Enhancing Electric Vehicle Reliability and Integration with Renewable Energy: A Multi-Faceted Review

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Abstract

Electric vehicles (EVs) are gaining attention due to their zero carbon emissions, but concerns about their reliability, especially critical components, persist. Previous research has primarily focused on EV drive motor reliability, neglecting the motor controller. To address this gap, this study assesses the reliability of the entire motor system in electric vans, including both drive motor and motor controller components. It predicts failure rates for these components, highlighting vulnerabilities and shortcomings in existing research, which can inform future design and maintenance. In addition, the integration of EVs and renewable energy resources has garnered attention, but concerns about component reliability have arisen. A novel approach called " Innovative Incentive-Driven Fuzzy Fault Tree Analysis " (IIFFTA) is introduced for power systems incorporating EVs and renewable energy, addressing vague and imprecise events and data deficiencies in conventional fault tree analysis. IIFFTA considers different component failure rates and probability values of fault occurrences, offering a more effective risk assessment method. Lastly, plug-in electric vehicles (PEVs) impact distribution systems, and this paper explores distribution feeder reconfiguration (DFR) as a reliability-enhancing strategy for coordinating vehicle-to-grid (V2G) services from PEV fleets within a stochastic framework. The study accounts for uncertainties related to network demand, energy prices, wind power generation, and PEV fleet behavior, employing a self-adaptive evolutionary algorithm (SOS) to address the stochastic optimization problem.

1. Introduction

In this paper, our primary focus lies in the investigation of the reliability of commercial vehicles, specifically pure electric vans, which now account for more than 90% of all commercial vehicle sales [1]. Within these vehicles, the motor system plays a pivotal role as it converts electric energy into mechanical energy to propel the vehicle. The importance of ensuring the reliability of the motor system cannot be overstated, as any reliability issues within this crucial component could potentially result in hazardous road accidents. Consequently, it becomes imperative to conduct a thorough examination of the motor system's reliability, pinpoint vulnerable components, and initiate design enhancements based on the findings [2][3]. To address this objective, substantial efforts have been made in the past. A comprehensive literature review reveals that previous research in this domain has predominantly focused on enhancing the control and fault tolerance performance of motor systems. For instance, researchers have delved into the fault tolerance performance of multi-phase permanent magnet synchronous motors, utilizing a multi-level Markov model [4], while similar investigations into motor drives have been carried out employing the Monte Carlo method to enhance fault tolerance mechanisms [5]. Further research has explored the reliability of control systems for automated guided vehicles (AGVs) using a combined fault tree and Petri net approach [6]. This work was subsequently extended in[7] through the incorporation of genetic algorithms into maintenance strategy optimization. Additionally, fault classification methods and fault-tolerant control strategies have been adopted to enhance the dynamic performance and control stability of electric vehicles [8]. Scholars have also scrutinized the reliability of drive motors and electronic converters for power supply. For example, the reliability of electric vehicle (EV) drive motors has been examined in [9][10] using a combined fault tree and Petri net approach. The study in[11] focused on investigating the fault causes related to winding insulation and bearings, which exhibit higher fault rates, using fault tree analysis. The reliability of bidirectional DC/DC converters in EVs was explored in [12], with estimations of component age and lifespan presented in [13], based on survey data and other relevant parameters.

However, it is apparent that previous research efforts have primarily concentrated on the analysis of drive motors, with limited attention given to the reliability issues within motor controllers. This oversight can potentially yield unreliable research conclusions, considering that drive motors and motor controllers are inherently interconnected. They are designed to function as a unified system and cannot be isolated for individual analysis. To address this gap in knowledge, a comprehensive reliability assessment of both components is essential, as this approach provides a more dependable prediction of the overall motor system's reliability. Surprisingly, no previous research has undertaken such an extensive examination of the entire motor system. This noteworthy research gap serves as a primary motivation for the present study. Furthermore, it is worth noting that both drive motors and motor controllers are comprised of multiple components. The structural configuration, types, and characteristics of these components may also exert an influence on the overall reliability of the motor system. Unfortunately, these factors have not been adequately considered in prior research. The objective of this study is to bridge these knowledge gaps by meticulously exploring the reliability aspects of all subassemblies and components within both the drive motor and motor controller. The anticipated outcome of this research is expected to significantly complement the existing body of knowledge related to electric vehicles and further contribute to the burgeoning electric vehicle industry.

Fault tree analysis, a highly effective methodology for conducting reliability and safety assessments, has a proven track record in investigating reliability issues in various systems [14]. Notably, it has been extensively applied to assess the reliability of diverse systems. For instance, fault tree analysis was employed to qualitatively and quantitatively evaluate potential failures in wind turbines [15]. It was determined that the majority of failures in floating turbines could be attributed to factors such as marine conditions, salt spray, and high wind speeds. Subsequent enhancements were made to the fault tree analysis method to accommodate qualitative analysis in complex systems with multiple components [16]. Additionally, dynamic fault tree analysis models have been developed for various applications, including estimating the average maintenance period of floating wind turbines [17]. Dynamic fault tree models have also been employed in assessing the reliability of fault-tolerant control systems and vehicle guidance systems in unmanned aerial vehicles [18][19]. Given the proven success of fault tree analysis in prior applications, this paper adopts this methodology to investigate the reliability of motor systems in pure electric vans." While the trend towards more sustainable energy sources is on the rise, marked by a growing shift toward renewable energy resources [20], the increasing proliferation of electric vehicles has created deeper interconnections between the power and transportation systems. This integration introduces new challenges in terms of potential fault occurrences across various systems. Consequently, a robust risk assessment method becomes essential for power systems that encompass both electric vehicles and renewable energy resources [21].

Efforts to enhance the reliability of power systems, especially with the incorporation of renewable energy resources through various techniques, have been proposed [22]. Electric vehicles are now interfaced with artificial intelligence and complex software systems, enabling them to understand real-world conditions, make autonomous decisions, and perform tasks without human intervention [23]. In addition, systems for communication and computation within electric vehicles have been introduced, alongside discussions on the stochastic design of vehicle communication reliability using probability theory [24]. Moreover, the integration of solar and wind power systems has been explored through the use of distribution generation systems, incorporating suitable non-linearity into conventional power systems to improve accuracy [25]. Innovative methods have been suggested, such as a tracking absorption approach for renewable power based on the interface between the demand and supply sides. This approach regulates the charging process of electric vehicles, enabling the efficient utilization of renewable energy resources and unrestricted electric power [26]. Methods have also been proposed for the efficient allocation of charging stations for electric vehicles within the power system without compromising performance [27]. The inclusion of renewable energy resources with electric vehicles necessitates an analysis of power systems based on the demand for electric vehicle charging [28]. The inherent variability and unpredictability of solar and wind energy systems can pose challenges for system operators in maintaining reliability. Consequently, a stochastic risk-constrained framework has been introduced to assess the impact of demand response on system reliability [29]. As power electronic technologies are increasingly integrated into the grid, the assessment of system reliability becomes crucial. Understanding the impact of equipment failure rates on overall system reliability is a key consideration [30]. Additionally, the incorporation of various energy storage systems into distribution networks can influence system reliability and utility outcomes [31][32]. The evolving grid, departing from its original design, is undergoing a transformative change in how power is generated and consumed [33].

The uncertainties associated with wind and solar power resources can affect system reliability. Consequently, a novel production rescheduling algorithm has been introduced to regulate production outputs, reducing energy flow deviations and mitigating the risk of overloads [34]. With the growing penetration of renewable power, many Independent System Operators (ISOs) are introducing ramp ability products to address the challenge of real-time power matching [35]. Furthermore, a novel approach has been presented to explore the effectiveness of applying reliability assessment to define reliability standards for grids with a high penetration of power converter-interfaced production [36]. The design of various components within the power system plays a crucial role in improving efficiency and reliability [37][38]. As electric vehicles gain prominence in the market, their design should adhere to a reliability-based approach [39]. In this context, a novel reliable motor called the 'magnetic steering motor' has been introduced to explore the concept of a magnetic discrepancy system for electric vehicles [40]. One of the primary advantages of renewable power systems is their ability to reduce carbon emissions across various levels. By integrating renewable energy with the grid, the need for units generated by thermal-based plants decreases, resulting in a reduction in carbon footprints [41]. Additionally, a general framework for electric vehicle charging stations has been proposed to assess the reliability of power electronics-based components in electric vehicles [42]. Furthermore, the reliability observation of hybrid electric vehicles is essential for their design, control, planning, and management [43][44]. Innovative energy conversion methods have been introduced for renewable-based power generation, allowing each element of renewable energy sources to operate optimally and generate maximum power [45].

To assess the reliability of power systems that incorporate wind energy with small hydropower plants, this article aims to evaluate their impact on system reliability [46]. Numerous stochastic computational methods for analyzing fuzzy systems have been introduced [47]. Due to the increasing prevalence of wind and solar generators, traditional reliability evaluation methods are inadequate due to the intermittency and uncertainty of these resources. As a result, new approaches have been introduced [48]. In both qualitative and quantitative research, fault trees are commonly employed to analyze the unreliability of electrical or mechanical systems [49]. To overcome these challenges and address the reliability issues associated with the integration of electric vehicles and renewable energy sources into the power grid, this article proposes an innovative reliability-oriented approach. This approach utilizes a novel incentive-based fuzzy fault tree analysis to resolve practical reliability investigation challenges associated with solar-wind-electric vehicle-connected power systems [50]. It is applied to derive different reliability indices and assess the probabilities of top event failures under varying loads.

The outcomes obtained from this approach are then compared with various existing methods, including the electrical loss minimization technique, chronological multiple-state probability model, system state generation method, and probabilistic minimal cut-set-based iterative methodology. It is worth noting that these existing techniques involve lengthy processes and demand additional time for assessing system reliability, making the proposed approach more efficient by comparison.

Plug-in Electric Vehicles (PEVs) serve as mobile electric loads and storage devices in the system, introducing additional operational constraints that offer advantages to distribution systems. However, these benefits can be offset by their impact on the availability of power supply to users. Simultaneously, the extensive integration of wind energy can potentially lower operational costs and reduce emissions. Still, the inherent variability of wind generation can pose challenges to network security and reliability [51]. The storage capacity of PEVs can play a crucial role in mitigating the intermittency of wind generation, thereby enhancing network reliability and reducing operational costs. PEVs are capable of drawing energy from the grid, storing it in their batteries, and injecting it back into the grid at different times and locations to help manage the fluctuations in wind generation. Through Vehicle-to-Grid (V2G) technology, grid operational costs can be lowered by utilizing the stored energy in PEVs, which can be transferred between locations without strictly adhering to conventional power flow rules [52]. Furthermore, the integration of V2G-enabled PEVs can make substantial contributions to the reliability and security of the distribution grid. As a result, extensive research has been conducted focusing on addressing the uncertainties associated with wind generation and the power from PEVs. Research has also evaluated the reliability and cost implications of PEVs and wind generation. Additionally, optimal scheduling of network power resources and wind generation while considering PEVs has been investigated [53], and reliability assessments considering PEVs have been addressed. Furthermore, references [54] delve into the characteristics, advantages, weaknesses, economics, and technical specifications of V2G technology. Among various methods proposed to enhance system reliability, such as accelerating fault prediction procedures and improving protection measures, Distribution Feeder Reconfiguration (DFR) stands out as a cost-effective strategy. DFR aims to identify the optimal network topology by altering its configuration [55].

While previous studies have primarily focused on DFR's capability to improve network reliability, they often lack a comprehensive model of DFR's ability to mitigate the impacts of PEVs and coordinate V2G services within a stochastic and reliable framework. Therefore, this paper introduces a stochastic DFR formulation, which optimally schedules V2G services and concurrently determines the most beneficial network topology from reliability and total cost perspectives. The improvement in reliability is measured with respect to the Energy Not Supplied (ENS) index. In addressing uncertainties linked to wind generation, PEVs, energy prices, and active/reactive load demand, a Monte Carlo simulation (MCS) method is employed. The optimization problem is then solved using a self-adaptive modified Symbiotic Organism Search (MSOS) algorithm, representing a powerful optimization technique. The SOS algorithm is a bio-inspired optimization approach based on simulating the interactive behaviors of diverse organisms within an ecosystem to find the optimal solutions in the search space. To enhance the performance of conventional SOS in complex optimization scenarios, a new modification phase has been incorporated into the algorithm. The proposed methodology is applied to a 69-bus IEEE distribution test system to validate its effectiveness. The results demonstrate that the stochastic DFR strategy, in conjunction with V2G technology, effectively reduces operating costs and strengthens network reliability. Furthermore, the proposed MSOS algorithm efficiently minimizes the defined objective functions.

2. Innovative Incentive-Driven Fuzzy Fault Tree Analysis (IIFFTA) Method

Figure 1. Construction of Fault Trees Using the Proposed Approach and Identification of Risk Factors

This section delves into the impact of integrating renewable energy resources and electric vehicles on the power system's reliability. It outlines both the advantages and disadvantages of incorporating these sources and electric vehicles into the conventional electrical power system. While some disadvantages exist, the advantages are prevalent due to their unlimited and cost-effective nature. Reliability stands as a pivotal focus in this research. Therefore, by leveraging past failure data and expert opinions, the primary and basic event failures are pinpointed. The major event failures in the grid-connected solar-wind and electric vehicle system encompass the following:

- Solar power system faults (SPSF)
- Wind power system faults (WPSF)
- Electric vehicle faults (EVF)

The fault tree diagrams are constructed to visualize the proposed power systems, illustrating the hierarchy from top events to basic events. The fault tree for the grid-linked power system with wind-solar energy resources, excluding electric vehicles, accounting for the system structure and different faults occurring in the solar-wind power system. The top event is the fault in the solar-wind power system, with sub element failures in the system branching into basic events.

The reliability assessment of the entire system is conducted over a chosen period of 2 years in this research. Solar power system faults encompass issues such as solar module faults, wiring faults, junction box faults, front glass failures, solder bond faults, encapsulation faults, system balance faults (DC and AC switches), circuit breakers, connectors, bypass diodes, DC combiners, inverter module faults, AC and DC contactors, cooling fan faults, operational faults, startup and stopping faults, converter faults, grid operation faults, and weather-related faults. Meanwhile, wind power system faults consist of rotor blade faults, generator faults, gearbox faults, mechanical brake faults, yaw system faults, hub faults, pitch system failures, startup faults, blade damage, shell damage, tip damage, different angle faults, sensor faults, structural faults, among others. Electric vehicle faults include failures in charge controllers, power converters, rotor shafts, startup faults, stopping faults, connector faults, battery modules, stator winding open circuits, eccentricity-related issues, battery temperature problems, overcharge and undercharge issues, bearing faults, slave controllers and master controllers of the battery management system, vehicle sensors, abnormal stator winding connections, control module failures, driver module issues, communication module problems, discharging module faults, transducer malfunctions, body hardware failures, paint-related problems, and power switch issues.

The primary challenge in calculating the failure probabilities of the grid-connected wind-solar energy resources and electric vehicles is the lack of comprehensive data on various component failures within the entire system. Therefore, the proposed methodology is employed to address this issue. Experts contribute their expertise by providing failure probabilities for all events. While there are known failure rates for 20 basic events from research papers and databases, the failure rates for the remaining events are determined using the proposed method. The fault tree model of the grid-connected renewable energy system with electric vehicles, showcasing the system's structure and the various faults occurring in both the solar-wind power system and electric vehicles.

3. Examination of Motor Controller Reliability

The motor controller comprises power electronic components and a protective housing shell. Given that the protective housing shell is inherently dependable and has minimal influence on the motor controller's reliability, it will not be a focal point of our subsequent investigation. The motor controller encompasses bus-bar capacitors, a control module, a driver module, a discharging module, a communication module, and IGBT. Recognizing that a fault occurring in any of these components can potentially result in motor controller failure. On one hand, they absorb the energy generated by the drive motor when power switching devices are rapidly turned off, particularly in emergency stop scenarios.

4. Novel Stochastic Distribution Feeder Reconfiguration Strategy

The novel DFR approach introduced in this study aims to determine the most optimal radial configuration for the distribution network while scheduling the provision of Vehicle-to-Grid (V2G) services by PEV fleets within a dependable and secure framework. This approach seeks to achieve several objectives, which encompass reducing the expenses associated with power exchange with the upstream network, minimizing overall active power losses, lowering the operational costs related to the aggregated PEVs, and ultimately enhancing the reliability of the network.

5. Reliability Matrices Assessment

Reliability matrices are fundamental tools in the field of reliability engineering and systems analysis. They serve as structured mathematical models for assessing the reliability and failure characteristics of complex systems. These matrices typically comprise a list of system components and their interconnections, where '1' often signifies a functioning or reliable connection, while '0' denotes a failure or non-reliable connection. Reliability engineers and analysts use these matrices to evaluate the overall reliability of intricate systems, where traditional analytical methods may become unwieldy or impractical. They allow for the calculation of important reliability metrics like system failure probabilities, availability, and mean time to failure. Reliability matrices are widely applied in diverse industries, including aerospace, telecommunications, manufacturing, and critical infrastructure, where ensuring the reliability and safety of systems and products is of paramount importance. They offer a systematic approach to addressing the complex interactions and dependencies that influence system reliability, making them indispensable tools for risk assessment and decision-making in design, maintenance, and operations.

While the aforementioned calculation results have indeed offered insights into the reliability of individual components, they represent mere static glimpses of the motor system's reliability. To address this limitation, we proceed to assess the unreliability indices for not only the drive motor and motor controller but also the entire motor system. This comprehensive evaluation of reliability aims to provide a more holistic and dynamic understanding of the motor system's dependability, incorporating the insights gleaned from the preceding calculations.

6. Significance of Review on Reliability of Vehicle-to-Grid Networks

This paper introduces an intelligent stochastic framework designed for the automation of future smart distribution grids as wind generation and PEV fleets become more prevalent. The primary goal is to utilize Distribution Feeder Reconfiguration (DFR) to minimize operational costs, enhance system reliability, and optimize Vehicle-to-Grid (V2G) provisioning by PEVs. Mobile and distributed PEVs prove highly effective in facilitating energy distribution across the network, resulting in reduced grid operation costs and improved stability in the face of renewable generation variability. The incorporation of storage systems, whether stationary or mobile, significantly enhances the Average Energy Not Supplied (AENS) metric. DFR plays an essential role in reducing network costs and losses while enabling the seamless integration of PEVs without additional expenses, ensuring a reliable power supply. Simulations reveal that applying the DFR technique effectively reduces the total network cost under various conditions. The optimization of our proposed objective functions also enhances network voltage security by minimizing maximum voltage deviations. This approach showcases favorable impacts on other critical targets, including bus voltage deviations. Furthermore, our research demonstrates that the evolutionary algorithm presented (MSOS) is competitive with other well-known methods for problem-solving and surpasses them in certain aspects.

Conclusion

To ensure a more accurate assessment of the overall reliability of pure electric vans' entire motor system, this paper conducts an in-depth investigation into the reliability aspects of both the drive motor and the motor controller using a fault tree analysis approach. Over time, as both the drive motor and motor controller age, their reliability gradually decreases, impacting their performance and safety. Regardless of the service time, the motor controller exhibits lower reliability compared to the drive motor within the entire motor system.. The increased number of electronic components leads to more intricate connections, thinner wiring, and additional through holes on the PCB, ultimately reducing the reliability of the control module. When evaluating the reliability of the motor system, it is imperative to address the reliability issues in both the drive motor and motor controller simultaneously. Focusing solely on the drive motor's reliability can lead to inaccurate predictions since the drive motor and motor controller are logically interconnected and always operate as a unified system in electric vehicles. Neglecting the reliability issues in the motor controller can result in an underestimation of the entire motor system's reliability. In an effort to enhance the overall reliability assessment of power systems that encompass both electric vehicles and renewable energy sources, this paper conducts a comprehensive exploration of reliability issues within the proposed system. The study leverages the Innovative Incentive-Based Fuzzy Fault Tree Analysis approach. Within this framework, fuzzy probability scores for basic events and prediction analysis factors for these events within the proposed system are meticulously calculated. Additionally, a probability analysis of fault occurrences is introduced to evaluate the impact of each basic event on the top event. These prediction analysis factors serve as a valuable tool for assessing the real consequences of basic events on the proposed system.

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