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Research Article

Reliability Analysis of the High-Voltage Power Battery System Based on the Polymorphic Fuzzy Fault Tree

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Accidents caused by the failure of high-voltage power battery systems are rising with the increase of pure electric commercial vehicles. The fault tree analysis method based on traditional reliability is no longer suitable for quantitative evaluation of polymorphic systems. In this paper, the polymorphic fuzzy fault tree of the high-voltage power battery system for pure electric commercial vehicles is established and analyzed qualitatively and quantitatively based on a combined theory of the polymorphic theory, fuzzy mathematical theory, group decision theory, and fault tree analysis theory. The results showed that the multistate reliability-analysis method of the fuzzy fault tree could describe the various fault states of the high-voltage power battery system. Through quantitative evaluation of the reliability of system, the low-temperature environment and CAN high and low reverse connection were the weakest links of the system, and the problem of the occurrence probability of each state of the unknown polymorphic bottom event in the sub-fault tree of the deteriorated-state mode was solved quickly using group decision-making to deal with fuzzy probability. It provides theoretical reference for system design and detection process, which has important practical significance for the improvement of high-voltage power battery system.

1. Introduction

The problems of energy and environmental protection are becoming more and more serious with the increased number of automobiles. At present, BYD, Dongfeng LiuQi, BAIC, and other major vehicle enterprises have focused on pure electric commercial vehicles with energy conservation, environmental protection, and large cargo capacity. With promoted pure electric commercial vehicles, the accidents on the reliability of the high-voltage power battery system also increase year by year. According to the statistics of the GGII (Gao Gong Industrial Research Institute), there were 34 fire accidents caused by battery problems in domestic electric vehicles from January to May 2021, involving up to 38 vehicles. Each accident is a severe challenge to the reliability of the high-voltage power battery system. The system produces hundreds of amperes of charge and discharge currents in the working process, which seriously threatens the safety of vehicles and drivers.

Reliability analysis methods have been widely used in engineering fields in continuous development. Huang et al. [1] proposed the fault tree analysis (FTA) and applied it to the design of the militia missile launch control system to predict the failure probability of missile launch in the 1960s. Subsequently, Dhillon et al. [2] of Boeing Company developed a program of the fault tree analysis method, which reduces the workload of data processing in the reliability research at the early stage of aircraft design and promotes fault-tree analysis algorithms. Rahman et al. [3] of MIT applied the fault tree analysis method in the risk assessment of nuclear power plants and listed all the causes of nuclear power plant failures in 1974. Yang et al. [4] proposed a diagnosis method that combined the fault tree analysis with an expert system to develop a fault diagnosis expert system to meet the fault diagnosis function of the DC charging pile. Lanza et al. [5] analyzed the reliability of feedback fault information to establish the machine-tool fault diagnosis and prediction system. Besides, the reliability guarantee system is built in the designing, manufacturing, and assembly process of NC machine tools. The reliability analysis method is also applied to the field of fault diagnosis, and the fault diagnosis method proposed by Xin et al. [6–8] can effectively solved the problem of mechanical reliability. The fuzzy fault tree analysis method is proposed to solve fuzzy probability in practical engineering.

The fuzzy fault tree analysis was first proposed by Tanaka et al. [9]. Fuzzy probability is used to replace accurate probability to solve the uncertain probability in the fault tree analysis. Singer [10] used L-R-type fuzzy numbers to represent the occurrence probability of bottom events and further developed the fuzzy fault tree analysis method. Yuhua and Datao [11] combined expert heuristics with the fuzzy set theory to solve the fuzziness of failure probability of some bottom events in oil and gas transmission pipelines. Liu et al. [12] proposed a reliability analysis method based on the Bayesian network and T-S (Takagi-Sugeno) fault tree. The nodes in the Bayesian network are represented by the fuzzy probability, and the fault degree of the system is represented by fuzzy variables. This technology is applied to the reliability analysis of the injection system of the chemotherapy robot. Yin et al. [13] proposed a safety evaluation method for natural gas storage tanks based on the fuzzy fault-tree analysis method of similarity aggregation.

The theory of the multistate system (MSS) provides a new way for the reliability analysis of complex systems. Satyanarayana and Prabhakar [14] studied the reliability of networked systems to propose the idea of solving the reliability of a system by simply computing the sum of the probabilities of acyclic subgraphs in the 1970s. Iscioglu [15] proposed a new method to evaluate the MRL (mean residual lifetime) function of a one-unit, three-state system using the conditional residual function. Borges et al. [16] proposed the Monte Carlo parallel reliability analysis method, which has high efficiency in testing the actual power system model and can evaluate the reliability of a large-scale power grid. Mahadevan et al. [17] used the Bayesian network to compare with the traditional reliability analysis methods of series and parallel systems, with its effectiveness verified. Considering the impact of component degradation and different maintenance strategies, Mohammadhasani [18] used the Markov maintenance model to quantify the effectiveness of maintenance activities. These models are coupled with the fault tree method, providing a more practical and accurate fault tree analysis tool. Research on the smoothness of commercial vehicles has expanded the application of reliability in engineering [19, 20].

Among the numerous causes of the functional failure of the high-voltage power battery system, the occurrence probability of power battery system failure caused by insulation failure is assumed to be between 0.02 and 0.03. Namely, the accurate occurrence probability is a fuzzy number. Among the reasons for the degradation of the high-voltage power battery system, the oxidation and reduction of battery electrolyte is a dynamic process, that is, a multistate event. Therefore, after considering the limitation of the traditional fault tree analysis method on the fuzziness and polymorphism of the high-voltage power battery system of pure electric commercial vehicles, the multistate fuzzy fault tree analysis method is used to analyze its reliability.

The work took a high-voltage power battery system of pure electric commercial vehicles as an example and applied theories such as the multistate theory and fuzzy mathematics to establish a multistate fuzzy fault tree for the high-voltage power battery system. Minimum reliability was 0.4607, and maximum reliability was 0.5370 for the high-voltage power battery system. Furthermore, low-reliability events directly affecting the reliability of the system were identified.

The following items have been accomplished: (1) A complete multistate fuzzy fault tree for high-voltage power battery systems of pure electric commercial vehicles was established to solve the functional-failure mode, deteriorated-state mode, and subfault tree models to analyze the reliability of high-voltage power battery systems. (2) Qualitative and quantitative analyses were performed on all bottom events of the subfault tree causing the functional failure mode. The weak links causing the system failure were identified by the fuzzy-probability importance of each bottom event. (3) For the problem of unknown probability of multistate bottom events in each state, group decision-making was used to deal with fuzzy probabilities, thus solving the subfault trees in the state deterioration mode.

The remainder of the work is organized as follows. Section 2 introduces the basic theory of the polymorphic fuzzy fault tree analysis method. The polymorphic fuzzy fault tree of the high-voltage power battery system of pure electric commercial vehicles is established and analyzed in Section 3. Section 4 solves the fuzzy-probability importance of each bottom event of the subfault tree in the functional failure mode. Finally, the conclusions are summarized in Section 5.

2. Basic Theory of the Polymorphic Fuzzy Fault Tree Analysis Method

2.1. Fault Tree Analysis. The fault tree analysis (FTA) [21] can analyze all the possible causes of system failure in the system design process. A "tree" logic block diagram is drawn to identify the basic events causing system failure. Qualitative analysis is used to solve the probability of system failure and the importance of the bottom event.

2.1.1. Qualitative FTA

(1) Cut Set and Minimum Cut Set. The set composed of the bottom events causing the occurrence of the top event of the fault tree is called the cut set. The set consisting of the minimum number of bottom events causing the occurrence of the top event of the fault tree is called the minimum cut set.

(2) Method of Solving the Minimum Cut Set. There are two methods of solving for the minimum cut set, the downward method (Fussell-Vesely) and the upward method (Semanderes) [22]. The downward method starts from the top event layer by layer down and lists "OR" gate events and top events into different lines. Besides, "AND" gate events and

top events are listed in the same line. The non-minimum cut set is eliminated to obtain the minimum cut set until the basic events can no longer be decomposed. The upward method, i.e., proceeding from the bottom to the top, replaces the corresponding logic gate symbols with set symbols and expresses the fault tree structure-function in terms of event symbols and set operators. Finally, the expressions for the top event are listed to find the minimum cut set.

2.1.2. Quantitative FTA

(1) Calculation of the Occurrence Probability of Top Events. In the quantitative analysis of the fault tree, the probability of the top event can be calculated according to the occurrence probability of the bottom event and structural function. The probability of the occurrence of base event $X_i (i = 1, 2, \cdots, n)$ is assumed to be $P(X_i)(i = 1, 2, \cdots, n)$. When the logic gate is "OR" and "AND," and the occurrence of the base event is independent of each other, the calculation method of the probability of the top event is as follows:

(1) When the fault-tree logic gates are logical "OR" gates, the probability of at least one bottom event occurring is

$$\begin{aligned} P_{\cup} &= 1 - [1 - P(X_1)] \times [1 - P(X_2)] \times \cdots \times [1 - P(X_n)] \\ &= 1 - \prod_{i=1}^{n} [1 - P(X_i)] \end{aligned} \tag{1}$$

(2) When the fault-tree logic gates are logical "AND" gates, the probability of n bottom events occurring simultaneously is

$$P_{\cap} = P(X_1) \times P(X_2) \times \cdots \times P(X_n) = \prod_{i=1}^{n} P(X_i) \tag{2}$$

(2) Calculation of probability's Importance of the Bottom Event. Importance is the magnitude of the contribution of the minimum cut set or bottom event to the occurrence of the top event, and the importance of the bottom event to the top event is positively related to its probability importance. If the probability's importance of a bottom event is close to 1, then the system must fail once that bottom event occurs.

Probability's importance is defined as

$$I_i(t) = \frac{\partial g(Q(t))}{\partial Q_i(t)}, \tag{3}$$

where Q is the unreliability of the system.

(3) Calculation of Subsystem Reliability. According to the traditional reliability theory, the general expression of the function between reliability and failure probability is

$$R(t) = e^{-\int_0^t \lambda(t) dt}, \tag{4}$$

where $\lambda(t)$ is the failure probability.

When $\lambda(t)$ is a constant, i.e., $\lambda(t) = \lambda$. Then, the reliability of the system is

$$R(t) = e^{-\lambda}. \tag{5}$$

According to the relationship between reliability and unreliability, the relationship between unreliability and failure probability is

$$F(t) = 1 - R(t) = 1 - e^{-\lambda}. \tag{6}$$

2.2. Fuzzy Fault Tree Analysis

2.2.1. L-R Fuzzy Number. The occurrence probability of the bottom event of the high-voltage power battery system of pure electric commercial vehicles is fuzzy. A fuzzy number is used to analyze the fault tree.

Generally, fuzzy numbers are described by reference functions. Let L and R be the reference functions of fuzzy numbers, if

$$\mu_{\tilde{A}}(x) = \begin{cases} L\left(\dfrac{m-x}{\alpha}\right), x \le m, \alpha > 0, \\ R\left(\dfrac{x-m}{\beta}\right), x \ge m, \beta > 0. \end{cases} \tag{7}$$

Then, the fuzzy number $\tilde{A}$ in Equation (7) is defined as L-R fuzzy number. It is recorded as $\tilde{A} = (m, \alpha, \beta)_{LR}$, where m is the mean value of fuzzy number $\tilde{A}$, α and β are the upper and lower confidence limits of fuzzy number $\tilde{A}$, and $\mu_{\tilde{A}}(x)$ is the membership function of $\tilde{A}$. When α and β are equal to 0, $\tilde{A}$ is no longer a fuzzy number but a regular clear number. Moreover, larger α and β indicate more ambiguous $\tilde{A}$ [22]. α and β are generally taken as 10 to 20% of fuzzy mean m [23]. The commonly used membership functions of L-R fuzzy numbers are triangular and normal.

(1) Triangular. The triangular membership function can be expressed as

$$\mu_{\tilde{A}}(x) = \begin{cases} 0, & x < m - \alpha, \\ 1 - \dfrac{m-x}{\alpha}, & m - \alpha \le x \le m, \\ 1 - \dfrac{x-m}{\beta}, & m < x \le m + \beta, \\ 0, & x > m + \beta. \end{cases} \tag{8}$$

Figure 1 shows the triangular membership function.

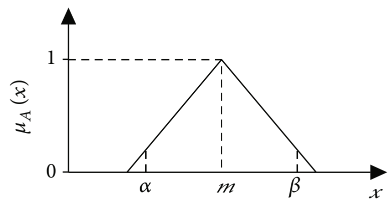

Figure 1: Triangular membership function

The λ-cut set interval of triangular fuzzy number $\tilde{A} = [(m-\alpha), m, (m+\beta)]$ is

$$\tilde{A}_\lambda = [(m-\alpha) + \alpha \bullet \lambda, (m+\beta) - \beta \bullet \lambda]. \tag{9}$$

If there are two triangular fuzzy numbers $\tilde{A}$ and $\tilde{B}$, there are four algorithms for expansion according to the classical extension principle [24] for any λ in interval [0, 1].

(1) Fuzzy-number addition:

$$\tilde{A}_\lambda + \tilde{B}_\lambda = \left[L_A^\lambda, R_A^\lambda\right] + \left[L_B^\lambda, R_B^\lambda\right] = \left[L_A^\lambda + L_B^\lambda, R_A^\lambda + R_B^\lambda\right]. \tag{10}$$

(2) Fuzzy-number subtraction:

$$\tilde{A}_\lambda - \tilde{B}_\lambda = \left[L_A^\lambda, R_A^\lambda\right] - \left[L_B^\lambda, R_B^\lambda\right] = \left[L_A^\lambda - L_B^\lambda, R_A^\lambda - R_B^\lambda\right]. \tag{11}$$

(3) Fuzzy-number multiplication:

$$\tilde{A}_\lambda \times \tilde{B}_\lambda = \left[L_A^\lambda, R_A^\lambda\right] \times \left[L_B^\lambda, R_B^\lambda\right] = \left[L_A^\lambda \times L_B^\lambda, R_A^\lambda \times R_B^\lambda\right]. \tag{12}$$

(4) Fuzzy-number division:

$$\tilde{A}_\lambda / \tilde{B}_\lambda = \left[L_A^\lambda, R_A^\lambda\right] / \left[L_B^\lambda, R_B^\lambda\right] = \left[\frac{L_A^\lambda}{L_B^\lambda}, \frac{R_A^\lambda}{R_B^\lambda}\right]. \tag{13}$$

(2) Normal. The normal membership function can be expressed as

$$\mu_{\tilde{B}}(x) = \begin{cases} \left(\dfrac{m-x}{\alpha}\right)^2, & x \in \left[m - \alpha\sqrt{-ln\lambda}, m\right), \\ R(x) = e^{-((x-m)/\beta)^2}, & x \in \left(m, m + \beta\sqrt{-ln\lambda}\right], \\ 1, & x = m, \\ 0, & \text{others}. \end{cases} \tag{14}$$

The interval of the λ-cut set of normal type membership function $\tilde{B}$ can be obtained as

$$\tilde{B}_\lambda = \left[m - \alpha\sqrt{-ln\lambda}, m + \beta\sqrt{-ln\lambda}\right]. \tag{15}$$

Figure 2 shows the normal membership function.

2.2.2. Fuzzy Operator of the Fault Tree Analysis. The logic gate operator is used to calculate the probability of the basic bottom event, thus obtaining the probability of the top event of the traditional fault tree [25]. The system's occurrence probability of the top event, namely, the failure probability of the top event, can be accurately obtained by the bottom-event occurrence probability and structure function. Besides, system reliability can be obtained. Fuzzy number $\tilde{F}_i$ is introduced to represent the occurrence probability of the basic bottom event in the process of analyzing the fuzzy fault tree, and the fuzzy logic gate operator is used to replace the traditional one, which can obtain the fuzzy number of the occurrence of the top event [26].

Probability $\tilde{F}_i$ of the bottom event represented by a triangular fuzzy number that λ-cut set is

$$\begin{aligned} \tilde{F}_{1\lambda} &= [(m_1 - \alpha_1) + \lambda\alpha_1, (m_1 + \beta_1) - \lambda\beta_1], \\ \tilde{F}_{2\lambda} &= [(m_2 - \alpha_2) + \lambda\alpha_2, (m_2 + \beta_2) - \lambda\beta_2], \\ &\vdots, \\ \tilde{F}_{i\lambda} &= [(m_i - \alpha_i) + \lambda\alpha_i, (m_i + \beta_i) - \lambda\beta_i], \\ &\vdots, \\ \tilde{F}_{n\lambda} &= [(m_n - \alpha_n) + \lambda\alpha_n, (m_n + \beta_n) - \lambda\beta_n]. \end{aligned} \tag{16}$$

According to the characteristics of fault-tree logic "AND" and "OR" gates, the fuzzy operators of a triangular fuzzy number "AND" and "OR" gates are as follows.

(1) Logic "AND" gate:

$$\begin{aligned} \tilde{F}_{S\cap} &= \prod_{i=1}^{n} \tilde{F}_{i\lambda} = \tilde{F}_{i\lambda} \bullet \tilde{F}_{2\lambda} \bullet \tilde{F}_{3\lambda} \bullet \cdots \bullet \tilde{F}_{(n-1)\lambda} \bullet \tilde{F}_{n\lambda} \\ &= \left[\prod_{i=1}^{n} [(m_i - \alpha_i) + \lambda\alpha_i], \prod_{i=1}^{n} [(m_i + \beta_i) + \lambda\beta_i]\right]. \end{aligned} \tag{17}$$

(2) Logic "OR" gate:

$$\begin{aligned} \tilde{F}_{S\cup} &= 1 - \prod_{i=1}^{n} \left(1 - \tilde{F}_{i\lambda}\right) \\ &= \left[1 - \prod_{i=1}^{n} [1 - (m_i - \alpha_i) - \lambda\alpha_i], 1 - \prod_{i=1}^{n} \cdot [1 - (m_i + \beta_i) + \lambda\beta_i]\right]. \end{aligned} \tag{18}$$

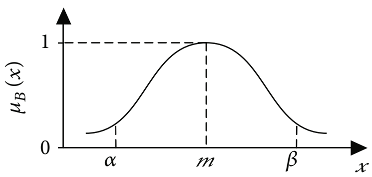

Figure 2: Normal membership function.

Probability $\tilde{F}_i$ of the bottom event represented by a normal fuzzy number that λ-cut sets is

$$\begin{aligned} \tilde{F}_{1\lambda} &= \left[m_1 - \alpha_1\sqrt{-\ln\lambda}, m_1 + \beta_1\sqrt{-\ln\lambda}\right], \\ \tilde{F}_{2\lambda} &= \left[m_2 - \alpha_2\sqrt{-\ln\lambda}, m_2 + \beta_2\sqrt{-\ln\lambda}\right], \\ &\vdots, \\ \tilde{F}_{i\lambda} &= \left[m_i - \alpha_i\sqrt{-\ln\lambda}, m_i + \beta_i\sqrt{-\ln\lambda}\right], \\ &\vdots, \\ \tilde{F}_{n\lambda} &= \left[m_n - \alpha_n\sqrt{-\ln\lambda}, m_n + \beta_n\sqrt{-\ln\lambda}\right]. \end{aligned} \tag{19}$$

Similarly, the fuzzy operators of "AND" and "OR" gates of normal fuzzy numbers are as follows.

(1) Logic "AND" gate:

$$\begin{aligned} \tilde{F}_{S\cap} &= \prod_{i=1}^{n} \tilde{F}_{i\lambda} = \tilde{F}_{i\lambda} \bullet \tilde{F}_{2\lambda} \bullet \tilde{F}_{3\lambda} \bullet \cdots \bullet \tilde{F}_{(n-1)\lambda} \bullet \tilde{F}_{n\lambda} \\ &= \left[\prod_{i=1}^{n}\left(m_i - \alpha_i\sqrt{-\ln\lambda}\right), \prod_{i=1}^{n}\left(m_i + \beta_i\sqrt{-\ln\lambda}\right)\right]. \end{aligned} \tag{20}$$

(2) Logic "OR" gate:

$$\begin{aligned} \tilde{F}_{S\cup} &= 1 - \prod_{i=1}^{n}\left(1 - \tilde{F}_{i\lambda}\right) \\ &= \left[1 - \prod_{i=1}^{n}\left[1 - \left(m_i - \alpha_i\sqrt{-\ln\lambda}\right)\right], 1 - \prod_{i=1}^{n} \right. \\ &\quad \left. \cdot \left[1 - \left(m_i + \beta_i\sqrt{-\ln\lambda}\right)\right]\right]. \end{aligned} \tag{21}$$

2.3. Polymorphic Fuzzy Fault-Tree Analysis

2.3.1. Multistate Fault Gate. When the input event of the system top event contains one or more multistate events, this logic gate is called a polymorphic fault gate. Supposing there are n polymorphic input events $X_i (i = 1, 2, \cdots, n)$ in the fault gate, i.e., the state of the input event meets $S_{X_i} \in \{0, 0.5, 1\}$, $S_{X_i} \in \{\text{normal, degradation, failure}\}$. Then the state of top event U satisfies the following equation:

$$S_U = \begin{cases} 0, & \sum_{i=1}^{n} S_{X_i} = 0, \\ 0.5, & S_{X_i} \leq 0.5 \text{ and } \sum_{i=1}^{n} S_{X_i} \neq 0, \\ 1, & \text{others}. \end{cases} \tag{22}$$

Equation (22) shows that when the states of input polymorphic events are all 0, that is, all input polymorphic events are normal, and the state of output events is also normally 0. When the state of the input polymorphic event is 0.5 or a combination of 0 and 0.5, namely, the input polymorphic event is in a degraded state or a combination of the degraded state and normal state, and the state of the output event is also degraded. When at least one of the input polymorphic events is in state 1, that is, the state of at least one input event is in a failure state, and the output of the whole system is in a failure state.

2.3.2. Analysis of the Deteriorated-State Mode. Aiming at the problem to determine the exact probability of polymorphic bottom events in different states in the deteriorated-state mode, the work used group decision-making, expert experience, and fuzzy numbers. The probability of polymorphic bottom events in each state was obtained by averaging, defuzzifying, and normalizing the obtained fuzzy probability.

(1) Fuzzy Probability Obtained according to the Language Variables. Seven linguistic variables are introduced to combine fuzzy probability with linguistic variables [27]. Table 1 shows the relationship between language variables and the fuzzy probability.

The last column of Table 1 represents the triangular fuzzy number corresponding to the language variable, and this method can convert the expert experience into a fuzzy probability expressed in triangular fuzzy numbers (see Table 1). Namely, it is a constant under the membership function, and its value corresponds to the fuzzy probability and solved the problem of probability unknown.

If q experts are participating in the decision-making that the language variable of the bottom event X_i given by the k-th decision-maker in the j $(j = 1, 2, \text{and } 3)$, state is transformed into the fuzzy probability as $\tilde{P}_{ij}^{k} = (\alpha_{ij}^{k}, m_{ij}^{k}, \beta_{ij}^{k})$ $k = 1, 2, \cdots, q$.

(2) Fuzzy-Probability Averaging. The obtained fuzzy probability is mathematically averaged. Then, the fuzzy probability of bottom event X_i in state j is

$$\tilde{P}_{ij}^{`} = \frac{\tilde{P}_{ij}^{1} + \tilde{P}_{ij}^{2} + \cdots + \tilde{P}_{ij}^{q}}{q}. \tag{23}$$

Table 1: Correspondence between language variables and the fuzzy probability.

Serial number	Fuzzy language	Semantic symbols	Triangular fuzzy number
1	Very high	VH	(0.9, 1.0, 1.0)
2	High	H	(0.7, 0.9, 1.0)
3	Generally high	GH	(0.5, 0.7, 0.9)
4	Medium	M	(0.3, 0.5, 0.7)
5	Generally low	GL	(0.1, 0.3, 0.5)
6	Low	L	(0, 0.1, 0.3)
7	Very low	VL	(0, 0, 0.1)

(3) Defuzzification. After the fuzzy probability is processed by the mean area method, the accurate probability of each bottom event X_i in state j is obtained as follows:

$$P'_{ij} = \frac{\tilde{P}'_{ij}(1) + 2\tilde{P}'_{ij}(2) + \tilde{P}'_{ij}(3)}{4}. \tag{24}$$

(4) Normalization. The accurate probability of the bottom event in each state is normalized to ensure that the sum of the probabilities of the bottom event in each state is 1. After processing, the accurate probability of each bottom event X_i in state j is obtained as

$$P_{ij} = \frac{P'_{ij}}{\sum_{j=1}^{3} P'_{ij}}. \tag{25}$$

3. Fault-Tree Analysis of the High-Voltage Power Battery System

3.1. Working Principle of the High-Voltage Power Battery System. The high-voltage power battery pack provides electricity for pure electric commercial vehicles. Its high-voltage DC output flows the high-voltage power equipment such as the steering power motor, brake air pump motor, and DC/DC motor inverter. The high-voltage current flowing through the motor inverter is converted into a three-phase alternating current and flows into the high-voltage drive motor and electric air conditioner motor through the high-voltage wiring harness. Figure 3 shows the working principle of the high-voltage power battery system.

3.2. Establishment of the Fault Tree for the High-Voltage Power Battery System. The fault types of the high-voltage power battery system of pure electric commercial vehicles mainly include the battery-module fault and battery-management-system fault. Battery module faults are mainly single-cell and battery-pack ones. Single-cell faults are manifested by electrolyte decomposition, active substance shedding, and the internal short circuit of the battery. Battery pack faults are manifested by single-cell inconsistency, and charging faults and battery-management-system faults are manifested by no communication, electromagnetic interference, and low drive voltage.

For the high-voltage power battery system, the power battery system fault was selected as the top event, and two intermediate events were established—the functional failure mode and state deterioration mode. The functional-failure mode was divided into battery module failure and battery management system failure to analyze the bottom event, and these two events were regarded as intermediate ones of a lower level. Then, the battery module fault and battery management system fault were analyzed until they were decomposed into events that could not be decomposed, i.e., the bottom event of the subfault tree of the functional failure mode. Meanwhile, the subfault tree of the deteriorated-state mode was decomposed and analyzed. Besides, the events of the established polymorphic fuzzy fault tree of the high-voltage power battery system were coded. The fault of the power battery system was recorded as T, and Table 2 shows the event definition and code.

According to Table 2, the polymorphic fault tree of the high-voltage power battery system of pure electric commercial vehicles is simplified as shown in Figure 4.

3.3. Qualitative Analysis of the Fault Tree. When the minimum cut set of the polymorphic fault tree is calculated, only the qualitative analysis of the subfault tree of functional failure mode is carried out due to polymorphic events and polymorphic fault gates in the subfault tree of the deteriorated-state mode. The fault tree established in the work uses the downward method according to the principle of multiplication of the “AND” gate and the addition of the “OR” gate.

$$\begin{aligned}
U_1 &= E_5 + V_1 + V_2,\\
V_1 &= W_1 + W_2,\\
V_2 &= W_3 + W_4 + W_5,\\
W_1 &= S_1 + S_2 + S_3,\\
W_2 &= S_4 + S_5,\\
W_3 &= E_{21} + E_{22} + E_{23},\\
W_4 &= E_{24} + E_{25} + E_{26} + E_{27} + E_{28},\\
W_5 &= S_6 + S_7,\\
S_1 &= E_6 + E_7 + E_8,\\
S_2 &= E_9 + E_{10},\\
S_3 &= E_{11} + E_{12},\\
S_4 &= E_{13} + E_{14},\\
S_5 &= E_{15} + K_1 + K_2,\\
S_6 &= E_{29} + E_{30},\\
S_7 &= E_{31} + E_{32},\\
K_1 &= E_{16} + E_{17},\\
K_2 &= E_{18} + E_{19} + E_{20}.
\end{aligned} \tag{26}$$

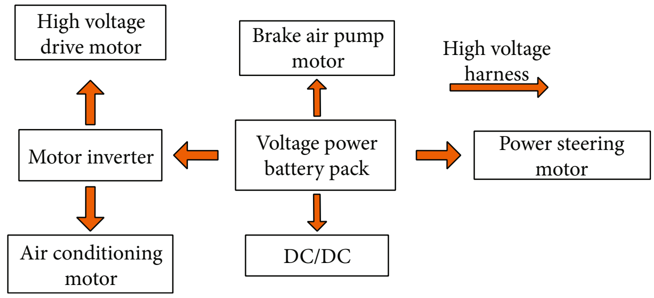

FIGURE 3: Working principle of the high-voltage power battery system.

TABLE 2: Event definitions and codes.

Event name	Event code	Event name	Event code
Functional-failure mode	U_1	Deteriorated-state mode	U_2
Battery module failure	V_1	Management system failure	V_2
Battery unit failure	W_1	Battery pack failure	W_2
No CAN communication	W_3	Inaccurate signal	W_4
No execution	W_5	Overtemperature	S_1
Short circuit	S_2	Low voltage	S_3
Monomer inconsistency	S_4	Charging fault	S_5
Fan failure	S_6	Main relay fault	S_7
Cannot be charged	K_1	High charge voltage	K_2
Electrolyte redox	E_1	Positive material phase change	E_2
Negative electrode material aging	E_3	Aging of diaphragms and increased porosity	E_4
Insulation failure	E_5	Fan not ON	E_6
Loose connection	E_7	Increased internal resistance of the battery	E_8
Plate damage	E_9	Short circuit	E_{10}
Low SOC	E_{11}	Capacity attenuation	E_{12}
Inconsistent voltage	E_{13}	Inconsistent temperature	E_{14}
Charger fault	E_{15}	Shedding of active substances	E_{16}
Battery deformation	E_{17}	Low-temperature environment	E_{18}
Late life	E_{19}	High SOC	E_{20}
No external internal resistance	E_{21}	CAN high and low reverse connection	E_{22}
Software bug	E_{23}	Impact fault	E_{24}
Bias fault	E_{25}	Electromagnetic interference	E_{26}
Sampling circuit fault	E_{27}	Connection line failure	E_{28}
Line damage	E_{29}	Damaged cooling fan	E_{30}
No working power supply	E_{31}	Low driving voltage	E_{32}

Then,

$$U_1 = E_5 + E_6 + E_7 + E_8 + \cdots + E_{30} + E_{31} + E_{32}. \qquad (27)$$

Therefore, the minimum cut set of the functional failure mode's subfault tree of the power battery system is $\{E_5\}$, $\{E_6\}$, $\{E_7\}$, $\{E_8\}$, $\cdots$, $\{E_{31}\}$, $\{E_{32}\}$, where the minimum cut set contains 28 basic base events.

3.4. Quantitative Analysis of Fault Tree. Two intermediate events of the functional failure mode and deteriorated-state mode are selected for analysis to more accurately reflect the failure mode of the high-voltage power battery system. The subfault tree of functional failure mode is solved by the fuzzy fault tree analysis, and the subfault tree of deteriorated-state mode is solved by group decision-making and fuzzy probability.

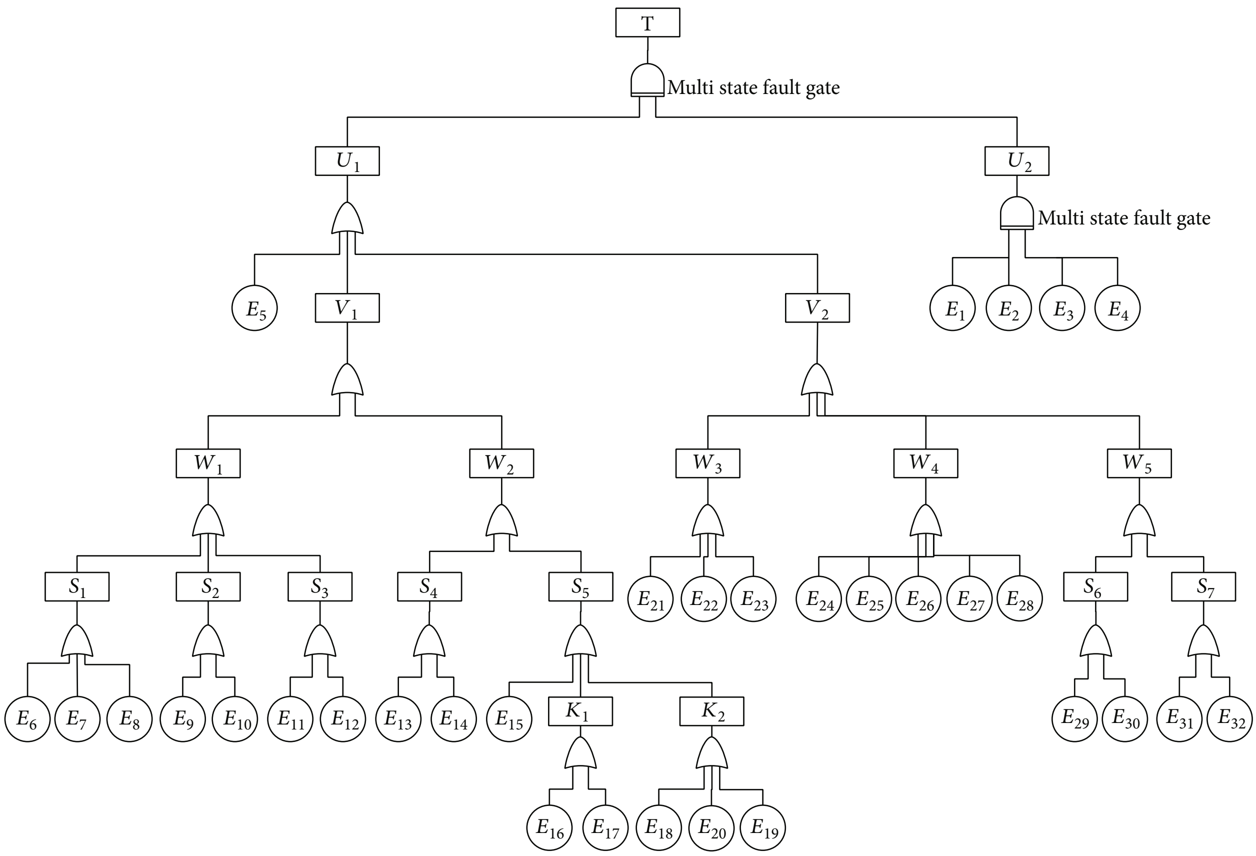

Figure 4: Multistate fault tree of the high-voltage power battery system.

3.4.1. Quantitative Analysis of the Subfault Tree of the Functional Failure Mode. According to the data and relevant experience and the probability of subfault tree bottom event of the functional failure mode (see Table 3).

In Table 3, m represents the mean of the fuzzy number, which is a dimensionless number, indicating the size of the fuzzy probability of the occurrence of the bottom event. The larger the mean of m, the greater the fuzzy probability of the occurrence of the bottom event, and the smaller of m, the smaller the fuzzy probability of the bottom event occurring. According to the reference of [23], the upper and lower limits of α and β take 10 to 20% of the fuzzy mean m, considered the harshness of the actual working environment of the high-voltage power battery system and the ambiguity of the probability of causing system failure, and according to Figure 1, the larger the value of α and β, the larger the fuzzy probability interval, and the reverse is the opposite, when α and β take 10% of the mean of m, and the probability interval is contained in the 20% probability interval of α and β taking m, so in order to make the probability interval better represent the fuzzy probability of the event occur and then selected α and β as 20% of m in combination with the data.

The interval of each bottom event can be obtained using Table 3, Equation (16), and the triangular membership function.

Since top event $U_1 = E_5 + E_6 + E_7 + E_8 + \cdots + E_{30} + E_{31} + E_{32}$, Equation (18) is used to select the triangular membership function. The probability section of top event U_1 varies with λ (see Figure 5 for the scattering curve).

The interval of each bottom event can be obtained from Table 3, Equation (19), and the normal membership function.

Similarly, when the normal membership function is selected, the probability of top event U_1 varies with λ (see Figure 6 for the scattering curve).

By comparing Figures 5 and 6, it can be seen that whether triangular membership function or normal membership function is selected, the probability interval of the top event becomes smaller and smaller with increased λ. When λ is equal to 1, the interval is an accurate number, consistent with the theory. However, for the normal membership function, when λ tends to 0, the fuzzy operator of the top event tends to infinity. The closer it is to 0, the greater the fuzzy probability interval of the top event. When $\lambda \in (0, 1]$, the whole probability interval about the change of λ is nonlinear, and the absolute value of the slope of the upper and lower bounds of the top-event probability curve decreases as λ increases. That is, the closer it is to 0, the greater the changing trend of the curve; the closer it is to 1, the more gentle the change of the curve.

When λ takes the special value of 0.01, Equation (21) is used to obtain that the probability interval of top-event occurrence is [0.4230, 0.7644] and the corresponding reliability interval of the top event is [0.4656, 0.6551]. Compared with the triangular fuzzy operator, the interval is too

Table 3: Probability of the bottom event of the functional failure mode.

Event code	m	α	β
E_5	0.026	0.0052	0.0052
E_6	0.046	0.0092	0.0092
E_7	0.016	0.0032	0.0032
E_8	0.016	0.0032	0.0032
E_9	0.026	0.0052	0.0052
E_{10}	0.018	0.0036	0.0036
E_{11}	0.1	0.02	0.02
E_{12}	0.05	0.01	0.01
E_{13}	0.016	0.0032	0.0032
E_{14}	0.016	0.0032	0.0032
E_{15}	0.01	0.002	0.002
E_{16}	0.01	0.002	0.002
E_{17}	0.06	0.012	0.012
E_{18}	0.12	0.024	0.024
E_{19}	0.016	0.0032	0.0032
E_{20}	0.05	0.01	0.01
E_{21}	0.028	0.0056	0.0056
E_{22}	0.14	0.028	0.028
E_{23}	0.02	0.004	0.004
E_{24}	0.014	0.0028	0.0028
E_{25}	0.025	0.005	0.005
E_{26}	0.016	0.0032	0.0032
E_{27}	0.026	0.0052	0.0052
E_{28}	0.02	0.004	0.004
E_{29}	0.018	0.0036	0.0036
E_{30}	0.016	0.0032	0.0032
E_{31}	0.014	0.0028	0.0028
E_{32}	0.012	0.0024	0.0024

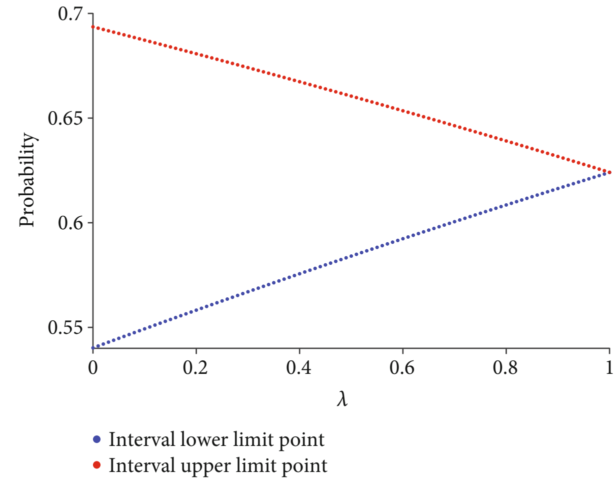

Figure 5: Probability interval distribution of top events changing with λ under the triangular membership function.

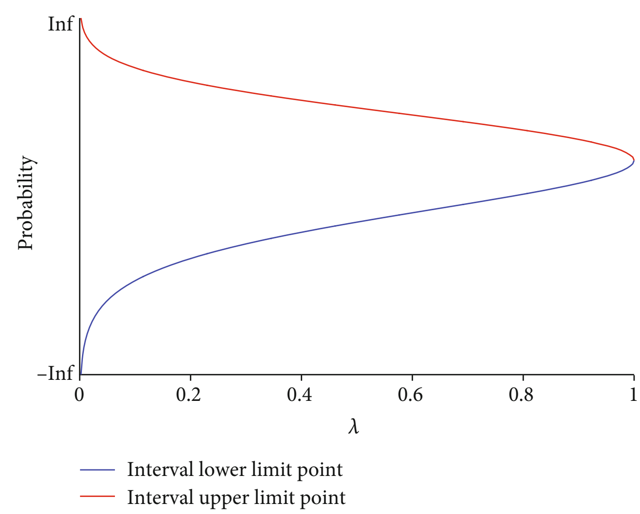

Figure 6: Probability interval distribution of top events changing with λ under the normal membership function.

fuzzy and has no practical significance. Therefore, considering the fuzziness of the occurrence probability of the bottom event and the rationality of operation, the triangular fuzzy operator is selected to calculate the fuzzy probability interval of the top event.

Figure 5 shows that the upper and lower limits of the probability of top-event occurrence are approximately linear. Hence, the least square linear fitting and the intercept interval for the occurrence of the top event of the functional failure mode are used to obtain

$$\tilde{F}_{U_1} = [0.0838\lambda + 0.5415, -0.0694\lambda + 0.6947]. \tag{28}$$

Therefore, please see as follows:

(1) When $\lambda = 1$, the probability of the bottom event of the functional failure mode is a certain value, and that of the functional failure U_1 of the high-voltage power battery system of the top event is

$$\tilde{F}_{U_1,\lambda=1} = 0.6253 \tag{29}$$

When $\lambda = 1$, the reliability of functional failure mode U_1 of the high-voltage power battery system of the top event can be obtained from Equation (5).

$$R_{U_1,\lambda=1} = 0.5351. \tag{30}$$

(2) When $\lambda = 0$, the probability of the bottom event of the functional-failure mode is a fuzzy number and $\tilde{F}_{U_1}$ is an interval range, i.e., the probability interval

of function-failure U_1 of the high-voltage power battery system of the top event is

$$\tilde{F}_{U_1,\lambda=0} = [0.5415, 0.6947] \tag{31}$$

That is, the minimum probability of top event U_1 is 0.5415, and the maximum is 0.6947.

When $\lambda = 0$, the reliability interval of functional failure mode U_1 of the high-voltage power battery system of the top event can be obtained from Equation (5).

$$R_{U_1,\lambda=0} = [0.4992, 0.5819]. \tag{32}$$

3.4.2. Quantitative Analysis of the Subfault Tree in the Deteriorated State. According to the definition of a polymorphic fault gate, when U_1 does not occur and U_2 is in a degraded state, the power battery system is in a degraded state and is not recognized as failure. At this time, the high-voltage power battery system of pure electric commercial vehicles does not need immediate maintenance, consistent with the actual operation condition. When U_1 occurs or U_2 is in a failure state, the high-voltage power battery system is in a failure state and needs to be overhauled.

The decision information of the decision-maker is collected by group decision-making because the probability of each bottom event in each state of the subfault tree of the deteriorated-state mode cannot be accurately obtained. According to the conclusion of the relationship between group size and decision-making, when the number of group decision-makers is 2-5, consensus can be obtained; moreover, 5-11 people are the most effective to draw more correct conclusions.

Consequently, the work collected the probability of four polymorphic bottom events in each state from five experts and combined the language variables of expert opinions with the corresponding triangular fuzzy numbers (see Table 4).

(1) Averaging of Fuzzy Probability. According to the corresponding relationship between language variables and fuzzy probability in Table 1 and Equation (23), the mean value of the fuzzy probability of each polymorphic bottom event in each state is determined as follows:

$$\begin{aligned}
&\tilde{P}'_{1-0} = (0.82,0.96,1.0), \tilde{P}'_{1-0.5} = (0.1,0.22,0.38), \tilde{P}'_{1-1} = (0, 0, 0.1),\\
&\tilde{P}'_{2-0} = (0.82,0.96,1.0), \tilde{P}'_{2-0.5} = (0.1,0.26,0.46), \tilde{P}'_{2-1} = (0, 0, 0.1),\\
&\tilde{P}'_{3-0} = (0.82,0.96,1.0), \tilde{P}'_{3-0.5} = (0.08,0.2,0.38), \tilde{P}'_{3-1} = (0, 0, 0.1),\\
&\tilde{P}'_{4-0} = (0.86,0.98,1.0), \tilde{P}'_{4-0.5} = (0.1,0.24,0.42), \tilde{P}'_{4-1} = (0, 0, 0.1).
\end{aligned} \tag{33}$$

(2) Defuzzification of the Fuzzy Probability. The fuzzy probability is defuzzified according to Equation (24) to convert the obtained fuzzy probability into accurate probability, that is,

$$\begin{aligned}
&P'_{1-0} = 0.935, P'_{1-0.5} = 0.230, P'_{1-1} = 0.025,\\
&P'_{2-0} = 0.935, P'_{2-0.5} = 0.270, P'_{2-1} = 0.025,\\
&P'_{3-0} = 0.935, P'_{3-0.5} = 0.215, P'_{3-1} = 0.025,\\
&P'_{4-0} = 0.955, P'_{4-0.5} = 0.250, P'_{4-1} = 0.025.
\end{aligned} \tag{34}$$

(3) Normalization of exact probability. According to Equation (25), the accurate probability of polymorphic bottom events occurring in each state is normalized to obtain

$$\begin{aligned}
&P_{1-0} = 0.7857, P_{1-0.5} = 0.1933, P_{1-1} = 0.0210,\\
&P_{2-0} = 0.7602, P_{2-0.5} = 0.2195, P_{2-1} = 0.0203,\\
&P_{3-0} = 0.7957, P_{3-0.5} = 0.1830, P_{3-1} = 0.0213,\\
&P_{4-0} = 0.7764, P_{4-0.5} = 0.2033, P_{4-1} = 0.0203.
\end{aligned} \tag{35}$$

According to the structural characteristics of a multistate fault gate, when at least one bottom event state is 1, the system's top-event output is in the failure state. According to the calculated occurrence probability of each state of the polymorphic bottom event, the probability of each polymorphic bottom event in state 1 is substituted into Equation (1). The occurrence probability of the sub-fault tree of the top event in the deteriorated-state mode is

$$\begin{aligned}
P_{U2} &= 1 - (1 - P_{1-1}) \times (1 - P_{2-1}) \times (1 - P_{3-1}) \times (1 - P_{4-1})\\
&= 0.0804.
\end{aligned} \tag{36}$$

According to Equation (5), the subfault tree reliability in the deteriorated mode can be obtained.

$$R_{U_2} = 0.9228. \tag{37}$$

(1) $R_{U1,\lambda=1} = 0.5351$ when $\lambda = 1$. The reliability of the high-voltage power battery system of pure electric commercial vehicles is

$$R_T = 0.4938 \tag{38}$$

(2) $R_{U1,\lambda=0} = [0.4992, 0.5819]$ when $\lambda = 0$. The reliability of the high-voltage power battery system of pure electric commercial vehicles is

$$R_T = [0.4607, 0.5370] \tag{39}$$

Table 4: Expert opinion and fuzzy probability of the bottom event in each state.

Bottom event		E_1			E_2			E_3			E_4	
State	0	0.5	1	0	0.5	1	0	0.5	1	0	0.5	1
Expert 1	VH	GL	VL	H	L	VL	VH	GL	VL	H	VL	VL
Expert 2	VH	GL	VL	VH	GL	VL	VH	L	VL	VH	L	VL
Expert 3	H	VL	VL	VH	GL	VL	H	VL	VL	VH	GL	VL
Expert 4	H	VL	VL	H	L	VL	H	L	VL	VH	M	VL
Expert 5	VH	M	VL	VH	M	VL	VH	M	VL	VH	GL	VL

4. Fuzzy Probability Importance of the Bottom Event

Similar to the probability's importance of the bottom event of the traditional fault tree, the fuzzy probability's importance of the bottom event also refers to the degree to which the probability of the top event is affected when the probability of the bottom event changes. According to the definition of Equation (3), the fuzzy probability's importance is

$$I_h(j) = \frac{\partial h(p)}{\partial p_j}, j = 1, 2, 3, \cdots, n, \tag{40}$$

where $h(p) = h(p_1, p_2, p_3, \cdots, p_n)$ is the unreliability function of the top event; p_j the fuzzy probability of the occurrence of the jth bottom event. Triangular fuzzy numbers were selected to analyze the probability of bottom events of the subfault tree of the functional failure mode in the work. Besides, the logic gates of the subtree of the established functional failure mode are "OR" gates, so we can obtain

$$h(p) = 1 - \prod_{i=1}^{n}\left(1 - \tilde{F}_{i\lambda}\right)\left[1 - \prod_{i=1}^{n}[1 - (m_i - \alpha_i) - \lambda\alpha_i], 1 - \prod_{i=1}^{n} \cdot [1 - (m_i + \beta_i) + \lambda\beta_i]\right], \tag{41}$$

$$p_j = [(m_i - \alpha_i) + \lambda\alpha_i, (m_i + \beta_i) - \lambda\beta_i]. \tag{42}$$

Equations (40), (41), and (42) are used to obtain

$$I_h(j) = \frac{\partial h(p)}{\partial p_j} = \prod_{i=1, i\neq j}^{n}\{[1 - (m_i - \alpha_i) - \lambda\alpha_i], [1 - (m_i + \beta_i) + \lambda\beta_i]\}. \tag{43}$$

It can be seen from the previous chapters that in the high-voltage power battery system of pure electric commercial vehicles, although the probability of each fault of the bottom event is low, the reliability of the whole system is only 0.4938. Therefore, the probability's importance of each bottom event is vital for the prevention and improvement of top events. The bottom event of the subfault tree of the functional failure mode is taken as the research object. According to Equation (43), $\lambda = 0$ is introduced to obtain the interval of probability's importance of each bottom event of the subfault tree in the functional failure mode (see Table 5). Figure 7 shows the broken line of the interval of probability's importance.

Table 5: Interval of probability's importance of the bottom event.

Code	Probability interval	Code	Probability interval
E_5	[0.3163, 0.4695]	E_6	[0.3243, 0.4773]
E_7	[0.3124, 0.4657]	E_8	[0.3124, 0.4657]
E_9	[0.3163, 0.4695]	E_{10}	[0.3132, 0.4665]
E_{11}	[0.3482, 0.4998]	E_{12}	[0.3260, 0.4789]
E_{13}	[0.3124, 0.4657]	E_{14}	[0.3124, 0.4657]
E_{15}	[0.3102, 0.4635]	E_{16}	[0.3102, 0.4635]
E_{17}	[0.3302, 0.4830]	E_{18}	[0.3580, 0.5086]
E_{19}	[0.3124, 0.4657]	E_{20}	[0.3260, 0.4789]
E_{21}	[0.3171, 0.4703]	E_{22}	[0.3683, 0.5178]
E_{23}	[0.3140, 0.4673]	E_{24}	[0.3117, 0.4650]
E_{25}	[0.3159, 0.4692]	E_{26}	[0.3124, 0.4657]
E_{27}	[0.3163, 0.4695]	E_{28}	[0.3140, 0.4673]
E_{29}	[0.3132, 0.4665]	E_{30}	[0.3124, 0.4657]
E_{31}	[0.3116, 0.4650]	E_{32}	[0.3109, 0.4642]

According to Table 5, the fuzzy importance ranking of the bottom event can be obtained as follows.

$$I_h(22) > I_h(18) > I_h(11) > I_h(17) > \cdots > I_h(16) = I_h(15). \tag{44}$$

In terms of the event definition and code in Table 2, the maximum importance interval of CAN high and low reverse connection probability is [0.3683, 0.5178], and the minimum is [0.3102, 0.4635]. The relationship between the importance of each probability is as follows: CAN high and low reverse connection > low-temperature environment > low SOC > battery deformation > $\cdots$>shedding of active substances = charger fault.

In the light of the previous section, the higher the probability's importance of the bottom event, the greater the impact on the high-voltage power battery system of pure electric commercial vehicles. Figure 7 shows that

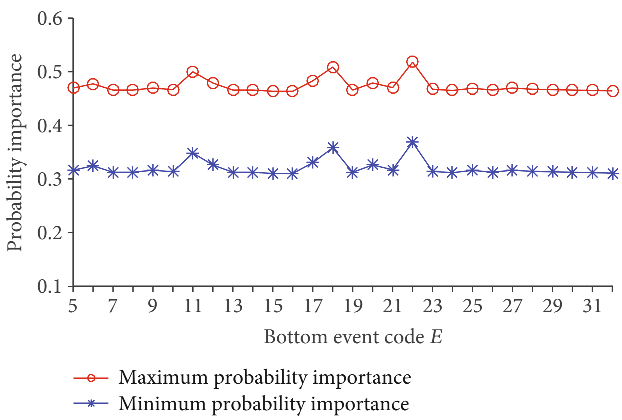

FIGURE 7: Broken lines of importance interval of bottom event's probability of the high-voltage battery system.

the probability's importance of the bottom event coded as E_{11}, E_{17}, E_{18}, and E_{22} is higher than that of other bottom events. The corresponding bottom events are low SOC, battery deformation, low-temperature environment, CAN high, and low reverse connection. Compared with the four bottom events, the fluctuation of the probability's importance interval of the other bottom events is relatively small, and the changing trend of the broken line chart of the corresponding probability's importance interval is relatively flat. Therefore, these four bottom events with probability's high importance are the weak links of the high-voltage power battery system. We should focus on the optimization and timing detection of these four bottom events.

During designing, testing, and optimizing the high-voltage power battery system of pure electric commercial vehicles, the bottom event with a high probability of importance is selected according to the probability's importance interval curve of the high-voltage battery system, which can improve the tests of the whole system to a certain extent and reduce the occurrence of serious failures.

5. Conclusions

Taking a pure electric commercial vehicle as an example, the work analyzed the reliability of the high-voltage power battery system. The basic theory of polymorphic fuzzy fault-tree analysis, the working principle of the high-voltage power battery system and fault type, and the polymorphic fuzzy fault tree of the high-voltage power battery system were introduced to divide the fault tree into two sub-fault trees (functional failure and deteriorated-state modes) for qualitative and quantitative analysis.

The triangular membership function was selected as the fuzzy operator for the bottom event of the subfault tree in the functional failure mode by comparing the influences between the triangular membership function and the normal membership function on the probability interval of the top event. It could solve the subfault tree in a functional failure mode with better effect and obtain its reliability. For the subfault tree in the deteriorated-state mode, the expert experience and triangular fuzzy numbers were combined by the group decision theory, with the fuzzy probability averaged, defuzzified, and normalized. Accurate probability was obtained to solve the subfault tree in the deteriorated-state mode and the reliability of the high-voltage power battery system.

Finally, the fuzzy probability's importance analysis of bottom events of the functional failure mode showed that the key weak links of the system were low SOC, Battery deformation, low-temperature environment, CAN high, and low reverse connection. In system design and fault detection, checking according to the importance of probability can improve system's fault detection. The calculation results showed that although the state deterioration mode did not play a decisive role in system failure, it is still a potential safety hazard to system failure from the reliability of the whole high-voltage power battery system as well as an indispensable detection link in the process of fault detection.

Data Availability

The dataset and codes of the work for the simulation are available from the corresponding author if requested.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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References

[1] H. Huang, X. Tong, and M. J. Zuo, "Posbist fault tree analysis of coherent systems," *Reliability Engineering & System Safety*, vol. 84, no. 2, pp. 141–148, 2004.

[2] B. S. Dhillon, *Design reliability: fundamentals and applications*, CRC press, 1999.

[3] F. A. Rahman, A. Varuttamaseni, M. Kintner-Meyer, and J. C. Lee, "Application of fault tree analysis for customer reliability assessment of a distribution power system," *Reliability Engineering & System Safety*, vol. 111, pp. 76–85, 2013.

[4] S. Yang, H. Li, Y. Yue, J. Hao, W. Luo, and M. Zhao, "Summary on reliability analysis of distributed power access on distribution network," *AIP Conference Proceedings. AIP Publishing LLC*, vol. 1955, no. 1, article 040016, 2018.

[5] G. Lanza, P. Werner, D. Appel, and B. Behmann, "Increased trustability of reliability prognoses for machine tools," in *Glocalized Solutions for Sustainability in Manufacturing*, J. Hesselbach and C. Herrmann, Eds., pp. 225–228, Springer, Berlin, Heidelberg, 2011.

[6] X. Li, H. Shao, S. Lu, J. Xiang, and B. Cai, “Highly-efficient fault diagnosis of rotating machinery under time-varying speeds using LSISMM and small infrared thermal images,” *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 2022.

[7] H. Cao, H. Shao, X. Zhong, Q. Deng, X. Yang, and J. Xuan, “Unsupervised domain-share CNN for machine fault transfer diagnosis from steady speeds to time-varying speeds,” *Journal of Manufacturing Systems*, vol. 62, pp. 186–198, 2022.

[8] L. Xin, S. Haidong, J. Hongkai, and X. Jiawei, “Modified Gaussian convolutional deep belief network and infrared thermal imaging for intelligent fault diagnosis of rotor-bearing system under time-varying speeds,” *Structural Health Monitoring*, vol. 21, no. 2, pp. 339–353, 2022.

[9] H. Tanaka, L. T. Fan, F. S. Lai, and K. Toguchi, “Fault-tree analysis by fuzzy probability,” *IEEE Transactions on Reliability*, vol. 32, no. 5, pp. 453–457, 1983.

[10] D. Singer, “A fuzzy set approach to fault tree and reliability analysis,” *Fuzzy Sets Systems*, vol. 34, no. 2, pp. 145–155, 1990.

[11] D. Yuhua and Y. Datao, “Estimation of failure probability of oil and gas transmission pipelines by fuzzy fault tree analysis,” *Journal of Loss Prevention in the Process Industries*, vol. 18, no. 2, pp. 83–88, 2005.

[12] Y. Liu, Z. Zhang, and M. Zhong, “Reliability analysis on the injection system by mapping TS fault trees into Bayesian networks,” in *3rd International Conference on Mechatronics, Robotics, and Automation*, pp. 1134–1139, Shanghai, China, 2015.

[13] H. Yin, C. Liu, W. Wei, K. Song, D. Liu, and Y. Dan, “Safety assessment of natural gas storage tank using similarity aggregation method based fuzzy fault tree analysis (SAM-FFTA) approach,” *Journal of Loss Prevention in the Process Industries*, vol. 66, article 104159, 2020.

[14] A. Satyanarayana and A. Prabhakar, “New topological formula and rapid algorithm for reliability analysis of complex networks,” *IEEE Transactions on Reliability*, vol. R-27, no. 2, pp. 82–100, 1978.

[15] F. Iscioglu, “A new approach in the mean residual lifetime evaluation of a multi-state system,” *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, vol. 235, no. 4, pp. 700–710, 2021.

[16] C. L. Borges, D. M. Falcao, J. C. Mello, and A. C. Melo, “Composite reliability evaluation by sequential Monte Carlo simulation on parallel and distributed processing environments,” *IEEE Transactions on Power Systems*, vol. 16, no. 2, pp. 203–209, 2001.

[17] S. Mahadevan, R. Zhang, and N. Smith, “Bayesian networks for system reliability reassessment,” *Structural Safety*, vol. 23, no. 3, pp. 231–251, 2001.

[18] F. Mohammadhasani and A. Pirouzmand, “Multi-state unavailability analysis of safety system redundant components with aging effect under surveillance testing,” *Progress in Nuclear Energy*, vol. 126, no. 1, article 103415, 2020.

[19] K. Chen, S. He, E. Xu, R. Tang, and Y. Wang, “Research on ride comfort analysis and hierarchical optimization of heavy vehicles with coupled nonlinear dynamics of suspension,” *Measurement*, vol. 165, article 108142, 2020.

[20] S. He, T. Tang, M. Ye, E. Xu, J. Deng, and R. Tang, “A domain association hierarchical decomposition optimization method for cab vibration control of commercial vehicles,” *Measurement*, vol. 138, pp. 497–513, 2019.

[21] P. O'Connor and A. Kleyner, *Practical reliability engineering*, John Wiley & Sons, 2012.

[22] J. P. Sawyer, “Fault tree analysis of mechanical systems,” *Microelectron and Reliability*, vol. 54, no. 4, pp. 653–667, 1994.

[23] J. Zhang, “Reliability analysis of high voltage electric system of pure electric passenger car based on polymorphic fuzzy fault tree,” *Journal of Intelligent & Fuzzy Systems*, vol. 38, no. 4, pp. 3747–3754, 2020.

[24] H. O. Wang and K. Tanaka, *Fuzzy control systems design and analysis: a linear matrix inequality approach*, John Wiley & Sons, 2004.

[25] H.-Z. Huang, Z.-J. Liu, Y. Yanfeng Li, and L. H. Liu, “A warranty cost model with intermittent and heterogeneous usage,” *Maintenance and Reliability*, vol. 4, pp. 9–15, 2008.

[26] R. Kenarangui, “Event-tree analysis by fuzzy probability,” *IEEE Transactions on Reliability*, vol. 40, no. 1, pp. 120–124, 1991.

[27] C. D. Wickens, W. S. Helton, J. G. Hollands, and S. Banbury, *Engineering Psychology and Human Performance*, Routledge Publishers, 5th edition, 2021.