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Research on Safety Evaluation Methods in the Maintenance of Hybrid Vehicles

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Abstract: With increasing emphasis on environmental problems, hybrid vehicles have become an important development direction of the automobile industry, and the safety assessment in the maintenance process has been particularly valued. This study establishes a systematic hybrid vehicle maintenance safety evaluation method, focusing on three key technologies: battery management system (BMS) fault diagnosis, high-voltage system isolation, and power battery safety detection. The multisource data fusion technology is used to carry out real-time monitoring and fault warning of BMS; adopt the design concept based on high-voltage interlock to realize the effective isolation of the automotive high-voltage system; and reconstruct the battery state through the simulation model to comprehensively evaluate the health of the power battery. In the experimental part, by randomly selecting the models of the main hybrid vehicles on the market, a database was built that covers more than 100 typical faults and a number of fault diagnosis algorithms were compared and tested on the actual car. The research results show that the evaluation method has reached the industry-leading level in terms of fault detection rate, fault location accuracy, and response time. The diagnostic precision rate has increased by an average of 15% and the response time has been reduced by 30%. The research not only provides a scientific and systematic safety evaluation tool for the maintenance of hybrid vehicles but also lays a theoretical foundation for the formulation and upgrading of training standards for the automotive maintenance industry.

1. Introduction

Due to the use of high-voltage battery system and high-power electric drive system, hybrid electric vehicles have great safety hazards in the maintenance process. The voltage used by electric vehicles is much higher than the safe voltage that the human body can withstand, once the accident such as leakage or electric shock occurs, it will cause serious injury to the maintenance personnel[1]. In addition, improper operation in the maintenance may also cause short circuit, generate electric sparks, and even cause serious consequences such as fire and explosion. Therefore, the safety assessment in the maintenance process of hybrid electric vehicles is particularly important and urgent[2].

At present, there is a lack of systematic evaluation methods for the maintenance safety of hybrid electric vehicles. Traditional safety evaluation methods, such as fault tree analysis (FTA), event tree analysis (ETA), etc., mostly focus on the essential safety of equipment or process, and it is difficult to fully consider the comprehensive impact of many factors such as human, machine, environment and pipe. However, the maintenance of hybrid electric vehicles involves many factors such as vehicle structure, operating procedures, personnel skills, protective equipment, emergency treatment, etc. A more comprehensive and quantitative safety assessment model needs to be built.

From the perspective of system safety, this paper intends to comprehensively consider the risk factors in the maintenance process of hybrid electric vehicles, and build a multi-level safety evaluation index system. On this basis, the analytic Hierarchy process (AHP) and fuzzy comprehensive evaluation method are introduced to establish a quantitative evaluation model of hybrid electric vehicle maintenance safety. By collecting the data of 10 typical maintenance cases of an automobile 4S shop, the proposed evaluation method is empirically studied to verify its effectiveness and operability. The results show that this method can objectively evaluate the safety risk level of hybrid electric vehicle maintenance operations, identify key influencing factors, and provide a basis for the formulation of targeted safety control measures.

This study enriches and develops the theories and methods of safety assessment in the field of hybrid electric vehicle maintenance, which is of great significance to guide the safety management practice of automobile maintenance enterprises. Future research can further expand the sample size, optimize the weight of indicators, and improve the applicability and accuracy of the evaluation model. In addition, this method can be combined with other quantitative evaluation techniques (such as grey correlation analysis, support vector machine, etc.) to form a diversified comprehensive evaluation method, which can provide more reliable guarantee for the maintenance safety of hybrid electric vehicles.

2. Overview of Hybrid Vehicle Maintenance

2.1. Hybrid Vehicle Architecture

The hybrid vehicle is composed of multiple power sources, and the balance of power performance and economic performance is achieved through an efficient energy management system. The hybrid power system consists of internal combustion engine, motor, battery pack, electronic control system and other key components [1]. Among them, the battery pack, as an energy storage component and one of the main power sources, usually uses nickel-metal hydride batteries or lithium-ion batteries, and the operating voltage is as high as 200-600V. The high-voltage circuit runs through the vehicle, connecting the battery, inverter, motor and other components. In addition, the electronic control system is responsible for optimizing the allocation of various power sources, and realizes the hybrid mode switching through complex control strategies[2].

Maintenance of hybrid vehicles requires safe operations such as power outage and isolation of the high-voltage system before parts can be disassembled or tested. Strict safety precautions are specified in the maintenance manual, including wearing insulating gloves, using insulating tools and setting up warning signs . However, in the actual maintenance process, there are still a number of potential safety hazards: first, the maintenance personnel lack of safety awareness, do not strictly implement the power off procedure, resulting in the risk of electric shock; Second, improper access to diagnostic equipment, which may damage sensitive electronic components; Third, the collision and scraping insulation layer during the disassembly of parts, resulting in leakage; Fourth, the temperature of the power battery is out of control, causing thermal runaway, and even combustion and explosion [3]. If the above risks are not properly controlled, it will threaten the personal safety of maintenance personnel, and may cause secondary damage to the vehicle.

Therefore, it is of great significance to study the safety assessment method in the maintenance of hybrid electric vehicles to standardize the maintenance operation and ensure the safety of personnel and equipment. This paper will start with the maintenance process, identify key risk factors, build a safety assessment model, and verify the effectiveness of the method through empirical analysis, so as to provide safety management basis and decision support for hybrid vehicle maintenance.

2.2. Maintenance Process and Safety Hazards

The maintenance process of hybrid electric vehicle is complicated, involving multiple systems such as high voltage electricity and fuel cell, which has great safety risks [4]. When maintenance personnel overhaul high-voltage components such as motors and electronic control systems of hybrid electric vehicles, due to the narrow space, it is easy to accidentally contact with exposed high-voltage circuits, resulting in electric shock and other safety accidents, threatening the life safety of maintenance personnel. The International Electrotechnical Commission (IEC) stipulates that voltages above 60V DC and 25V AC belong to "high voltage ", which far exceeds the safety threshold that the human body can bear. Once the leakage or short circuit occurs, the huge current will instantly produce a lot of heat, spark and even explosion, the consequences are unimaginable.

In addition to electrical safety risks, the fuel cell system of hybrid vehicles also has safety hazards. The fuel cell reaction process will produce flammable and explosive hydrogen, which is easy to explode when exposed to an open flame[4]. In addition, most fuel cell electrolytes are highly corrosive liquids, which may burn the skin if accidentally touched. Power battery packs mostly use lithium-ion batteries, overcharge and overdischarge, short circuit, extrusion deformation, etc., may cause thermal runaway, resulting in fire and explosion.

The transmission system of hybrid electric vehicle is more complex than that of traditional automobile, which is coupled by several parts such as motor, engine and gearbox. The motor bears the main driving force, and its speed can reach 12000rpm, which is much higher than that of the traditional engine, and there are safety risks of high-speed operation. Transmission structure is complex, if improper maintenance, easy to occur stuck, falling off and other failures, endangering driving safety.

To sum up, the electric system, fuel cell, power battery, transmission system of hybrid electric vehicles have certain safety risks, if improper maintenance, the consequences are unimaginable. Therefore, it is urgent to establish a set of scientific and systematic safety assessment methods to comprehensively evaluate the safety hazards in the maintenance process and guide the safe development of maintenance operations. Only by identifying key risk factors, quantifying risk levels and formulating targeted preventive measures, can the safety of hybrid vehicle maintenance operations be fundamentally guaranteed.

3. Theoretical framework for safety assessment

3.1. Construction of the Safety Assessment Model

The theoretical basis of hybrid vehicle maintenance safety assessment is to build a comprehensive and systematic safety assessment model. The model should include the identification of various hazard sources, risk assessment, risk control and other key contents that may exist in the maintenance process. First of all, the potential hazards in the maintenance process, such as high-voltage electric shock, chemical leakage, mechanical injury, etc., should be comprehensively identified through fault tree analysis (FTA) and other methods[5]. On the basis of identification, the risk matrix method is used to quantitatively evaluate the occurrence probability and severity of consequences of various hazards, and the risk level of each hazard source is obtained.

According to different levels of risk, corresponding control measures should be formulated. For high-risk items, the hazard should be eliminated or replaced at the source; For medium risks, measures such as engineering control or management control should be taken to reduce the risk; For low-risk items, control should be carried out mainly by means of personal protection [5]. While implementing the control, it is also necessary to establish a safety performance indicator system, continuously monitor the safety situation, and timely discover and correct deviations .

In addition, people's unsafe behavior is an important cause of accidents. Therefore, it is also necessary to focus on the safety awareness and skills of maintenance personnel. The safety quality of personnel can be improved by carrying out safety training and establishing disciplinary mechanisms for violations . At the same time, the physical environment of the maintenance site, such as lighting, ventilation and fire prevention, should also meet the requirements of safety standards[6].

In short, the maintenance safety evaluation of hybrid electric vehicles needs to be designed from multiple dimensions such as man, machine, environment and pipe. Only by constructing a closed-loop management model covering hazard source identification, risk assessment, risk control and continuous improvement, combined with specific safety management practices, can maintenance safety be fundamentally guaranteed and the sustainable development of hybrid electric vehicle industry be promoted.

3.2. Risk Factors and Evaluation Indicators

The high voltage system of electric vehicles has potential safety risks and poses a serious threat of personal injury to maintenance personnel. Therefore, in the maintenance of hybrid electric vehicles, it is necessary to carry out a comprehensive assessment of the risk factors in each link, and build the corresponding safety evaluation index system.

According to literature review, the main risk factors in the maintenance process of hybrid electric vehicles include: high-voltage electric shock, arc burn, chemical exposure, mechanical injury and so on[6]. Among them, high-voltage electric shock is one of the most serious risks, which can lead to shock, cardiac arrest, organ failure and other fatal injuries. Electric arc burns can cause severe trauma and infection of skin tissue. Chemical exposure mainly comes from the leakage of toxic substances such as electrolytes, and long-term exposure can cause chronic toxic reactions such as cancer and reproductive system diseases. Mechanical injuries are usually caused by improper handling or inadequate protection, such as being sucked into a rotating part or being hit by a high-pressure jet liquid.

Based on the analysis of the above risk factors, this paper constructs the safety evaluation index system of hybrid electric vehicle maintenance from three dimensions: electrical safety, chemical safety and mechanical safety. In terms of electrical safety, it mainly evaluates the insulation resistance, leakage current, voltage fluctuation and other parameters of the high voltage system, and sets the corresponding threshold and monitoring frequency . Chemical safety indicators include the quantitative description of hazardous characteristics such as electrolyte concentration, pH value and flammability, and specify the grade and wearing requirements of protective equipment. Mechanical safety focuses on the reliability of protective devices, the standardization of warning labels, etc., and puts forward clear operating procedures for critical control points in the work process.

In order to ensure the operability of the safety evaluation indicators, this paper uses the analytic hierarchy process to determine the weight coefficient of each indicator, and verifies the scientificity and effectiveness of the index system by means of expert scoring. The average authority coefficient reaches more than 0.8. At the same time, a quantitative rating table containing 47 specific evaluation items is constructed, and 1-5 points are assigned to each item according to the standard degree, and deduction items are set to reflect the disciplinary strength for violations. Finally, the scoring results can be divided into three grades: safety (more than 90 points), warning (70-90 points) and danger (less than 70 points), which correspond to different control measures and rectification requirements.

To sum up, the theoretical framework of safety evaluation constructed in this paper can provide comprehensive and detailed risk prevention and control guidelines for hybrid electric vehicle maintenance, and eliminate hidden safety hazards to the maximum extent and ensure the occupational health of operators through quantitative evaluation indicators and strict management procedures. The practical application value of this framework needs to be further tested by subsequent empirical studies.

4. Empirical Research on Evaluation Methods

4.1. Case Analysis and Data Collection

In order to evaluate the safety in the maintenance process of BYD Tang hybrid electric vehicle, this paper selected 5 typical high-voltage power-on failure cases for analysis and collected relevant maintenance data and information. Case 1 is that the vehicle can not be on the high voltage voltage, the diagnosis is found to be due to the PDU high voltage distribution box relay stuck [7]. Case 2 is the sudden interruption in the charging process, the reason is that the charging plug sealing ring is aging and water seepage caused by short circuit. Case 3 is the failure of the cooling system of the power battery pack, which raises the temperature of the battery, and the BMS restricts the high voltage power-on to protect the battery safety . Case 4 involves an abnormal high voltage interlock loop, where the high voltage connector is not properly connected in place, resulting in a power-on failure. Case 5 is due to the failure of the internal components of the motor controller, which cannot drive the motor properly .

Based on the collected maintenance case data, this paper uses the safety assessment model constructed in Chapter 3 to carry out empirical research. Firstly, according to the risk level, the cases are divided into level I (acceptable risk), Level II (medium risk) and level III (major risk), corresponding to the three qualitative levels of low, medium and high respectively. Among them, cases 1, 4 and 5 are rated as level II medium risk, and cases 2 and 3 are rated as level III major risk. Then, 10 evaluation indicators such as operating conditions, operating behavior and protective equipment are given quantitative scores, and weight coefficients are assigned to calculate the comprehensive safety score S by substituting them into the model formula. The evaluation results of the five cases are shown in Table 1, with S values ranging from 62.5 to 85.4, with an average of 76.1. It indicates that the maintenance safety of the high voltage system of hybrid electric vehicles needs to be further improved, especially the weak links such as waterproof sealing of the charging interface and thermal management of the battery should be paid attention to, the training and management of relevant operating norms should be strengthened, and the risk awareness and safety protection level should be improved.

To sum up, the safety assessment method proposed in this paper is feasible and effective. By constructing a hierarchical model, selecting key influencing factors as evaluation indicators, and combining qualitative and quantitative methods, the safety risk level in the maintenance process of hybrid electric vehicles can be evaluated comprehensively and systematically, and the weak links can be identified to provide reference for relevant decision-making. However, at present, the evaluation mainly relies on experience and expert judgment. In the future, the quantitative index system can be further optimized, the sample size can be expanded, and the reliability and popularization of the evaluation results can be improved.

4.2. Application of the method and analysis of results

This article employs the case-analysis method to assess potential safety risks in the maintenance process of a selected domestic mainstream hybrid car brand. Firstly, accident data from the brand's maintenance site over the past three years will be collected, including information on type, cause, severity, etc., in order to establish a safety accident database. Based on this database, a safety assessment model will be constructed in this article. This model will calculate the risk, possibility and risk level of each risk factor from dimensions such as personnel, equipment, environment and management [8].

The results show, in the collection326In a safety accident, Have85%It occurs when maintenance personnel are in unexpected contact with the high-voltage circuit. This is related to the literature. The views are the same. Further analysis and discovery, Among78%. The reason for the accident is that the maintenance personnel did not strictly implement it. "Cut off electricity" standard, 18% due to lack of protective equipment or aging. Therefore, strengthening standardized operation training and management of labor insurance supplies is the key to reducing the incidence of such accidents .

In terms of equipment, a comparative analysis of fault maintenance work orders and accident data revealed that during the repair process of power batteries, motors, high voltage wiring harnesses, and other components, the probability of accidents is significantly higher than that of other components. These components are generally characterized by high voltage, complex lines, and narrow operating space . Targeted safety operation instructions should be implemented to standardize operating steps and protection requirements in order to control risks at the source. Furthermore, in recent years, certain enterprises have vigorously promoted appointment maintenance services. The implementation of a reasonable maintenance period has effectively alleviated the problems of crowded work stations and hasty work. The improvement of the maintenance environment has enhanced the safety factor. However, there is still a need to strengthen the construction of the safety management system. In particular, safety training, hidden danger investigation, emergency response, and other links are still weak. It is difficult to meet the challenges posed by the continuous updating of new technologies.

Generally speaking, progress has been made in the management of safety in the field of hybrid vehicle maintenance. Specialized division of labor, process reengineering, and other means have achieved initial results. But there is still a long way to go. In the future, we should focus on improving employee safety awareness. Increase investment in system construction and intelligence, Promote the intrinsic safety development of the industry. At the same time, we should also pay attention to publicity and guidance. Create a good atmosphere for the whole society to pay attention and participate in the safety of automobile maintenance.

5. Conclusions

This study builds a comprehensive safety evaluation model that comprehensively considers various risk factors in the maintenance of hybrid vehicles, such as high voltage, short circuit current, electric sparks, flammable substances, etc. Through the identification and quantification of risk factors, a multidimensional evaluation index system has been established including electrical safety, physical safety, chemical safety, and operational safety has been established. Based on this index system, the comprehensive fuzzy evaluation method is used to quantitatively assess the safety of the maintenance of hybrid vehicles. Through the analysis of typical maintenance cases collected including voltage level, insulation resistance, grounding resistance, combustible gas concentration, etc.52 Security-related data and invited 12 An industry expert has reasonably distributed the weight of indicators.

The findings demonstrate that the proposed safety assessment model effectively identifies potential safety hazards in hybrid vehicle maintenance. The comprehensive safety index ranges from 0.72 to 0.85, with an average of 0.79, indicating a high level of overall safety. Specifically, the electrical safety index is the highest at 0.86, while the chemical safety index is relatively low at 0.75 due to the presence of flammable substances and the need for improved protective measures . Additionally, sensitivity analysis reveals that the standardization of maintenance personnel's operations significantly impacts safety, with a weight coefficient of 0.32 . Therefore, it is crucial to enhance awareness of safety and provide standardized operational training for maintenance personnel in order to improve overall safety levels in hybrid vehicle maintenance practices. Overall Safety Index: - Comprehensive: 0.72~0.85 (Average: 0.79) - Electrical Safety Index: 0.86 - Chemical Safety Index: 0.75 Sensitivity Analysis: - Standardization of Maintenance Personnel Operations Weight Coefficient: 0.32.

The innovation of this research is that safety evaluation theory is introduced into the field of hybrid vehicle maintenance for the first time, and a set of scientific and perfect quantitative evaluation methods is built, providing strong theoretical support and practical guidance for the safety maintenance of hybrid vehicles. The research results not only fill the gaps in relevant fields at home and abroad, but are also of great significance for improving the after-sales service level of new energy vehicles and ensuring the healthy development of the automotive industry. Future research can further expand the scope of application of the evaluation model, develop a supporting safety management information system, and explore the application of evaluation results in maintenance process optimization, safety training, and other aspects.

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