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Fault Tree Analysis of the Reliability of Electric Vehicles in India

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Abstract

Innovations for electric vehicles have advanced quickly in latest decades. Large-scale business use of these vehicles is still constrained by reliability-related issues. By utilising fault tree (FT) and Monte Carlo simulation, a mathematical prototype is created that includes the reliability traits of all major electrical parts of the vehicle system, including the battery, motor, drive, controllers. The research demonstrates that by raising the component restoration rates, the vehicle's survivability can be raised. A thorough discussion of this paradigm is provided, along with a presentation and analysis of the reliability estimations based on an electric vehicle. This research on the reliability design and maintenance of an electric vehicle can be supported by the ideas that are outlined in the paper. Additionally, the findings of this study may be helpful to those who build electric vehicle, especially when upgrading the components efficiency and planning for reliability increase.

Keywords

Electric Vehicle, Fault Tree, Monte Carlo Simulation, EV Component Analysis

1. Introduction

Around 28% of the world's total energy is consumed by transportation networks, which are primarily powered by refined petroleum and are the main cause of emissions in densely congested regions (Zhang *et al.* [1]). To lessen the effects of the aforementioned issues, there has been a growing eagerness to switch from conventional combustion cars to electric vehicles (EVs). Electric vehicles are thought to be a key technique in reducing worries about the sharp increase in the price of petroleum, the deterioration of air pollution, and global warming brought on by greenhouse gas emissions. Furthermore, the aggregate system's reliability is decreased by the integration of a huge proportion of power electronic devices to the vehicle's driving systems.

Moreover, the reliability of the overall system is decreased by the integration of a large quantity of power electronic devices into car drive systems (Song & Wang, [2]). People are mostly worried about the vehicle's dependability, safety, price, and maintainability when buying one. PEVs are built with numerous electronic systems and elements (Ehsani *et al.*, [3]). These devices are very prone to failure. These vehicles' systems are consequently less dependable than those in IC-powered, mechanically propelled vehicles. To achieve a higher degree of reliability, the vehicle system needs to be constructed with reliable components.

Three different failure or risk rates are encountered during a component's life cycle at three different phases. It has a constant failure rate during its useful life, a diminishing failure rate in its early life, and a rising failure rate in its wear-out phase. Reliability is the likelihood that a breakdown won't occur in a given period of time (Balagurusamy, [4]).

Low reliability is primarily caused by inaccurate production methods and poor design. Unreliable maintenance procedures, human errors brought on by carelessness, forgetfulness, poor judgement, etc., and also inadequate maintenance practices all add to unreliability of a system (Agarwal, [5]). Regardless the greatest efforts of the designer, a system cannot be completely dependable. During functioning, the system is prone to malfunction. It could be expensive with regard to time and money, or occasionally risky in terms of safety.

Suggesting novel techniques for analysing the reliability while taking into consideration failures that may arise over the lifetime of the power system is necessary to examine the difficulties in the realm of the reliability of EVs, according to Harting *et al.* [6]. A failure in one EV component can result in the system failing, according to the majority of studies done so far. This is due to the significance of assessing the reliability of electric vehicles.

Investigating reliability concerns in diverse systems has been done widely using fault tree analysis, a reliable tool for undertaking reliability and safety evaluation. For instance, Kang *et al.* [7] quantitative and qualitative evaluation of the probable breakdowns of a wind turbine using the fault tree analysis technique revealed that the preponderance of drifting engine failures is caused by marine environments. The dynamic fault tree analysis framework was evolved by Zhang *et al.* [8] to ascertain the ordinary maintenance span of a floating windmill; the fault tree designs were established for evaluating the reliability of a fault-tolerant information system and a vehicle guidance method in drones. The fault tree evaluation technique was enhanced by Nguyen *et al.* [9] to integrate operating the approximate evaluation of intricate methods comprising multicomponent methods.

1.1. Electric Vehicle Scenario in India

In India, the EV market is currently very tiny. For the past two years, sales of electric vehicles have stalled at 2000 units annually. However, there is a goal to sell only electric vehicles by 2030, and as of 2020, that goal has a compound yearly growth rate of 28.12%. India's first electric vehicle, the Mahindra Reva, was unveiled in 2001 and has since sold a small number of cars. Toyota introduced the Prius hybrid model in 2010, and the Camry hybrid approach in 2013. A few towns have started using electric buses and hybrid cars as a pilot project.

1.2. Research Gap

The reliability of the overall EV components system may also be impacted by the kind, design, and attributes of elements. This, although, has also never been taken into account. By investigating the concerns of all main components and elements in EV, the study aims to close these knowledge gaps. The findings of this study should be a useful addition to what is already known about electric vehicles and will help the newly developing electric vehicle sector.

1.3. Research Objectives

The study's primary goals are:

- To create a mathematical model for an electric vehicle system's reliability analysis. All of the essential elements of the vehicle system's reliability traits are included in the prototype.
- To investigate the logical relationships between the fault events, how the reliability of the electric vehicle is influenced by these fault events, and how appropriate maintenance practises can increase the vehicle's availability.

2. Literature Review

A relatively new field of study is fault tree analysis reliability modelling and assessment of electric cars in India. Creating a fault tree analysis (FTA) model to assess the dependability of electric cars in India is the main goal of this study. The battery, motor, and control system are just a few examples of the parts and systems that make up electric cars as the researchers of this study investigate their dependability in India.

Utilizing sustainable energy has benefited several companies, particularly the car industry (Gandoman *et al.*, [10]). By adopting electric vehicles (EV), big businesses have made a tremendous advancement in the realm of renewable energy. Assessing the dependability and safety of these cars is one of the primary difficulties in the EV field. As a result, the idea of the dependability and safety of EV's elements is seen as a crucial issue. In particular, the lifespan efficiency of an EV's electrical system is greatly influenced by the reliability and safety evaluation of key electrical elements. This essay offers a thorough analysis of the reliability of EV parts from several angles. Additionally, research has been done on the reliability and safety issues that ought to be considered when looking at the destiny of EVs.

The inclusion of large-scale cluster electric cars (EVs) and the randomization of their spatial-temporal transfers are anticipated to have an impact on the distribution network's ability to operate safely and profitably (Cheng *et al.*, [11]). This study looks at the spatial-temporal forecast of the charging load for EVs before assessing the dependability of the distribution network that has been pierced by a large-scale cluster of EVs. Trip chain technologies, the Monte Carlo approach, and Markov decision process (MDP) theories are used to accurately forecast the charging load. A spatial-temporal transfer framework for EVs is also developed, and on the basis of this models, an EV energy usage method and a charging load prediction method are built while taking temperature, and the subjective intention of the EV owner in various situations into account. A number of numerical simulations are run using the traffic-distribution system of a regular city as an instance to evaluate the suggested prediction concept and assessment approach.

In addition to having an effect on load growth, the large-scale deployment of electric vehicles (EV) in the future will also present possibilities for the electrical industry (Bremermann *et al.*, [12]). In particular, this new type of load is not taken into account by the current approaches for the long-term assessment of supply security. This study offers, as its main commitment, an EV concept relying on the Nonhomogeneous Poisson procedure, which has been evolved in order to better demonstrate motorised citizen mobility and the EV possibility to discharge spinning reserve to electric systems. While the electric elements of generating systems are typically simulated by the Markov procedure. To evaluate the influence of EV when assessing the suitability of generating systems, a sequential Monte Carlo simulation (SMCS) that incorporates both Poisson and Markov procedures is used as the simulation approach. With a customized form of the IEEE RTS-96 that incorporates renewable resources, the suggested frameworks are examined.

EV growth in distribution networks could present a range of benefits and difficulties for the electrical network (Ghaedi *et al.*, [13]). This concern is significant since electric vehicle owners want to maximise their earnings, which can lead to a variety of issues in distribution networks, including greater losses, congestion, and increasing network expenses. As a result, research is needed into various facets of this novel technique, including its reliability and failure rate. In order to do this, the offered research proposes a reliability framework for various kinds of electric vehicles relying on Markov theory. The primary innovation is to ascertain the influence of the failure rate of each electric vehicle's assembled elements on the total failure of the vehicle. The failure of the primary constituent elements is taken into account in the reliability analyses for these electric cars that have been suggested. Numerical findings related to the reliability assessment of these cars are provided to evaluate various electric vehicle kinds from a reliability perspective. The reliability of the compound plug-in hybrid electric car is greater than that of the other techniques, according to the numerical findings of the reliability study of several kinds of electrical vehicles.

Due to their high energy density, low maintenance needs, and variety of potential shapes, chemistries, and efficiency levels, lithium-ion (Li-ion) batteries have enticed a lot of obsessions in latest days (Gandoman *et al*., [14]). For primary equipment producers, the reliability and safety of Li-ion batteries has grown to be a crucial issue, particularly for the efficiency of upcoming electric vehicles. To evaluate the total Li-ion battery behaviours over its lifecycle, dependability and safety assessment are key factors. In order to assess the dependability and safety of batteries in electric vehicles, this study describes the function, method, and results of various failures. Furthermore, it has been researched how Li-ion battery deterioration affects the five primary failure modes as well as capacity and power fading while developing reliability assessment frameworks to address current problems.

The electronic circuits are analysed and evaluated using a paradigm provided in this study (Ghavami & Singh, [15]). Various charging stages are examined along with the basic layout of EV charging systems, which includes multi-phase interleaved charger topologies. A fault-tolerant multi-phase interleaved charging system allows the controller to identify, isolate, and reconfigure faults with 100% coverage. Using MIL-HDBK-217, component level dependability is estimated. To examine the fault-tolerant multi-phase interleaved charger topology's dependability, a Markov approach is developed. The mean time to failure (MTTF) and mean time to first failure (MTTFF) reliability indexes are described and computed. The suggested systematic approach can be used to evaluate and compare the reliability of other kinds of EV chargers, which can aid in understanding and improving designs for charging infrastructures.

Electric vehicles can be viewed from the perspective of a power grid as ad hoc moving loads (Anand *et al*., [16]). To evaluate how electric vehicles affect the efficiency and dependability of power distribution systems, a novel probabilistic method is indeed suggested in this research. It is suggested to use a two-layer stochastic approach to estimate the requirement for charging electric vehicles. The concept consists of an electrical network layer that describes the demands for EV charging and a traffic layer that represents the spatial and temporal distributions of EV. Electric car movements in the traffic layer are recorded using a dynamic hidden Markov theory. Taking into account sequential Monte Carlo simulation is used to predict electric car travel patterns and charging needs. Reliability experiments on an experimental test system are conducted using the suggested method and the frameworks, and a number of analytical findings are shown.

EVs are acquiring acceptance for variety of reasons, such as falling costs and growing environmental and climate consciousness (Sanguesa *et al*., [17]). In addition to reviewing current battery technology developments and charging techniques, this article also discusses fresh study challenges and undeveloped business potential. More specifically, the worldwide EV market's situation right now and its future potential are examined. The paper offers a thorough sketch of battery technology, extending from lead-acid batteries to lithium-ion, because the battery is one of the essential elements of EVs. Furthermore, we discuss the various EV charging methods that are available as well as concepts for energy management and battery energy optimisation. Finally, we conclude our research by describing our hopes for this fields near future and also the research topics that are still open to both industrial and academic entities.

3. Methodology

3.1. Reliability

Reliability of a unit (or a product) is the probability that it will give satisfactory performance for a specified period under specified operating conditions.

Quantitatively, reliability of a system in time "t" is the probability that it will not fail in a given environment before time t. If T is a random variable representing the time till the failure of the system starting with an initial operable condition at $t = 0$, then reliability $R(t)$ of system is given by

$$R(t) = P[T > t] = 1 - P[T \le t] = 1 - F(t) \tag{1}$$

where $F(t)$ is the unreliability of the system.

Thus, reliability is always a function of time. It also depends on environmental conditions which may or may not vary with time.

In terms of probability density function of T, namely $f(t)$, we get

$$R(t) = \int_t^{\infty} f(x)\,\mathrm{d}x \tag{1.1}$$

The stator core failure, stator winding failure, bearing failure, rotor failure, axis system fault, motor system fault, switches faults, controller and driving system faults, etc. are among the faults in electric cars.

Motor system fault

Numerous factors can lead to motor system faults. It might be an issue with the power supply, a bad motor, loose connections, or the wiring. If the issue is with the cabling, it might be brought on by faulty wiring, short circuiting, or loose connections. If it has to do with the motor, it might be brought on by rotor damage, worn-out bearings, or a malfunctioning motor driver. If it is a power source issue, it might be brought on by a bad power supply, poor grounding, or poor voltage control.

Switches failure

Switches can malfunction for a number of causes, such as physical damage from outside sources, electrical surge damage, and fabrication flaws. An inconsistent connection or a full loss of connectivity may result from a failed switch. No connectivity, sporadic connectivity, sluggish reaction times, and port flapping are typical signs of a bad switch.

3.2. Stochastic Simulation

In order to predict methods of mathematical, physical, and engineering challenges, Monte Carlo simulation is a numerical technique based on probabilistic mathematical statistics analysis. It uses statistical experimentation and stochastic simulation of random parameters.

Stochastic simulation of reliability function:

Step 1. Initialize the (life) probability distribution function and set the number of simulation cycles m.

Step 2. Generate the life time from their life distribution functions.

Step 3. Using transition rules, a system life value is obtained.

Step 4. Repeat steps 1 - 3 for m times, m samples of system life are obtained.

Step 5. Average life of system is obtained by calculating the average value of m samples of system life obtained in step4.

Computer simulations employ the Monte Carlo method, which not only handles large amounts of data rapidly but also eliminates subjective data, enhancing the objectivity of the outcomes.

We initiate the training simulation in accordance with the methodology (**Figure 1**).

3.3. Mathematical Model

The reliability function $R(t)$ is shown in Equation (2), where $\lambda(t)$ represents the failure rate

$$R(t) = \mathrm{e}^{-\lambda t} \tag{2}$$

Mean time to failure (MTTF) is time period unit system fails, it is described by the Equation (2.1)

$$\mathrm{MTTF} = \int_0^{+\infty} R(t)\,\mathrm{d}t \tag{2.1}$$

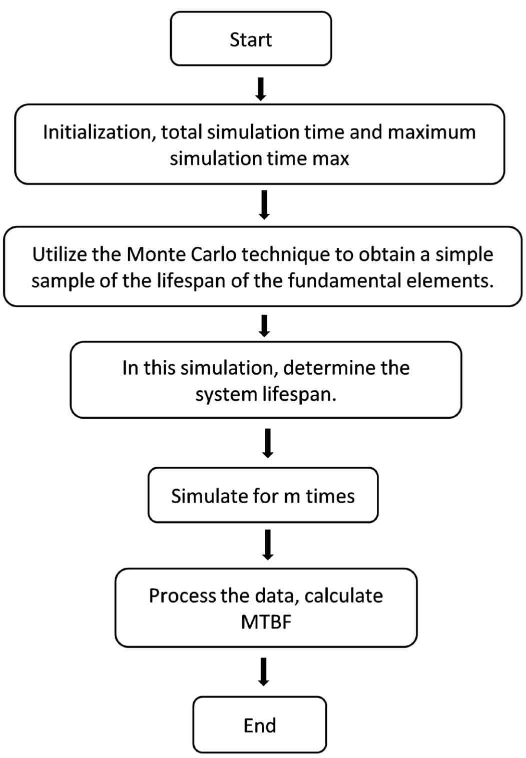

Figure 1. Simulation process.

For constant failure rate, MTTF is expressed as

$$\text{MTTF} = \frac{1}{\lambda} \tag{2.2}$$

A Markov chain method can be used to develop a mathematical model for the analysis of electric car system reliability. A particular kind of mathematical model that depicts the progression of occurrences over time is a Markov chain. In this scenario, the probability of the electric vehicle system being in a particular state at any given moment would serve as the Markov chain's representation of the reliability of the system. States like totally operational, partially operational, or completely inoperable could stand in for various degrees of reliability. The information collected from the electric vehicle system and its components would be used to calculate the probabilities of transition between states.

The transition probabilities are given by:

$$p_{ij} = \lim_{s \to 0} q_{ij}^{*}(s) \tag{3}$$

where, $q_{ij}(t)$ is the probability density function of first passage time from a regenerative state i to a regenerative state j or to a failed state j without visiting any other regenerative state in $(0, t]$ and * is the symbol for Laplace Transformation, e.g.

$$q_{ij}^{*}(s) = \int_{0}^{\infty} \mathrm{e}^{-st} q_{ij}(t)\,\mathrm{d}t$$

The frequency of component replacements, maintenance visits, or visits for repairs, for example, could all be included in the statistics. The Markov chain can forecast the probability that the electric vehicle system will be in a particular state at any given moment using this data.

4. Results and Discussion

4.1. Fault Tree Analysis of the Electric Vehicle Using Monte Carlo Simulation

A fault tree has been constructed for all faults which helps in identifying how the failure of an individual component leads to system failure. Fault tree analysis analyses the causes and effects of a system failure. Fault tree helps to understand the interdependence between components of a system.

After performing the Monte Carlo simulation, a total of 10,000 times, we arrive at the reliability curve shown in **Figure 2** and importance level of fundamental events for electric cars using the aforementioned direct sampling theory.

From the graph it is shown that System reliability of the electric vehicle will decrease with respect to age, use, environmental conditions, and battery degradation.

4.2. Reliability Study of the Proposed System Architecture of Electric Vehicle

The fault tree of proposed system and battery system involves current monitors,

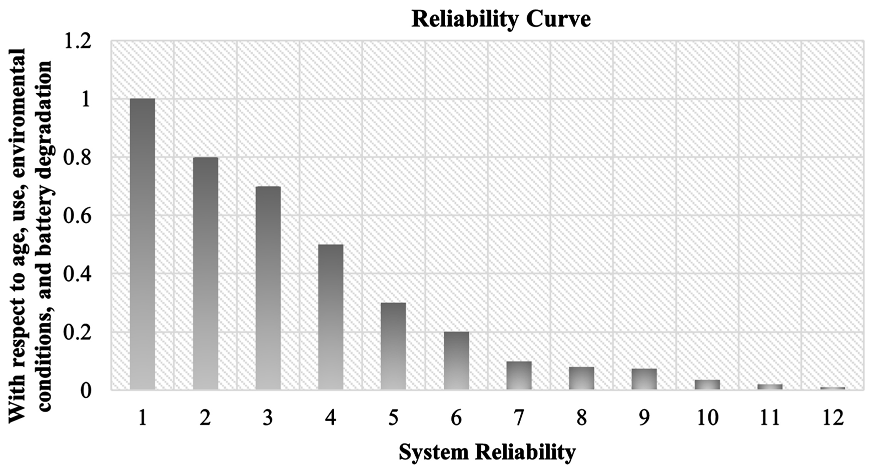

Figure 2. Reliability curve of electric vehicle.

sensors as signal detection elements shown in Figure 3 and Figure 5. A BMS (battery management system) controller is a device that monitors and manages the performance of a battery system, typically in an electric vehicle or solar energy system. The controller is responsible for monitoring the battery's temperature, charge level, and overall health, as well as providing power and charging control. It is also responsible for safety features, such as overcharge protection, short-circuit protection, and thermal protection. BMS controllers are designed to maximize battery performance, while extending its life, and protecting it from damage. The BMS controller can resolve the operational state of each battery cell dependent on the signals gathered and can immediately send feedback to the system. According to the above explanation, any one of these parts could fail and cause the battery system as a whole to malfunction. Moreover, it is still unclear how much of an impact these parts may have on the overall reliability of the power source system and how the battery system's reliability will change over time. Battery system reliability research is carried out to provide answers to these queries.

The knowledge they offer still only represents "snapshots" of the reliability of the battery system, despite the fact that the findings have shown the dependability of specific battery system components. In order to gain a more thorough knowledge of the battery system's reliability, the reliability indices of the complete battery system and its interconnecting elements are assessed Figure 4.

In Figure 5 the first event is 'Battery System Failure' and the basic events from eb1 to eb16 are the failure events of battery system components. In the model, gb1 to gb8 are logic gate events or intermediate events, which are the logical combination of the relevant basic events. All these events are explained in Table 1.

From Figure 5 it is clear that the reliability of battery system relies on connectors, battery module, controllers and other associated components. So, the reliability of the system depends upon the failure rates and probability density functions of these components and the failure rates can be estimated by

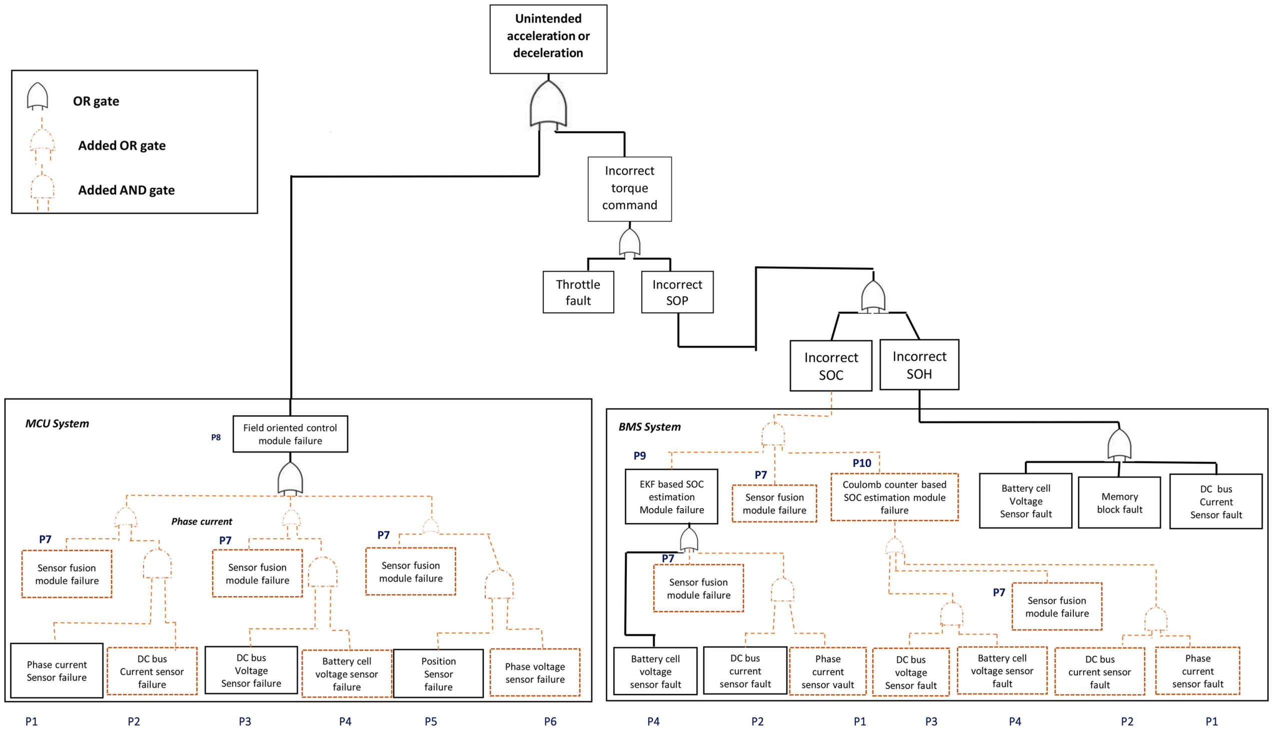

Figure 3. Proposed architecture of fault tree analysis of EV.

Table 1. Failure of BMS-analysis.

Intermediate Event	Code	Failure Rate	Intermediate Event	Code	Failure Rate
Failure of battery system connectors and battery module	*gb*1	$\lambda_{gb1} = 3.44$	Failure of connectors for battery system	*gb*5	$\lambda_{gb5} = 0.382$
Failure of BMS controller	*gb*2	$\lambda_{gb2} = 1.402$	Failure of battery module	*gb*6	$\lambda_{gb6} = 3.058$
Failure of power electronic components	*gb*3	$\lambda_{gb3} = 2.33$	Failure of master controller	*gb*7	$\lambda_{gb7} = 1.159$
Failure of signal detection components	*gb*4	$\lambda_{gb4} = 0.028$	Failure of slave controller	*gb*8	$\lambda_{gb8} = 0.243$

Basic Event	Code	Failure Rate	Basic Event	Code	Failure Rate
Failure of signal connector for battery system	*eb*1	$\lambda_{eb1} = 0.051$	Failure of PCB for slave controller	*eb*9	$\lambda_{eb9} = 0.005$
Failure of power connector for battery system	*eb*2	$\lambda_{eb2} = 0.085$	Failure of SMCs for slave controller	*eb*10	$\lambda_{eb10} = 0.018$
Failure of battery cells module	*eb*3	$\lambda_{eb3} = 1.002$	Failure of communication chip for slave controller	*eb*11	$\lambda_{eb11} = 0.004$
Failure of signal connectors for battery cells	*eb*4	$\lambda_{eb4} = 0.011$	Failure of fuse for main circuit	*eb*12	$\lambda_{eb12} = 2.058$
Failure of fastening screw for battery module	*eb*5	$\lambda_{eb5} = 0.001$	Failure of relay for main circuit	*eb*13	$\lambda_{eb13} = 0.272$
Failure of PCB for master controller	*eb*6	$\lambda_{eb6} = 0.013$	Failure of current sensor	*eb*14	$\lambda_{eb14} = 0.004$
Failure of SMCs for master controller	*eb*7	$\lambda_{eb7} = 0.018$	Failure of voltage sensor	*eb*15	$\lambda_{eb15} = 0.018$
Failure of master chip	*eb*8	$\lambda_{eb8} = 0.252$	Failure of temperature sensor	*eb*16	$\lambda_{eb16} = 0.006$

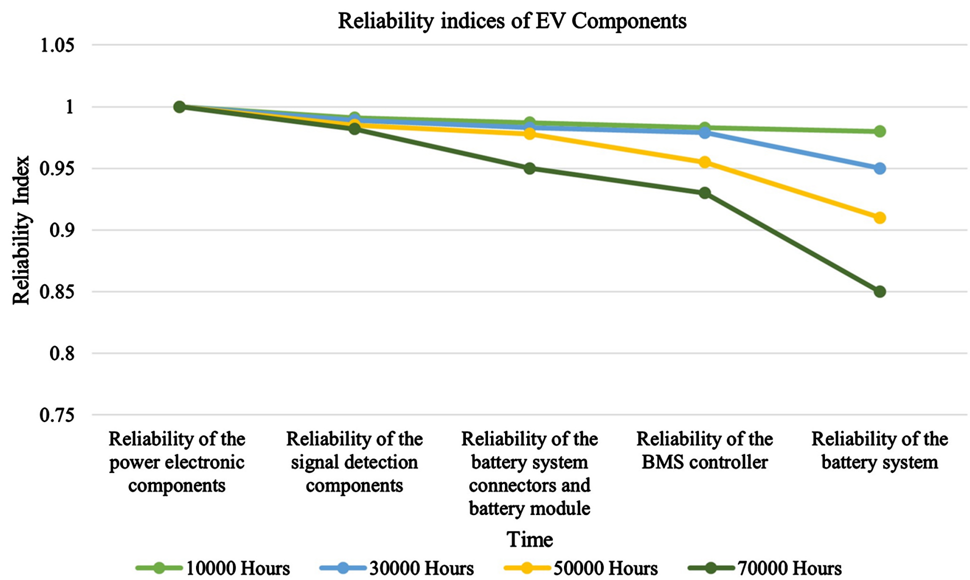

Figure 4. Reliability indices of the EV components over time.

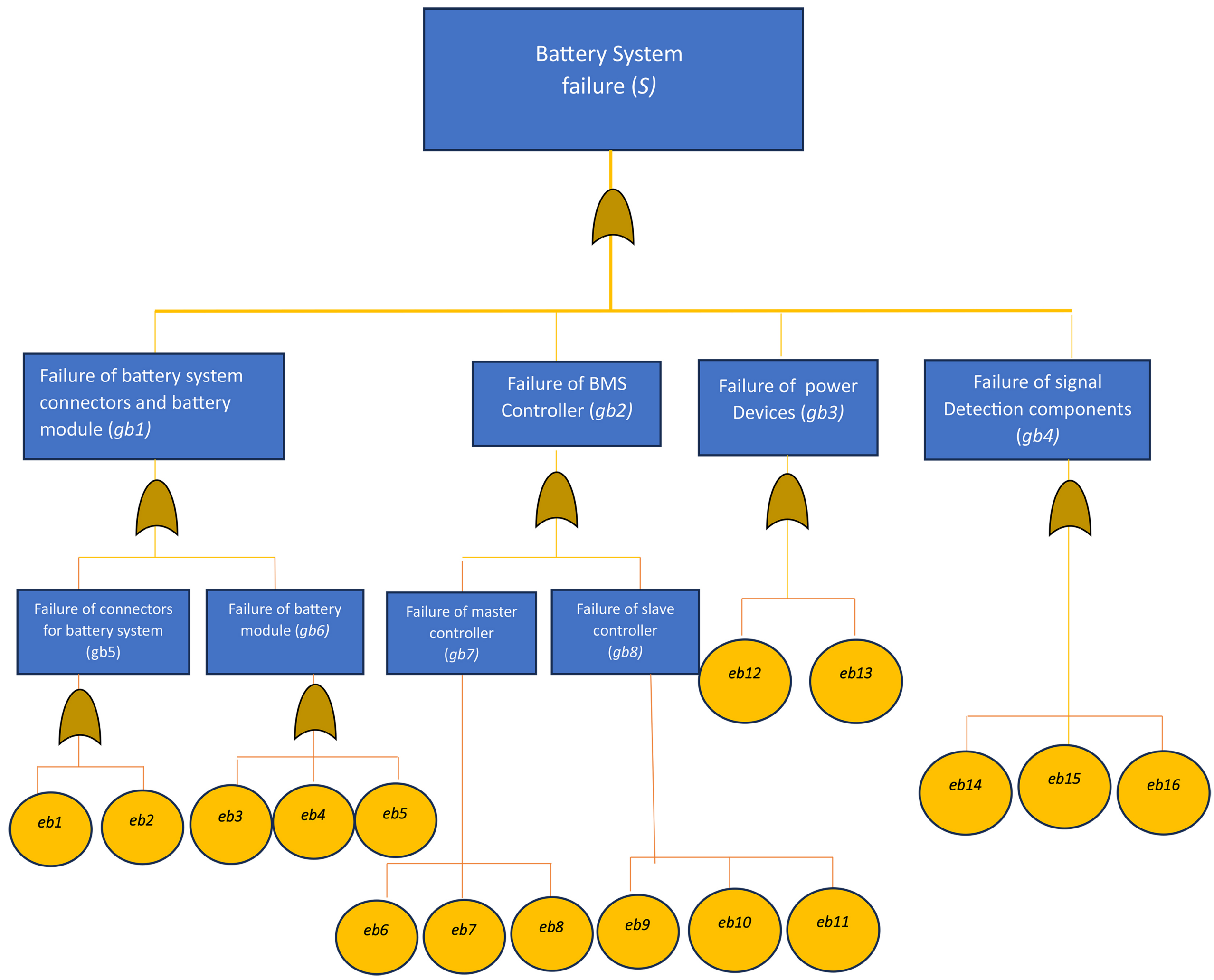

Figure 5. BMS-Fault tree analysis.

$$\lambda_{gb1} = \lambda_{gb5} + \lambda_{gb6}, \lambda_{gb2} = \lambda_{gb7} + \lambda_{gb8}, \lambda_{gb3} = \lambda_{eb12} + \lambda_{eb13}$$
$$\lambda_{gb4} = \lambda_{eb14} + \lambda_{eb15} + \lambda_{eb16}, \lambda_{gb5} = \lambda_{eb1} + \lambda_{eb2}, \lambda_{gb6} = \lambda_{eb3} + \lambda_{eb4} + \lambda_{eb5} \quad (4)$$
$$\lambda_{gb7} = \lambda_{eb6} + \lambda_{eb7} + \lambda_{eb8}, \lambda_{gb8} = \lambda_{eb9} + \lambda_{eb10} + \lambda_{eb11}$$

Table 1 and Table 2 displays the component failure rates and MTTFs. The battery module is excluded from both the failure rates of individual devices' parts and the failure rates of the entire system. It has been found that the EV-based BLDC (Brushless DC drive) is more reliable than the traditional BLDC drive.

4.3. Unreliability Measure

In order to obtain better understanding of the reliability, in Figure 6, the calculation outcomes using Equations (1), (2) and (4) for the motor system's service life at 10,000, 30,000, 50,000, and 70,000 hours, correspondingly, are displayed.

From Figure 6 it is observed that reliability of motor controller and drive motor is decreasing with the increase of service time, the motor controller is less reliable than drive motor and the complete motor system has lesser reliability.

Table 2. The failure rates and MTTFs of the elements of EV.

Reliability index	Motor controller	BLDC drive	DC Drive
Failure rate	1.2033	17.652	26.15
MTTF	5.3522	0.954	2.154

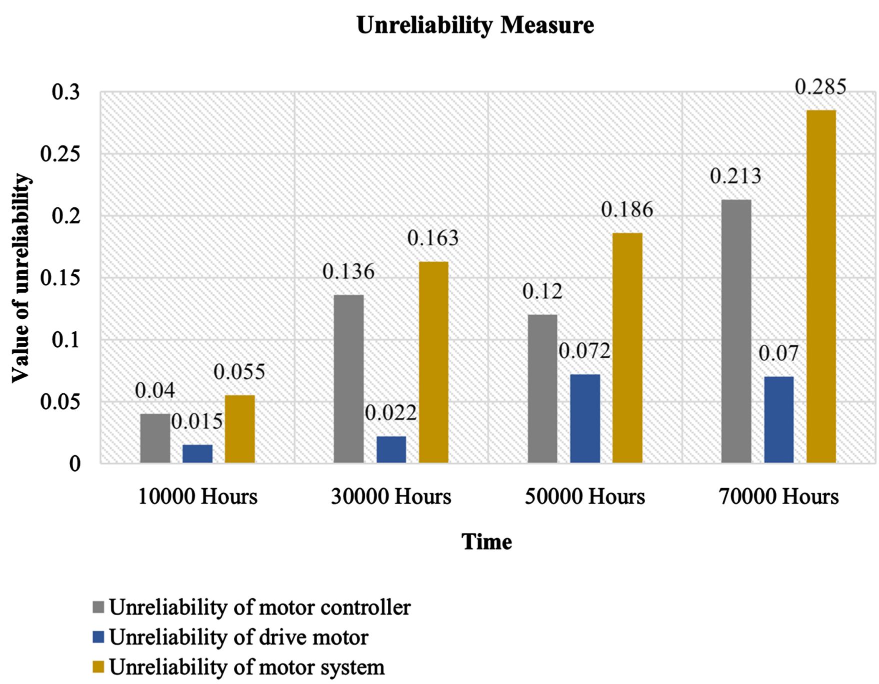

Figure 6. Findings of the estimation of the drive motor and motor controller's unreliability measure.

5. Conclusions

In conclusion, this study has proposed a mathematical model for the reliability analysis of an electric vehicle system, including all essential elements of the vehicle's reliability characteristics. Using the Monte Carlo simulation and Fault Tree Analysis technique, the logical relationships between fault events and the effect of these events on the reliability of the electric vehicle have been investigated. The results of this study have shown that the reliability of the EV-based BLDC (Brushless DC drive) is higher than that of the traditional BLDC drive. Furthermore, the reliability of the battery system and its components was evaluated over time. This study has provided a comprehensive understanding of the reliability of electric vehicles and should be useful for further studies in the field. Moreover, the obtained results can guide the decision makers in making better designs.

When assessing the lifespan of an EV's electrical elements in terms of planning, service, and upkeep, reliability and safety are crucial considerations given the developments made in the realm of EVs. The most important electrical parts of EVs are the battery pack, and electric motor, all of which ought to be evaluated from a dependability and safety perspective. This research provided a thorough analysis of reliability assessment and its use with respect to the major electrical elements of EVs.

The battery pack poses the most problematic dependability and safety issues of all the essential components. Chemical, temperature, electrical, and mechanical considerations are key factors in determining the battery pack's dependability and safety. In addition, the hardware and software (electrical/electronic, configuration software, and computation) are the primary challenges that must be examined when assessing the reliability of EVs.

By enhancing reliability and safety, the cost of the EV has been reduced altogether by 2/3, which is crucial for growing market penetration. The battery pack, electric motor, and current electronic devices all contribute to a rise in the failure rate of EVs. The range of electric motors, battery packs, available today complicates the scenario even further, but it also makes it more affordable.

For future work three distinct angles can be taken on reliability: the manufacturing process, the selling period, and the lifetime of EVs. As a result, adding fresh methods and indexes to the reliability assessment process increases lifetime and is advantageous for EV planning and maintenance. The system could also be evaluated by showing unique modified simulations for the major problems, like the thermal and electrical management of EVs.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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