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Assessing Reliability and Economic Viability of Different EV Charging Station Configurations

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Abstract

With the increasing popularity of electric vehicles (EVs) as a mode of transportation, companies are prioritizing the development of charging infrastructure to cater to customer needs. Despite efforts to align charging station designs with distribution system requirements, maintaining reliability for EV charging ports remains challenging. To enhance reliability, a novel 56-ported design incorporating both uniform and non-uniform port arrangements has been proposed. These configurations have been tested with distribution systems ranging from 50 to 500 kW. Reliability assessments were conducted using standards outlined failure rate estimation and monte-carlo functions for evaluating port probability functions in terms of failure rate and reliability. By analyzing the failure rates of individual ports, an evaluation process was introduced to determine the overall success rate of the charging station. The failure rate of the proposed 56-ported charging station was further evaluated using the binomial distribution method. Additionally, cost estimation procedures were implemented considering the failure and success rates of individual port maintenance for the proposed configuration. The findings indicate that achieving lower failure rates and maintenance costs is possible through improved port arrangement reliability and enhanced voltage stability.

1. Introduction

In recent years, the global focus on addressing climate change has spurred increased interest in electric vehicles (EVs) as a sustainable transportation option. Key drivers behind this shift include concerns over pollution and fossil fuel scarcity [1]. Governments are incentivizing the installation of EV charging stations by offering financial support to companies. However, the surge in EV charging demand presents challenges for power system engineers, who must strategically distribute Electric Vehicle Charging Stations (EVCS) to meet the needs of densely populated areas while minimizing power losses and ensuring grid stability [2],[3]. To address these challenges, various studies have been conducted to assess the impact of EV adoption on distribution networks and optimize the placement of charging infrastructure. Methodologies have been developed to analyze investment costs, energy losses, and distribution network reliability [4]. Additionally, research has focused on developing accurate load models to improve system stability and implementing intelligent scheduling systems to manage EV charging effectively.

Novel approaches have also been proposed for optimizing the placement and capacity of EV parking lots, taking into account factors such as system costs, reliability constraints, and future EV adoption rates [5],[6]. Techniques such as genetic algorithms and particle swarm optimization have been employed to enhance voltage profiles and optimize charging station placements. Moreover, probabilistic models have been introduced to account for uncertainties in power systems and improve the accuracy of voltage stability assessments [7]. The effectiveness of these methodologies has been demonstrated through case studies using distribution network topologies and planning area maps. Findings indicate the significant impact of charging strategies on EV charging systems, emphasizing the importance of strategic charging station placement to minimize power losses and maintain grid stability [8].

In summary, the integration of EV charging infrastructure into distribution systems poses significant challenges but also offers opportunities for enhancing grid reliability and sustainability. By employing advanced modeling techniques and strategic planning approaches, we can address these challenges and optimize the performance of EV charging networks. The reliability evaluation of charging stations based on port arrangements will be discussed further in the subsequent sections.

2. Methodology

In essence, the capacity of a charging station is primarily determined by the availability of parking spaces for vehicles. However, the mere presence of parking areas is insufficient when it comes to configuring and installing the port arrangement necessary to provide charging services to customers. This is because the installation of a charging station relies heavily on the capital investment required and the expenditure associated with achieving the maximum charging port capacity within a specific area [9],[10]. Before proceeding with the installation of a charging station, it is imperative to subject the selected port configuration to a reliability test. This step ensures that budget allocations are appropriately directed towards procuring the necessary ports, thereby guaranteeing the reliability and effectiveness of the charging infrastructure [11]. By conducting such tests, stakeholders can make informed decisions regarding the optimal configuration and placement of charging ports, thereby maximizing the utility and accessibility of the charging station for end-users [12].

In assessing the reliability of the charging port arrangement, the initial step involves accounting for uncertain plug-in conditions. Both uniform and non-uniform port designs are examined to accommodate the charging needs of this uncertain plug-in system [13], [14]. The fluctuating operational conditions of electric vehicles (EVs) highlight the potential for increased failure rates in charging stations due to variations in load on the charging ports. The occurrence of failures in charging stations is contingent upon customers' demands to charge their vehicles at different power ratings [15]. However, higher rates of port failures can disrupt services, necessitating the replacement of failed ports to ensure consistent charging availability. This replacement process is influenced by the quality of materials used, which in turn is governed by the benchmark of capital investment allocated for port maintenance [16]. Therefore, cost estimation is crucial to allocate maintenance budgets for procuring quality replacement products and enhancing charging facilities. Product longevity is evaluated to verify product quality, adhering to the standards outlined in the IEEERTS [17], [18]. Using the proposed methodology, reliability is estimated in terms of failure rates for each port within the charging port arrangement. The capacity and functionality of the charging station hinge on the port arrangement and configurations. While uniform port layouts are commonly employed in EV charging stations, they require larger installation areas [19].

Furthermore, ensuring equal space allocation for vehicles poses a challenge in providing parking spaces equipped with charging capabilities. However, diagnosing failures and maintaining uniform ports are relatively simpler and less expensive compared to non-uniform ports. This is because non-uniform port structures operate across a range of power ratings, complicating maintenance efforts [20]. Non-uniform port configurations are preferable for installations with limited space, while uniform ports offer advantages such as lower maintenance requirements, longer lifespans, and greater reliability [21]. Taking these factors into account, considerations for installation features, failure rates, reliability, and maintenance costs are weighed for both uniform and non-uniform port arrangements [22]. In line with these considerations, a 56-ported charging station structure has been proposed, incorporating both uniform and non-uniform configurations.

3. Assessment of EV Charging Station Port Reliability

For evaluating the combined configuration of uniform and non-uniform charging port arrangements within the proposed 56-port charging station, a stepwise evaluation approach has been proposed. The selection process for the distribution system, installation area, system configuration, and appropriate probability method has been primarily influenced by the aim of achieving a reliable charging station [23]. The chosen approach for evaluating the necessary charging station capacity with 56 ports in an area is the binomial distribution. The proposed 56-ported charging station has been configured with a combination of uniform and non-uniform configurations, allowing for a specific population of ports. To ensure optimal charging facilities, a suitable port pattern has been designed considering the capabilities of the parking lot [24]. The reliability of the charging port, in terms of failure rate, significantly impacts the quality of charging facilities. Failure chances of ports can occur due to the intermediate charging patterns of EVs, necessitating a methodology that accounts for both real and hypothetical scenarios. To address these aspects, a probability statistical methodology is required to evaluate the reliability of individual ports within the charging station [25].

Reliability estimation has been proposed based on the binomial distribution to determine the probability function of the proposed 56-ported configuration. The binomial distribution is chosen due to its applicability to both uniform and non-uniform configurations, allowing for accurate comparison of probability evaluations [26]. The charging station, with a power source ranging from 50 to 500 kW, has been selected for analysis, following the workflow specified by standards for uniform and non-uniform systems. In setting up the system, 56 ports are considered, and reliability methods are incorporated. Within this scheme, the random charging process of EVs is taken into account for evaluating reliability at different repetitive combinations [27]. The parking lot is equipped with a dual batched system of charging ports, with 20 individual ports in the uniform system and 16 in the non-uniform system. The repeatability method is employed to determine the reliability of products, occurring whenever a random arrangement configuration is chosen. Consequently, the failure rate of the system's interfaces is evaluated based on IEEERTS standards.

4. Ensuring Voltage Stability in EV Charging Stations with Reliable Port Arrangements

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 [28], [29].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.

5. Significance of results

This research introduces a methodology for evaluating the reliability probability of EV charging stations, considering both uniform and non-uniform port arrangements. Within a 50-500 kW distribution system context, a 56-ported charging station configuration is proposed for commercial deployment. This configuration comprises a combination of 20 and 16-ported uniform and non-uniform charging port arrangements. The reliability of these port configurations is assessed using a logic of repetitive combination. However, non-uniform port configurations are prone to higher failure rates due to uneven port arrangements within individual batches. Reliability estimation for each port in each configuration is conducted following IEEERTS standards, employing mathematical extensions of binomial probability. Evaluation of the proposed system's failure rates indicates that the 20-ported uniform configuration exhibits a 2% failure rate at an expected probability of 0.625/10^6 hours, while the 16-ported non-uniform configuration demonstrates 4% and 3% failure rates at expected probabilities of 0.215 and 0.385/10^6 hours, respectively, with repetitive combinations of 4 and 3. Based on port failure rates, the estimated product replacement cost is calculated as maintenance cost. For the 20-ported charging stations, maintenance costs are determined to be 24.97 p.u. in terms of failure rate and 24.03 p.u. in terms of success rate at higher port configurations. Similarly, the higher port structure of the 16-ported charging stations (4 repetitive combinations) incurs maintenance costs of 24.85 p.u. in terms of failure rate and 30.14 p.u. in terms of success rate.

Analysis suggests that uniform port configurations provide superior charging facilities compared to non-uniform systems. Additionally, voltage stability analysis concludes that the proposed charging station configuration can provide services with

85% reliability of voltage stability. Overall, the proposed 56-ported uniform and non-uniform configuration offers charging facilities for EV customers with superior features, including lower failure rates, maintenance costs, and higher reliability.

6. Conclusion

The assessment of reliability and economic viability across various configurations of Electric Vehicle (EV) charging stations unveils crucial insights for stakeholders in the transportation and energy sectors. Through meticulous evaluation methodologies, we have scrutinized the performance of different charging station setups, considering factors such as port arrangements, distribution system capacity, and maintenance costs. Our findings underscore the significance of reliability in ensuring seamless charging services for EV users. By examining the failure rates of charging ports within uniform and non-uniform configurations, we have delineated the advantages and challenges associated with each setup. The analysis reveals that uniform port configurations tend to offer better charging facilities, with lower failure rates and maintenance costs compared to non-uniform systems. Moreover, the economic viability of EV charging stations has been scrutinized, taking into account factors such as installation costs, maintenance expenses, and product replacement. This assessment aids in determining the most cost-effective charging station configuration, thereby maximizing returns on investment while delivering quality service to customers. By synthesizing reliability and economic considerations, we have provided valuable insights for decision-makers tasked with deploying EV charging infrastructure. Our study emphasizes the importance of striking a balance between reliability and cost-effectiveness to ensure the widespread adoption and sustainability of EV charging networks. In essence, this research contributes to the ongoing efforts to build resilient and economically viable EV charging infrastructure, thereby fostering the transition towards a cleaner and more sustainable transportation ecosystem.

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