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Reliability study on non-contact traction power supply system based on fuzzy grey relational FTA

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Abstract: The traction power supply system based on Inductively Coupled Power Transfer (ICPT) technology is one of the new traction power supply technologies that will be developed in the future. As the core part of rail transit energy transfer and conversion, the traction power supply system is not only the critical system for the safe operation of rail transit, but also the main source of its failures, so it is of great significance to study its reliability. In this paper, the reliability analysis of the non-contact traction power supply system based on mobile ICPT technology is carried out using the method of (Fault Tree Analysis) FTA combined with triangular fuzzy theory and grey relational theory. Firstly, the fault tree of the system is established, and the minimum cut sets and structure function of the fault tree are obtained. Then the triangular fuzzy numbers are introduced to represent the probability of the bottom events, and the fuzzy probability of the top event and the fuzzy importance of the bottom events are determined, after that, the maximum probability of failure of the top event is obtained. Finally, the grey relational degrees of each minimum cut set are obtained and ranked. Furthermore, in order to prove the correctness of this method, the trapezoidal fuzzy FTA is introduced and compared with it. Both research results show that the loosely coupled transformer and Insulated Gate Bipolar Transistor (IGBT) module are the weak links of the system. The results obtained are consistent and realistic, which proves the correctness of the method selected in this article.

Key words: FTA, grey relational degree, ICPT technology, reliability research, trapezoidal fuzzy number, triangular fuzzy number

1. Introduction

In order to ensure up to 10 MW of electrical power with the increasing speed of rail transit, the train must use multiple power receiving modules to receive power and perform power quality management to meet the operational needs. The traditional catenary system power supply method seriously restricts the development of rail transit [1]. The power transmission equipment in the power supply system is fully wired, therefore, there will be problems of equipment wear and maintenance costs increase. In addition, the catenary has no backup and is erected in the open air, which is prone to cracks and another unreliable phenomenon such as carbon deposition, vibration offline, lightning strike trip, etc. [2]. In order to overcome the adverse effects caused by the traditional contact traction power supply, applying Inductively Coupled Power Transfer (ICPT) technology to a traction power supply system will be the future development direction of new traction power supply technology [3]. However, there are still many deficiencies in the current non-contact traction power supply system based on ICPT technology. For example, the working conditions of high-frequency inverters and loosely coupled transformers will affect their reliability to varying degrees. Same as the contact traction power supply system, if the non-contact traction power supply system fails, it is very likely to cause the train to stop, slow down, and delay, etc. Therefore, it is necessary to conduct reliability research on the non-contact traction power supply system based on ICPT technology.

At present, the application research of ICPT technology in the rail transit traction power supply system mainly focuses on the development of high-power high-frequency resonant inverter power supply, the compensation network, segmented power supply technology, resonance compensation and parameter optimization, magnetic coupling mechanism design and optimization, and system modeling, optimization and control, electromagnetic interference and engineering applications, etc. [4]. There are few achievements in the research of its reliability. However, there are relatively many studies on the reliability of the traditional contact traction power supply system. Relevant results include both the reliability research of equipment performance, that is, the failures of equipment such as a traction substation [5], catenary [6,7], traction transformer, circuit breaker [8]. It also includes reliability analysis of the service environment of the traction power supply system, such as the impact of weather factors [6] and power quality problems [9] on system performance. It can be seen that the reliability research of the traditional traction power supply system has been more comprehensive, but in order to make the results of reliability studies of the traction power supply system more accurate and practical, these problems should also be resolved: 1) the ambiguity and greyness of the failure data of system components; 2) the complexity and variability of the environment in which the system is located; 3) the lack of maintenance modes.

Fault Tree Analysis (FTA) is the most basic reliability research method, and it is widely used for the reliability evaluation of complex systems and projects [10–12]. However, FTA requires that the failure probability of each component of the system is a certain value. In practical engineering applications, there is often uncertainty in the failure probability of the system and components. Based on this, the fuzzy number theory and FTA are combined to solve the ambiguity of the system failure probability. Such as the triangular fuzzy number [13, 14], trapezoidal fuzzy number [15, 16], L–R type fuzzy number [17] and fuzzy D–S evidence reasoning [18] to describe the failure rate of the basic event. In addition to randomness and ambiguity, there is also greyness in the probability of system failure rate, so the grey relational theory is introduced to solve the problem of uncertainty in the correlation between fault events due to lack of fault information, that is to use the fuzzy grey relational analysis method to complete the reliability study of the system [19, 20]. Moreover, in order to make the reliability study of the system more accurate, some studies have also combined them with other methods, such as the Markov method [21, 22], Analytic Hierarchy Process (AHP), improved entropy weight method [23, 24], Monte Carlo [25], etc. It shows that the improvement of the traditional FTA has matured, which has been used to solve many problems, but it has not yet been used in the field of reliability research of the non-contact traction power supply system.

The power supply mode of the ICPT system with rail transit as the application background is a dynamic power supply mode, that is, a non-contact traction power supply system based on mobile ICPT technology, which is a complex large-scale system. At present, domestic and foreign scholars have rarely studied its reliability. Considering that the amount of fault data of the non-contact traction power supply system is small, and there are a lot of uncertainties and incompleteness in the data acquisition and processing process, this paper aiming at the problem that the traditional FTA cannot conduct reliability research on the uncertainty of system failure, FTA combined with triangular fuzzy theory and grey relational theory is used to complete the reliability research of the non-contact traction power supply system based on mobile ICPT technology. Although the method adopted in this paper can solve the problem of reliability in the absence of a failure rate, it also has some disadvantages. For example, the construction of the fault tree is susceptible to human factors, the confirmed analysis goals and system boundaries will affect the structure of the fault tree, which will lead to deviation in the results of reliability study.

2. Structure and fault tree model of non-contact traction power supply system based on mobile ICPT technology

In the practical application of ICPT technology, power transmission methods mainly include static power supply and dynamic power supply. The dynamic power supply can be used for traction power supply for rail transit [28] and the dynamic charging for new energy vehicles [4] and other occasions. Traction power for rail transit, that is, the non-contact traction power supply system based on mobile ICPT technology can well solve many problems caused by all the wire connections in the traditional traction power supply system. The dynamic energy transfer method can improve the flexibility of electricity and can supply power to electric equipment in real time, so it is of great significance for the research of mobile ICPT technology that can realize dynamic energy transfer in high-power applications. Through the analysis of the topology and working principle of the ICPT system and the non-contact traction power supply system based on mobile ICPT technology, the main factors affecting its operational reliability are obtained, and the fault tree of the system is established.

2.1. Structure and working principle of non-contact traction power supply system based on mobile ICPT technology

2.1.1. The topology and working principle of ICPT system

The general principle block diagram of the ICPT system is shown in Fig. 1. The system is mainly divided into two parts: the transmitting end and the receiving end. The transmitting part mainly completes the conversion of the input power frequency grid voltage into high-frequency

Alternating Current (AC), which is transmitted to the receiving part through electromagnetic induction of a loosely coupled transformer. Then, the receiving part converts the received high-frequency AC into Direct Current (DC) for use by the load [27]. Fig. 2 shows a circuit diagram of the ICPT system of the LCCL single inverter [28], which aims to illustrate the composition of ICPT system components (power switching devices use Insulated Gate Bipolar Transistor (IGBT) modules). Fig. 1 and Fig. 2 show that the main components of the ICPT system are: a high-frequency inverter, primary side compensation device, loosely coupled transformer, secondary side compensation device, rectifier, etc.

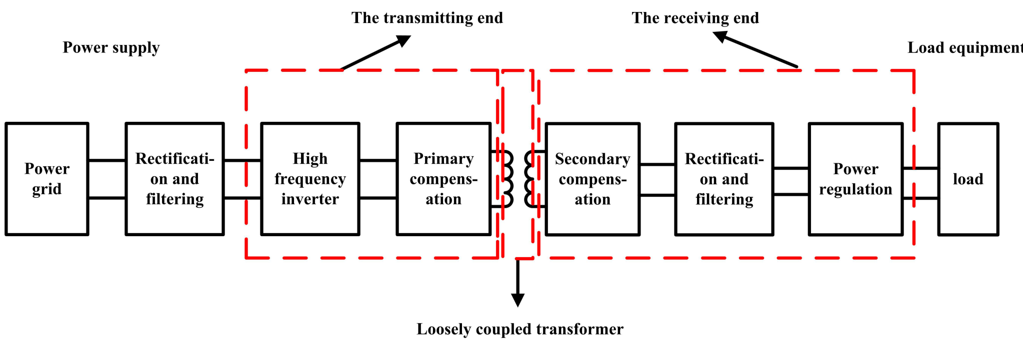

Fig. 1. Functional block diagram of the ICPT system

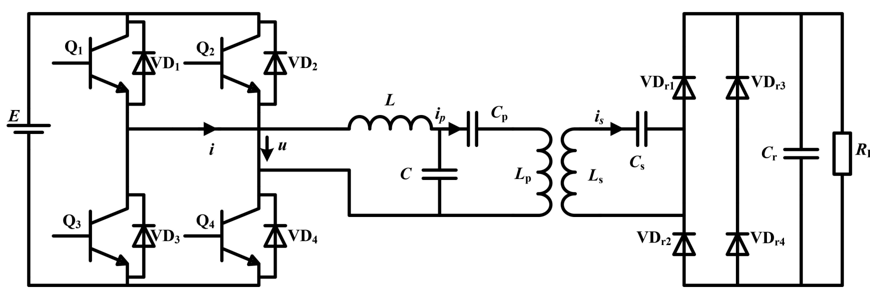

Fig. 2. ICPT system of LCCL single inverter

2.1.2. Structure and operating principle of non-contact traction power supply system based on mobile ICPT technology

The non-contact traction power supply system of rail transit based on mobile ICPT technology is divided into centralized and segmented power supply modes. Among them, the segmented power supply mode can be divided into centralized and distributed power feeding mode according to the number of power conversion devices. The centralized feeding mode can be also divided into the current bus centralized feeding mode and the voltage bus centralized feeding mode according to the difference between the current or voltage distribution for the ICPT system. In the non-contact traction power supply system with rail transit as the application background, in order to consider resource saving and system reliability issues, the voltage bus centralized feed mode is selected. Its framework is depicted in Fig. 3. Fig. 4 presents a schematic diagram of the segmented non-contact

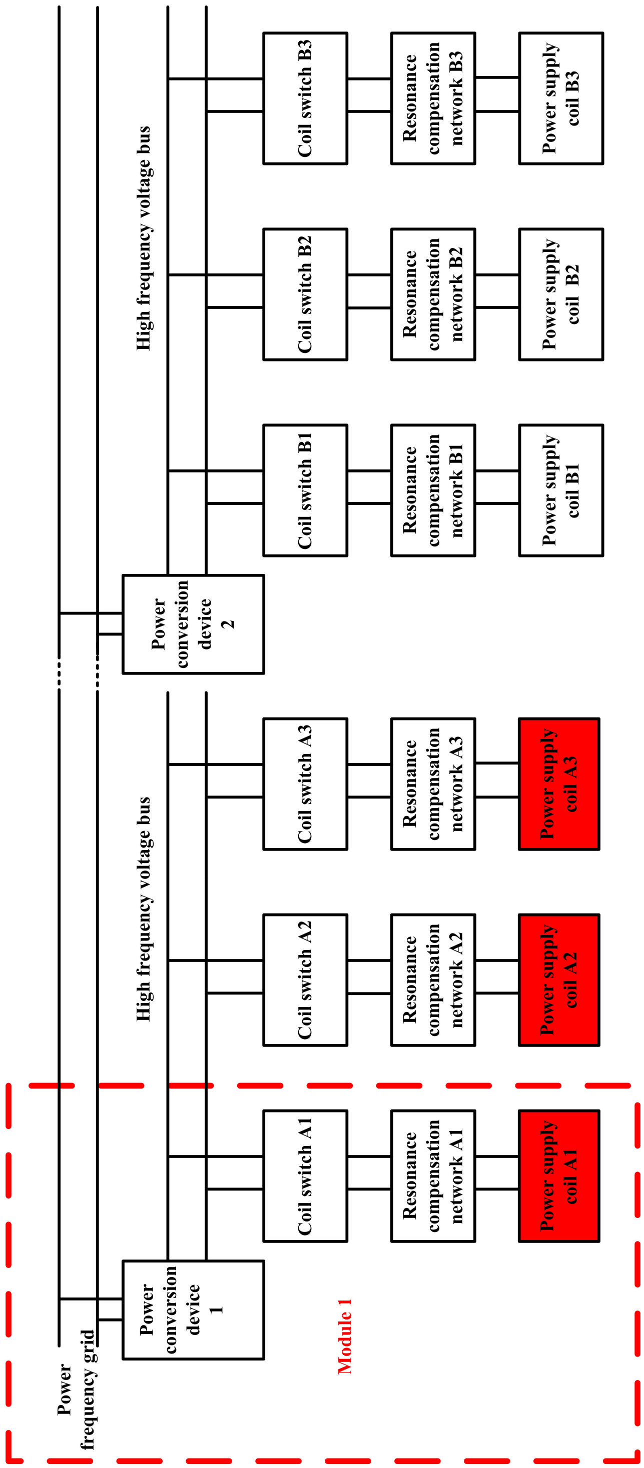

Fig. 3. The block diagram based on voltage bus centralized feed mode

traction power supply mode. The red parts of the two figures correspond to each other, that is, Fig. 3 and Fig. 4 respectively show the power supply and load end of the system, which is designed to illustrate the application background of the ICPT system in this article.

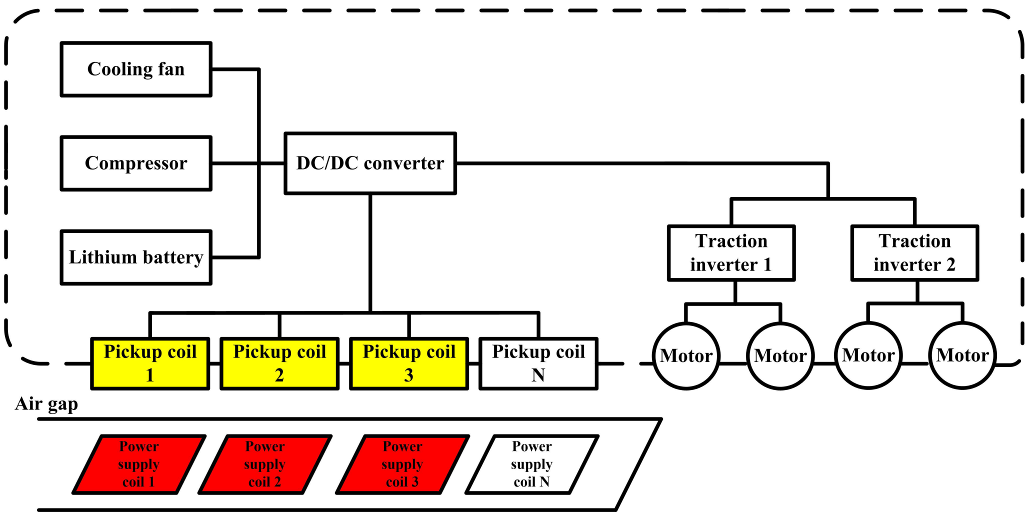

Fig. 4. Schematic diagram of segmented non-contact traction power supply

2.2. Construction of fault tree of non-contact traction power supply system based on mobile ICPT technology

FTA is one of the commonly used methods for large complex systems when conducting reliability research. The top event is determined through top-down analysis, and then the direct and indirect causes of the top event are gradually found until the basic events are found. Then we adopt drawing software and use the correct logical relationship to construct the corresponding fault tree. Finally, the fault tree is qualitatively analyzed and quantitatively calculated to obtain the weak links of the system, and corresponding measures as well as suggestions are given according to the obtained results [29].

The analysis of the above-mentioned non-contact traction power supply system shows that the main factors affecting its reliability are: traction substation failure, ICPT system failure, primary side converter failure, secondary side converter failure, high frequency inverter failure, traction substation failure, IGBT module failure, antiparallel diode failure, primary compensation module failure, loosely coupled transformer failure, secondary compensation module failure, rectifier diode failure and other failures. In this paper, module 1, as shown in Fig. 3, is used to construct the fault tree. According to the analysis, the fault tree of the non-contact traction power supply system based on mobile ICPT technology is shown in Fig. 5, and various fault events are presented as Table 1 in detail. Here the top event is denoted as T, the intermediate event is denoted as M_i, and the bottom event is denoted by x_i.

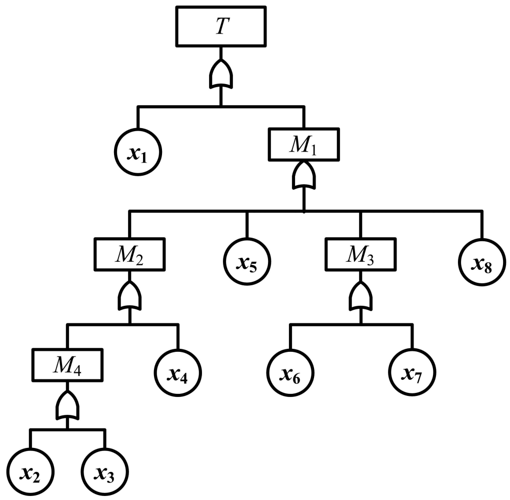

Fig. 5. The fault tree of the non-contact traction power supply system

Table 1. Number and name of the bottom event

Event number	Event name	Event number	Event name
T	Non-contact traction power supply system loses power	x_3	Antiparallel diode failure
M_1	ICPT system failure	x_4	Primary compensation module failure
M_2	Primary converter failure	x_5	Loosely coupled transformer failure
M_3	Secondary side converter failure	x_6	Secondary compensation module failure
M_4	High-frequency inverter device failure	x_7	Rectifier diode failure
x_1	Traction substation failure	x_8	Other faults
x_2	IGBT module failure		

3. Analysis of fault tree of non-contact traction power supply system combined with triangular fuzzy theory

By analyzing the fault tree shown in Fig. 5, the minimum cut sets are obtained, and then the triangular fuzzy number is introduced to represent the occurrence probability of the basic events of the system, and the fuzzy probability of the top event of the system is obtained according to the "OR gate" fuzzy operator. Based on the median method, the fuzzy importance of the bottom event is calculated. Finally, the grey relational theory is used to obtain the grey relational degree of each minimum cut set relative to the top event and sort them, and then the weak links of the system are obtained. Because the fault tree of the non-contact traction power supply system based on the mobile ICPT adopts all "OR gates", as plotted in Fig. 4, according to the calculation method of the minimum cut set, that is, the downward method [29], eight bottom events $\{x_1\}$, $\{x_2\}$, $\{x_3\}$,

$\{x_4\}$, $\{x_5\}$, $\{x_6\}$, $\{x_7\}$, $\{x_8\}$ are all first-order minimum cut sets. Therefore, the eight minimum cut sets are $K_1 = \{x_1\}$, $K_2 = \{x_2\}$, $K_3 = \{x_3\}$, $K_4 = \{x_4\}$, $K_5 = \{x_5\}$, $K_6 = \{x_6\}$, $K_7 = \{x_7\}$, $K_8 = \{x_8\}$, so the structure function of the fault tree is:

$$H(x_i) = x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 + x_8 .$$

3.1. Determine the fuzzy probability of the bottom event of the system based on the triangular fuzzy number

The precise probability of basic events is often difficult to determine. Fuzzy numbers are often used to represent the occurrence probability of bottom events. There are many forms of fuzzy numbers. Triangular fuzzy numbers, trapezoidal fuzzy numbers and normal fuzzy numbers are common. Among them, the membership functions of the triangular fuzzy number and trapezoidal fuzzy number are shown in the following Fig. 6. $\mu_p(x)$ is the membership function of x, and the trapezoidal fuzzy number will be described in detail later. Here, the triangular fuzzy number, which is relatively easy to perform algebraic operations, is used to express the occurrence probability of the above minimum cut sets [13].

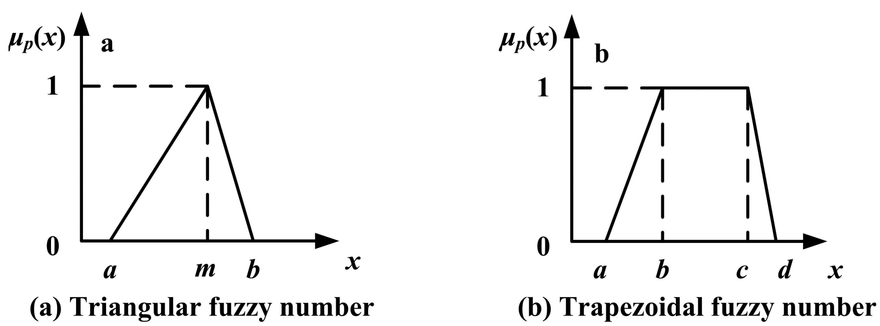

Fig. 6. The membership function of fuzzy number

The membership function of the triangular fuzzy number is given by the following expression:

$$\mu_p(x) = \begin{cases} 0, & x < a \\ \dfrac{x-a}{m-a}, & a \le x \le m \\ \dfrac{b-x}{b-m}, & m \le x \le b \\ 0, & x > b \end{cases} .$$

Therefore, the triangular fuzzy number can also be expressed by three parameters a, m, b as:

$$P = (a, m, b) = \left[(m - \alpha) + \alpha\lambda, m, (m + \beta) - \beta\lambda\right], \quad \lambda \in [0, 1], \tag{1}$$

where: a is the left radius value of the triangular fuzzy number, b is the right radius value, α, β are the upper and lower confidence limits of the triangular fuzzy number, and λ is the confidence level.

The non-contact traction power supply system based on mobile ICPT technology, which is only used in the field of experimental lines, urban rail applications and electric vehicle wireless charging, has not yet been widely used in practice [4]. Therefore, this article only conducts theoretical reliability research on the system, and the data used in this article are all from the "GJB299C-2006 Electronic Equipment Reliability Prediction Manual". Assuming α, $\beta = 0.005$ [19], according to the relevant data in the "GJB299C-2006 Electronic Equipment Reliability Prediction Manual", the triangular fuzzy number is used to represent the probability of occurrence of each bottom event, the details are shown in Table 2 (Unit: 10^{-6}/h).

Table 2. The fuzzy probability of the bottom events represented by the triangular fuzzy number

Event number	**Event name**	***a***	***m***	***b***
x_1	Traction substation failure	0.1182	0.1232	0.1282
x_2	IGBT module failure	0.1468	0.1518	0.1568
x_3	Antiparallel diode failure	0.0360	0.0410	0.0460
x_4	Primary compensation module failure	0.1543	0.1593	0.1643
x_5	Loosely coupled transformer failure	0.1718	0.1768	0.1818
x_6	Secondary compensation module failure	0.0310	0.0360	0.0410
x_7	Rectifier diode failure	0.0649	0.0699	0.0749
x_8	Other faults	0.0695	0.0745	0.0795

3.2. Determine the fuzzy probability of the top event and the fuzzy importance of the bottom event

The fault tree of the system built in this paper use all "OR gates", the triangular fuzzy operator of "OR gate" can be formulated as:

$$p^{or} = 1 - \prod_{i=1}^{n}(1 - p_i) = \left(1 - \prod_{i=1}^{n}(1 - a_i), 1 - \prod_{i=1}^{n}(1 - m_i), 1 - \prod_{i=1}^{n}(1 - b_i)\right). \tag{2}$$

According to the structure function $H(x_i) = x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 + x_8$ of the system and the fuzzy probability of each basic event $p_i = (a_i, m_i, b_i)$, the fuzzy probability of the top event T of the system can be determined by the following formula:

$$P_T = P\left[H(x_1, x_2, x_3, \ldots, x_n)\right] = (a_T, m_T, b_T). \tag{3}$$

From Equations (2) and (3), the triangular fuzzy probability of the top event of the system is calculated as:

$$P_T = (0.5717 \times 10^{-6}/\text{h}, 0.5904 \times 10^{-6}/\text{h}, 0.6084 \times 10^{-6}/\text{h}).$$

At this time, $\lambda = 0$, so according to expression (1), the confidence interval of the top event corresponding to the different confidence λ levels can be obtained as detailed in Table 3 (Unit: 10^{-6}/h). It expresses the minimum value of the system failure probability, which is

0.5717×10^{-6}/h, the maximum value is 0.6084×10^{-6}/h, and the most likely failure probability of the system is 0.5904×10^{-6}/h.

Table 3. Confidence intervals of failure probability of the top event

λ	a	m	b
0	0.5717	0.5904	0.6084
0.1	0.5736	0.5904	0.6066
0.2	0.5754	0.5904	0.6048
0.3	0.5773	0.5904	0.6030
0.4	0.5792	0.5904	0.6012
0.5	0.5811	0.5904	0.5994
0.6	0.5829	0.5904	0.5976
0.7	0.5848	0.5904	0.5958
0.8	0.5867	0.5904	0.5940
0.9	0.5885	0.5904	0.5922
1	0.5904	0.5904	0.5904

The median values of the fuzzy probabilities of the top event and the bottom events are denoted as m_{Tz} and m_{Tiz}, respectively. Then the expression of m_{Tz} is shown in (4):

$$m_{Tz} = \begin{cases} a + \sqrt{\dfrac{(m-a)(b-a)}{2}}, & m-a > b-m \\ b + \sqrt{\dfrac{(b-m)(b-a)}{2}}, & m-a < b-m \end{cases}. \tag{4}$$

When calculating m_{Tiz}, firstly, we must find out the probability that the top event T will still occur when the bottom event x_i does not fail. It is given by the following formula:

$$P_{T_i} = P\left[H(x_1, x_2, x_3, \ldots, x_{i-1}, 0, x_{i+1}, \ldots, x_n)\right] = (a_{Ti}, m_{Ti}, b_{Ti}). \tag{5}$$

Finally, the fuzzy importance of the bottom event (relative to the top event T) should be calculated, the mathematical expression is written as:

$$e_i = m_{Tz} - m_{Tiz}. \tag{6}$$

According to Formulas (4) and (5), the median value of the fuzzy probability of the top event is $m_{Tz} = 0.5902 \times 10^{-6}$/h. Similarly, the set of medians of all bottom events can be obtained as:

$$\begin{gathered} \{m_{T1z}, m_{T2z}, m_{T3z}, m_{T4z}, m_{T5z}, m_{T6z}, m_{T7z}, m_{T8z}\} = \{0.5627 \times 10^{-6}/\mathrm{h},\ 0.5097 \times 10^{-6}/\mathrm{h}, \\ 0.5727 \times 10^{-6}/\mathrm{h},\ 0.5126 \times 10^{-6}/\mathrm{h},\ 0.5023 \times 10^{-6}/\mathrm{h},\ 0.5750 \times 10^{-6}/\mathrm{h}, \\ 0.5595 \times 10^{-6}/\mathrm{h},\ 0.5573 \times 10^{-6}/\mathrm{h}\}. \end{gathered}$$

Then, according to Formula (6), we can get the set determining the fuzzy importance of each bottom event as:

$$\{e_1, e_2, e_3, e_4, e_5, e_6, e_7, e_8\} = \{0.0275 \times 10^{-6}/\mathrm{h},\ 0.0805 \times 10^{-6}/\mathrm{h},\ 0.0175 \times 10^{-6}/\mathrm{h},$$
$$0.0776 \times 10^{-6}/\mathrm{h},\ 0.0879 \times 10^{-6}/\mathrm{h},\ 0.0152 \times 10^{-6}/\mathrm{h},\ 0.0307 \times 10^{-6}/\mathrm{h},\ 0.0329 \times 10^{-6}/\mathrm{h}\}.$$

3.3. Calculate the grey relational coefficient and grey relational degree of each minimum cut set of the system

Grey theory is a new method to study the problem of uncertainty with little data and poor information. To find the grey relational coefficient of each minimum cut set of the system, the comparison sequence (the pattern vector to be checked) and the reference sequence (the characteristic matrix) must be determined first. Then, the comparison sequence and the reference sequence should be normalized for the following calculation of the fuzzy grey relational coefficient. The comparison sequence $\boldsymbol{X}_0$ here is obtained by averaging the fuzzy importance of each basic event, and its expression is defined as:

$$\boldsymbol{X}_0 = [x_0(1), x_0(2), x_0(3), \ldots, x_0(n)] = \left[\frac{e_1}{\bar{e}},\ \frac{e_2}{\bar{e}},\ \frac{e_3}{\bar{e}},\ \ldots,\ \frac{e_n}{\bar{e}}\right], \tag{7}$$

where: $\bar{e} = \frac{1}{n}\sum_{i=1}^{n} e_i$, $i \in [1, n]$, n is the number of the bottom event.

From Equation (7), the comparison sequence of the non-contact traction power supply system based on mobile ICPT technology can be determined as:

$$\boldsymbol{X}_0 = (0.5952,\ 1.7424,\ 0.3788,\ 1.6797,\ 1.9026,\ 0.3290,\ 0.6645,\ 0.7121).$$

The reference sequence in this paper is represented by the fault characteristic matrix $\boldsymbol{F}$. We use K_i $(i = 1, 2, \ldots, k)$ to represent the minimum cut set, and x_i $(i = 1, 2, \ldots, n)$ to denote the bottom event. It is not difficult to find that each minimum cut set K_i is randomly combined by n bottom events $x_1, x_2, \ldots, x_n$. When constructing the fault characteristic matrix, we use the characteristic vector F_i $(i = 1, 2, \ldots, k)$ to represent the corresponding minimum cut set. If the bottom event x_i appears in the minimum cut set K_i, take $x_k(i) = 1$, otherwise take $x_k(i) = 0$. Therefore, the characteristic matrix composed of k minimum cut sets forms the reference sequence $\boldsymbol{F}$ in the grey relational model. In this paper, there are eight bottom events in the non-contact traction power supply system. The bottom events contained in the minimum cut set are taken as "1" in the characteristic matrix, and the rest are taken as "0". Then, its reference sequence (characteristic matrix) $\boldsymbol{F}$ is given as in the following equation. According to Formula (8), the grey relational coefficients between $\boldsymbol{X}_0$ and $\boldsymbol{F}$ can be obtained as shown in Table 4.

$$\boldsymbol{F} = \begin{bmatrix} F_1 \\ F_2 \\ \vdots \\ F_k \end{bmatrix} = \begin{bmatrix} x_1(1) & x_1(2) & \cdots & x_1(n) \\ x_2(1) & x_2(2) & \cdots & x_2(n) \\ \vdots & \vdots & \cdots & \vdots \\ x_k(1) & x_k(2) & \cdots & x_k(n) \end{bmatrix} \Longrightarrow \boldsymbol{F} = \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \\ F_7 \\ F_8 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$\gamma\left[x_0(i), x_k(i)\right] = \frac{\min\limits_i \min\limits_k \Delta_{0k}(i) + \rho \max\limits_i \max\limits_k \Delta_{0k}(i)}{\Delta_{0k}(i) + \rho \max\limits_i \max\limits_k \Delta_{0k}(i)}, \tag{8}$$

where: $x_0(i)$ denotes the element in the reference sequence $\boldsymbol{X}_0$, $x_k(i)$ is the element in the comparison sequence (characteristic matrix) $\boldsymbol{F}$. $\Delta_{0k}(i) = |x_0(i) - x_k(i)|$, $\max\limits_i \max\limits_k \Delta_{0k}(i)$, respectively, represent the minimum and maximum values in $\Delta_{0k}(i)$, and ρ is the resolution coefficient, usually about 0.5. Then the grey relational degree γ_k of the minimum cut set K_i can be obtained according to the following formula:

$$\gamma_k = \frac{1}{n}\sum_{i=1}^{n} \gamma\left[x_0(i), x_k(i)\right]. \tag{9}$$

Table 4. Correlation coefficients

$\gamma[x_{0(i)}, x_{k(i)}]$	$i = 1$	$i = 2$	$i = 3$	$i = 4$	$i = 5$	$i = 6$	$i = 7$	$i = 8$
$k = 1$	0.9138	0.4600	0.9317	0.4710	0.4342	0.9679	0.7669	0.7450
$k = 2$	0.8013	0.7317	0.9317	0.4710	0.4342	0.9679	0.7669	0.7450
$k = 3$	0.8013	0.4600	0.7880	0.4710	0.4342	0.9679	0.7669	0.7450
$k = 4$	0.8013	0.4600	0.9317	0.7598	0.4342	0.9679	0.7669	0.7450
$k = 5$	0.8013	0.4600	0.9317	0.4710	0.6684	0.9679	0.7669	0.7450
$k = 6$	0.8013	0.4600	0.9317	0.4710	0.4342	0.7639	0.7669	0.7450
$k = 7$	0.8013	0.4600	0.9317	0.4710	0.4342	0.9679	0.9630	0.7450
$k = 8$	0.8013	0.4600	0.9317	0.4710	0.4342	0.9679	0.7669	1

Finally, the minimum cut sets are sorted according to the grey relational degrees. The larger the relational degree, the more sensitive the minimum cut set is to the fault, and the greater the possibility of the top event, and vice versa. The grey relational degree of each minimum cut set can be calculated from Table 4 and Formula (9) as:

$$\{\gamma_1, \gamma_2, \gamma_3, \gamma_4, \gamma_5, \gamma_6, \gamma_7, \gamma_8\} = \{0.7266, 0.7312, 0.6793, 0.7291, 0.7334, 0.6718, 0.7113, 0.7218\}.$$

According to the calculation results, the grey relational degree of each minimum cut set is ranked, and the result is $\gamma_5 > \gamma_2 > \gamma_4 > \gamma_1 > \gamma_8 > \gamma_7 > \gamma_3 > \gamma_6$.

This result reflects that the minimum cut set $\{x_5\}$, that is, the loosely coupled transformer, has the greatest impact on the loss of the contactless traction power supply system, followed by the minimum cut set $\{x_2\}$, i.e., the IGBT module. These two modules are the key directions for improving the reliability.

4. Analysis of fault tree of non-contact traction power supply system based on trapezoidal fuzzy number

For comparison and explanation, the trapezoidal fuzzy number is introduced here to represent the probability value of each bottom event of the fault tree shown in Fig. 4, and the definition of "critical importance" in the traditional FTA is analogous to the "fuzzy critical importance" of the trapezoidal fuzzy FTA. Finally, the minimum cut sets are sorted according to the "fuzzy critical importance" and the weak links of the system are determined.

4.1. Determine the fuzzy probability of top event and base events based on trapezoid fuzzy number

The membership function image of the trapezoidal fuzzy number is presented in Fig. 6.

The membership function expression can be written as:

$$\mu_P(x) = \begin{cases} \dfrac{x-a}{b-a}, & a \le x < b \\ 1, & b \le x \le c \\ \dfrac{d-x}{d-c}, & c < x \le d \\ 0, & \text{others} \end{cases},$$

where: p is the trapezoidal fuzzy number, denoted as $p = (a, b, c, d)$, and the interval $[b, c]$ is called the relatively most probable interval. When $a = b = c = d$, p loses its ambiguity, as a certain value, when a is greater than 0, p is a positive trapezoidal fuzzy number. This paper uses positive trapezoidal fuzzy number for Fault Tree Analysis.

The "OR gate" fuzzy operator of the trapezoidal fuzzy number is defined by (10):

$$\begin{aligned} p^{or} &= 1 - \prod_{i=1}^{n}(1-p_i) = \\ &= \left(1 - \prod_{i=1}^{n}(1-a_i),\ 1 - \prod_{i=1}^{n}(1-b_i),\ 1 - \prod_{i=1}^{n}(1-c_i),\ 1 - \prod_{i=1}^{n}(1-d_i)\right). \end{aligned} \tag{10}$$

According to the structure function of the system $H(x_i) = x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 + x_8$ and the fuzzy probability $p_i = (a_i, b_i, c_i, d_i)$ of each basic event represented by the trapezoidal fuzzy number, the fuzzy probability of the top event of the system can be determined as:

$$P_T = P\left[H(x_1, x_2, x_3, \ldots, x_n)\right] = (a_T,\ b_T,\ c_T,\ d_T)\,. \tag{11}$$

According to the relevant data in the "GJB299C-2006 Electronic Equipment Reliability Prediction Manual", the bottom events of the fault tree can be expressed by the trapezoidal fuzzy number as shown in the following Table 5 (Unit: 10^{-6}/h).

It can be calculated from Equations (10) and (11) that the fuzzy number of the occurrence probability of the top event T is:

$$P_T = (0.5303 \times 10^{-6}/\text{h}, 0.5823 \times 10^{-6}/\text{h}, 0.6035 \times 10^{-6}/\text{h}, 0.6963 \times 10^{-6}/\text{h}),$$

the mean of which is $\widetilde{P_T} = 0.6031 \times 10^{-6}$/h. That is, the most likely probability of the top event T is 0.6031×10^{-6}/h, which is basically consistent with the results based on the triangular fuzzy grey relational FTA.

Table 5. The fuzzy probability of the bottom events represented by the trapezoidal fuzzy number

Event number	Event name	*a*	*b*	*c*	*d*
x_1	Traction substation failure	0.0951	0.1000	0.1051	0.1252
x_2	IGBT module failure	0.0664	0.0792	0.1321	0.3310
x_3	Antiparallel diode failure	0.0334	0.0474	0.0558	0.0412
x_4	Primary compensation module failure	0.0074	0.0089	0.0178	0.0296
x_5	Loosely coupled transformer failure	0.0682	0.0952	0.1361	0.4081
x_6	Secondary compensation module failure	0.0167	0.0201	0.0402	0.0671
x_7	Rectifier diode failure	0.0315	0.0378	0.0531	0.1575
x_8	Other faults	0.0695	0.0745	0.0765	0.0795

4.2. Analysis of fuzzy critical importance of trapezoidal fuzzy fault tree

It can be seen from the previous contents that the structure function of the system is:

$$H(x_i) = x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 + x_8 .$$

The trapezoidal fuzzy number of the probability of the basic event is p_{xi}, and its membership function is $\mu_p(x_i)$, then the fuzzy critical importance $F_G(i)$ of the basic event i could be expressed as follows [16]:

$$F_G(i) = \frac{\int\limits_0^1 x\mu_{p_{x_i}}\,\mathrm{d}x \cdot \int\limits_0^1 \mu_{p_A}\,\mathrm{d}x}{\int\limits_0^1 \mu_{p_{x_i}}\,\mathrm{d}x \cdot \int\limits_0^1 x\mu_{p_A}\,\mathrm{d}x} \left(\frac{\int\limits_0^1 x\mu_{p_{Ai1}}\,\mathrm{d}x}{\int\limits_0^1 \mu_{p_{Ai1}}\,\mathrm{d}x} - \frac{\int\limits_0^1 x\mu_{p_{Ai0}}\,\mathrm{d}x}{\int\limits_0^1 \mu_{p_{Ai0}}\,\mathrm{d}x} \right), \tag{12}$$

where:

$$p(p_{xi}, \ldots, p_{xi-1}, 1, p_{xi+1}, \ldots, p_{xn}) = p_{Ai1}, \quad p(p_{xi}, \ldots, p_{xi-1}, 1, p_{xi+1}, \ldots, p_{xn}) = p_{Ai0},$$

which are the fuzzy failure probabilities of the top event when $x_i = 1$ and $x_i = 0$ for the basic event i, which can be calculated according to Equations (10) and (11).

$$\frac{\int\limits_0^1 x\mu_{p_{x_i}}\,\mathrm{d}x \cdot \int\limits_0^1 \mu_{p_A}\,\mathrm{d}x}{\int\limits_0^1 \mu_{p_{x_i}}\,\mathrm{d}x \cdot \int\limits_0^1 x\mu_{p_A}\,\mathrm{d}x}$$

represents the ratio of the average of p_{xi} to the mean value of the fuzzy probability P_T of the top event, which includes the magnitude of the occurrence probability of the basic event in the fuzzy critical importance.

$$\left(\frac{\int_0^1 x\mu_{p_{Ai1}}\,\mathrm{d}x}{\int_0^1 \mu_{p_{Ai1}}\,\mathrm{d}x} - \frac{\int_0^1 x\mu_{p_{Ai0}}\,\mathrm{d}x}{\int_0^1 \mu_{p_{Ai0}}\,\mathrm{d}x} \right)$$

denotes the fuzzy importance of the basic event, that is, the difference between the mean value of the fuzzy failure probability of the top event when the basic event is $x_i = 1$ and $x_i = 0$, respectively.

From Equation (12), the fuzzy critical importance of the basic event i can be obtained as:

$$\{F_G(1), F_G(2), F_G(3), F_G(4), F_G(5), F_G(6), F_G(7), F_G(8)\} =$$
$$= \{0.1285, 0.1886, 0.0504, 0.0175, 0.2255, 0.0403, 0.0765, 0.0873\}.$$

The order from the largest to the smallest is:

$$F_G(5) > F_G(2) > F_G(4) > F_G(1) > F_G(8) > F_G(7) > F_G(3) > F_G(6).$$

The greater the fuzzy critical importance, the greater the impact of the event on the top event, therefore, the bottom events $\{x_5\}$ and $\{x_2\}$ are the weak links of the system. The comparison of the results obtained by the two reliability analysis methods of the triangular fuzzy grey relational FTA and trapezoidal fuzzy FTA are demonstrated in Table 6.

Table 6. Comparison of reliability analysis results

Reliability analysis method	**Evaluation index**	**Index calculation value**	**System weaknesses**
Triangular fuzzy grey relational FTA	Grey relational degree of minimal cut set γ_i	0.7334, 0.7312	Loosely coupled transformer, IGBT module
Trapezoidal fuzzy FTA	Fuzzy critical importance of minimal cut set $F_G(i)$	0.2255, 0.1886	Loosely coupled transformer, IGBT module

Table 6 reveals that the weak points of the system obtained by using the triangular fuzzy grey relational FTA and trapezoidal fuzzy FTA are both the loosely coupled transformer and IGBT module, which are the key components that affect system reliability. The structure failure will greatly reduce the reliability of the power supply system and seriously threaten the operation of the system. Thus, special attention should be paid to real-time fault monitoring and running status tracking of important components such as a loosely coupled transformer and IGBT module.

5. Conclusions

In view of the ambiguity and greyness of the system failure probability, based on the traditional FTA, the triangular fuzzy number and the grey relational theory are combined to complete the reliability study of the non-contact traction power supply system based on mobile ICPT that can quickly and accurately obtain weak links of the system.

1. The fault tree of the system is established, and the fuzzy probability of the bottom event is obtained by using the triangular fuzzy number, in addition, the grey relational degree of the minimum cut set relative to the top event was sorted, namely:

$$\gamma_5 > \gamma_2 > \gamma_4 > \gamma_1 > \gamma_8 > \gamma_7 > \gamma_3 > \gamma_6.$$

   Then the trapezoidal fuzzy FTA is introduced to compare with it, and the fuzzy critical importance of each minimum cut set is ranked as:

$$F_G(5) > F_G(2) > F_G(4) > F_G(1) > F_G(8) > F_G(7) > F_G(3) > F_G(6).$$

   The conclusions of the two methods are consistent and in line with reality, that is, the loosely coupled transformer and IGBT module have the greatest impact on the reliability of the non-contact traction power supply system, and the results obtained can provide references for preventing accidents and improving the reliability of the system.
2. Using the triangular fuzzy median value theorem and combining with the confidence level λ, the most likely probability of the top event of the system is $P_T = 0.5904 \times 10^{-6}$/h, which is basically the same as the result obtained based on the trapezoid fuzzy FTA.
3. In the next step, we will conduct more in-depth research and analyze reliability issues arising from the internal structure of the system and components. In addition, we will consider building an experimental platform and combining it with simulation software to obtain small sample failure data of the system and components to improve the accuracy of reliability research.

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