Research Article

Reliability Assessment Based on GO Method of Metro Traction System

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In order to improve the reliability of the metro traction system (MTS), the whole life cycle of metro vehicles can be operated safely and reliably. A reliability assessment method based on the GO method of the MTS is proposed. In this paper, the reliability assessment is completed without operation service failure of the metro vehicle. The maintainability and shutdown correlation of many electrical components in the MTS are considered. An accurate algorithm with shared signals is used. Then the quantitative and qualitative reliability assessment of the system is achieved with the goal of traction system providing traction for the vehicle. The evaluation identifies the weak links of the system. Comparing the completely independent quantitative calculation result of each component with the accurate quantitative calculation results, it is found that the complex correlation in the repairable system has an important effect on the reliability of the system. A comparative analysis is performed on the calculating results of the GO method and fault tree analysis (FTA) method. The results demonstrate that the reliability analysis of the MTS by the GO method is feasible and reasonable. The principle of the method is simple and the logic is clear. It can not only objectively reflect the working process of the MTS, but also fully characterize the complex correlation with shut down fault in the MTS. The qualitative assessment results of the system show that the cut set probability of the pantograph is the highest, which should be the focus of the MTS.

1. Introduction

As a typical representative of urban rapid rail transit, the metro has played an important role in alleviating urban traffic congestion. The traction system is one of the core subsystems of the metro vehicle. Its reliability directly determines whether the vehicle can operate safely. The reliability assessment for the traction system has great significance to the design, production, operation, and maintenance of metro.

Traction system is a complex system. The reliability of the traction system is still a challenge, for safety-critical and mission-critical applications. In recent years, many reliability analysis methods have been proposed to enhance the safety of engineering structures [1–3]. These studies are mainly the reliability analysis on a subsystem or an important module in the traction system such as traction

inverter system [4], IGBT module [5, 6], traction motor [7], and pantograph [8]. The purpose of their reliability research is to improve the reliability of the traction system. As a whole, there are few studies on the reliability of the traction system. Liu et al. [9] have put forward a program to evaluate the reliability of CRH3 high-speed electric multiple units (EMUs) traction drive system based on reliability block diagram model. The CRH3 high-speed EMUs running in different lines are studied, but the complex correlation of traction drive system components and degradation (derating) conditions are not considered. Meng et al. [10] have proposed three states of the system: safety, subsafety, and failure. Based on the three states, they established the Markov state transfer model of CRH3 EMU traction drive system and evaluated reliability. This paper focuses on that the impacts of different components on the system reliability are compared and analyzed. The reliability of the high-speed

train traction drive system is studied, but the reliability assessment of the MTS is relatively deficient. In this case, the paper proposed an MTS reliability assessment based on the GO method.

Go method is an effective system reliability analysis method, which is especially suitable for system reliability analysis with multiple states and time series [11]. The method has been widely used in the reliability analysis of power system, water supply system, transportation system, manufacturing system, nuclear energy system, and other electromechanical integrated complex systems. It has made some achievements [12–22]. Therefore, this paper selects the GO method to evaluate the reliability of the MTS. There are three degraded (derated) conditions of metro vehicles. In this paper, the corresponding degraded (derated) condition is determined to evaluate the reliability of the metro vehicle without operation service failure [23, 24]. The system GO model is established with the goal of traction system providing traction for the vehicle. The maintainability and shutdown correlation of many electrical components in the MTS are considered. An accurate algorithm with shared signals is used [25, 26]. Then the quantitative and qualitative reliability assessment of the system is achieved.

In this work, the GO method for the reliability analysis of the MTS is presented. Section 2 establishes the reliability index of the MTS components. Section 3 introduces the operators commonly used in MTS and reliability evaluation steps of the system. Section 4 takes a MTS as an example to illustrate the effectiveness and practicality of the GO method. The GO model of the system is established, and the quantitative and qualitative reliability assessment is achieved. The FTA is used for comparative analysis. Finally, Section 5 summarizes and concludes.

2. Determination of MTS Components' Reliability Index

Traction system is an important part of the metro vehicle, which directly determines whether the vehicle can transport passengers safely, quickly, and efficiently. Therefore, it is necessary to analyze a comprehensive and in-depth reliability analysis of the MTS to find out the fault-prone links of the system. It can provide the basis for the establishment of reasonable system reliability management measures and help to improve the reliability of the system [27]. According to different functional units of the MTS, it mainly includes the following parts: current collection device, high-speed circuit breaker, traction inverter, filter, traction motor, etc. Taking a MTS as an example, its composition structure is shown in Figure 1.

The vehicle consists of two motor cars M_p with a pantograph, two motor cars M without pantograph, and two trailers TC. The pantograph obtains power from the catenary to supply power to the traction motors of the own car and the adjacent car. The electric energy is converted into mechanical energy by traction motor, so that the vehicle can obtain traction. The circuit diagram of the MTS is shown in Figure 2.

It can be seen from Figure 2, the vehicle achieves 1500 V DC from the catenary through the pantograph, then flows through the main isolating switch Q1, and finally supplies it to the vehicle traction system through high-speed circuit breaker. After the high-speed circuit breaker is turned on, the current flows through the filter reactor L1 and the charging circuit. First, the charging contactor is turned on to make the voltage of the supporting capacitor reach the voltage value set by the system requirements. Then, the charging contactor is turned off, and the separating contactor is turned on. Finally, the direct current is inverted into three-phase alternating current through the traction converter and supplied to the traction motor. The working process diagram of the MTS is obtained, as shown in Figure 3.

It can be seen from Figure 3 that the MTS is mainly composed of pantograph, surge arrester, isolating switch, high-speed circuit breaker, wave filter, charging circuit, converter, converter controller, and motor. As these components can continue to be used after maintenance, the MTS is an engineering repairable system. The failure rules of components of the system can be approximately regarded as following the exponential distribution. After continuous work, they have the system average characteristics of stable operation stage [28]. According to the historical maintenance information and experience value of the metro vehicle, its reliability parameters are obtained through probability and statistical analysis [29, 30], as shown in Table 1.

3. Reliability of the MTS Based on the GO Method

GO method is a success-oriented method for system reliability analysis, which is suitable for complex system reliability analysis. Taking the traction system providing traction for the metro vehicle as the successful goal, GO operator is used to represent the components of the system. The signal flow of the connection operator is used to represent the transmission path of electric energy received by traction motor. Reliability assessment for the MTS is achieved without operation service failure of the metro vehicle based on the GO method principle of the repairable system. There are three degraded (derated) conditions of metro vehicles. A metro vehicle has 4 motor cars. When the traction system of one motor car fails, the train traction system will output at 75% of the traction capacity, which will not affect the operation service of the metro train. If two motor cars lose traction, the train traction system will output at 50% of the traction capacity, and the remaining two motor cars will pull all the cars to the terminal station with normal operation and the car will stop operation for maintenance. If three cars lose traction, the train traction system will output at 25% of the traction capacity, and the remaining one motor car will pull all the cars to the nearest station to lay down all the passengers and then return to the terminal station to stop operation for maintenance. Both two conditions affect the operation service of the metro vehicle. So at least 3 of 4

FIGURE 1: Structure diagram of the MTS.

FIGURE 2: Circuit diagram of the MTS.

FIGURE 3: Working process diagram of the MTS.

TABLE 1: Reliability parameters of the MTS.

Components	Failure rate (h^{-1})	Average maintenance time (h)	Failure probability
Pantograph	1.25×10^{-5}	24	0.0003
Surge arrester	4.2×10^{-6}	6	0.0000252
Isolating switch	4.2×10^{-6}	14	0.0000588
High-speed circuit breaker	4.2×10^{-6}	12	0.0000504
Wave filter	4.146×10^{-6}	12	0.00004976
Controller of converter	2.488×10^{-5}	6	0.00014927
Charging resistor	4.146×10^{-6}	6	0.00002488
Charging contactor	1.244×10^{-5}	6	0.00007464
Separating contactor	1.244×10^{-5}	6	0.00007464
IGBT	2.488×10^{-5}	12	0.00029856
Overvoltage chopper	4.146×10^{-6}	6	0.00002488
Voltage sensor	8.292×10^{-6}	9	0.00007463
Current sensor	8.292×10^{-6}	9	0.00007463
Supporting capacitance	8.292×10^{-6}	9	0.00007463
Traction motor	4.2×10^{-6}	24	0.0001008

motor cars work normally, so as not to affect the operation service of metro trains.

3.1. GO Operator Selection. Type 1 operator is a two-state unit. It is the most commonly used operator in MTS. The surge arrester, isolating switch, high-speed circuit breaker, wave filter, charging circuit, and traction motor are two-state components, which we use operator 1. Type 5 operator is a signal generator. It can simulate the input unit. Pantograph is the input of the system, which is represented by type 5 operator. Similarly, controller of the converter signal is also represented by type 5 operator. Type 6 operator is a unit controlled by two control signals, such as a converter, and DC electrical signal and control signal are two input signals. Type 10 operator is the AND gate. It can simulate the logical relationship that all signals in this structure work normally and the parallel unit can work normally. In the MTS, when four traction motors of a vehicle have electric energy, the traction system of this vehicle is successful. Type 11 operator is the K -out-of- M gate. It can represent a parallel repairable system composed of M identical repairable units, among which K units work normally and the system works normally. In the MTS, 3-out-of-4 gate is used. Overall, the five types of operators are used in MTS. These operators are shown in Figure 4. S is the input signal, R is the output signal, and subscript is different input signals.

3.2. Reliability Evaluation Steps of the MTS. The units may have shutdown correlation in a repairable system. As a repairable system, if the MTS is shut down due to some failure components, the fault-free components will stop working with the system shutdown, and no fault will occur again. If the system is repaired, these components will return to work. The components are not independent and have shutdown correlation. The failure laws of these components can be regarded as obeying the exponential distribution. In other words, the failure rate and maintenance rate are a constant. The most worthy of attention for MTS is the average characteristic of system. In this paper, the MTS is used as a repairable system for the quantitative calculation of steady-state reliability. The detailed analysis and calculation process is as follows:

- (1) Perform system analysis. According to the structure, working principle and functional composition of the system, the function, boundary, and success rule of the system are determined, and the working process diagram of the system is given. The system reliability index is defined according to the historical fault accumulation data.
- (2) Develop system GO model. According to the working process diagram of the system, operators are used to represent repairable components, and signal flow is used to connect operators. A system GO model is established composed of operators and signal flow.

- (3) Determine the reliability data of all operators in the system. There are some simplified equivalent elements of series structure with shutdown correlation. It is necessary to calculate the parameters of each simplified equivalent element according to equations (1)–(4).

Assuming that the operator corresponds to M shutdown-related series components and the shutdown failure number $I = 1$, the equivalent failure rate of the series structure is the sum of the failure rates of all components. Due to shutdown, there is only one component failure in the failure mode of the series structure. There cannot be two or more components fail at the same time. Therefore, the parameters of the simplified equivalent unit are expressed as follows:

$$\lambda_R = \sum_{i=1}^M \lambda_i, \quad (1)$$

$$\lambda_R \tau_R = \sum_{i=1}^M \lambda_i \tau_i, \quad (2)$$

$$P_R(1) = \frac{1}{1 + \lambda_R \tau_R}, \quad (3)$$

$$P_R(2) = \frac{\lambda_R \tau_R}{1 + \lambda_R \tau_R}, \quad (4)$$

where λ_R is the failure rate of the simplified equivalent unit, τ_R is the average maintenance time of the simplified equivalent unit, P_R is the state probability of the simplified equivalent unit, λ_i is the failure rate of the component, and τ_i is the average maintenance time of the component.

- (4) Perform GO operation. According to the GO method for the repairable system, the quantitative calculation of the system is carried out, and the steady-state reliability characteristic quantity of the system is obtained.

The series structure with shutdown correlation should be calculated separately. After obtaining the equivalent reliability parameters of the structure, the equivalent element is used to replace the structure. Then the GO method is used to calculate directly. If the input signal has a shared signal, the shared signal shall be separated first in the process of direct calculation. Then the shared signal shall be combined after the calculation of logic operators. According to equations (1)–(4), the parameters of equivalent units with the shutdown-related series structure in the system are calculated. And the GO method is used to calculate directly according to equations (5)–(32).

The single signal generator operator has no input and only one output signal. It is the input signal of the system. Therefore, the data of the operator are that of the output signal. The output signal data can be written as follows:

FIGURE 4: The operators of the MTS.

$$P_R(1) = P_C(1), \quad (5)$$

$$P_R(2) = P_C(2), \quad (6)$$

$$\lambda_R = \lambda_C, \quad (7)$$

$$\mu_R = \mu_C, \quad (8)$$

where λ_C is the failure rate of the operator, μ_C is the maintenance rate of the operator, P_C is the state probability of the operator, λ_R is the failure rate of the output signal, μ_R is the maintenance rate of the output signal, and P_R is the state probability of the output signal.

The input signals of the operators in the two-state units and the operators are shutdown-related. The number of shutdown failures $I = 1$, if one of the input signals and operators stops working, the other will stop without failure. So there is no failure of the input signals and operators at the same time. The output signal data can be expressed as follows:

$$G_1 = P_S(1) \cdot P_C(1), \quad (9)$$

$$G_2 = P_S(1) \cdot P_C(2) + P_S(2) \cdot P_C(1), \quad (10)$$

$$P_R(1) = \frac{G_1}{G_1 + G_2}, \quad (11)$$

$$P_R(2) = \frac{G_2}{G_1 + G_2}, \quad (12)$$

$$\lambda_R = \lambda_S + \lambda_C, \quad (13)$$

$$\mu_R = \frac{\lambda_R}{((\lambda_S/\mu_S) + (\lambda_C/\mu_C))}, \quad (14)$$

where λ_S is the failure rate of an input signal, μ_S is the maintenance rate of an input signal, P_S is the state probability of an input signal, λ_C is the failure rate of operator, μ_C is the maintenance rate of operator, P_C is the operator's state probability, G_1 is the success state probability of the output signal, G_2 is the failure state probability of the output signal, λ_R is the failure rate of the output signal, μ_R is the maintenance rate of the output signal, and P_R is the state probability of the output signal.

The main input signal and the second input signal of the operator controlled by two control signals have a

shutdown correlation with the operator. The number of shutdown failures $I = 1$, if one of the two input signals and operators stops working, the other two will stop without fault. Therefore, there is no status of two or three simultaneous faults among the two input signals and operators. The success probability G_1 of the output signal is the probability that two input signals and operators are in the success state. The failure state G_2 of the output signal is the total probability that one of the two input signals and operator is in the failure state, and the other two are in the success state. The output signal data are expressed as follows:

$$G_1 = P_{S1}(1) \cdot P_{S2}(1) \cdot P_C(1), \quad (15)$$

$$G_2 = P_{S1}(2) \cdot P_{S2}(1) \cdot P_C(1) + P_{S1}(1) \cdot P_{S2}(2) \cdot P_C(1) + P_{S1}(1) \cdot P_{S2}(1) \cdot P_C(2), \quad (16)$$

$$P_R(1) = \frac{G_1}{G_1 + G_2}, \quad (17)$$

$$P_R(2) = \frac{G_2}{G_1 + G_2}, \quad (18)$$

$$\lambda_R = \lambda_{S1} + \lambda_{S2} + \lambda_C, \quad (19)$$

$$\mu_R = \frac{\lambda_R}{((\lambda_{S1}/\mu_{S1}) + (\lambda_{S2}/\mu_{S2}) + (\lambda_C/\mu_C))}, \quad (20)$$

where λ_{S1} is the failure rate of the main input signal, μ_{S1} is the maintenance rate of the main input signal, P_{S1} is the state probability of the main input signal, λ_{S2} is the failure rate of the second input signal, μ_{S2} is the maintenance rate of the second input signal, P_{S2} is the state probability of the second input signal, λ_C is the failure rate of the operator, μ_C is the maintenance rate of the operator, P_C is the state probability of the operator, G_1 is the success state probability of the output signal, G_2 is the failure state probability of the output signal, λ_R is the failure rate of the output signal, μ_R is the maintenance rate of the output signal, and P_R is the state probability of the output signal.

The N input signals of AND gate operator shutdown fault number $I = 1$, if one of the N input signals fails, the output signal will be in the failure state. The rest of the $N - 1$ input signals will also stop running and will not fail again.

Therefore, two or more components cannot fail at the same time. The output signal data can be described as follows:

$$\lambda_R = \sum_{i=1}^N \lambda_{Si}, \quad (21)$$

$$\mu_R = \frac{\lambda_R}{\sum_{i=1}^N (\lambda_{Si}/\mu_{Si})}, \quad (22)$$

$$P_R(1) = \frac{1}{1 + \lambda_R \tau_R}, \quad (23)$$

$$P_R(2) = \frac{\lambda_R \tau_R}{1 + \lambda_R \tau_R}, \quad (24)$$

where λ_{Si} is the failure rate of the input signal, μ_{Si} is the maintenance rate of the input signal, λ_R is the failure rate of the output signal, μ_R is the maintenance rate of the output signal, and P_R is the state probability of the output signal.

K -out-of- M gate represents that in the parallel repairable system composed of M same repairable units, if K units work normally, the system works normally. The parallel repairable system has shutdown correlation, maintenance correlation, and redundancy correlation. The output signal data can be described as follows:

$$a_i = \begin{cases} (M-i+1)\lambda, & \text{when } J=0 \text{ or } M-i+2 < K, \\ K\lambda, & \text{when } J=0 \text{ and } M-i+2 \geq K, \end{cases} \quad (25)$$

$$b_i = \begin{cases} i\mu, & i \leq L, \\ L\mu, & i > L, \end{cases} \quad (26)$$

$$P_i = P_0 \prod_{j=1}^i \frac{a_j}{b_j}, \quad (27)$$

$$G = \sum_{i=0}^I P_i, \quad (28)$$

$$P_R(1) = \sum_{i=0}^{M-K} \frac{P_i}{G}, \quad (29)$$

$$P_R(2) = \sum_{i=M-K+1}^I \frac{P_i}{G}, \quad (30)$$

$$\lambda_R = P_{M-K} \cdot \frac{a_{M-K+1}}{\sum_{i=0}^{M-K} P_i}, \quad (31)$$

$$\mu_R = P_{M-K+1} \frac{b_{M-K+1}}{\sum_{i=M-K+1}^I P_i}, \quad (32)$$

where M is the total number of input signals. K is at least number of successful input signals required for output signal success. I is the number of shutdown failures. It represents that when I input signals fail, the system is in shutdown maintenance state, and the rest of the input signals are no longer in failure state. L is the number of maintenance. When $L = M$, it means there is no maintenance-related situation. J is redundancy indication. When $J = 0$, it means there is no redundancy correlation. a_i and b_i are transfer rates. a_i represents the transition rate from the state with $i-1$ failure units to the state with i failure units. b_i represents the transition rate from the state with i failure units to the state with $i-1$ failure units. P_R is the state probability of the output signal. λ_R is the failure rate of the output signal. μ_R is the maintenance rate of the output signal.

Using the reliability parameters of system output signal flow, the reliability characteristic quantity of the MTS in the stable operation state is calculated by equations (33)–(38):

$$A = \frac{\text{MTBF}}{\text{MCT}} = \frac{\mu}{\lambda + \mu}, \quad (33)$$

$$\bar{A} = 1 - A = \frac{\text{MTTR}}{\text{MCT}} = \frac{\lambda}{\lambda + \mu}, \quad (34)$$

$$f = A\lambda = \bar{A}\mu = \frac{1}{\text{MCT}}, \quad (35)$$

$$\text{MTBF} = \frac{1}{\lambda}, \quad (36)$$

$$\text{MTTR} = \frac{1}{\mu}, \quad (37)$$

$$\text{MCT} = \text{MTBF} + \text{MTTR}, \quad (38)$$

where A is the average working probability (steady-state availability), $\bar{A}$ is the average failure probability (steady-state unavailability), f is the average number of failures per unit time, λ is the failure rate, μ is the maintenance rate, MTBF is the mean time between failures, MTTR is the average maintenance time, and MCT is the average life cycle.

Through the above analysis, the accurate reliability parameters of the MTS signal flows are determined. The accurate quantitative calculation results of the system reliability evaluation are obtained. The proposed flow diagram of the analysis process is shown in Figure 5.

4. Example

4.1. Establishing the GO Model of the MTS. Considering no operation service failure, GO model of the MTS is established with the goal of traction system providing traction for the vehicle based on Figure 3 and the principle of GO method. As shown in Section 3.1, five types of operators are used in the MTS. In order to simplify the GO model, an operator is used to represent the equivalent element composed of multiple series components, such as charging

FIGURE 5: The flow diagram of the analysis process of the MTS.

circuit and converter. The GO model of the MTS is shown in Figure 6.

In Figure 6, there are two numbers in the operator symbol. The first is used to represent the type of operator, and the second represents the number of the operator. The numbers on the signal line mean the numbering of signals. If four traction motors of a vehicle have power, the traction system of this vehicle is successful. This logical relationship is represented by type 10 operator. At least three motor cars work normally, and then the metro vehicle works normally and does not affect operation services. This logical relationship is represented by type 11 operator. The system starts from operator 5-1 and 5-2, ends with operator 11-47. From

the input operator 5-1 and 5-2, according to the operation rules of the operator, the output signal 47 of the system can be calculated step by step. The reliability characteristic quantity of all signal flows in the system can be obtained. The reliability characteristic quantity of the MTS can be obtained according to the data of the output signal 47. The operators in Figure 6 are detailed in Table 2.

4.2. Quantitative Calculation of Reliability for the MTS.

The basic data used in the calculation are the failure rate of the components λ_i and the average maintenance time of the components τ_i , which can be obtained from Table 1.

FIGURE 6: Go model of the MTS.

TABLE 2: Data of operators for the MTS.

Number	Type	Representative components
1, 2	5	Pantograph
3, 4	1	Surge arrester
5, 6	1	Isolating switch
7, 8, 9, 10	1	High-speed circuit breaker
11, 12, 13, 14	1	Wave filter
15, 16, 17, 18	1	Charging circuit
19, 20, 21, 22	5	Controller of converter
23, 24, 25, 26	6	Converter
27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42	1	Traction motor
43, 44, 45, 46	10	AND gate
47	11	3-out-of-4 gate

4.2.1. Reliability Parameter Calculation of Series Structure. In Figure 6, operator 15 represents the charging circuit. It is equivalent unit composed of charging resistance, charging contactor, and separating contactor. Operators 16, 17, and 18 are the same as operator 15. Operator 23 represents converter modules. It is equivalent unit composed of IGBT, overvoltage chopper, voltage sensor, current sensor, and supporting capacitor. Operators 24, 25, and 26 are the same as operator 23. In view of the shutdown correlation of the components, the reliability

parameters of operators 15, 16, 17, 18, 23, 24, 25, and 26 can be obtained from equations (1)–(4) with corresponding λ_i and τ_i , as shown in Table 3.

Operators 7, 11, and 15 can be assumed to be shutdown-related serial components. The reliability parameters of them can be obtained from equations (1)–(4) and recorded as operators 15*. Operators 8, 12 and 16, 9, 13 and 17, 10, 14 and 18 are calculated in the same way, and the equivalent reliability parameters are obtained, as shown in Table 4.

TABLE 3: Reliability parameters of operators 15 (16–18) and 23 (24–26).

Operator number	Failure rate (h^{-1})	Average maintenance time (h)	Working probability	Failure probability
15 (16–18)	2.9026×10^{-5}	6	0.99982584	0.00017416
23 (24–26)	5.3902×10^{-5}	10.1539832	0.99945271	0.00054729

TABLE 4: Reliability parameters of operators 11* (12*–14*).

Operator number	Failure rate (h^{-1})	Average maintenance time (h)	Working probability	Failure probability
15* (16*–18*)	3.7372×10^{-5}	7.3399336	0.9997257	0.0002743

4.2.2. Reliability Parameter Calculation of Single Signal Generator. The steady-state quantitative analysis of the MTS after long-time operation is to calculate the steady-state reliability characteristic quantity of the system output signal flow 47. The system is divided into two ways, starting from the input operators 1 and 2, respectively, and the operators are calculated quantitatively one by one along the signal flow sequence. Operators 1 and 2 represent pantograph, which provide input signals for the system. Operators 19, 20, 21, and 22 are the control signals of the converter and provide the secondary input signals for the converter. The reliability parameters of operators 1, 2 and 19, 20, 21, 22 can be obtained from equations (5)–(8) with corresponding λ_i and τ_i , as shown in Table 5.

4.2.3. Reliability Parameter Calculation of Two-State Element. In Figure 6, it is assumed that the two components represented by operators 3 and 5 in one of the two paths are two unit structures related to shutdown. Then quantitative calculation of them should be carried out separately. Their equivalent reliability parameters can be obtained from equations (9)–(14) with the failure rate of an input signal λ_s , the maintenance rate of an input signal μ_s , the failure rate of operator λ_c , and the maintenance rate of operator μ_c . λ_c and μ_c are corresponding λ_i and μ_i . λ_s and μ_s are reliability parameter of the previous operator, which is shown in Table 5. Operators 4 and 6 of the other paths are similar, and the equivalent reliability parameters are obtained, as shown in Table 6.

4.2.4. Calculation of Reliability Parameters of Components Controlled by Two Control Signals. In Figure 6, operator 23 represents the converter, which is a component controlled by two control signals. The reliability parameters of operator 23 can be obtained from equations (15)–(20) with the failure rate of the main input signal λ_{S1} , the maintenance rate of the main input signal μ_{S1} , the failure rate of the second input signal λ_{S2} , the maintenance rate of the second input signal μ_{S2} , the failure rate of the operator λ_c , and the maintenance rate of the operator μ_c . λ_{S2} , μ_{S2} , λ_c , and μ_c are corresponding λ_i and μ_i . λ_{S1} and μ_{S1} are reliability parameter of the previous operator, which is shown in Tables 4 and 5. Operators 24, 25, and 26 are similar, and the reliability parameters are obtained, as shown in Table 7.

4.2.5. Reliability Parameters of AND Gate. In Figure 6, operator 43 is the AND gate operator. According to reliability parameters λ and μ of traction motor in Table 1, operator 43 is calculated by equations (21)–(24) and recorded as operator 43*. It does not include shared signal 23. Operators 44, 45, and 46 are similar, and the reliability parameters are obtained, as shown in Table 8.

4.2.6. Shared Signal Processing. Since the reliability parameters of AND gate output signal 43* do not include shared signal 23, it is necessary to combine the calculation with them. According to the operation rules of two-state element and the reliability parameters in Tables 7 and 8, operator 43* is calculated and recorded as operator 43**. It does not include shared signal 5. Operators 44**, 45**, and 46** are similar, and the reliability parameters are obtained, as shown in Table 9.

4.2.7. Reliability Parameters of 3-Out-of-4 Gate. In Figure 6, operator 47 is the 3-out-of-4 gate operator, so $M = 4$, $K = 3$, and $I = 2$. The MTS has no maintenance correlation and redundant structure, so $L = 4$ and $J = 0$. According to the reliability parameters in Table 9, operator 47 is calculated by equations (25)–(32) and recorded as operator 47*. It does not include shared signals 5 and 6. The reliability parameters are obtained, as shown in Table 10.

4.2.8. Shared Signal Processing. Since the reliability parameters of 47* do not include shared signals 5 and 6, it is necessary to combine the calculation with them. The accurate equivalent reliability parameters of signal 47 are obtained according to the operation rules of two control signal unit and the reliability parameters in Tables 6 and 10. The reliability parameters of signal flow 47 are obtained, as shown in Table 11.

The reliability analysis results in Table 11 take the shutdown correlation of system components into account. All components are regarded as completely independent for system reliability analysis. The analysis results are compared with Table 11, as shown in Table 12.

It can be seen from Table 12 that the system failure probability is reduced by 0.018% after considering the shutdown correlation. This is because the failure state of three or four branches at the same time cannot occur after

TABLE 5: Reliability parameters of operators 1 (2) and 19 (20–22).

Operator number	Failure rate (h^{-1})	Average maintenance time (h)	Working probability	Failure probability
1 (2)	1.25×10^{-5}	24	0.9997	0.0003
19 (20–22)	2.488×10^{-5}	6	0.99985073	0.00014927

TABLE 6: Reliability parameters of operators 3 (4) and 5 (6).

Equivalent signal flow number	Failure rate (h^{-1})	Average maintenance time (h)	Working probability	Failure probability
3 (4)	1.67×10^{-5}	19.4730539	0.9996748	0.0003252
5 (6)	2.09×10^{-5}	18.3732058	0.9996160	0.0003840

TABLE 7: Reliability parameters of operators 23 (24–26).

Equivalent signal flow number	Failure rate (h^{-1})	Average maintenance time (h)	Working probability	Failure probability
23 (24–26)	1.16154×10^{-4}	8.3587995	0.9990297	0.0009703

TABLE 8: Reliability parameters of operator 43* (44*–46*).

Equivalent signal flow number	Failure rate (h^{-1})	Average maintenance time (h)	Working probability	Failure probability
43* (44*–46*)	1.68×10^{-5}	24	0.9995970	0.0004030

TABLE 9: Reliability parameters of operator 43** (44**–46**).

Equivalent signal flow number	Failure rate (h^{-1})	Average maintenance time (h)	Working probability	Failure probability
43** (44**–46**)	1.32954×10^{-4}	10.3349622	0.9986275	0.0013725

considering the shutdown correlation, which slightly operators, which represent the functional components of the

TABLE 10: Reliability parameters of operator 47*.

Equivalent signal flow number	Failure rate (h^{-1})	Average maintenance time (h)	Working probability	Failure probability
47*	2.180281×10^{-6}	5.1674811	0.999988734	0.000011266

TABLE 11: Reliability parameters of operator 47.

Equivalent signal flow number	Failure rate (h^{-1})	Average maintenance time (h)	Working probability	Failure probability
47	4.3980281×10^{-5}	17.7185443	0.99922100	0.00077900

reduces the system failure probability. The analysis shows that the influence of complex correlation in the repairable system on the reliability of the system cannot be ignored.

According to equations (25)–(30), the characteristic value of system reliability is calculated with the reliability parameters of operator 42 in Table 11. The quantitative assessment of the MTS is completed. The results are shown in Table 13.

4.3. Qualitative Calculation of Reliability Assessment for the MTS. The qualitative analysis of reliability assessment for the MTS is directly carried out with state probability. Suppose that there are M operators in the GO model besides logical

system, respectively. If one of the M operators is in the failure state, its success probability is zero. The state probability of the other operators is unchanged, and the success probability of the system is calculated directly. If the success probability of the system is zero, the failure state of the operator is a first-order cut set of the system. All the first-order cut sets of the system can be calculated by M operators in turn. Among M operators, two operators are taken out of the first-order cut set, and all the second-order minimum cut sets can be obtained by the same method. Similarly, each order cut set of the system can be obtained. If a lower order cut set is included in the combination of higher order, it is not necessary to calculate the system success probability, so the cut set obtained is the minimum cut set.

TABLE 12: Reliability analysis results of the MTS when considering different correlations.

Correlations	<i>I</i>	<i>L</i>	<i>J</i>	Failure rate (h^{-1})	Average maintenance time (h)	Working probability	Failure probability
Shutdown	2	4	0	4.3980281×10^{-5}	17.7185443	0.99922100	0.00077900
Completely independent	4	4	0	4.3981900×10^{-5}	17.7288280	0.99922086	0.00077914

TABLE 13: Reliability characteristic value of the MTS.

Eigenvalue type	Average working probability	Average downtime probability	Average failure times per unit time (h^{-1})	Failure rate (h^{-1})	Maintenance rate (h^{-1})	Average working time (h)	Average maintenance time (h)	Average life cycle (h)
Characteristic value	0.99922134	0.00077866	4.3946035×10^{-5}	4.3980281×10^{-5}	0.056438	22737.463	17.7185443	22755.18154

FIGURE 7: The fault tree model of the MTS.

The MTS has 42 function operators to represent the system components. Through the qualitative analysis of the state probability, it is found that there are 6 first-order minimum cut sets and 486 second-order minimum cut sets. The combination of operator failures in the minimum cut set represents the combination of system component failures. The product of these components failure probabilities represents the probability of the minimum cut set. Through calculation and analysis, there are two first-order minimum cut sets with the greatest probability according to Table 1. The probability is 0.0003, and they are composed of pantograph. It shows that the pantograph is the weak link of the system and should be taken as the focus on the maintenance of the MTS.

4.4. Reliability Analysis of the MTS Based on FTA. To verify the effectiveness of the GO method, FTA is introduced to determine the reliability of the MTS. Take the MTS failure as the top event, the fault tree model is established as shown in Figure 7. The event represented by the corresponding code in failure tree is shown in Table 14. There are 42 bottom

events in the system, and the failure probability of bottom events is shown in Table 1.

Through the simulation analysis of the fault tree model, it can be concluded that the system has 6 first-order minimum cut sets and 486 second-order minimum cut sets. The first-order minimum cut set probability of pantograph failure is the highest, which is consistent with the qualitative analysis result of the GO method. And it can be concluded that the failure probability of the metro traction system is 0.000779087. The calculation result of the GO method is 0.000779. The quantitative calculation results of the two methods are close. It shows that the reliability analysis of metro traction system by the GO method is reasonable, but the results are slightly different. The main reason is that the correlation in the repairable system is not considered by fault tree. The reliability of the repairable system is reduced to a certain extent. Comparing the GO model and fault tree model of the MTS, it can be seen that the GO model can intuitively reflect the working process of MTS. The GO model has a clear logic and compact structure. The logic confusion caused by the multilevel of fault tree is not easy to happen in the GO model.

TABLE 14: The event represented by the corresponding code in failure tree.

Number	Code	Event
1	T	The MTS failure
2	U	High voltage apparatus failure
3	U1	High voltage apparatus 1 failure
4	U2	High voltage apparatus 2 failure
5	M1	Each branch failure
6	M2	Branch 1 failure
7	M3	Branch 2 failure
8	M4	Branch 3 failure
9	M5	Branch 4 failure
10	M6	Motor system failure
11	M7	Converter system failure
12	M8	Motor system failure
13	M9	Converter system failure
14	M10	Motor system failure
15	M11	Converter system failure
16	M12	Motor system failure
17	M13	Converter system failure
18	X1	Pantograph failure
19	X2	Pantograph failure
20	X3	Surge arrester failure
21	X4	Surge arrester failure
22	X5	Isolating switch failure
23	X6	Isolating switch failure
24	X7	High-speed circuit breaker failure
25	X8	High-speed circuit breaker failure
26	X9	High-speed circuit breaker failure
27	X10	High-speed circuit breaker failure
28	X11	Wave filter failure
29	X12	Wave filter failure
30	X13	Wave filter failure
31	X14	Wave filter failure
32	X15	Charging circuit failure
33	X16	Charging circuit failure
34	X17	Charging circuit failure
35	X18	Charging circuit failure
36	X19	Controller of converter failure
37	X20	Controller of converter failure
38	X21	Controller of converter failure
39	X22	Controller of converter failure
40	X23	Converter module failure
41	X24	Converter module failure
42	X25	Converter module failure
43	X26	Converter module failure
44	X27	Traction motor failure
45	X28	Traction motor failure
46	X29	Traction motor failure
47	X30	Traction motor failure
48	X31	Traction motor failure
49	X32	Traction motor failure
50	X33	Traction motor failure
51	X34	Traction motor failure
52	X35	Traction motor failure
53	X36	Traction motor failure
54	X37	Traction motor failure
55	X38	Traction motor failure
56	X39	Traction motor failure
57	X40	Traction motor failure
58	X41	Traction motor failure
59	X42	Traction motor failure

5. Conclusion

This paper proposed a reliability assessment based on the GO method of the MTS. The reparability and shutdown correlation of many electrical components in the MTS are considered. The accurate quantitative calculation and qualitative analysis of the system are completed by this method without operation service failure of the metro vehicle. The accurate quantitative calculation results are compared with the quantitative calculation result of all components regarded as completely independent. It is found that the complex correlation in the repairable system has an important effect on the reliability of the system. To verify the correctness and feasibility of the GO method in reliability analysis of the MTS, the analysis results of the GO method are compared with the simulation results of FTA. The qualitative results based on FTA and the qualitative results based on the GO method are consistent. The quantitative results based on FTA is approaching the quantitative results based on the GO method. The comparison results show that the GO method is correct and feasible for the reliability analysis of the MTS considering shutdown correlation. The principle of the GO method is simple and the logic is clear. It can not only objectively reflect the working process of the MTS, but also fully characterize the complex correlation with shut down fault in the MTS. It has theoretical guiding significance for the reasonable formulation of reliability management measures for the MTS.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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