Received December 1, 2019, accepted December 9, 2019, date of publication December 13, 2019, date of current version December 31, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2959723

A Research Into the Reliability of Equipment-Integrated System Regarding High-Speed Train Based on Network Model

MAN LI, YANHUI WANG, AND LIMIN JIA
[1]State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, Beijing 100044, China
[2]School of Traffic and Transportation, Beijing Jiaotong University, Beijing 100044, China
[3]Beijing Research Center of Urban Traffic Information Sensing and Service Technology, Beijing Jiaotong University, Beijing 100044, China

Corresponding authors: Yanhui Wang (wangyanhui@bjtu.edu.cn) and Limin Jia (lmjia@bjtu.edu.cn)

This work was supported in part by the State Key Laboratory of Rail Traffic Control and Safety under Grant RCS2018ZT007 and in part by the China Postdoctoral Science Foundation under Grant 2018M641176.

ABSTRACT The equipment-integrated system with highly coupled and correlated characteristics has become the main mode of the modern production system. Reliability plays an important role in the production of the system and its normal and efficient operation. Firstly, aimed at the composition of equipment-integrated system and its working mechanism, a method for evaluating the reliability of the node based on the network model is proposed in this paper, including correlation reliability of node, use reliability of node. Secondly, reliability calculation model of equipment-integrated system based on improved Markov is established considering the analysis of the basic structure principle and fault statistic method of high-speed train system. Thirdly, through the quantitative analysis of the reliability network model of the traction supply system, the reliability of the subsystem and the components of the system are calculated, with the key nodes of the system obtained by the structure analysis of the system. Results show that the network model is suitable for equipment-integrated system regarding high-speed train, and the modeling process from the local point to the whole system is simple and effective. With the network model of traction supply subsystem, the reliability of subsystems and components of the system are obtained, which provide a basis for the maintenance of the equipment-integrated system with respect to the high-speed train.

INDEX TERMS Equipment-integrated system, high-speed train, network theory, reliability model, Markov process.

I. INTRODUCTION

Equipment-integrated system is one of the complex physical systems including mechanical, electrical, liquid, light and other physical processes, which is designed to achieve specific functions. Based on the transmission, transformation and evolution of various media such as matter flow, energy flow and information flow, the equipment-integrated system is also a complex equipment, which is composed of multi-level composite, interconnected electronic components, mechanical parts and other complex equipment [1]. Equipment-integrated systems play an important role in social progress and national economic development [2].

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

In order to qualitatively and quantitatively analyze the system reliability, a variety of reliability models and analysis methods for equipment-integrated systems have been proposed. Among them, the common methods are reliability block diagram method [3], [4], fault tree method [5]–[7], Markov process [8], [9], Petri net [10]–[12] and so on.

It should be pointed out that the traditional method of reliability analysis is difficult to describe the impact of component relativity and working conditions, so it is not suitable for large-scale equipment-integrated systems such as high-speed train systems. The current Bayesian method is more effective to solve the problem of function and timing related network reliability calculation, but the modeling of the network is mostly transformed from fault tree or dynamic fault tree [13], which ignored the functional structure of the system and the functional relevance within the system. With the networking and complexity of the product and system, the research on the reliability of the network system gradually arises, and various algorithms of network reliability are emerging [14]–[16]. The network minimum set enumeration method is used to collect the non-related elements in the network state set and to obtain the reliability value of the network system by principle of inclusion-exclusion [17]. However, these enumeration methods are unavoidably related to state combinatorial explosion problems and they can only be used for small network analysis (low density networks with less than 20 nodes) [18]. Therefore, some scholars have done some work in the approximate calculation. Network reliability is simplified based on network topology by the graph transformation method [19]. Some special structures in the network, such as triangular structure [20] and polygon structure [21], are used to simplify the network structure until the whole network shrinks into one link. And finally the network reliability is solved. According to the algorithm of the strong link part of the network, Shogan [22] got the closest boundary of the system reliability. Van Slyke and Frank [23] obtained the Kruskal-Katona reliability bounds based on subgraph statistics and some generalized properties. The algorithm of approximation is still NP hard problem. A new perspective to study the reliability of the network for large-scale network is needed for improve the network reliability analysis framework. Thus, Zang *et al.* [24] introduced the Binary Decision Diagram (BDD) theory to study network reliability. In 2003, Chang *et al.* [25] used EED (Edge Expansion Diagram) method to solve the two terminal network cut sets of the network for streaming networks, and then calculated the unreliability of the network by BDD method. Binary decision graphs [26] are widely used in the reliability analysis of two-state networks. But the shortcoming of the use of binary decision diagram is obvious for the multi-state network. It can neither deal with too many Boolean variables, nor consider the network node state between the dependencies. In order to extend the application of BDD, in 2007, Xing [27] began to apply the Multiple Decision Diagram (MDD) to the reliability of multi-state network system. In 2010, based on Xing's work, Terruggia and Bobbio [28] studied the performance reliability of multi-state weighted probability networks by using multi-valued decision graphs (MDD). And they proposed a calculation method of performance reliability based on MDD network.

So far, the study of network reliability has made great progress. But the use of network models is still limited to computer networks, biological networks, transportation networks and infrastructure lifeline systems. There are few articles on the reliability of network research methods for equipment-integrated systems. As network characteristics of distributed equipment-integrated systems are increasingly prominent, it is inevitable to study the reliability of equipment-integrated systems by using network model.

In this paper, a method for evaluating the reliability of the node and system based on the network model is established, aiming at the composition of equipment-integrated system and its working mechanism. Through the quantitative analysis of the reliability network model of the traction supply system, the reliability of the subsystem and the components of the system are obtained, with the key nodes of the system obtained by analyzing the structure of the system.

II. THE NETWORK MODEL OF EQUIPMENT-INTEGRATED SYSTEM

A. RELEVANT ASSUMPTIONS AND DEFINITIONS

Based on the characteristics of equipment-integrated system, the complex connection mode, relationship, multi-state variables, etc., according to system theory and network theory, the reliability model of equipment-integrated system is constructed. In order to facilitate the research, with the assumptions involved as follows:

1) The equipment unit is the smallest part in equipment-integrated system, and system is an integral whole. The equipment unit is abstracted into node with the attributes in the network. Here the function relation is described as attribute;

2) There are two kinds of normal and fault conditions in the equipment unit, equipment units interact through the directed connected edges. The failure rate of all equipment units in the system are subject to exponential distribution. All equipment are repaired immediately after failure, and the life distribution of the system is the same as the original one;

3) The functions of the equipment units are described as the relevant properties, and the physical connection mode of the equipment-integrated system is fixed.

Definition 1 (Equipment-Integrated Subsystem): The equipment-integrated subsystem is aimed at achieving the function of the integration system as a whole, which is composed of the mutual dependence, restriction and interaction. The equipment-integrated system is represented as S, $S = \{S_1, S_2, \ldots, S_n\}$ where the S_i is the ith subsystem. $S_i = \{n_{i1}, n_{i2}, \ldots, n_{in}\}$, and the n_{ij} is the jth unit of the ith subsystem.

Definition 2 (Equipment-Integrated System Unit): The equipment-integrated system units with certain mechanical, electrical or information attributes undertake the necessary components of a specific function and constitute the subsystem. It is an independent and indivisible entity expressed as n_{ij}, where $i = 1, 2, \ldots, n$; $j = 1, 2, \ldots, m$. Each node has a set of attributes that are specifically and securely related, with a definitely physical meaning expressed as $x(n_{ij}) = \{a(n_i), b(n_i), \ldots\}$.

Definition 3 (The Connection Edge of Equipment-Integrated System Unit): In the equipment-integrated system, the relationship between the equipment units is expressed through different ways of connection. There are mainly 3 categories, i.e., mechanical, electrical, and information network, expressed as e^m, e^e, e^i. If the component n_{ri} and the component n_{rj} are connected by an edge, it is expressed $e_{ij}^v = \left\{n_{ri}, n_{rj}\right\}$, $i = 1, 2, \ldots, n$; $j = 1, 2, \ldots, n$; $v = \{m, e, i\}$.

B. THE CONNECTION MODE OF EQUIPMENT-INTEGRATED SYSTEM UNIT

In the equipment-integrated system, the relationship between equipment units is different from different connection methods, i.e., mechanical, electrical, and information connections, with the specific connection methods as follows:

Mechanical connection is connected by fasteners. It can be divided into two types, the detachable connection and non-detachable connection. The main ways of the form falls into bolt, screw, screw thread fastening, pin, etc. The main ways of the latter are riveting, welding, bonding and so on.

Electrical connection involves the way of transferring power from one part to another through wires, cables, etc. The components of general electrical connection comprise mainly the electrical connection parts (such as terminals, etc.), wire and cable, wire fixation equipment and wire protection equipment (such as separate wire sheath, etc.) and others. By providing the appropriate mechanical force, the electric connecting component can be reliably fixed together with the different conductor parts to realize the electric connection [29].

Information connection is the connection of the form of the feedback signal. The equipment element transmits information from one end to the other through the transmission medium, with the information received by the other side. There are two kinds of transmission media, wired and wireless. The former is a telephone line or a special cable. The latter transmits information through radio, microwave and satellite technology. The information connection includes information transfer and reception.

C. NETWORK MODEL CONSTRUCTION OF THE EQUIPMENT INTEGRATED SYSTEM

Network nodes represent the equipment set $N = \{n_1, n_2, n_3, \ldots\}$, Network edges represent the connections between the units including mechanical relations e_{kl}^m, electrical relations e_{kl}^e and information relations e_{kl}^i. According to design parameters and physical structure of the system, a weighted system structure network model is constructed as $G = (G_m, G_e, G_i)$. $G_m = (N_m, E_m, X_m, Y_m)$, $G_e = (N_e, E_e, X_e, Y_e)$, $G_i = (N_i, E_i, X_i, Y_i)$. Here, N is the set of nodes, E is the set of edges, X is the set of node attributes, and Y is the set of edge attributes. The construction steps of the network are as follows. The network model is constructed as shown in Fig.1.

① Each unit is abstracted as a node in a network ignoring its realistic meaning.

② Determine the function relationship between the units (mechanical, electrical and information). If there is a function relationship between two units, add a directed edge between them.

③ Delete isolated node, with a network model formed.

According to the above-mentioned network model $G = (G_m, G_e, G_i)$, the characterizing parameters of network are analyzed, three networks are determined. The attributes of node includes failure rate λ_i, inherent reliability $r'(n_i)$, reliability $r_t'(n_{ij})$, and relevance reliability $r_t''(n_{ij})$ (in chapter three, the calculation method of specific narrative attribute node). With reference to mechanical, electrical, information connections of the functional properties, the strength is used to indicate the effects of different connection modes.

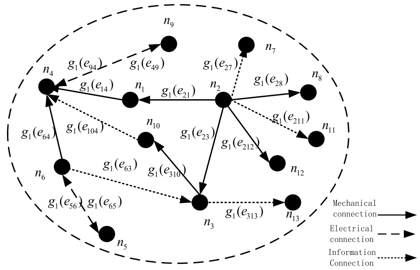

FIGURE 1. Network model of the equipment-integrated system.

Definition 4 (Connection Strength $c\left(ue_{ij}^v\right)$): The connection strength is the influence degree of the interaction of the different connection modes between the equipment units. Each side has a class collection (mechanical, electrical, information). According to the relevant statistical results and expert experience, it can be quantified. The connection strength reflects the influence degree of edge connection by $c\left(ue_{ij}^v\right)\left(0 < c\left(ue_{ij}^v\right) \leq 1\right)$. From the whole life of equipment, it also reflects its design and manufacturing should be given due attention. In the process of studying the reliability and fault propagation of equipment-integrated system, the value of the connection strength should be determined according to the experience of the relevant design, manufacturing engineers, field operators and maintenance professionals. Welding is the most stable connection mode, instead of a removable connection. In the model of equipment-integrated system, based on the fault data and expert experience, the fault propagation property of edges is analyzed in order to emphasize the close relationship between the equipment units. The influence degree of the connected equipment units after the fault occurs, represented by the fault propagation probability.

Definition 5 (Fault Propagation Probability $\eta\left(ue_{ij}^v\right)$): The probability of the node status which is directly connected to the side after the failure of the node, is called fault propagation probability. It can be extracted from the fault history data, and also estimated according to the system parameters. A calculation method is presented in this paper. Under the premise of the available data, and in the causal relationship of n_{ri} and n_{rj} exist, the number of changes, within the prescribed time or period, is firstly determined as n_{ri} changes, and therefore the number n_{rj} of changes is determined as $K\left(n_{rj}\right)$, with the formula for the fault propagation probability calculated:

$$\eta\left(ue_{ij}^v\right) = \frac{K\left(n_{rj}\right)}{K\left(n_{ri}\right)} \tag{1}$$

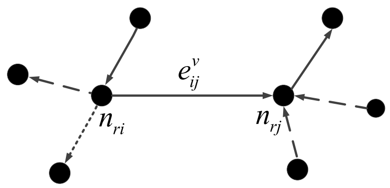

FIGURE 2. Schematic diagram of edge effect strength.

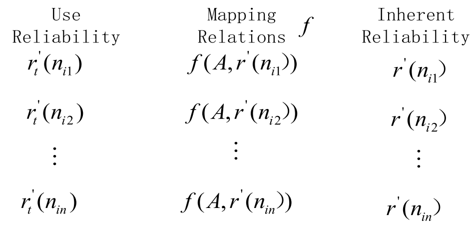

FIGURE 3. Mapping relations of the use reliability and the inherent reliability.

The function relationship between equipment units is shown in Fig.2. The direction of edge represents the relation of node coupling. In the weighted network, the coupling strength between nodes is an important factor to restrict the fault development. Considering the influence of nodes affected by multiple nodes, it is necessary to carry out non-dimensional data processing to the original data.

Definition 6 (Action Strength): The action strength of the connecting edge is the comprehensive reflection of the degree of the relationship between the nodes, so we should comprehensively consider the two factors of the connection strength between the nodes and the fault probability propagation between the nodes. In order to simplify the expression of $g_v\left(e_{ij}\right)$ and the reliability network model, the interaction strength of the side edge is expressed by and $v = 1, 2, \ldots, n$, n represents the subsystem, with the expressions as follows:

$$g_v\left(e_{ij}\right) = c\left(ue_{ij}^{v}\right)\eta\left(ue_{ij}^{v}\right) \tag{2}$$

According to different types and intensity analysis method, the effect of each edge is calculated, and the strength of edge is used as the attribute of the edge. It means that the reliability analysis of two interacting nodes is carried out by analyzing the strength of the side effect.

III. NODE RELIABILITY CALCULATION OF EQUIPMENT-INTEGRATED SYSTEM

A. RELEVANT DEFINITIONS

In the network model, node is the equipment unit. Generally, the reliability is the probability of a product to perform a specific function within specified conditions and time. In this model, node reliability is related to the inherent reliability and the factors that affect the use of the process, with the probability of its normal operation as the use reliability of the node. The reliability of the node is obtained by fusing the use reliability of the node and the connection reliability of node [30]. The basic involved terms are defined as follows:

Definition 7 (Inherent Reliability of Node): The reliability index is determined by the component in the planning stage, so the design reliability of component is the inherent attribute of node. The inherent reliability of the S_i subsystem of the jth node is expressed by $r'\left(n_{ij}\right)$.

Definition 8 (Use Reliability of Node): After the component is put into use, the reliability of node presents the probability that the unit completes its specific function in the expected period of use under specified conditions. The use reliability of the S_i subsystem jth node of the t moment is expressed by $r_t'(n_{ij}) = p(t < T)(i = 1, 2, \cdots, n; j = 1, 2, \cdots, m)$ and $r_t'(n_{ij}) \in [0, 1]$.

Definition 9 (Correlation Reliability of Node): After the introduction of the related variables, and the consideration of the interaction between two units, the correlation reliability of nodes is the impact probability of other units on the unit in the expected period of use under the specified conditions. The correlation reliability is expressed by $r_t''\left(n_{ij}\right) = p\left(t < T\right)\left(i = 1, 2, \ldots, n; j = 1, 2, \ldots, m\right)$.

Definition 10 (Node Reliability): With specified time and specified conditions, the node reliability is the probability that the unit completes its specific functions. The use reliability of the S_i subsystem jth node of the t moment is expressed by $r_t'\left(n_{ij}\right) = p\left(t < T\right)\left(i = 1, 2, \ldots, n; j = 1, 2, \ldots, m\right)$ and $r_t'\left(n_{ij}\right) \in [0, 1]$. With reference to the use reliability of node, the node is the most reliable, with no fault and abnormal one; otherwise we will have the weakest reliability, $r_t\left(n_i\right) = 1$.

B. CALCULATION OF NODE RELIABILITY

In the reliability network model of equipment-integrated system, the reliability of the unit involves not only the independent reliability of node (the reliability and reliability of the node are used as independent reliability in this paper), but also the influence of the potential reliability caused by the interaction between nodes (it is expressed by the correlation reliability). The reliability of the node is the probability that a node can perform its normal operation in the research of the independent reliability and the associated reliability of nodes.

1) USE RELIABILITY CALCULATION OF NODE

Actually, the use reliability and the inherent reliability of the node unit are related to the above-mentioned factors, so the use reliability of the node units can be expressed as follows:

$$r_t'(n_{ij}) = f\{a_1, \ldots, a_5, r'(n_{ij})\} = f\{A, r'(n_{ij})\} \tag{3}$$

And $A = \{a_1, a_2, \ldots, a_5\}$. $f\{\cdot\}$ is the change of the influence of the inherent reliability and the conditions of the node. It is the change trend of the use reliability of the node $r_t'(n_{ij})$.

The specific influence degree of each factor to the node unit can not only be given according to the expert's experience value, but also obtained through a lot of experimental data. In the case of an equipment-integrated system in the same route and conditions of long-term use, a large amount of historical failure data are obtained, with the reliability parameters of each node uses as the use reliability of node, which are obtained through analysis of the fault data. The use reliability obtained from historical data and the inherent reliability of each node form a one-to-one correspondence. The relationship of the use reliability and the inherent reliability can be expressed as $r'_t(n_{ij}) = f(A, r'(n_{ij}))$.

According to a large amount of data, the corresponding relationship of each node is calculated through the data fitting, as $f(\cdot)$. In this way, the use reliability of any unit can be obtained in the prescribed time with the formula of $f(\cdot)$.

2) CORRELATION RELIABILITY CALCULATION OF NODE

The correlation reliability of node is one of the measures to consider the potential impact of other nodes on the reliability of this node. The fault propagation caused by the unreliable state of the system node is studied, leading to the reduction of the reliability of the associated other nodes. So there is the unreliability of the node, expressed as $f_t(n_{ij})$.

$$f_t(n_{ij}) = 1 - r'_t(n_{ij}) \tag{4}$$

The calculation steps of the node of correlation reliability are as follows:

① Related to use reliability $r'_t(n_{ij})$, the unreliability of the node is $f_t(n_{ij}) = 1 - r'_t(n_{ij})$.

② List a set of descriptions of the unreliability of the node as $\{f_t(n_{i1}), f_t(n_{i2}), \ldots, f_t(n_{in})\}$.

③ Determine the effect strength of the edge. In the second chapter, the interaction strength of the action edge between the nodes is calculated, and the action edge or the edge without action is 0.

④ Adjust the intensity of the action, making it into a matrix form. And $g_v(e_{ii}) = 0$.

$$Q = \begin{bmatrix} g_v(e_{11}) & g_v(e_{12}) & \ldots & g_v(e_{1n}) \\ g_v(e_{21}) & g_v(e_{22}) & \ldots & g_v(e_{2n}) \\ \vdots & \vdots & \ldots & \vdots \\ g_v(e_{n1}) & g_v(e_{n2}) & \ldots & g_v(e_{nn}) \end{bmatrix}$$

⑤ Determine the correlation unreliability of the node as $f'_t(n_{ij})$

$$\begin{aligned} f &= B \times Q \\ &= [f_t(n_{i1}), f_t(n_{i2}), \ldots, f_t(n_{in})] \\ &\quad \times \begin{bmatrix} g_v(e_{11}) & g_v(e_{12}) & \ldots & g_v(e_{1n}) \\ g_v(e_{21}) & g_v(e_{22}) & \ldots & g_v(e_{2n}) \\ \vdots & \vdots & \ldots & \vdots \\ g_v(e_{n1}) & g_v(e_{n2}) & \ldots & g_v(e_{nn}) \end{bmatrix} \\ &= [\sum_j^n f_t(n_{ij}) g_v(e_{j1}), \sum_j^n f_t(n_{ij}) g_v(e_{j2}), \ldots, \sum_j^n f_t(n_{ij}) g_v(e_{jn})] \end{aligned}$$

$$\sum_j^n f_t(n_{ij}) g_v(e_{jn})$$

$$= f_t(n_{in}) g_v(e_{nn}) + \sum_j^{n-1} f_t(n_{ij}) g_v(e_{jn})$$

$$= \sum_j^{n-1} f_t(n_{ij}) g_v(e_{jn})$$

And the correlation unreliability of the node is $f'_t(n_{ij}) = \sum_j^{n-1} f_t(n_{ij}) g_v(e_{jn})$.

⑥ The correlation reliability of the node:

$$r''_t(n_{ij}) = 1 - f'_t(n_{ij}) \tag{5}$$

3) CALCULATION METHOD OF NODE RELIABILITY

In the equipment-integrated system, the safety state around the node with multiple edges is directly affected when the event of failure occurs. With the expansion of the scope of the spread of the fault, the reliability of the node will be reduced, which is likely to stop running. So when analyzing the reliability of nodes, it is essential to analyze the influence of the potential factors on the reliability.

The previous research about the reliability of the node didn't consider the influence of the surrounding equipment units. In this paper, in order to study the reliability of node equipment more accurately, the reliability of the equipment is studied considering both the use reliability and the correlation reliability of the nodes.

The node reliability is closely related to the properties and uses of the node, which can be expressed as a functional form. For example, the $r_t(n_{ij})$ of the node is changed with the use of its own reliability and the associated reliability of its associated nodes, which can be expressed as:

$$r_t(n_{ij}) = f(r'_t(n_{ij}), r''_t(n_{ij})) \tag{6}$$

Here $r'_t(n_{ij})$, $r''_t(n_{ij})$ respectively indicates the use reliability and the correlation reliability of the nodes. By using the reliability of the node, it can be known that the failure rate of the node itself is $\lambda(n_{ij})$ in the reliability network model of equipment-integrated system. If there are several nodes in the working state which are connected with it, the direction of the interaction between the nodes are analyzed respectively, and the number of all nodes that have a direct effect on the node is recorded as ω_i. The fault influence degree of the related nodes is $\lambda_e(n_{ij}) = \ln f'_t(n_{ij})$. So when a node in the network, the node fault equivalent rate can be converted by the following formula.

$$\lambda'(n_{ij}) = \lambda(n_{ij}) + \sum^{\omega} \lambda_e(n_{ij}) \tag{7}$$

The formula for calculating the reliability of the node is as follows:

$$r_t(n_{ij}) = e^{-\lambda'(n_{ij})} \tag{8}$$

When the node life is not subject to the exponential distribution, the reliability of the node at different times can be calculated through the reliability function of the node when calculating the reliability of the target node.

IV. RELIABILITY CALCULATION OF EQUIPMENT-INTEGRATED SYSTEM BASED ON IMPROVED MARKOV

A. IMPROVED MARKOV PROCESS

In the method of system reliability analysis, the traditional Markov process is to study the unit of each node as independent individuals. But in fact, node units inside the system are interconnected. The state of system at the last moment may change with the states of system internal equipment, and the state of the equipment will have a corresponding impact on the equipment status associated with the system. So in this paper, through the improvement of the state transition matrix, the effect of the state of the equipment is considered in the system state transition matrix, which makes up the traditional problem of the relationship between the equipment.

Each state in the generated state set can be divided into two classes: normal state and fault state, respectively expressed as W, F.In the state space of a smaller number of sets, the reliability analysis and calculation of the system network model are carried out by Markov process [31]. With the assumed system under the current state of the known, the future state depends only on a given normal conditions or boundary conditions, and it is only related to the time of the test process, with no relation to the time of the system's previous state and the beginning of the experiment. Therefore, the system is a Markov process time [32].

If the $X(t)$ indicates the status of a system at the t time, there are any state $k, l \in \Omega_G$. State transition can be carried out at any moment. As for the equipment unit in the system, failure directly affect the function of equipment unit. So in a very short time, there will not be two and more than two nodes of state transition, and the basic assumption is obviously reasonable.

The probability of the system process state leaving the k state into the l state is P_{kl}. As for fixed $k, l \in \Omega_G$, the function $P_{kl}(t)$ becomes the transition probability one, and in a sufficiently short period of time Δt, the transition probability function satisfies the following formula.

$$P_{kl}(\Delta t) = a_{kl}\Delta t + o(\Delta t), \quad k, l \in \Omega_G, \ k \neq l \tag{9}$$

Here $\{a_{kl} : k, l \in \Omega_G, k \neq l\}$ is given, and $a_{kl} \geq 0$, then a_{kl} is called as the conversion rate of the k state enters the l state, and then the system's state transition matrix is:

$$A_G = \begin{bmatrix} a_{00} & a_{01} & \dots & a_{0r} \\ a_{10} & a_{11} & \dots & a_{1r} \\ \vdots & \vdots & \dots & \vdots \\ a_{r0} & a_{r1} & \dots & a_{rr} \end{bmatrix}$$

The diagonal elements in the matrix are given in the following formula.

$$a_{kk} = -\sum_{\substack{l=0 \\ l\neq k}}^{r} a_{kl} \tag{10}$$

The steps to build a transition matrix A_G are as follows:

(1) List and describe the status of system $\Omega_G = \{0, 1, \dots, r\}$.

(2) Determine the conversion rate a_{kl}.

The improved transfer matrix method is as follows: the conversion rate of the unit node is determined according to the function strength $g(e_{ij})$, the failure rate λ_i, and the maintenance rate of the node μ_i.

① In the case of the state k, the state value of the node unit n_{ks} is 1, and the state value of n_{kt} is 0, while in the state l, the state value of the node unit n_{ks} is 0, and the state value of n_{kt} is 1, $a_{kl} = \{ \begin{matrix} g(e_{st}), e_{st} \in E \\ 0, other \end{matrix}$, $a_{lk} = \{ \begin{matrix} g(e_{ts}), e_{ts} \in E \\ 0, other \end{matrix}$.

② In the case of the state k, the state value of the subsystem n_{ks} is 1, and the state value of n_{kt} is 0, while in the state l, the state value of the subsystem n_{ks} is 1, and the state value of n_{kt} is 1, $a_{kl} = \{ \begin{matrix} \lambda(n_{kt}) \\ 0, other \end{matrix}$, $a_{lk} = \{ \begin{matrix} \mu(n_{kt}) \\ 0, other \end{matrix}$.

③ In the case of the state of k, the state values of the subsystem n_{ks} and n_{kt} are 0, while in the state l, only one of the state values of the subsystem n_{ks} and n_{kt} is 1, $a_{kl} = \{ \begin{matrix} \lambda(n_{ks}) \text{or} \lambda(n_{kt}) \\ 0, other \end{matrix}$, $a_{kl} = \{ \begin{matrix} \mu(n_{ks}) \text{or} \mu(n_{kt}) \\ 0, other \end{matrix}$.

(3) Fill in the matrix diagonal elements a_{kk}.

For example, a subsystem consists of 4 nodes, and the function relationship between the nodes is shown in Fig.4. The rates of failure and repair of the nodes are known, as λ_i and μ_i, $(i = 1, 2, 3, 4)$. Suppose the state space coverage of a system is more than 99.5% and the state of the maximum probability of the system is (0, 0, 0, 0), (1, 0, 0, 0), (0, 1, 0, 0), (0, 0, 1, 0), (0, 0, 0, 1), (1, 0, 1, 0). Note the above-mentioned state set is $\Omega_G = \{0, 1, 2, 3, 4, 5\}$, and the improved conversion rate matrix and the traditional transfer matrix are respectively expressed as A_G and A_{G1}, shown at the bottom of the next page.

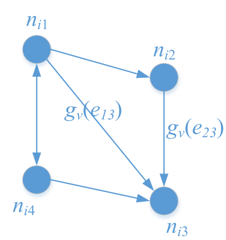

FIGURE 4. Subsystem composition.

From the two transfer matrix, we can see that the traditional matrix only analyzes the direct influence of the current state on the next state without considering the potential influence of the node states. But in the actual condition, when the fault occurs, it will have an impact on the node (state 2 will have an impact on the state 3). The improved state transition matrix takes into account the relationship between the nodes. After the failure of a node, it is bound to affect the state of the other node through the associated edge. While the influence of this kind of node status is not related to the order of occurrence of failure, it is only related to the active and passive role of the interaction between the node states. So the improved state transition matrix can reflect the dynamic change process of the system more than the traditional state transition matrix. So it is reasonable and feasible in theory [8].

B. RELIABILITY CALCULATION OF EQUIPMENT-INTEGRATED SYSTEM

In the most likely state space, the reliability research not only overcomes the problem of huge state space, but also the Markov theory is put in application, with many reliability indexes obtained. At the same time, because the state of the study object accounts for more than 95% or even a higher proportion of the state of the network, rendering the reliability index a better position to reflect the system, which can be used to analyze and calculate the availability of large scale network system [33].

If the system enters the steady state ($t \to \infty$), the probability is $P_k(t)$. The steady state value of the system is independent of the state of the system when the system is stable, but it is related to the initial state of the system. After the state transition matrix is obtained, the following indexes are important to analyze the stability and reliability of the system.

1) SYSTEM STEADY-STATE AVAILABILITY: A_W

The system availability is defined as the average ratio time of the system to work properly. That is $A_W = \sum_{k\in W} P_k(t)$, and $P_k(t)$ satisfies the linear equations:

$$\begin{cases} (P_0(t), P_1(t), \ldots, P_k(t)) \times A_G = (0, 0, \ldots, 0) \\ \sum_{l=0}^{r} P_k(t) = 1 \end{cases} \tag{11}$$

2) MEAN TIME TO FIRST FAILURE OF THE SYSTEM (MTFF)

If the fault state of Ω_G is defined as the absorption state, that is to say, once the system enters the absorption state, the system cannot leave the state unless it is restarted. Given that the initial state distribution of the system is $Q_W(0)$, the matrix B_G is the matrix of the row and column to get rid of the fault state in the matrix A_G, thus the mean time to first failure of the system is MTFF, $MTFF = x_0 + x_1 + \ldots + x_w$, and $x_0, x_1, \cdots, x_w$ satisfy the following equation.

$$(x_0, x_1, \ldots, x_w) B_G = -Q_W(0) \tag{12}$$

3) SYSTEM STEADY-STATE FAILURE FREQUENCY: M_G

$$M_G = \sum_{k\in W} P_k(t) \sum_{l\in F} a_{kl} \tag{13}$$

According to the above-mentioned reliability indexes of the system model, the relatively weak subsystem and equipment unit can be found by means of quantitative analysis of the equipment-integrated system from top to bottom. These key equipment units can also be viewed as the weak link in the system. In the future daily inspection and maintenance, they need to focus on maintenance and inspection in order to improve the reliability of the system, and ensure that the equipment-integrated system can operate efficiently and safely.

V. RELIABILITY VERIFICATION OF HIGH-SPEED TRAIN EQUIPMENT-INTEGRATED SYSTEM

High speed train, as a typical equipment-integrated system, is respectively assembled by thousands of components, with more complex system structure, digital electronics, information processing and the increasing integration leading to the dependencies in function. In this paper, the reliability of equipment-integrated system is studied through the example of CRHX high-speed train. The highest running speed of the CRHX high-speed train set is 250km/h, which can operate on both the line (designated interval) and the passenger dedicated line. The high-speed train set involves 8 groups, 4 dynamic and 4 tows, and it is composed of two power units, each of which is composed of 2 high-speed trains and 2 trailers. The whole vehicle is composed of more than 9 thousand parts, a complex equipment-integrated system, which is closely connected, interdependently and mutually restricted by mechanical, electrical and information connections. According to the characteristics of system and

$$A_G = \begin{bmatrix} -\sum\limits_{k\neq l} a_{0l} & \lambda_1 & \lambda_2 & \lambda_3 & \lambda_4 & 0 \\ \mu_1 & -\sum\limits_{k\neq l} a_{1l} & g_v(e_{12}) & g_v(e_{13}) & g_v(e_{14}) & \lambda_3 \\ \mu_2 & 0 & -\sum\limits_{k\neq l} a_{2l} & g_v(e_{23}) & 0 & 0 \\ \mu_3 & 0 & 0 & -\sum\limits_{k\neq l} a_{3l} & 0 & \lambda_1 \\ \mu_4 & g_v(e_{41}) & 0 & g_v(e_{43}) & -\sum\limits_{k\neq l} a_{4l} & 0 \\ 0 & \mu_3 & 0 & \mu_1 & 0 & -\sum\limits_{k\neq l} a_{5l} \end{bmatrix}$$

$$A_{G1} = \begin{bmatrix} -\sum\limits_{k\neq l} a_{0l} & \lambda_1 & \lambda_2 & \lambda_3 & \lambda_4 & 0 \\ \mu_1 & -\sum\limits_{k\neq l} a_{1l} & 0 & 0 & 0 & \lambda_3 \\ \mu_2 & 0 & -\sum\limits_{k\neq l} a_{2l} & 0 & 0 & 0 \\ \mu_3 & 0 & 0 & -\sum\limits_{k\neq l} a_{3l} & 0 & \lambda_1 \\ \mu_4 & 0 & 0 & 0 & -\sum\limits_{k\neq l} a_{4l} & 0 \\ 0 & \mu_3 & 0 & \mu_1 & 0 & -\sum\limits_{k\neq l} a_{5l} \end{bmatrix}$$

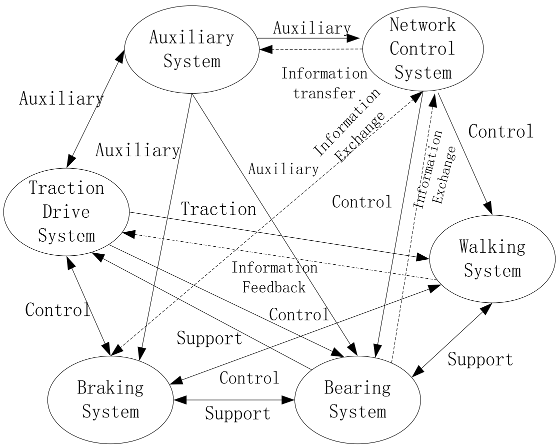

FIGURE 5. Composition of high-speed train system.

function structure, the CRHX high-speed train system is divided into several subsystems, such as traction power supply, walking, braking, load bearing, network control and auxiliary power supply and so on. After the high-speed train system is divided according to the function, the relationship between the subsystems is shown as Fig.5.

A. HIGH-SPEED TRAIN SYSTEM

From the perspective of system theory, the research object is divided into three system levels according to the function: system level, subsystem level and equipment unit level. A subsystem is composed of several equipment units, and the object system is composed of several subsystems. These subsystems are used as the intermediate transition level of the equipment unit and the whole research object is to study the reliability of the equipment-integrated system. And the equipment unit of the integration system, the smallest unit, is an integral part of the system.

According to actual operation fault data of the CRHX, the high-speed train system is divided into three levels: system level (as the first level system), subsystem level (as the second level system), and equipment unit level (as the third level system). The second level system includes a walking subsystem, a braking subsystem, a traction power supply subsystem, a bearing subsystem, a network control subsystem and an auxiliary power supply subsystem. Taking the traction power supply subsystem as an example, the third-level system includes the pantograph, VCB (main circuit breaker), traction transformer, traction converter, traction motor, etc. The specific distribution of the system and its subsystems are shown in Tab.1.

According to the existing two years of CRHX type EMU fault data, the data of the second level system are analyzed. Since the bearing subsystem contains more equipment, the bearing subsystem is the highest frequency of failure of the system. And the frequency of auxiliary power supply subsystem and traction power supply subsystem is relatively high. Secondly, the walking subsystem is prone to failure. The most difficult fault system is the braking subsystem.

TABLE 1. System associated tables at all levels.

Second Level	Third level system
The traction power supply subsystem	VCB (main circuit breaker)
	Traction transformer
	Traction converter
	Traction motor
	Pantograph

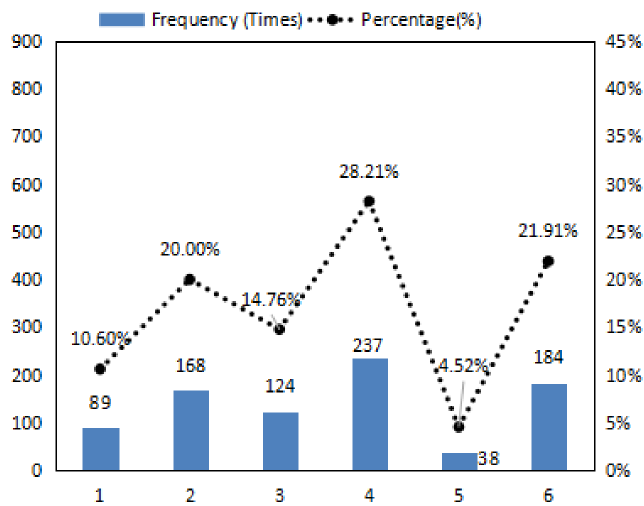

FIGURE 6. The frequency distribution of the second level system.

The statistical results of failure frequency distribution are shown in Fig.6. From the figure, it can be more intuitive to see that the frequency of the failure of the system is not so different. Note of Figure 6, 1–Walking subsystem, 2–Braking subsystem, 3–Traction power supply subsystem, 4–Bearing subsystem, 5–Network control subsystem, 6–Auxiliary power.

According to the existing two years of CRHX type EMU fault data, the data of the third level systems are analyzed (taking the traction power supply subsystem as an example). The failure frequency distribution of equipment units in the one hundred thousand km is shown in Tab.2.

TABLE 2. The failure frequency distribution of equipment units.

Third level subsystem	Frequency	Travel kilometers (One hundred thousand)
Pantograph	34	410.01
VCB(main circuit breaker)	2	146.44
Traction transformer	22	316.56
Traction converter	51	649.18
Traction motor	15	217.74

B. NETWORK MODEL CONSTRUCTION OF INTEGRATED SYSTEM OF HIGH-SPEED TRAIN EQUIPMENT

1) NETWORK MODEL CONSTRUCTION OF TRACTION POWER SUPPLY SUBSYSTEM

The following is a detailed description of the traction power supply subsystem for high-speed train CRHX type EMU.

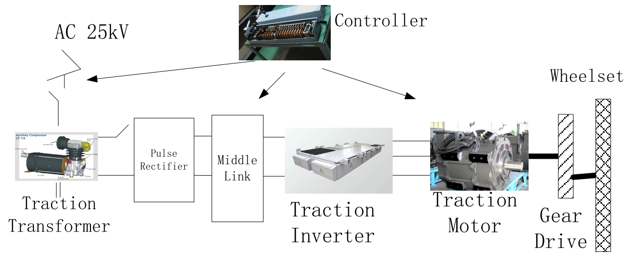

FIGURE 7. Composition structure of traction power supply subsystem.

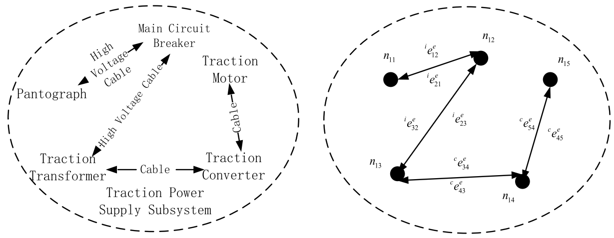

FIGURE 8. The connection mode and network expression of traction power supply subsystem unit.

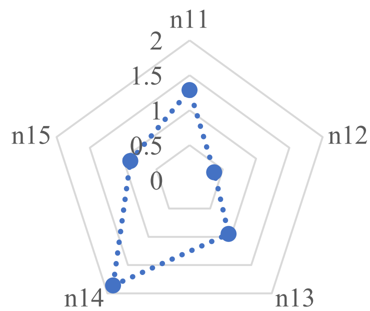

FIGURE 9. The node failure rate.

The high-speed train traction power supply subsystem obtains AC 25kv from the contact network mainly through pantograph. Then it is transmitted to the traction transformer through high voltage electrical equipment. And it outputs 1500V AC to the traction converter after decompression. Then the alternating current is changed into direct current by a pulse rectifier. Next it is transmitted to the traction inverter through the intermediate link DC circuit. The traction inverter outputs three-phase AC with adjustable voltage and frequency, which drives the traction motor. The torque and speed of the traction motor are transmitted to the bogie wheel sets through the gear box, which drives the train to run. The composition principle diagram of the high speed train traction power supply subsystem is shown in Fig.7.

The basic units of traction power supply subsystem are composed of the pantograph, VCB (main circuit breaker), traction transformer, traction converter and traction motor.

TABLE 3. Node name and symbol expression.

Node name	Node symbol
Pantograph	n_{11}
VCB (main circuit breaker)	n_{12}
Traction transformer	n_{13}
Traction converter	n_{14}
Traction motor	n_{15}

After the traction power supply subsystem is divided, the name of the equipment unit and the expression of corresponding node are shown in Tab.3.

The connection mode between nodes: (1) The pantograph receives single phase AC point from the contact network, and it is connected to the main circuit breaker through a high voltage cable connector; (2) It is connected to the traction transformer winding through a high voltage cable; (3) The low pressure side of traction transformer constitutes three windings. Two of them are the secondary windings which provide electric power for the traction converter through the cable connector. The rest is the tertiary winding which provides electric power for the EMU of auxiliary circuit (such as lighting, air conditioning, etc.), control circuit and communication circuit and so on; (4)The traction converter provides electric power through the cable for the traction motor in power operation, and it also has the function of protection when electric motor is carrying out the feedback of regenerative power in braking.

The connection structure of the traction power supply subsystem is shown in Fig.8.

2) ATTRIBUTE VALUE CALCULATION OF NODE AND EDGE

① Node attribute. In the model of system reliability network, the attribute value of the node is the failure rate of the equipment unit. The failure rate of each node is obtained by the failure frequency of each node and the number of kilometers involved in the fault data statistics. Among the nodes involved, some of the nodes belong to the electronic unit, and some are the mechanical unit. In the analysis of statistical fault data, once the failure occurs, the mechanical class node has carried out maintenance. So node failure distribution follows exponential distribution, with the statistic results of attribute values of each node shown in Fig.9.

② Edge attribute. In the network model of system reliability, the attribute value of the edge is the action strength between the equipment units. The category analysis of the connected edges between the nodes of the third subsystems is carried out. The connection strength of the connected edges is shown in Fig.10, which is given from the relevant expert experience.

Through the fault correlation analysis of existing fault data, the probability of failure propagation among nodes is obtained. The attribute value of each edge is obtained with calculation formula of the action strength, and the results are shown in Tab.4.

C. NODE RELIABILITY CALCULATION

In this paper, due to the fact that the inherent reliability of node units is not complete, a simple calculation method is put forward in the case of a large number of available

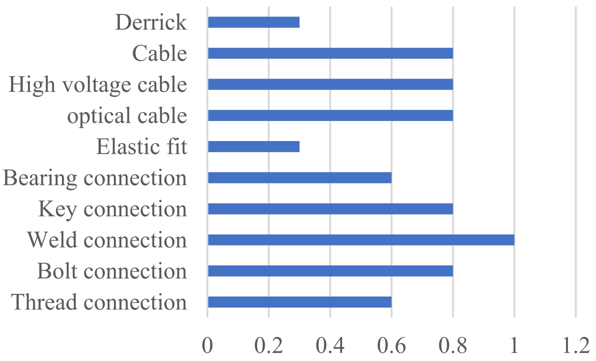

FIGURE 10. The quantitative value of the connection strength.

TABLE 4. The action strength.

Edge	Fault propagation probability$\eta({}^{u}e_{ij}^{v})$	Action strength$g_v(e_{ij})$
${}^{i}e_{12}^{e}$	0.36	0.29
${}^{i}e_{21}^{e}$	0.06	0.05
${}^{i}e_{23}^{e}$	0.09	0.07
${}^{i}e_{32}^{e}$	0.25	0.2
${}^{c}e_{34}^{e}$	0.43	0.34
${}^{c}e_{43}^{e}$	0.54	0.43
${}^{c}e_{45}^{e}$	0.29	0.23
${}^{c}e_{54}^{e}$	0.32	0.26

fault data: the use reliability of the unit used in the historical data is obtained through the failure rate.

In the high-speed train system, the reliability of the node unit follows exponential distribution. The use reliability of the node is obtained through the failure rate of the n_{ij} node at t time. The formula is as follows:

$$r_t'(n_{ij}) = f(\lambda(n_{ij})) = e^{-\lambda(n_{ij})} \tag{14}$$

The correlation reliability of the node is calculated by formula (4). In the constructed reliability network model, only the nodes n_{24} and n_{27} belong to the correlation combination. According to the correction method of the related nodes, the correlation reliability of the nodes is modified. According to the calculation method of node reliability, the reliability of the node is calculated. The use reliability, correlation reliability and reliability of the nodes are shown in Tab.5.

Because of the influence of the potential reliability of the connection node on the node, the reliability of the node is generally smaller than that of the node. Among them, the n_{14} nodes (gear box) are most affected, with the n_{33} node (traction transformer) again. In addition, the n_{32} node (main circuit breaker) and the n_{34} node (traction converter) change is also relatively obvious. In the constructed reliability network model, the reliability of the n_{14} node and the n_{15} node (wheel sets) is relatively low in the S_1 subsystem; the reliability of the n_{212} node (emergency brake electromagnetic valve), the n_{24} node (electric-pneumatic change-over valve) and the n_{211} node (pressure regulating valve) is relatively low in the S_2 subsystem; the reliability of the n_{33} node and the n_{34} node is relatively low in the S_3 subsystem. In the daily maintenance or fault prevention work, the status of the above nodes calls for focused monitoring.

TABLE 5. Reliability value of nodes.

Node symbol	Use reliability $r_t'(n_{ij})$	Correlation reliability $r_t''(n_{ij})$	Reliability $r_t(n_{ij})$
n_{11}	0.9872	0.9998	0.9870
n_{12}	0.9963	0.9944	0.9907
n_{13}	0.9905	0.9918	0.9824
n_{14}	0.9816	0.9945	0.9761
n_{15}	0.9911	0.9958	0.9869

D. RELIABILITY CALCULATION OF HIGH-SPEED TRAIN EQUIPMENT-INTEGRATED SYSTEM

1) STATE ANALYSIS OF TRACTION POWER SUPPLY SUBSYSTEM

According to the fault data of the CRHX high-speed train system, the maintenance time of each node is subject to the exponential distribution of $\mu_i = 0.01 (i = 1, 2, \ldots, 6)$, and the coverage rate of the given state space is $\pi \geq 99.0\%$.

The steady-state availability of each node in the network after a long run is the node reliability. In the construction of the model of subsystem reliability network, the average value of the five nodes of traction supply system is $\bar{p}(S_1) = 0.9893$. The number of nodes to allow to fail is $i_{\max}(S_1) = 1$ in the subsystem which meets the requirement of coverage. After the data of the 5 nodes of the traction power supply subsystem and the actual fault data are processed to meet the coverage rate of $\pi \geq 99.0\%$, the maximum probability state is determined. In the state of traction subsystem, there is a state with no node failure, and there are four states of a node failure, with the above-mentioned five states as follows:

$$(0, 0, 0, 0, 0), (0, 0, 0, 1, 0), (0, 0, 1, 0, 0), (0, 0, 0, 0, 1), (1, 0, 0, 0, 0)$$

The above-mentioned states are respectively recorded as $0'', 1'', 2'', 3'', 4''$. In these States, the $4''$ state is the fault state, and the rest is normal.

According to the improved Markov process theory, the electronic state transition matrix of traction power supply subsystem is as follows:

$$A_{S_3} = 10^{-2} \begin{bmatrix} -4.99 & 1.86 & 1.29 & 0.95 & 0.89 \\ 1 & -1.66 & 0 & 0.43 & 0.23 \\ 1 & 0 & -1 & 0 & 0 \\ 1 & 0.34 & 0 & -1.34 & 0 \\ 1 & 0.26 & 0 & 0 & -1.26 \end{bmatrix}$$

2) THE CALCULATION OF RELIABILITY INDEX OF TRACTION POWER SUPPLY SUBSYSTEM

The corresponding reliability index can be obtained by using the state transition matrix of the traction power supply subsystem and related equations are solved with MATLAB.

① Subsystem steady-state availability

According to the state space of the traction power supply subsystem, the following equations are solved:

$$\begin{cases} (P_{0''}(t), P_{1''}(t), \cdots, P_{4''}(t)) \times A_{S_3} = (0, 0, \cdots, 0) \\ \sum_{l=0''}^{4''} P_k(t) = 1 \end{cases}$$

Get:

$S_1 : P_{0''}(t) = 0.1633, P_{1''}(t) = 0.2627, P_{2''}(t) = 0.2107, P_{3''}(t) = 0.2001, P_{4''}(t) = 0.1633$. The subsystem steady-state availability is shown as:

$$\begin{aligned} A_{W(S_1)} &= \sum_{k \in W} P_{k''}(t) \\ &= P_{0''}(t) + P_{1''}(t) + P_{2''}(t) + P_{3''}(t) = 0.8367 \end{aligned}$$

② Mean time before the first failure of the subsystem, $MTFF(S_1)$

The fault state falls into the absorbed one, and all the units are able to work properly at the beginning of the system. The initial state distribution is $Q_W(0) = (1, 0, \cdots, 0)$. The corresponding sub matrix is B_{S_1} where the fault state of the A_{S_1} matrix is removed. The mean time before the first failure of the subsystem is $MTFF(S_1) = x_{0''} + x_{1''} + x_{2''} + x_{3''}$.

Solving the equations to get:

$$\begin{aligned} S_1 : x_{0''} &= 264.62, \quad x_{1''} = 266.47, \quad x_{2''} = 264.62, \\ x_{3''} &= 406.91 \\ MTFF(S_1) &= 1202.6 \end{aligned}$$

Then the steady-state failure frequency of subsystem is

$$\begin{aligned} M_{S_1} &= \sum_{k \in W} P_{k''}(t) \sum_{l \in F} a_{k''l''} = P_{0''}(t) a_{0''4''} + P_{1''}(t) a_{1''4''} \\ &= 0.2058 \end{aligned}$$

Using the state transition matrix of the traction power supply subsystem, we can get the corresponding reliability index. Then the reliability index and the steady-state failure frequency of traction power supply subsystem is calculated.

VI. CONCLUSION

According to the composition of equipment-integrated system and the working mechanism, this paper puts forward the principle of the division of the main body structure of the subsystem and the equipment unit, and combines the network-related knowledge to establish the connection relationship between the equipment units, and constructs the network model of equipment-integrated system.

Different from the traditional method, which depends on the node failure rat, the calculation method of node reliability is proposed, considering both the correlation between the nodes and the independent reliability. In a possible system modal space, the quantitative evaluation method of system reliability is studied by using the improved method of Markov process. The state transition matrix is improved mainly based on the influence of the unit state between the components of the equipment-integrated system. The reliability of equipment-integrated system is evaluated by using the steady-state availability, failure frequency and failure time of the system and so on. Based on the analysis of the basic structure principle and fault statistic method of the high-speed train system, the system model is established and the comprehensive analysis is carried out.

Through a quantitative analysis of the network model of traction supply system, the reliability of subsystems and components are obtained to provide a basis for the maintenance of high-speed trains. In the future work, we will focus on the environmental factors and the impact on node and system reliability.

ACKNOWLEDGMENT

The authors would like to thank the anonymous reviewers for their valuable comments and suggestions that lead to a substantially improved manuscript.

REFERENCES

[1] Z. Jue, *Coupling Design Theory and Method of Complex Electromechanical System*. Beijing, China: China Machine Press, 2007, p. 7.

[2] X. Zhong, M. Ichchou, and A. Said, "Reliability assessment of complex mechatronic systems using a modified nonparametric belief propagmion algorithm," *Reliab. Eng. Syst. Safe*, vol. 95, no. 11, pp. 1174–1185, 2010.

[3] H. Fukuoka, "Reliability evaluation method for the railway system: A model for complicated dependency," *Quart. Rep. RTRI*, vol. 43, no. 4, pp. 192–196, 2002.

[4] J.-Q. Liu, X.-G. Cui, B.-C. Sun, G.-G. Wang, D.-J. Jiang, and C. An, "Research on reliability of high voltage apparatus system of CRH3 electric multiple units," *J. China Railway Soc.*, vol. 5, pp. 22–27, Jun. 2013.

[5] C. Hu and J. W. Yao, "Reliability analysis for electric multiple units based on fault tree Monte Carlo method," *China Railway Sci.*, pp. 52–59, 2013.

[6] T. Hua, "FTA-based research on reliability of numerical control system," *Equip. Manuf. Technol.*, pp. 19–20, 2006.

[7] T. Xijin, H. Zhengyou, Y. Min, and Q. Qingquan, "Analysis on reliability of the subway station-level integrated supervisory and control system based on dynamic fault tree analysis," *J. China Railway Soc.*, vol. 33, no. 7, pp. 52–60, 2011.

[8] J. Xue and K. Yang, "Dynamic reliability analysis of coherent multistate systems," *IEEE Trans. Rel.*, vol. 44, no. 4, pp. 683–688, Dec. 1995.

[9] B. Dimitrov, Rykov, and P. Stanchev, "On multistate reliability systems," in *Proc. 3rd Int. Conf. Math. Methods Rel.*, Trondheim, Norway, 2002, pp. 201–204.

[10] A. Adamyan and D. He, "Sequential failure analysis using counters of Petri net models," *IEEE Trans. Syst., Man, Cybern. A, Syst., Humans*, vol. 33, no. 1, pp. 1–11, Jan. 2003.

[11] S. Chun and S. Ge, "Xu Yingqiu. Hydraulic system reliability modeling and analysis based on stochastic failure Petri net," *Chin. Hydraul. Pneum.*, vol. 1, pp. 29–31, 2006.

[12] Y. Wang, M. Li, and L. Li, "The research of system reliability calculation method based on the improved Petri net," in *Proc. Int. Conf. Inf. Technol. Appl. (ITA)*, Nov. 2013, pp. 279–281.

[13] Z. Xiaojie, Z. Haitao, M. Qiang, Z. Wei, and H. Hongzhong, "Reliability analysis of satellite system based on dynamic fault tree," *J. Astronaut.*, vol. 30, no. 3, pp. 1249–1255, 2009.

[14] J. Xue, "On multistate system analysis," *IEEE Trans. Rel.*, vol. R-34, no. 4, pp. 329–337, Oct. 1985.

[15] T. Aven, "Reliability evaluation of multistate systems with multistate components," *IEEE Trans. Rel.*, vol. R-34, no. 5, pp. 473–479, Dec. 1985.

[16] J. C. Hudson and K. C. Kapur, "Reliability analysis for multistate systems with multistate components," *IEEE Trans.*, vol. 15, no. 2, pp. 127–135, Jun. 1983.
[17] J. A. Buzacott, "Node partition formula for directed graph reliability," *Networks*, vol. 17, no. 2, pp. 227–240, 1987.
[18] J. Yu, "Research on the reliability and importance of communication network," Southeast Univ., Nanjing, China, Tech. Rep., 2009.
[19] A. Rosenthal and D. Frisque, "Transformations for simplifying network reliability calculations," *Networks*, vol. 7, no. 2, pp. 97–111, 1977.
[20] M. S. Choi and C. H. Jun, "Some variants of polygon-to-chain reductions in evaluating reliability of undirected network," *Microelectron. Rel.*, vol. 35, no. 1, pp. 1–11, 1995.
[21] J. P. Gadani, "System effectiveness evaluation using star and delta transformations," *IEEE Trans. Rel.*, vol. R-30, no. 1, pp. 43–47, Apr. 1981.
[22] A. W. Shogan, "Sequential bounding of the reliability of a stochastic network," *Oper. Res.*, vol. 24, no. 6, pp. 1027–1044, 1976.
[23] R. Van Slyke and H. Frank, "Network reliability analysis: Part I," *Networks*, vol. 1, no. 3, pp. 279–290, 1971.
[24] X. Zang, D. Wang, H. sun, and K. S. Trivedi, "A BDD-based algorithm for analysis of multistate systems with multistate components," *IEEE Trans. Comput.*, vol. 52, no. 12, pp. 1608–1618, Dec. 2003.
[25] Y.-R. Chang, S. V. Amari, and S.-Y. Kuo, "OBDD-based evaluation of reliability and importance measures for multistate systems subject to imperfect fault coverage," *IEEE Trans. Depend. Sec. Comput.*, vol. 2, no. 4, pp. 336–347, Oct./Dec. 2005.
[26] F.-M. Yeh, S.-K. Lu, and S.-Y. Kuo, "OBDD-based evaluation of k-terminal network reliability," *IEEE Trans. Rel.*, vol. 51, no. 4, pp. 443–451, Dec. 2002.
[27] L. Xing, "Efficient analysis of systems with multiple states," in *Proc. 21st Int. Conf. Adv. Inf. Netw. Appl.*, vol. 5, May 2007, pp. 666–672.
[28] R. Terruggia and A. Bobbio, *QoS Analysis of Weighted Multi-State Probabilistic Networks Via Decision Diagrams*. Berlin, Germany: Springer, 2010.
[29] E. Zio and L. R. Golea, "Analyzing the topological, electrical and reliability characteristics of a power transmission system for identifying its critical elements," *Rel. Eng. Syst. Saf.*, vol. 10, no. 1, pp. 67–74, 2012.
[30] O. Doguc and J. E. Ramirez-Marquez, "A generic method for estimating system reliability using Bayesian networks," *Rel. Eng. Syst. Saf.*, vol. 94, no. 2, pp. 542–550, 2009.
[31] H. Guo and X. Yang, "Automatic creation of Markov models for reliability assessment of safety instrumented systems," *Rel. Eng. Syst. Saf.*, vol. 93, no. 6, pp. 829–837, 2008.
[32] H. Fazlollahtabar, M. Saidi-Mehrabad, and J. Balakrishnan, "Integrated Markov-neural reliability computation method: A case for multiple automated guided vehicle system," *Rel. Eng. Syst. Saf.*, vol. 135, pp. 34–44, 2015.
[33] J.-J. Jiang, L. Zhang, Y.-Q. Wang, Y.-Y. Peng, K. Zhang, and W. He, "Markov reliability model research of monitoring process in digital main control room of nuclear power plant," *Saf. Sci.*, vol. 49, no. 6, pp. 843–851, 2011.

MAN LI received the Ph.D. degree from Beijing Jiaotong University, in 2017.

She is currently with the State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University. Her current research interests include intelligent railway systems reliability and safety, complex system analysis and evaluation, and passenger flow organization in urban rail transit networks.

YANHUI WANG received the Ph.D. degree from the University of Science and Technology Beijing, Beijing, China, in 2003.

He is currently with the State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University. His current research interests include rail transit operation reliability and safety, intelligent transportation systems, urban rail transit network operation management, and traffic model.

LIMIN JIA received the Ph.D. degree from the China Academy of Railway Sciences Beijing, in 1991.

He is currently with the State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University. His current research interests include safety science and engineering, control science and engineering, transportation engineering, safety technology and engineering, and system science.