IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received 29 January 2024, accepted 21 February 2024, date of publication 1 March 2024, date of current version 18 March 2024.
Digital Object Identifier 10.1109/ACCESS.2024.3372574

RESEARCH ARTICLE

Research on Reliability Allocation Method for Traction Power Supply System of Electrified Railways in Mountainous Areas

LIKE PAN[1], YUJIE TIAN[2], SHAN MA[2], WENRUI DAI[1], AND LIMING CHEN[1]
[1]China Academy of Railway Sciences Corporation Ltd., Beijing 100081, China
[2]School of Electrical Engineering, Southwest Jiaotong University, Chengdu 611730, China
Corresponding author: Liming Chen (13810305638@163.com)

This work was supported by the Research Project of China Academy of Railway Sciences Corporation Ltd., under Grant 2023YJ271.

ABSTRACT The electrified railways in mountainous areas are faced with multiple difficulties such as weak power grids, special climatic environments, complex and dangerous geographical conditions, which poses a great challenge to the reliable power supply of the traction power supply system (TPSS). In order to ensure that the overall reliability level of the TPSS meets the design requirements, this paper proposes a reliability allocation method for the TPSS of electrified railways in mountainous areas. Firstly, based on the characteristics of the interconnected power supply system of traction substation group (TSG) of the electrified railways in mountainous areas, the special topology of the TPSS, as well as the logical relationships between each power supply area and each equipment are sorted out. Secondly, the reliability allocation model of the interconnected power supply system of the TSG is established, and the reliability index of the system is allocated layer-by-layer from the whole system to the TSG according to the design requirements of the overall reliability level of the system. Finally, the reliability allocation model of the traction substation is established, and the reliability index is allocated to the underlying equipment of the traction substation, so as to clarify the reliability requirements of each power supply area and equipment. The results indicate that the reliability allocation results calculated by the proposed method can assist designers to be informed of the reliability objectives of each subsystem and power supply equipment, and can provide insights for related reliability design.

INDEX TERMS Electrified railway in mountainous areas, interconnected power supply system, reliability allocation, improved AGREE allocation method.

I. INTRODUCTION

Since the railway network in the western region of China is sparse, the development and construction of railways have seriously restricted the local socio-economic development. The national ‘‘14th Five-Year Plan’’ railway development plan points out that it is necessary to comprehensively promote railway construction in the western region, especially the construction of new lines in blank areas in the northwest region [1], [2]. With the increasing demand for electrified railway transportation in western mountainous areas, the safety and reliability of the traction power supply system (TPSS) is the primary guarantee for the normal operation of electric locomotives and high-quality railway operation.

The TPSS of electrified railways in mountainous areas usually has the following characteristics: (1) extremely weak external power grid and low power supply reliability [3]. Electrified railways in mountainous areas usually cross remote areas and unmanned areas with few high-voltage substations and weak network structures; Secondly, the power grid is often exposed in the wild and power supply equipment is prone to aging. (2) The harsh and variable meteorological conditions affect the reliability of the TPSS [4]. The electrified railways in mountainous

The associate editor coordinating the review of this manuscript and approving it for publication was Tariq Masood.

areas pass through high-altitude areas, where meteorological conditions such as lightning, continuous snow, and canyon wind change sharply, meanwhile intrude power supply lines, destroy power supply facilities, and cause poor power supply. (3) The difficult terrain, complex geology and special engineering requirements pose challenges to the reliability of the TPSS [5]. The electrified railways in mountainous areas have a high ratio of bridges to tunnel, long section of tight slope, and high design gradient. The sudden geological disasters such as earthquakes, landslides, and mudslides along the route will lead to serious consequences such as tilting of the contact network pillars, tunnel collapses, and the destruction of mechanical balance of high-voltage equipment.

In summary, the TPSS of electrified railways in mountainous areas is faced with enormous challenges from factors such as weak power grid conditions, special climatic environments, and complex terrain [6]. In order to ensure the long-term stable operation of mountainous railways, it is urgent to put forward newer and higher requirements for the reliability of the entire TPSS, including the external power grid. Therefore, it is necessary to study the reliability allocation design method suitable for western mountainous railways combined with the expected reliability requirements of the TPSS in the early stage of railway construction. It can provide theoretical support for the forward design scheme of the TPSS by predicting the reliability parameters of key power supply facilities.

At present, experts and scholars from different fields have conducted extensive research on reliability allocation. Reference [7] proposes a comprehensive factor reliability allocation method considering the influence of two-layer factors, which aims at the reliability allocation problem of complex mechanical systems under multiple influencing factors. Reference [8] comprehensively considers the relationship between the maintenance costs of wind turbines and unit reliability and establishes a reliability allocation model for wind turbines. Reference [9] considers the intermediate degradation process and proposes a methodology named integrated factor evaluation-analytic hierarchy process-T-S fuzzy fault tree analysis to allocate the reliability index of industrial robot systems. Reference [10] proposes a system reliability allocation method based on generalized Birnbaum importance, which comprehensively considers the reliability range, manufacturing complexity, and technical feasibility of components.

To further address the shortcomings of the AGREE allocation method in the use of specific systems, [11] proposes an improved AGREE allocation method, and it is capable of dealing with complex connections between avionic subsystems compared with the widely used reliability allocation methods. Reference [12] discusses the deficiency of AGREE method, such as the depiction of importance and its applicability, and designs new allocation models for both serial and parallel connection systems. Reference [13] proposes a modified AGREE reliability allocation method suitable for power converters by combining the characteristics of power converters and using the technical maturity as a complexity index. Reference [14] establishes a reliability allocation model for complex networks by constructing the importance of network components and realizes reliability allocation for complex networks based on the improved AGREE allocation method. The above research on the improvement of the AGREE allocation method is conducive to this paper to propose a reliability allocation method that is adaptable to the interconnected power supply system of the TSG of electrified railways in mountainous areas.

However, there is currently limited research on the reliability allocation of TPSS. Reference [15] proposes a reliability allocation method based on the certainty reliability, and transforms the reliability allocation problem into the optimization problem of the sum of the system opportunity cost, which was solved by the sequential quadratic programming algorithm. Reference [16] proposes a fuzzy synthesis evaluation method for allocating the reliability of the components and units of the catenary system. The method takes into account the factors influencing the reliability level of the components and units of the catenary system as well as the weights of the factors.

In order to focus on the higher requirements for the reliability of TPSS posed by weak external power grids of electrified railways in mountainous areas, this paper adopts the interconnected power supply system of the TSG of electrified railways. However, the above reliability allocation methods of the TPSS are not applicable to this new type of power supply scheme, for this reason, the AGREE allocation method is improved in this paper. With the goal of meeting the expected reliability requirements of the system, this paper establishes a reliability allocation model for the interconnected power supply system of the traction substation group (TSG), and carries out a reliability allocation design. The logical relationships between various power supply areas and equipment within the system are firstly sorted out based on the special topological structure of the TPSS of electrified railways in mountainous areas. Then, from the perspectives of importance and complexity of power supply equipment, the reliability index of the interconnected power supply system of the TSG is allocated layer by layer based on the improved AGREE allocation method. Finally, the reliability allocation is carried out for the traction substation and the reliability parameter requirements are clarified for key TPSS equipment within the traction substation.

The improved AGREE allocation method proposed in this paper has the following advantages over the traditional allocation method: ① The proposed method addresses the inability of traditional methods to directly allocate reliability to complex systems with logical relationships such as series, parallel, and r/n voting [14]. ② The method of calculating the importance of power supply equipment has been improved, and the problem that the traditional method requires historical fault data for reliability assignment has been solved.

This paper is organized as follows: In Section II, problems of adopting traditional traction power supply system in electrified railways in mountainous areas are analyzed, and the topologies of the interconnected power supply system and the single-phase traction substation are given. In Section III, the principles of the traditional AGREE method are analyzed and the comparison between the improved AGREE allocation method and the traditional method is given. In Section IV, reliability allocation models for the interconnected power supply system and traction substations are established, and the reliability index is calculated. Finally, the conclusions of this paper are given in Section V.

II. INTERCONNECTED POWER SUPPLY SYSTEM OF TRACTION SUBSTATION GROUP

The chapter describes the problems of adopting traditional TPSS structure for electrified railways in mountainous areas, and the interconnected power supply system of TSG is adopted in order to effectively eliminate the number of electric split-phase and improve the quality of electric power. On this basis, the topologies of the interconnected power supply system and single-phase traction substations are described, laying the foundation for the reliability allocation models later.

A. EXITING PROBLEMS OF TRADITIONAL TRACTION POWER SUPPLY SYSTEM

The traditional TPSS has problems of power quality and electric phase separation. The asymmetry of single-phase traction load causes the asymmetry of three-phase current in the power system, generates negative sequence current and increases motor loss as well as power grid loss. At the same time, the nonlinear characteristics of traction load affect the TPSS to generate harmonic currents, which will cause electromagnetic interference to communication signals. As the railways in the mountainous areas of western China are constructed successively, the increases in power of electric locomotives and in traction load have caused negative sequence and other power quality problems to become more prominent with the goal of meeting the requirements of high-speed traction force on large slopes.

In order to improve the power quality of the TPSS and reduce the negative sequence impact, the installation of electric phase separation at the exit of the traction substation and the location of the section post is required for commonly used measures, such as phase sequence rotation, power supply with separated phases and sections, and the usage of different transformer wiring forms. However, the tight slope sections of railways in the western mountainous areas are long, and it is inevitable to set up electric phase separation on long and steep slopes. When the electric locomotives pass through electric phase separation, there are hidden dangers that jeopardize railway transportation safety, such as speed reduction and slope stops [17]. Aiming at the negative sequence, harmonic and other power quality problems in the TPSS mentioned above, some scholars have proposed the interconnected power supply scheme of the TSG, which can effectively eliminate electric phase separation in the maximum range without generating crossing power [6]. And it is widely used in electrified railways in mountainous areas.

B. INTERCONNECTED POWER SUPPLY SCHEME OF TRACTION SUBSTATION GROUP

This paper proposes to use the interconnected power supply technology of the TSG, which is defined as: multiple traction substations are powered by different sectional buses of the same voltage level from the same substation in the power grid; the traction network interconnected power supply between each traction substation forms an interconnected power supply group; Two adjacent interconnected power supply groups are electrically connected by a ring network [18].

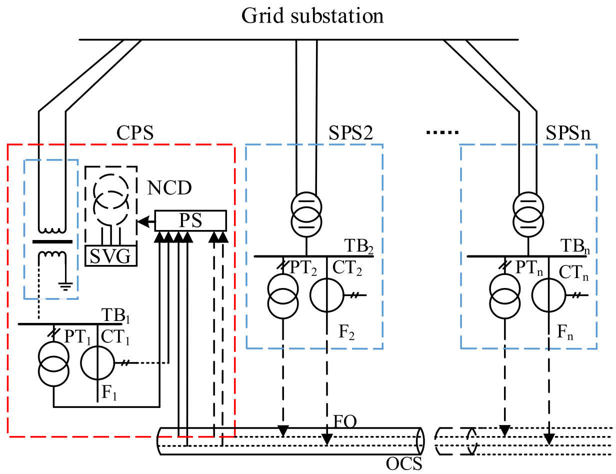

FIGURE 1. Topological structure diagram of the interconnected power supply system of TSG.

The topological structure of the interconnected power supply system of the TSG is shown in Fig.1, one of the traction substations in the TSG is the Central Traction Substation (CPS), which adopts a single-phase connected main transformer and Negative-sequence Compensation Device (NCD). The other traction substations are Single-phase Traction Substations (SPSs), which adopt single-phase connection traction transformers. Current transformers and voltage transformers are installed at the traction feeder F of each traction substation in order to collect real-time traction load current and voltage data within the current traction substation. The current and voltage data are transmitted in real time to the input end of controller PS of NCD through fiber optic network (FO) and the output end of controller PS is connected to the control end of NCD to achieve negative sequence real-time compensation, so as to ensure that the negative sequence at the power grid substation PPC meets national standards [19].

It can be considered that the negative sequence compensation device and the negative sequence centralized measurement and control system are structurally and functionally independent of the traction transformers. Therefore, in the reliability allocation design stage of the TSG, reliability allocation can be carried out separately for single-phase traction substations, negative sequence compensation devices and fiber optic networks, etc.

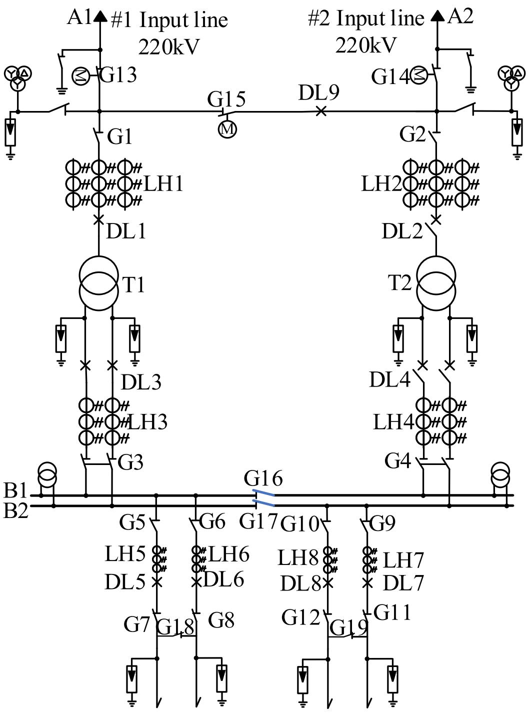

FIGURE 2. Topological structure diagram of traction substation.

C. TOPOLOGICAL STRUCTURE OF SINGLE-PHASE TRACTION SUBSTATION

The main wiring diagram of SPS is shown in Fig.2. Both 1 # and 2 # are 220kV power incoming lines, which are backed up by each other to meet the continuity of power supply in the substation; Traction transformer T1 and traction transformer T2 are mutually backup. Under normal circumstances, circuit breaker DL9 and isolation switch G15 are disconnected, and the left main transformer T1 is put into operation. When a fault occurs, circuit breaker DL9 and isolation switch G15 are closed, and the right main transformer T2 is put into operation; The substation leads out two feeder lines to supply power to the traction network, and each feeder line adopts a 100% backup mode. For equipment such as fuses, surge arresters, and transmission lines in substations, they can be approximated as fully reliable to simplify calculations. The normal working state of a substation is defined as both feeders are able to supply power to the contact network normally.

III. RELIABILITY ALLOCATION METHOD

Reliability allocation is the process of assigning the specified reliability indicators of a system from top to bottom to the various units that make up the system, thus clarifying the reliability requirements for each unit. Then, each unit is designed according to the assigned reliability indicators and appropriate components are selected to ensure reliability requirements of system. Reliability allocation methods are mainly divided into two categories: unconstrained allocation methods and constrained allocation methods [20], [21], [22]. The chapter introduces the principle of the traditional AGREE allocation method, and also analyzes the reasons why it is not applicable to the interconnected power supply system of TSG, and improves the method.

A. AGREE ALLOCATION METHOD

The AGREE method is a reliability allocation method proposed by the Electronic Equipment Reliability Advisory Group of the US Department of Defense. This method allocates reliability indicators based on the complexity and importance of various components within the system, and it has been widely used in engineering. The allocation method is as follows by assuming that the lifespan of each component in the system follows an exponential distribution [22].

$$\lambda_i = \frac{\eta_i \ln R_s}{\omega_i t_i} \tag{1}$$

In equation (1), R_s is the expected reliability of the system, η_i is the complexity of component i, ω_i is the importance of component i, t_i is the working time of component i, and λ_i is the failure rate assigned to component i.

As shown in equation (2), component complexity η_i $(0 < \eta_i < 1)$ can be calculated by the number of basic units of the entire system and the number of basic units of components.

$$\eta_i = \frac{n_i}{n_s} \tag{2}$$

In equation (2), n_i is the number of basic units of component i, and n_s is the number of basic units of the entire system.

Component importance ω_i $(0 < \omega_i < 1)$ reflects the degree of impact of component failures on the reliability of the entire system, and the calculation method is shown in equation (3):

$$\omega_i = \frac{f_i}{f_s} \tag{3}$$

In equation (3), f_i is the number of failures of component i, and f_s is the number of failures of the entire system caused by the failure of component i.

The AGREE method comprehensively considers two major factors: the importance and complexity of components.

For components with higher importance, because the failure of the component has a greater impact on the reliability of system, the failure rate allocated to the component is smaller, i.e., the reliability assigned to the component is higher; For components with higher complexity, the assigned failure rate is higher because of their complex composition, i.e., the reliability of component allocation is lower. But the AGREE method is only applicable to systems composed of multiple components in series.

B. IMPROVED AGREE ALLOCATION METHOD

In the process of reliability allocation for the interconnected power supply system of the electrified railway TSG in mountainous areas based on the traditional AGREE method, the following problems are faced: ① The interconnected power supply system of the electrified railway TSG in mountainous areas is a typical complex system composed of multiple subsystems and power supply equipment with various logical relationships such as parallel, series, r/n voting, etc., and it cannot be simply represented as a series system. Therefore, it is not possible to directly use equation (1) for reliability allocation [14]; ② At the design stage of the interconnected power supply system of the electrified railway TSG in mountainous areas, there is a lack of historical fault data and other information of power supply equipment. The importance of the traditional AGREE method is obtained through the historical fault data statistics of components, so the importance cannot be analytically calculated. In summary, this paper improves the traditional AGREE method based on the characteristics of the interconnected power supply system of the electrified railway TSG in mountainous areas.

In summary, this paper improves the traditional AGREE allocation method for the problem that it is not applicable to the interconnected power supply system of the TSG of electrified railways in mountainous areas. It is still assumed that the lifespan of each subsystem and power supply equipment in the interconnected power supply system of the electrified railway TSG in mountainous areas follows an exponential distribution. The improved equation (1) is shown in equation (4) in order to follow the two allocation principles of the AGREE method [12], [23]: ① Components with higher importance are assigned higher reliability; ② Components with higher complexity are assigned lower reliability.

$$\lambda_i \propto \frac{\eta_i}{\omega_i\, t_i} \tag{4}$$

For the definition of importance in the existing AGREE method, this paper adopts probability importance for analytically calculation, and the calculation method is shown in equation (5).

$$\omega_i = \frac{\partial R_s}{\partial R_i} \tag{5}$$

In the formula, R_i is the reliability assigned to component i. The probability importance reflects the extent to which changes in component failure rates affect changes in system failure rates.

Furthermore, since the failure rate λ_i and importance ω_i of component i are quoted to each other in equations (4) and (5), the analytical method cannot be used, and heuristic algorithms need to be utilized to perform iterative iteration without the need for information such as historical failure data. The solution process is shown in Fig.3, and the specific steps are as follows:

(1) Based on the topological structure of the interconnected power supply system of the electrified railway TSG in mountainous areas, sort out the series-parallel connection and other logical relationships between various power supply components, and determine the functional relationship between the system reliability R_s and power supply component reliability R_i;

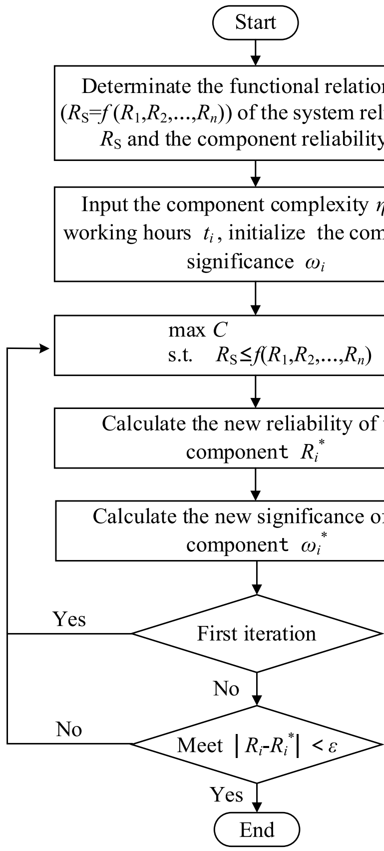

FIGURE 3. Reliability allocation flowchart based on improved AGREE method.

The reliability function relationship of the series system can be expressed as [24]:

$$R_s(t) = \prod_{i=1}^{n} R_i(t) \tag{6}$$

The reliability function relationship of the parallel system can be expressed as:

$$R_s(t) = 1 - \prod_{i=1}^{n} [1 - R_i(t)] \tag{7}$$

(2) The importance ω_i of all components within the system is initialized, i.e., the $\omega_1 = \omega_2 = \ldots = \omega_n = 1$. The complexity η_i and working time t_i of the component is determined;

(3) The reliability R_i of power supply components can be expressed using equation (8) according to equation (4);

$$R_i = \exp\left(-\lambda_i\, t_i\right) = \exp\left(-\frac{C\,\eta_i}{\omega_i}\right) \tag{8}$$

(4) The optimal solution C of equation (9) is solved using the binary search method with the goal of meeting the expected reliability requirements of the interconnected power supply system of TSG;

$$\begin{cases} \max C \\ s.t. R_s \leq f\left(R_1, R_2, \cdots, R_n\right) \\ C > 0 \end{cases} \tag{9}$$

(5) The optimal solution C obtained from step (4) is brought into equation (8) and the reliability R_i^* of the component is calculated;

(6) The component reliability R_i^* obtained from step (5) is added into equation (7) and the new component importance ω_i^* is calculated. If it is the first iteration, set the $\omega_i = \omega_i^*$ and repeat step (3). Otherwise, proceed to step (7);

(7) Determine whether the convergence condition $|R_i$-$R_i^*|<\varepsilon$ has been met (R_i^* is the newly calculated component reliability, R_i is the component reliability obtained from the previous iteration and ε is the assignment accuracy for reliability). if so, the iteration will be terminated; otherwise, continue to order $\omega_i = \omega_i^*$ and proceed to step (3).

IV. EXAMPLE ANALYSIS

A. RELIABILITY ALLOCATION MODELING

In this paper, the reliability allocation research is conducted taking the interconnected power supply system of the TSG along an electrified railway in the west of China under construction as an example. The topological structure of TPSS is shown in Fig.4.

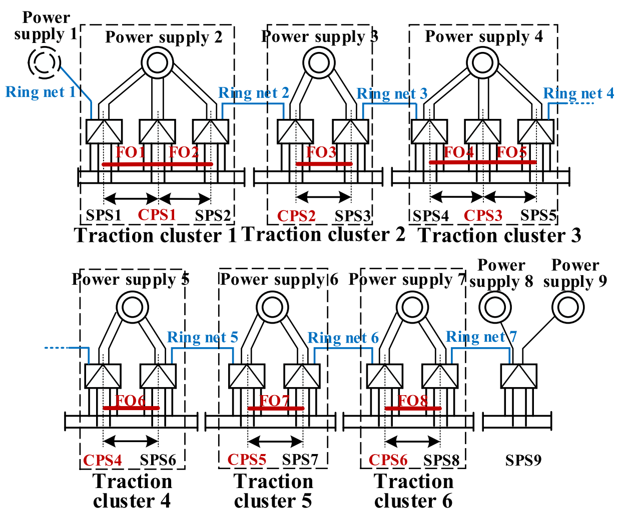

FIGURE 4. Topological structure diagram of TSG.

A total of 9 external power sources along the electrified railway supply power to 15 traction substations, forming 6 TSGs. Each TSG consists of a central traction substation and 1-2 single-phase traction substations. Once the power supply 2 is cut off, adjacent external power supply 1 supplies power to the traction substation TPSS1 in TSG1 through ring network 1, and the external power supply 3 supplies power to the traction substation TPSS3 in TSG1 through ring network 2, which ensures the normal operation of the three traction substations in the group.

1) MODELING OF RELIABILITY ALLOCATION FOR THE INTERCONNECTED POWER SUPPLY SYSTEM OF TRACTION SUBSTATION GROUP

By analyzing the topological structure and operation mode of the TSG along the electrified railways in the mountainous area, the logical relationships between the series and parallel power supply subsystems of the TSG are sorted out based on the reliability allocation block diagram metho. The reliability allocation model for the TSG is constructed, as specifically shown in Fig. 5 to 11.

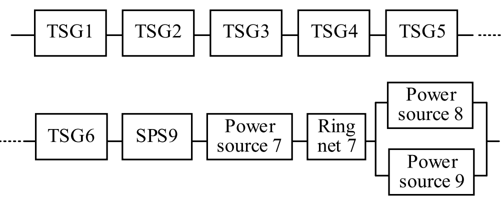

FIGURE 5. Reliability allocation model for TSG.

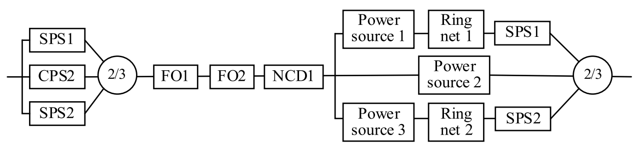

FIGURE 6. Reliability allocation model for TSG1.

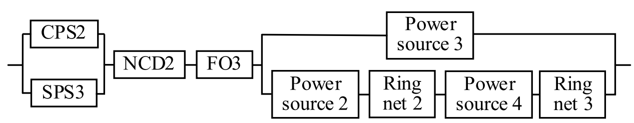

FIGURE 7. Reliability allocation model for TSG2.

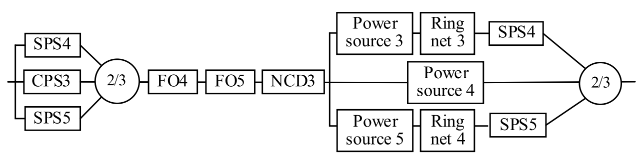

FIGURE 8. Reliability allocation model for TSG3.

2) MODELING OF RELIABILITY ALLOCATION IN TRACTION SUBSTATIONS

The traction substation is the core component of the interconnected power supply system for electrified railway TSG in mountainous areas. Its main task is to convert the 220kV AC power obtained from the external power grid into 27.5kV single-phase power frequency energy through traction transformers and other power supply equipment,

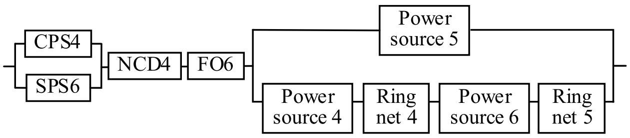

FIGURE 9. Reliability allocation model for TSG4.

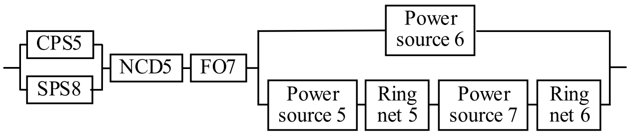

FIGURE 10. Reliability allocation model for TSG5.

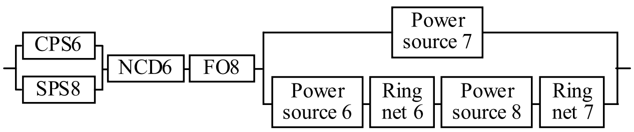

FIGURE 11. Reliability allocation model for TSG6.

and then supply it to electric locomotives for operation through the contact network. Therefore, in the process of reliability allocation, it is also necessary to conduct reliability allocation research on the traction substations that constrain the reliability of the TSG.

Taking the single-phase traction substation in Fig.3 as an example, the traction substation is divided into four power supply areas from top to bottom based on its actual operation mode and topology structure: incoming area, substation area, traction busbar area, and feeder area. The logical relationships between power supply equipment in each area are then analyzed in sequence, and the reliability allocation model for electrified railway traction substations in mountainous areas is constructed, which is shown in Fig. 12.

B. RELIABILITY ALLOCATION SOLUTION

1) RELIABILITY ALLOCATION SOLUTION FOR THE INTERCONNECTED POWER SUPPLY SYSTEM OF TRACTION SUBSTATIONS

Based on the expected reliability requirements of the interconnected power supply system of the electrified railway TSG in mountainous areas, the functional relationship between the reliability R_s of the TSG system and the reliability R_i of the power supply components is determined by analyzing the topology structure and operation mode of the system. Then, the importance and failure rate of each power supply subsystem of the TSG are iteratively solved using the improved AGREE distribution method. Finally, the reliability allocation for the interconnected power supply system of the TSG is conducted. When the heuristic algorithm converges, the reliability of the power supply subsystem hardly changes with iterative accuracy $\varepsilon = 0.0001$ and the allocation can be considered to be close to the real calculation.

Assuming that the expected reliability of the interconnected power supply system of the electrified railway TSG in

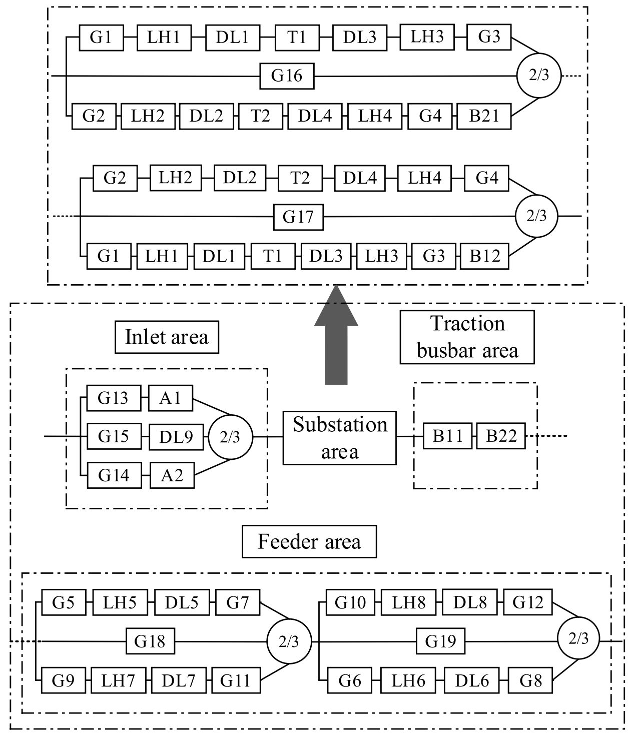

FIGURE 12. Reliability allocation model for traction substation.

this mountainous area is 99% (i.e., reliability $R_s = 0.99$), the reliability R_s will be allocated layer by layer to each power supply subsystem within the TSG. The specific reliability allocation results of each power supply subsystem within the interconnected power supply system of the TSG are shown in Table 1.

TABLE 1. Reliability allocation results of power supply system and power supply partition.

Power Supply Subsystem	Importance	Complexity	Failure Rate	Reliability
External Power	0.99201	0.25001	0.00201	0.99802
TSG1	0.99172	0.20765	0.00172	0.99833
TSG2	0.99103	0.12985	0.00102	0.99900
TSG3	0.99183	0.21901	0.00184	0.99816
TSG4	0.99114	0.13602	0.00114	0.99892
TSG5	0.99122	0.14725	0.00123	0.99878
TSG6	0.99101	0.12986	0.00170	0.99904

It can be seen that the reliability allocation results of the external power supply in the region is 99.802% from Table 1. The reliability allocation is carried out for the 8 power points of the external power supply, and the reliability allocation results of external power sources are shown in Table 2.

The reliability indicators are sequentially allocated to 6 CPSs and 9 SPSs within the group according to the reliability allocation results of the TSG. The reliability allocation results of each traction substation are shown in Table 3.

TABLE 2. Reliability allocation results of external power supply.

Serial Number	Importance	Complexity	Failure Rate	Reliability
1	0.91981	0.02781	0.00162	0.99844
2	0.93962	0.02782	0.00082	0.99921
3	0.93921	0.02777	0.00083	0.99922
4	0.93924	0.02779	0.00083	0.99916
5	0.93963	0.02784	0.00082	0.99915
6	0.92022	0.02782	0.00160	0.99842
7	0.90043	0.02776	0.08141	0.92177
8	0.90042	0.02779	0.08142	0.91278

TABLE 3. Reliability allocation results of traction substation.

Serial Number	Importance	Complexity	Failure Rate	Reliability
CPS1, SPS1-SPS2	0.99032	0.03330	0.00088	0.99912
CPS2, SPS3	0.99261	0.03332	0.00043	0.99957
CPS3, SPS4-SPS5	0.99027	0.03330	0.00012	0.99988
CPS4, SPS6	0.99263	0.03332	0.00045	0.99955
CPS5, SPS7	0.99258	0.03332	0.00043	0.99957
CPS6, SPS8	0.99261	0.03332	0.00036	0.99964
SPS9	0.99024	0.03017	0.00021	0.99975

TABLE 4. Reliability allocation results of fiber optic transmission systems.

Fiber Optic Transmission System	Importance	Complexity	Failure Rate	Reliability
FO1	0.92863	0.17102	0.09132	0.91273
FO2	0.91864	0.18184	0.08149	0.92174
FO3	0.92922	0.17438	0.07925	0.92381
FO4	0.93861	0.20004	0.07084	0.93161
FO5	0.92864	0.18623	0.08151	0.92172
FO6	0.91941	0.23332	0.07826	0.92472
FO7	0.92923	0.29233	0.06870	0.93361
FO8	0.93202	0.17101	0.07813	0.92484

Similarly, the reliability indicators are sequentially allocated to 8 fiber optic transmission systems and 6 NCDs within the group according to the reliability allocation results of the TSG. The reliability allocation results of the fiber optic transmission systems and negative sequence compensation devices are shown in Tables 4 and 5.

TABLE 5. Reliability allocation results of negative sequence compensation devices.

Negative Sequence Compensation Device	Importance	Complexity	Failure Rate	Reliability
NCD1	0.91872	0.21101	0.09034	0.91362
NCD2	0.91926	0.21103	0.07941	0.92366
NCD3	0.92855	0.21003	0.05695	0.94464
NCD4	0.93934	0.21217	0.08161	0.92163
NCD5	0.91924	0.21743	0.07083	0.93162
NCD6	0.92343	0.21102	0.08259	0.92073

It can be concluded that the importance and reliability assigned to the traction substations are relatively high by analyzing the reliability allocation results of the interconnected power supply system of the electrified railway TSG in mountainous areas. This is because the traction substation,

TABLE 6. Reliability allocation results of negative sequence compensation devices.

Power Supply Zoning	Power Supply Equipment	Importance	Failure Rate	Reliability
Entry Area	isolating switch G13~G15	0.94651	0.00169	0.99833
	power feed A1~A2	0.94651	0.00169	0.99833
	circuit breaker DL9	0.94651	0.00169	0.99833
Substation Area	isolating switch G1~G4	0.96374	0.00092	0.99908
	circuit breaker DL1~DL4	0.96373	0.00092	0.99908
	isolating switch G16~G17	0.97467	000013	0.99987
	transformer LH1~LH4	0.96374	0.00092	0.99908
	main transformer T1, T2	0.96374	0.00092	0.99908
Traction Bua Bar Area	traction bua bar B1	0.99973	0.00003	0.99998
	traction bua bar B2	0.99973	0.00003	0.99998
Feeder Area	isolating switch G5~G12	0.95932	0.00123	0.99878
	transformer LH5, LH6	0.95934	0.00123	0.99878
	isolating switch G18~G19	0.97955	0.00011	0.99989
	circuit breaker DL5, DL6	0.95939	0.00123	0.99878

the core component of the power supply system of the TSG, is responsible for the key task of converting electrical energy. Once a fault occurs, it will directly lead to power outages in the traction network and the electric locomotives fail to operate normally. Therefore, in the reliability design stage, it is necessary to allocate higher reliability indicators to the traction substation.

2) CALCULATION OF RELIABILITY ALLOCATION FOR TRACTION SUBSTATIONS

The reliability index requirements for traction substations along the railway can be clearly defined based on the reliability allocation results of the interconnected power supply system for the electrified railway TSG in the mountainous area. Based on this, continue to allocate the reliability of the traction substation, reallocate the reliability indicators of the traction substation to the key power supply equipment in the substation, and then clarify the reliability index requirements of the power supply equipment. In addition, if there is no NCD, the structure and function of the CPS and the SPS are the same, so the reliability allocation method of the ordinary traction substations can be used. Taking SPS9 as an example for reliability allocation, it can be seen that the reliability allocation result of SPS9 is 99.975% according to the reliability allocation results of the interconnected power supply system of the electrified railway TSG in mountainous areas. Then, the reliability allocation of each key power supply equipment in SPS9 is carried out based on the reliability allocation model of the electrified railway traction substation in mountainous areas. The allocation results are shown in Table 6.

From Table 6, it can be seen that busbar B1 and busbar B2 have the highest importance, which means that the probability of traction substation failure caused by traction busbar failure is relatively high. They are the key equipment that causes traction substation failure and also the weak link within the traction substation. In order to ensure the reliable operation of the traction substation, it is necessary to allocate high reliability to the traction busbar in the reliability design stage. In addition, for similar power supply equipment in different power supply zones, the reliability allocation results are different: taking the isolation switch as an example, G1∼G4 located in the substation area have an importance of 0.96374, and the allocated reliability is 99.908%; G5∼G12 located in the feeder area have an importance of 0.9593 and a reliability of 99.878%; located in the incoming area, G13∼G15 have an importance of 0.94651 and are assigned a reliability of 99.833%. This is because the substation area is a key link in the energy conversion of traction substations. When designing reliability, it is necessary to consider allocating high reliability to the key power supply equipment within the substation area.

V. CONCLUSION

This paper proposes a reliability allocation method for traction power supply system based on the improved AGREE method, which takes into account the characteristics of the interconnected power supply system of electrified railway TSG in mountainous areas. The TPSS of an electrified railway under construction in western China is used as an example in the case study, and the reliability allocation design results of each subsystem and key power supply equipment in the traction substation are obtained. The specific conclusions are as follows.

(1) This paper improves the traditional AGREE allocation method based on the special topological structure of the TPSS of electrified railways in mountainous areas and the logical relationship between each power supply area. It solves the problem of the lack of historical fault data of power supply equipment during the design stage of electrified railways.

(2) This paper establishes a reliability allocation model for the interconnected power supply system of TSG, and assigns the reliability index of the entire system to each subsystem layer by layer. On this basis, a reliability allocation model for the traction substation is established and reliability index is allocated to the underlying power supply equipment in the traction substation, which provide corresponding ideas for the reliability design of TPSS for electrified railways in mountainous areas.

(3) Through the method presented in this paper, it is possible to predict the reliability and failure rate of key TPSS equipment and facilities, using the reliability allocation design results of the TPSS of electrified railways in mountainous areas. This can be used to provide feedback and guidance for the forward design of the TPSS of electrified railways in mountainous areas.

(4) In the improved AGREE reliability allocation process, the importance of the power supply equipment is set to 1 as the initial value, but the failure of some power supply equipment will not directly lead to the failure of the whole system which signifies that its importance is actually much lower. In the future work, a more accurate way of presetting the importance of power supply equipment is required to reduce the number of iterations and increase the convergence speed of the algorithm.

REFERENCES

[1] J. Ma, "Development plan for modern comprehensive transportation system in the 14th five-year plan," *Railway Quality Control*, vol. 50, no. 2, pp. 9–23, 2022.

[2] *Mid-and-Long Railway Network Planning*, Nat. Develop. Reform Commission, Ministry Transp. P.R.C, China State Railway Group Co, Ltd., Beijing, China, 2016.

[3] X. Zhang and Z. J. Jia, "Challenges of construction, operation and maintenance in Sichuan grid and countermeasures," *High Voltage Eng.*, vol. 42, no. 4, pp. 1091–1099, 2016.

[4] Q. Li, H. Wang, and S. Xie, "Research on the application of bilateral power supply technology of electrified railway," *Electr. Railway*, vol. 32, no. 6, pp. 1–4, 2021.

[5] Z. Ren, Y. Xie, and W. Wang, "Research on the design technology of high-speed railway lines with long and steep slopes in tough mountainous areas," *Railway Standard Design*, vol. 67, no. 7, pp. 42–50, 2023.

[6] C. Lu and C. Cai, "Challenges and countermeasures for construction safety during the Sichuan–Tibet railway project," *Engineering*, vol. 5, no. 5, pp. 833–838, Oct. 2019.

[7] Q. Zhang, J. Li, L. Xie, and X. He, "Integrated factor reliability allocation method considering influences of two-layer factors," *China Mech. Eng.*, vol. 30, no. 19, pp. 2301–2305, 2019.

[8] T. Sun, W. Sun, and L. He, "Study in reliability optimal allocation way of windriven based on genetic algorithm," *Renew. Energy Resour.*, vol. 34, no. 5, pp. 699–704, 2016.

[9] B. Bai, C. Xie, X. Liu, W. Li, and W. Zhong, "Application of integrated factor evaluation-analytic hierarchy process-T-S fuzzy fault tree analysis in reliability allocation of industrial robot systems," *Appl. Soft Comput.*, vol. 115, Jan. 2022, Art. no. 108248.

[10] S. Si, M. Liu, Z. Jiang, T. Jin, and Z. Cai, "System reliability allocation and optimization based on generalized Birnbaum importance measure," *IEEE Trans. Rel.*, vol. 68, no. 3, pp. 831–843, Sep. 2019.

[11] R. Li, J. Wang, H. Liao, and N. Huang, "A new method for reliability allocation of avionics connected via an airborne network," *J. Netw. Comput. Appl.*, vol. 48, pp. 14–21, Feb. 2015.

[12] Y. Wang, X. Jia, J. Zhao, and Y. Tian, "Improvement of agree allocation method," in *Proc. 8th Int. Conf. Rel., Maintainability Saf.*, Jul. 2009, pp. 293–295.

[13] G. Du, L. He, J. Fang, and B. Zhang, "A modified AGREE reliability allocation method research in power converter," in *Proc. 10th Int. Conf. Rel., Maintainability Saf. (ICRMS)*, Aug. 2014, pp. 522–525.

[14] R. Li and W. Ren, "Network reliability allocation method based on heuristic algorithm," *J. Beijing Univ. Aeronaut. Astronaut.*, vol. 38, no. 2, pp. 228–232, 2012.

[15] B. Zhang, Y. Xu, and Y. Tao, "Reliability allocation method of urban transit braking system based on belief reliability," *J. Ordnance Equip. Eng.*, vol. 43, no. 9, pp. 115–120, 2022.

[16] Y. Wan, D. Ding, and B. Deng, "Application of fuzzy synthesis evaluation in reliability allocation of the catenary system," *J. Railway Engeneer Soc.*, vol. 6, pp. 74–77, Aug. 2006.

[17] Y. Guo, J. Lian, and K. Zhang, "Influence of auto-passing of neutral section on electric locomotive," *Electr. Drive Locomotive*, vol. 2, pp. 13–15, Jul. 2000.

[18] Q. Li, H. Wang, and W. Huang, "Interconnected power supply system of traction substation group and its key technologies for the electrified railway," *Trans. China Electrotech. Soc.*, vol. 36, no. 5, pp. 1064–1074, 2021.

[19] *Power Quality-Three-Phase Voltage Unbalance*, Standard GB/T 15543-2008, Standardization Admin. P.R.C, Beijing, China, 2008.

[20] Q. Zhang, Q. Huang, and Y. Zhang, "Research on the method of reliability allocation based on exponential distribution," *Ship Electron. Eng.*, vol. 30, no. 53, pp. 151–154, 2010.

[21] S. Bač kaliċ, D. Jovanoviċ, and T. Bač kaliċ, "Reliability reallocation models as a support tools in traffic safety analysis," *Accident Anal. Prevention*, vol. 65, pp. 47–52, Apr. 2014.

[22] Y. Xiang, D. Huang, and L. Huang, "Reliability allocation of BA system based on grey relative theory and AGREE," *Appl. Res. Comput.*, vol. 27, no. 12, pp. 4489–4491, 2010.

[23] Y. G. Zheng and K. D. Zhang, "Modified AGREE method and its application in reliability allocation of air separation plant," *Mech. Design*, vol. 13, pp. 8–9, May 1996.

[24] M. L. Shooman, *Probabilistic Reliability: An Engineering Approach*. Malabar, FL, USA: R.E. Krieger Publishing Company, 1990.

LIKE PAN was born in Shaanxi, China, in 1986. He received the Ph.D. degree in vehicle operation engineering from Beijing Jiaotong University, Beijing, China, in 2017.

His research interests include electrified railway traction power supply technology and pantograph-catenary coupling technology.

YUJIE TIAN was born in Sichuan, China, in 2000. She received the B.Eng. degree in electrical engineering from Chongqing Jiaotong University, Chongqing, China, in 2022. She is currently pursuing the M.Sc. degree with Southwest Jiaotong University, Sichuan.

Her research interests include the safety assessment and risk assessment of traction power supply systems.

SHAN MA was born in Chongqing, China. She received the master's degree from the School of Electrical Engineering, Southwest Jiaotong University. Her research interests include traction power system reliability and risk assessment.

WENRUI DAI is mainly engaged in primary and secondary equipment detection and fault analysis research in traction power supply system of electrified railways.

LIMING CHEN was born in Hebei, China, in 1979. He received the M.S. degree in engineering mechanics from Beijing University of Technology, Beijing, China, in 2006.

His research interests include electrified railway traction power supply technology and pantograph-catenary coupling technology.