V_{M.C}^{ind} \tag{10}$$

where $N_{port=}$ Number of charging ports in charging station
α = current rating factor of the port

A. COMPARISON OF MAINTENANCE COST OF FAILURE AND HEALTHY PORTS

Here the cost comparison of the proposed 36-ported uniform and non-uniform charging station configuration has been presented as per the considerations of failure rate and healthy port. Based on the port structure of 36-ported charging station maintenance cost has been evaluated for 20-ported uniform and 16-ported non-uniform configurations. The maintenance cost of 20 and 16 ported configurations has been compared as shown in Table 3.

TABLE 3. **Comparison of maintenance cost of the proposed 36-ported charging station configuration.**

Combination Of 20 & 16-Ported Batch System	Batches	No. of Ports/Batch	Maintenance Cost in terms of Failure Voltage ($F.V_{MC}$)	Maintenance Cost in terms of Stable Voltage ($S.V_{MC}$)
		20-ported batch system		
2	B-1	4	24.97	24.03
	B-2	4	24.97	24.03
	B-3	4	24.97	24.03
	B-4	4	24.97	24.03
	B-5	4	24.97	24.03
		16-ported batch system		
4 and 3	**B-1**	**1**	**24.14**	**24.86**
	B-2	3	24.80	26.19
	B-3	5	24.94	28.05
	B-4	7	24.85	30.14
[54]	combined	33	49.32	54.36
[55]	combined	33	45.42	51.62

The maintenance cost of the proposed charging station configuration has been evaluated in terms of per unit value. From Table 3 it is clear that the maintenance cost of the 20-ported uniform configuration is similar for batches involved in the port arrangement with the cost of **24.97 p.u** at the repetitive combination of 2 ports. The 20-ported uniform configuration is capable of providing constancy in voltage with the cost of **24.03 p.u** at **24.97 p.u** for maintenance cost. From Table 3 it can be observed that the 16-ported non-uniform configuration maintenance cost in terms of failure varies as per the ports involved in the charging station structure. From the evaluated cost of the 16-ported non-uniform configuration, it can be concluded that the charging services can be maintainable with the maximum and minimum costs of **24.85** and **24.14 p.u**. It can be concluded that the 20-ported uniform configuration has superior features in terms of maintenance cost compared with the 16-ported non-uniform configuration. It can be concluded that the 36-ported uniform and non-uniform charging station configuration is capable of providing charging facilities for EV applications with the allowable maximum maintenance cost of **24.85 p.u**. According to the failure rate of ports, the voltage stability has been evaluated for the proposed configuration. For a better understanding of the proposed configuration comparison has been presented.

It can be concluded that the [54] and [55] port configurations are configured with 33 ports but the maintenance of the ports has been involved with higher cost. Even though the proposed port configuration is populated with higher ports in the station it is capable of providing better reliability and maintenance cost.

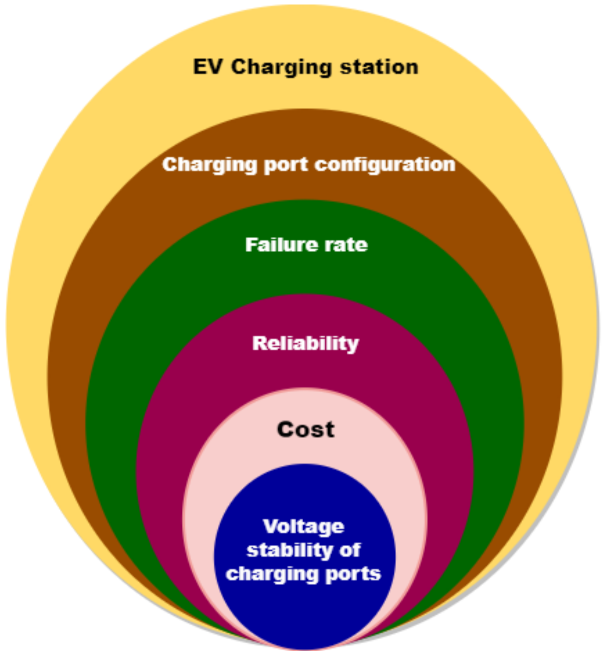

FIGURE 7. **The evaluation parameters of the reliability and voltage stability.**

VI. VOLTAGE STABILITY OF THE EV CHARGING STATION WITH THE RELIABLE PORTING ARRANGEMENT

The evaluation procedure for the reliability estimation of voltage stability in EV charging station configuration is shown in Fig. 7. The proliferation of EV fleets at charging stations has the potential to introduce voltage instability, unreliability, and higher maintenance in the charging station [46], [47], [48]. By the consideration of the above statement, the proposed charging station's voltage stability, reliability and maintenance requirements have been estimated. The estimation process has been initiated with the evaluation of maintenance costs for the proposed charging station. The reliability evaluation of the voltage stability helps maintain better reliability for charging facilities. The implementation of reliable EV charging stations can effectively mitigate maintenance expenses associated with the existence of an EV fleet.

The measurement of voltage stability plays a crucial role in guaranteeing the secure and dependable functioning of EV charging stations. Conducting routine voltage stability analysis can effectively mitigate voltage instability and optimize the performance of EV charging stations. The IEEE-33 bus test system demonstrates reliable performance in the context of charging station ports inside the power distribution system [49], [50].

The voltage stability index (VSI) is a measure that quantifies the power system's capacity to sustain consistent voltage levels across all buses within the system following the occurrence of a disturbance. The equation demonstrates that the voltage stability index is dependent on several factors, including the real power demand, reactive power demand, line reactance, bus voltage, and the quantity of EV charging ports. With the proliferation of EV charging ports, there will be a corresponding rise in both real power demand and reactive power demand. The aforementioned phenomenon may result in a reduction in the bus voltage, hence rendering the power system more vulnerable to voltage instability.

The VSI is influenced by the line reactance. An increased line reactance will render the power system more vulnerable to voltage instability. The inclusion of the bus voltage is a crucial element in the calculation of voltage stability. A decrease in bus voltage will render the power system more vulnerable to voltage instability. Through a complete understanding of the various factors that influence the VSI, it becomes feasible to undertake measures aimed at enhancing the voltage stability of the power system and mitigating the potential hazards associated with voltage instability [51], [52], [53]. Several supplementary factors can potentially impact the equation governing voltage stability. So, this study aims to investigate four key aspects related to EV charging ports: their location, type, control method, and operational circumstances within the power system. By taking into account all of these variables, it is feasible to formulate a voltage stability equation that is more precise for the IEEE 33 bus system of electric vehicle charging ports. The utilization of the IEEE 33 bus system for EV charging stations offers several advantages in that the system possesses scalability, enabling the examination of EV charging effects on power systems of varying sizes. Additionally, its flexibility allows for the investigation of diverse EV charging scenarios.

The utilization of the IEEE 33 bus system comprising EV charging ports serves as a significant asset in examining the effects of electric vehicle charging on the power grid. The utilization of this method enables the evaluation of the influence of EV charging on the voltage stability of the power supply. The reliability of voltage stability in the distribution system, as shown in Fig. 8 for a combination of uniform and non-uniform batched charging ports. The proposed 36-ported charging system has been considered for the estimation of failure rate and reliability of the voltage stability. The failure rate and reliability of the proposed system voltage stability have been represented in Fig. 8.

Based on the proposed configuration capacity and reliability of port configuration the reliability probability of voltage stability has been evaluated. The supporting results for the voltage stability have been represented pictorially as shown in Fig. 8. From Fig. 8 it can be concluded that the proposed 36-ported charging station is capable of providing the

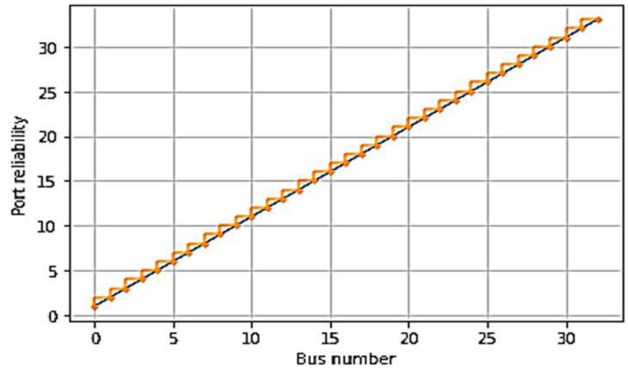

FIGURE 8. Voltage stability analysis for IEEE 33-bus system to examine the reliability of the EV charging station's port.

charging facilities with a reliability of 39% in terms of failure rate as shown in Fig 8. According to the statistical analysis of the binomial distribution function, the reliability probability of the proposed 36-ported charging station has been evaluated with the logic of repeatability of the port. Based on that the characteristics of the reliability of the individual port have been evaluated as shown in Fig. 8. According to the repeatability logic, the proposed system is capable to provide the charging facilities with a repeatability of 2. The actual 36-ports of probability has been applied for the 33 ports only due to the repeatability 2 and the initial trial of the first port must be constant. The orange color staircase intersection point represents the reliability of each port. For a better understanding, it can be represented pictorially. From Fig. 8, it can be observed that each concentrating circle represents the suitable port count of the proposed 36-ported system. In the proposed 36 ported uniform and non-uniform configuration capable of offering the repeatability of 2 ports healthy operation has been performed along with the 33 bus system. So, the reliability in terms of failure rate has been applied for the 33 ports due to the 2 healthy ports availability in the proposed port configuration. Based on the failure rate of the port the voltage stability of the reliability has been evaluated for 33 bus system. It can be observed that each port's reliability has intersected with the 33 bus linear failure rate possibility as shown in Fig. 8. The first port of the proposed configuration has been involved with the minimum reliability probability of $1.2/10^6$ hours and the 35^{th} port has been involved with the maximum reliability probability of $34.3/10^6$ hours as shown in Fig. 8. For a better understanding of the voltage stability and reliability of the proposed 36-ported system comparison has been performed with the conventional configurations as shown in Table 4.

From Table 4 it can be observed that the proposed 36-ported charging station configuration has been configured with reliable attributes of port arrangement. It is clear that the proposed 36-ported charging station configuration has provided superior voltage stability with a reliability of 85% compared with all other configurations. The reliability of the charging station has been maintained with the

TABLE 4. Voltage stability comparison of charging station in terms of reliability.

Port Configuration	No. of EV Charging Ports	Location of EV Charging Ports	Types of EV Charging Ports	Reliability of System
Single phase-20 kW [37]	10	Distributed throughout the power system	Level 2	75%
Single phase-20 kW [48]	10	Concentrated in a single area	Level 2	75%
Three phase-50 kW [49]	10	Distributed throughout the power system	Level 3	66%
Three phase-50 kW [50]	10	Concentrated in a single area	Level 3	69%
Proposed system Three phase 50 to 350 kW	36	Concentrated in a single area	Level 3	85%

help of materialized reliable configurations and port arrangement patterns of the charging station. To provide better reliable charging facilities the proposed system has been proposed with a better port arrangement pattern. The proposed 36-ported system is capable of providing the charging facilities with a reliability of 39% in terms of failure rate. According to the evaluations of the port reliability in terms of failure rate, the proposed 36-ported configuration reliability of voltage stability has been estimated by using Eq. (11).

$$\text{Reliability} = \frac{Number\ of\ failures}{Total\ operating\ time\ of\ units} * 100 \qquad (11)$$

It can be concluded that the proposed 36-ported charging station configuration is superior in charging facilities with a better failure rate, reliability and voltage stability.

VII. DISCUSSION

In this study, a 36-ported design with uniform and non-uniform ports is proposed. The proposed configuration contains 20 and 16 uniform and non-uniform charging ports. Distribution systems of 50-350 kW have been used. MIL-HDBK217F standards have been implemented to estimate the failure rate. The ports' probability function has been tested for failure rate and reliability using MILHBK-338B specifications. To determine charging station success, each port's failure rate is evaluated. Binomial distribution has been applied to estimate the port arrangement failure rate of the proposed 36-ported charging station. For the planned 36-ported charging system, the failure and success rates of port maintenance have been used to estimate cost. According to the operation and failure rate of the charging station, the voltage stability has been evaluated.

The suggested system failure rate assessments show that the 20-ported uniform configuration may provide charging facilities with a **2%** failure rate at **0.625/10^6 Hours**. The 16-ported non-uniform setup charges with **4 and 3%** failure at **0.215 and 0.385/10^6 Hours**. Port failure rates have been used to predict product replacement costs in maintenance terms. The 20-port charging stations cost **24.97 p.u.** to maintain due to failure and **24.03 p.u**. for success. A high port structure (4 repetitive) combination of 16 ports charging stations can provide facilities with **24.85 p.u.** failure rate and **30.14 p.u**. success rate maintenance cost. According to the investigation, uniform port layouts offer superior charging facilities than non-uniform systems. The voltage stability analysis shows that the suggested charging station architecture can provide services with 85% reliability. The suggested 36-ported uniform and non-uniform configuration can provide EV charging facilities with lower port arrangement failure and maintenance costs and improved reliability. Further extension of port involvement in charging stations can be possible with the proposed port configuration for different port occupations in the system and the reliability evaluation methodology can support the higher port configurations.

VIII. CONCLUSION

In this research work, the evaluation methodology of reliability probability has been introduced to evaluate the failure rate of the EV charging stations with the combination of uniform and non-uniform port arrangements. As per the consideration of a 50-350 kW distribution system, the 36-ported charging station configuration has been introduced for commercialization. The proposed 36-ported charging station configuration has been configured with the combination of 20 and 16-ported uniform and non-uniform charging port arrangements. The reliability of the port configuration has been evaluated with the logic of repetitive combination. However, the non-uniform ported configurations have higher possibilities of failure due to the unequal arrangements of ports in individual batches.

In this paper, the methodology of the reliability estimation for each port involved in each configuration as per the port arrangement has been evaluated by following the standards of MILHBK-217F with the mathematical extension of binomial probability. According to the failure rate evaluations of the proposed system, it can be decided that the 20-ported uniform configuration is capable of providing the charging facilities with a failure rate of **2%** at the expected probability of **0.625/10^6 Hours.** The 16-ported non-uniform configuration is capable of performing the charging functionality with **4 and 3%** failure at the expected probability of **0.215 and 0.385/10^6 Hours** with the repetitive combinations of 4 and 3. Based on the failure rate of the ports, the product replacement cost has been estimated in terms of maintenance cost. The 20 ported charging stations are providing the facilities with a maintenance cost of **24.97 p.u.** in terms of failure rate and

24.03 p.u. in terms of success rate at the higher port configuration 2 repetitive combinations. The higher port structure (4 repetitive) combination of the 16 ported charging stations is capable of providing the facilities with a maintenance cost of **24.85 p.u**. in terms of failure rate and **30.14 p.u** in terms of success rate. From the analysis, it can be claimed that the uniform port configurations are capable of providing better charging facilities than the non-uniform systems. From the analysis of the voltage stability, it can be concluded that the proposed charging station configuration is capable of providing services with 85% reliability of voltage stability. It can be concluded that the proposed 36-ported uniform and non-uniform configuration is capable of providing charging facilities for EV customers with the superior features of lesser failure, maintenance cost of port arrangement at higher reliability.

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