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Reliability Evaluation of a Metro Traction Substation Based on the Monte Carlo Method

KUNPENG LI[1], QIANQIAN YANG[2], ZHEN CUI[2], YUNYUN ZHAO[1], AND SHENG LIN[2]
[1]Guangzhou Metro Design and Research Institute Company, Ltd., Guangzhou 510010, China
[2]School of Electrical Engineering, Southwest Jiaotong University, Chengdu 610097, China

Corresponding author: Sheng Lin (shenglinm@163.com)

ABSTRACT The study of a metro traction power supply system reliability makes a significant contribution to researching on new power supply principles and configuration, and also providing a reference for system design and operation. According to the power supply structure and operation mode of the metro traction substation power supply system, based on the internal equipment, the reliability evaluation model of the traction substation is established by the block processing fault tree. An improved sequential Monte Carlo method is used to realize the quantitative reliability evaluation of the metro traction substation power supply system. The conclusions show that the reliability model and the sequential Monte Carlo simulation method proposed in this paper can obtain rich reliability indexes. Through visual simulation and theoretical calculation, the reliability of the metro traction power supply system can be effectively evaluated.

INDEX TERMS Metro traction substation, reliability assessment; fault tree analysis, block processing, sequential Monte Carlo simulation method.

I. INTRODUCTION

As the only source of power for the subway, the metro traction substation mainly undertakes the task of voltage level conversion, AC/DC conversion and power transmission to the metro train. Once it fails, it will directly affect the entire subway operation schedule, resulting in a considerable loss. Therefore, the reliability evaluation of the metro traction substation is particularly necessary. At present, some scholars have performed related research on the reliability of metro traction substation.

Reference [1] established a reliability assessment model by using the Fault Tree Analysis (FTA) [2]–[4], Failure Mode and Effects Analysis (FMEA) [5], and finally adopted the method of minimal cut sets [6] to make the probability of ‘‘top event failure probability’’ quantified. But it is difficult to judge the reliability of metro traction substation by the single indicator and without considering the maintainability factor of the equipment. In [7], the metro traction power supply system was used as a repairable system, and the reliability distribution of the system was carried out by the Goal-Oriented (GO) methodology [8] and the improved group analytic hierarchy process [9], which had certain subjectivity. Metro traction substation is a complex AC/DC hybrid system with a large number of states. The number of states increases exponentially with the increase of the number of devices. Therefore, the calculation of the reliability of the metro traction power supply system requires sufficient data to ensure the accuracy of the results. However, the sample statistics available in the actual operation of the subway are limited. Therefore, most of the current research methods are not conducive to the solution of the rich reliability index of the whole system, and the evaluation results need to be further improved in accuracy and persuasiveness.

In this paper, a combination of a regionalized fault tree and an improved sequential Monte Carlo method [10] is proposed. The effect of the bottom equipment repair rate on the simulation results is considered. Traverse the fault tree from bottom to top. Starting from the basic events of the system fault tree, through the intermediate events, the logical gate layer is used to nest up to the top event. Firstly, based on the idea of the power supply structure division of a subway traction substation, the reliability evaluation model of a traction substation is established by constructing regional fault trees. The model not only reduces the number of analysis components, but also avoids the repeated search of faults. Then, the sequential Monte Carlo simulation method is introduced to solve the reliability multi-index of the subway traction

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substation. The method can randomly simulate various states of systems according to certain steps. The MATLAB random number generator is used to generate random numbers that conform to the system model, and enough simulation data is used as a substitute for field test data. More extensive system reliability indices are obtained from multiple simulation results with high adaptability and strong persuasiveness, which greatly improves the calculation efficiency.

II. RELIABILITY EVALUATION INDICES AND MODEL OF A METRO TRACTION SUBSTATION

A. RELIABILITY EVALUATION INDICES OF A METRO TRACTION SUBSTATION

The reliability evaluation indices of the metro traction substation are generally expressed by time and probability [11]. Commonly used indicators include Mean Time Between Failure (MTBF), Mean Time To Repair (MTTR), steady-state availability and steady-state unavailability, etc. The literature [12] specifically defines the above indicators and their calculation methods.

B. TIME INDICATORS

a. *MTBF*. *MTBF* is the mathematical expectation of the system's trouble-free working time, and can be defined as

$$MTBF = \int_0^\infty f(t) \cdot tdt \tag{1}$$

where, $f(t)$ represents the probability of the first failure of the system between $(t, t + \Delta t)$, ie the failure density.

b. *MTTR*. *MTTR* is the expected value of the repair time, and can be defined as

$$MTTR = \int_0^\infty g(t) \cdot tdt \tag{2}$$

where $g(t)$ represents the repair density of the system.

C. PROBABILITY INDICATORS

The availability $A_v(t)$ refers to the probability that the system can work normally at time t when the system is operating normally at the beginning. In particular, when the failure rate and repair rates are constant, their time to failure and time to repair conform to the exponential distribution, the availability $A_v(\infty)$ of the system converges to a constant independent of t, ie, the steady-state availability A_v, calculated as

$$A_v = A_v(\infty) = \lim_{t\to\infty} A_v(t) = MTBF/(MTBF + MTTR) \tag{3}$$

Correspondingly, the steady-state unavailability is

$$A'_v = 1 - A_v \tag{4}$$

In particular, when the system failures and repairs conform to an exponential distribution, the steady-state unavailability can be expressed as

$$A'_v = 1 - A_v = 1 - \lim_{t\to\infty} A_v(t) = MTTR/(MTBF + MTTR) \tag{5}$$

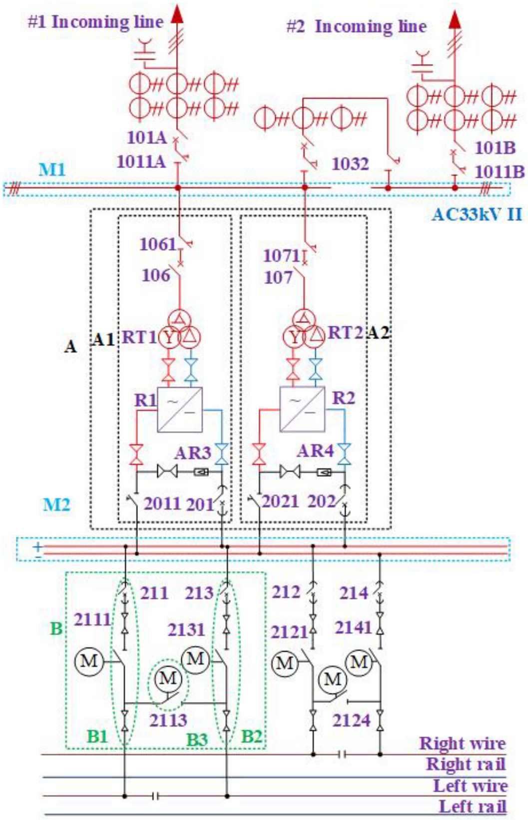

FIGURE 1. Wiring diagram of a certain traction substation of Guangzhou metro line 9.

D. RELIABILITY EVALUATION MODEL OF A METRO TRACTION SUBSTATION

The FTA model represents the logical relationship of a simple system through a fault tree. It starts from the least desirable event, pays attention to the basic causes and intermediate processes leading to system failure, and expresses the logical relationship of the system through the fault tree. It is very visual and intuitive. However, the metro traction substation is a complex system of AC and DC hybrids. The structure is large and the number of equipment is varied. It is necessary to simplify the system structure before reliability analysis. Considering the special position of the switching device in the system affecting the failure rate and the failure time, the power supply structure of the subway traction substation can be divided into different areas through components such as circuit breakers, disconnectors, tie switches and cables.

The structure of a traction substation of Guangzhou Metro Line 9 is shown in Fig.1. From top to bottom, its physical structure is, incoming part, 33 kV AC bus, step-down rectification part, 1500 V DC bus, left (right) feeder part and rail recirculation part. The incoming line belongs to the power supply part, and this paper evaluates the reliability of the traction substation, so it is not considered here. The failure of the rail recirculation zone is not directly related to the reliability of the entire system, so unconsidered either. Therefore, the whole system structure of the metro traction

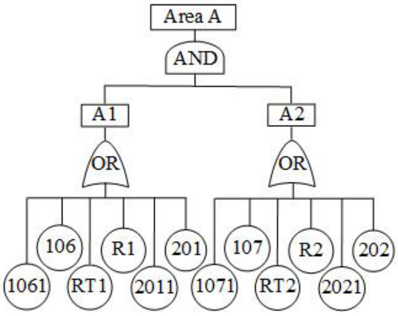

FIGURE 2. **The regional FTA models of area A.**

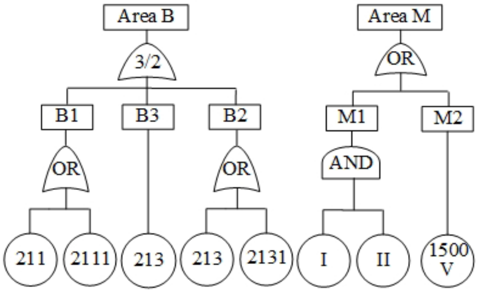

FIGURE 3. **The regional FTA models of area B and M.**

substation is divided into the following three parts: the step-down rectification zone, the left (right) line feed line section and the bus zone. The areas A, B, and M are numbered separately, and the specific electrical structure is shown by the dotted line in Fig.1.

Tree-shaped logic diagrams of regions A, B, and M can be obtained from the Fig.1 as shown in the Fig.2 and the Fig.3. Area A is the step-down rectification zone, as shown in Fig.2, it is composed of an A1 zone and an A2 zone. The area A1 includes key equipment: an isolating switch 1061, an isolating switch 2011, a circuit breaker 106, a circuit breaker 201, a step-down transformer RT1, and a rectifier R1. The area A2 structure is similar to the area A1 and includes key devices: an isolating switch 1071, a circuit breaker 107, a step-down transformer RT2, and a rectifier R2. The two electrical structures of the A1 area and the A2 area are identical, parallel and complementary. Each part has a fault tree model as shown in Fig.2 and Fig.3. Isolation switch 1061 (1071), circuit breaker 106 (107), traction transformer RT1 (RT2) and rectifier R1 (R2) are connected in series, then cascade to the paralleled isolating switch 2011 (2021) and circuit breaker 201 (202).

Area B is the left line feed line zone, and the left line feed line area is directly connected to the left line contact net, as shown in Fig.3, which is composed of the B1 area, the B2 area and the B3 area. The area B1 contains the key equipment, the electric isolation switch 2111 and the DC fast circuit breaker 211. The area B2 structure is similar to the area B1, which includes key equipment, for instance, an electric disconnecting switch 2131 and a direct current quick circuit breaker 213. The first two parts are in parallel complementary, and they both have a fault tree model as shown in Fig.3. The circuit breaker 211 (213) is connected in series with the isolating switch 2111 (2131). The third part is a normally open isolation switch 2113, it penetrates the first two parts and is responsible for the connection of the two areas. When the first part is faulty, the normally open 2113 is closed, and the second part is responsible for the power supply task of the first part. When the second part is faulty, the normally open 2113 is closed, and the first part is responsible for the power supply task of the second part. The three parts constitute a three-chosen-two system, which means when two or more partitions fail simultaneously in the B1, B2, and B3 partitions, the whole B partition fails.

Area M consists of a 33 kV medium voltage AC bus in the M1 area and a 1500 V low voltage DC bus in the M2 area as shown in Fig.3. Among them, the 33 kV medium voltage AC bus is divided into a bus I segment and a bus II segment. The fault tree model is shown in Fig.3. The two buses are connected in parallel. When the bus I segment fails, the bus II segment supplies power to the I segment. When the II segment bus fails, the I segment supplies power to the II segment. The failure of the DC bus will directly lead to the power failure of the entire metro traction substation.

III. METHOD FOR SOLVING RELIABILITY MODEL OF METRO TRACTION SUBSTATION

The regional fault tree model established by analyzing the logical relationship of the metro traction substation only provides a logical understanding of the logical relationship of each event. To obtain the reliability indices describing the performance of the subway traction substation, a sequential Monte Carlo simulation method is adopted to solve the model.

The essence of the sequential Monte Carlo method is to simulate the state transition process of each component in chronological order over a certain time span, thus establishing a virtual system state transition cycle. In the sequential Monte Carlo simulation, it is generally assumed that the duration of the state of the component is a random variable subject to an exponential distribution [6]. In order to obtain random variables subject to the exponential distribution, the inverse function method is usually used as

Let U denote a random variable uniformly distributed, and $F(X)$ denotes a cumulative probability distribution function of X, then $F(X)$ can be written as

$$F(X) = 1 - e^{-\lambda x} \tag{6}$$

According to the inverse function method,

$$U = F(X) = 1 - e^{-\lambda x} \tag{7}$$

Therefore,

$$X = F^{-1}(U) = -(1/\lambda)\ln(1 - U) \tag{8}$$

Since both U and 1-U obey the uniform distribution on [0, 1], therefore,

$$X = -(1/\lambda)\ln U \tag{9}$$

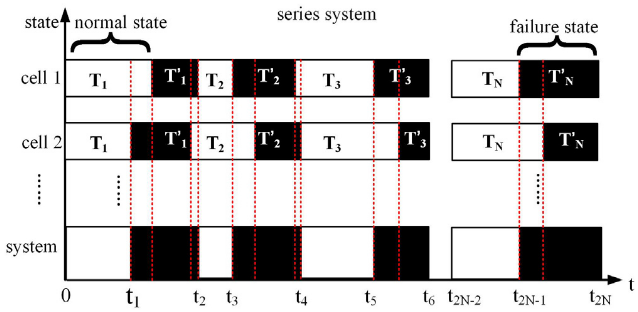

FIGURE 4. Series system timing states transition process.

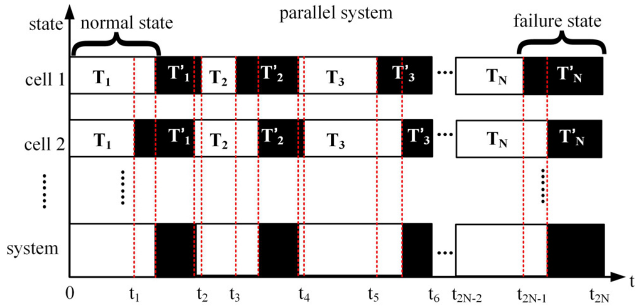

FIGURE 5. Parallel system timing states transition process.

Finally, according to the above formulas, the system state duration obeying the exponential distribution can be obtained. Based on the above analysis, the basic steps of the sequential Monte Carlo method are described as below

1. Specify the initial state of the component, usually assuming all components are in normal operation at the beginning.
2. Extract failure time T_i and repair time T_i' of each component according to the following formula

$$T_i = -(1/\lambda_i)\ln U \tag{10}$$

$$T_i' = -(1/\mu_i)\ln U \tag{11}$$

where, when the component is currently in the normal state, λ_i represents the failure rate of component i. when the component i is currently in the fault outage state. μ_i represents the repair rate of the component i.

3. Repeat the second step and record the timing state transition process of all components.

According to the series-parallel relationship between components, combine the timing state transition processes of all components to establish state transition schematic diagrams for pure series and parallel systems as shown in Fig.4 and Fig.5.

4. Analyze all system states obtained by sampling and calculate the reliability indices of the system.

Set the total number of simulation samples to FT, and the number of state samples to be extracted for each component is n. The process of the reliability evaluating of the traction substation using sequential Monte Carlo simulation is shown in Fig. 6.

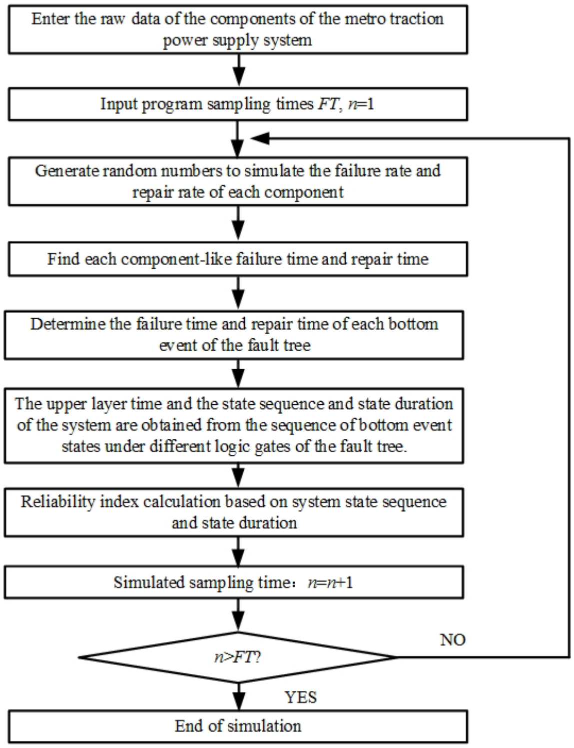

FIGURE 6. Flow chart of Monte Carlo method for solving fault tree.

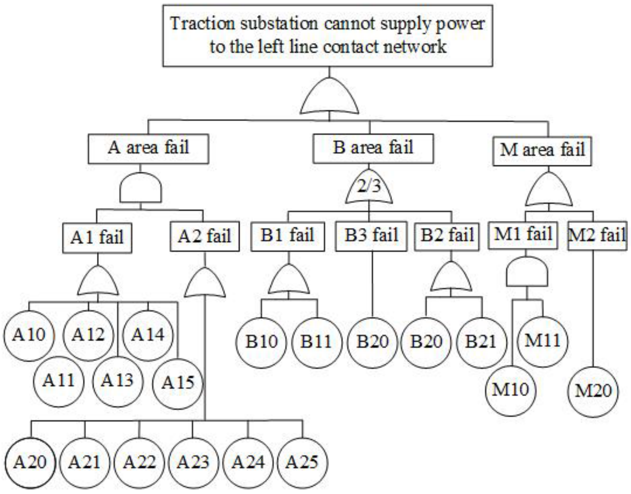

FIGURE 7. Fault tree model of subway traction substation.

IV. CASE STUDY

A. FAULT TREE ANALYSIS MODEL BASED ON BLOCK PROCESSING

According to the wiring diagram of the subway traction substation, combined with the power supply mode of the traction substation, the fault tree modeling based on the block processing is applied to the subway traction substation. First, a suitable top event is selected according to the analysis purpose. The fault tree is established as the top event by ''the traction substation cannot supply power to the left line contact network'', the block processed FTA model is established as shown in Fig.7.

TABLE 1. Fault tree bottom event of subway traction substation and its corresponding symbol system.

Event	Symbol	Event	Symbol	Event	Symbol
Disconnector 1061fail	A10	Breaker 201 fail	A15	Breaker 202 fail	A25
Breaker106 fail	A11	Disconnector 1071 fail	A20	Breaker 211 fail	B10
Transformer RT1 fail	A12	Breaker 107 fail	A21	Disconnector 2111 fail	B11
Rectifier R1 fail	A13	Transformer RT2 fail	A22	Breaker 213 fail	B20
Disconnector 2011 fail	A14	Rectifier R2 fail	A23	Disconnector 2113 fail	B30
Disconnector 2021 fail	A24	Disconnector 2131 fail	B21	33 kV bus I fail	M10
33 kV bus II fail	M11	1500V bus fail	M20	/	/

TABLE 2. Fault rate and repair rate of main equipment of subway traction substation.

Equipment	Failure rate λ	Repair rate μ	Equipment	Failure rate λ	Repair rate μ
High-voltage breaker	2.5114×10^{-6}	1/4	Middle-voltage breaker	2.8539×10^{-7}	1/4
Disconnector	1.7837×10^{-6}	1/4	Low-voltage breaker	2.3567×10^{-7}	1/4
Main transformer	1×10^{-3}	1/4	Traction transformer	1.83×10^{-4}	1/24
33 kV bus I	2.354×10^{-8}	1/4	Rectifier	9.134×10^{-6}	1/24
33 kV bus II	2.354×10^{-8}	1/4	1500 V bus	1.354×10^{-8}	1/24

There are 20 bottom events in the fault tree. The actual meanings of the symbols at the bottom of the fault tree are shown in Tab.1.

B. BASIC DATA

Most reliability research of metro traction power supply system default equipment failure and repair obey the exponential distribution, that is, the failure rates and repair rates of the components are constants [13], the reference data of the key equipment of the traction substation used in these papers [14], the specific values are shown in Tab.2, the unit is per hour.

This paper assumes that the same type of equipment has the same probability of failure in the same traction substation.

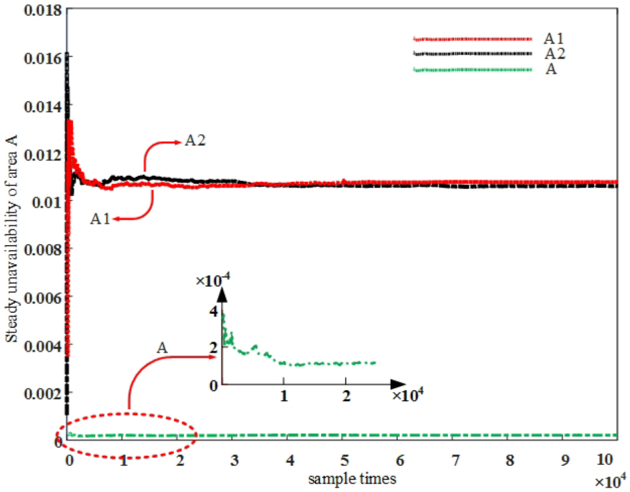

FIGURE 8. Steady state unavailability curves of area A.

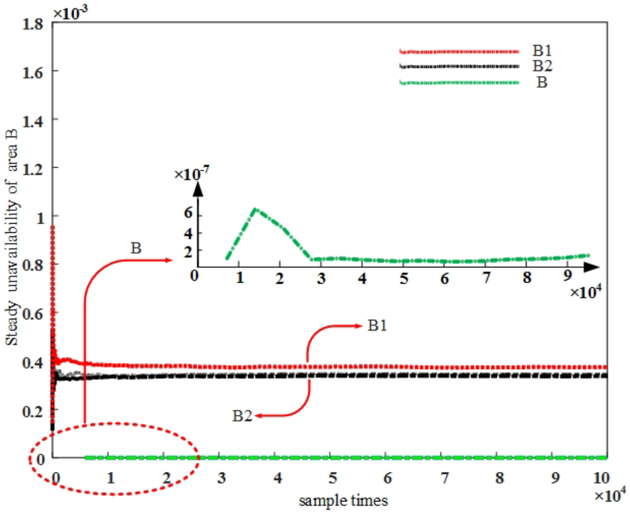

FIGURE 9. Steady state unavailability curves of area B.

TABLE 3. Reliability index table of A.

Reliability indicators	A1 area	A2 area	A area
$MTTR$(h)	18.67	18.54	9.28
$MTBF$(h)	1.72×10^{3}	1.73×10^{3}	8.4×10^{4}
Unavailability	1.1×10^{-2}	1.1×10^{-2}	1.12×10^{-4}
Availability	98.9%	98.9%	99.9888%

C. TRACTION SUBSTATION RELIABILITY EVALUATION INDICES

Tests show that the system unavailability tends to be stable when the number of simulation samples is set to 100000 times. The reliability indicators calculated are shown in Tables 3 to 5 below. Fig.8 to Fig.11 quantitatively depict the steady-state unavailability values for each zone of the metro traction substation.

Curves in Fig.8 to Fig.11 visually record the steady state power supply unavailability of each zone and the entire metro traction substation. It can be seen that the steady unavailability of the regions A1 and A2 tends to be 1×10^{-2} in the

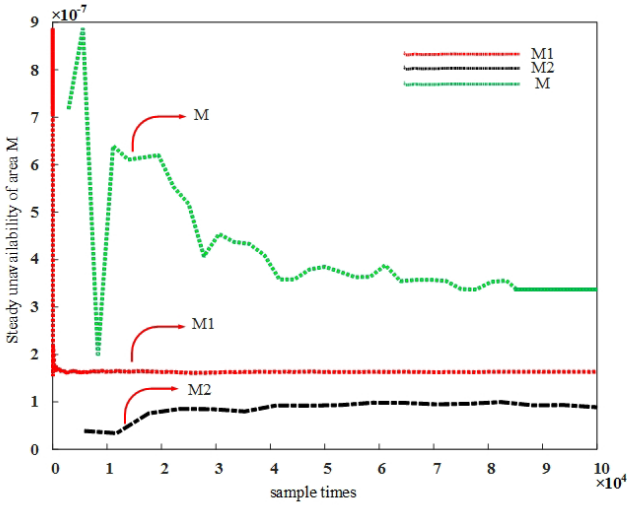

FIGURE 10. Steady state unavailability curve of area M.

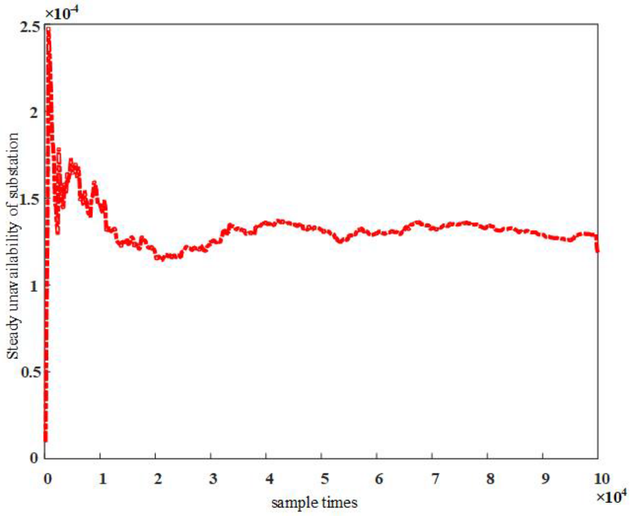

FIGURE 11. Steady state unavailability curve of substation.

TABLE 4. Reliability index table of B.

Reliability indicators	B1 area	B2 area	B area
MTTR(h)	6.01	5.99	3.60
MTBF(h)	1.74×10^4	1.60×10^4	2.79×10^7
Unavailability	3.9×10^{-4}	3.5×10^{-4}	1.25×10^{-7}
Availability	99.961%	99.965%	99.9999%

TABLE 5. Reliability index table of M AND traction substation.

Reliability indicators	M1 area	M2 area	M area	Traction substation
MTTR(h)	5.79	11.98	10.59	8.96
MTBF(h)	8.69×10^7	7.47×10^7	3.28×10^7	4.69×10^3
Unavailability	1.0×10^{-7}	1.7×10^{-7}	3.4×10^{-7}	1.25×10^{-4}
Availability	99.9999%	99.9999%	99. 9999%	99.9875%

case of separate operation. The unavailability of the entire region A is reduced to 1.12×10^{-4} when the two regions are connected in parallel, and the availability is up to 99.9888%. The single unavailability of the B1 and B2 regions tends to be 10^{-4}, and the unavailability of the entire B region decreases to 1.25×10^{-7}. The unavailability of the M zone is also 10^{-7}. After comprehensively considering the three zones, the availability curve of the entire substation shown in Fig.11 is obtained. The steady unavailability of the system tends to be 1.25×10^{-4}, and the availability is 99.9875%.

The reliability indicators of the traction system, *MTTR*, *MTBF*, the number of system failures, the approximate values of the steady unavailability and availability are shown in the following tables.

It can be quantitatively seen from Tab.3 to Tab.5 that the reliability of the medium voltage system A area is the lowest, and the average time between failures of the single A1 area and the A2 area is about 1.72×10^3 hours (72 days). The average time between failures of the entire area A after the A1 area and the A2 area are complemented in parallel is about 8.4×10^4 hours (9.6 years). The average time between failures of the B1 and B2 zones is approximately 4 years and 5.7 years, respectively, and the mean time between failures of the entire three-choice zone B is approximately 2.79×10^7 hours without regard to system equipment wear. At the same time, the average time between failures of the bus area is about 3.28×10^7 hours. It also can be seen from Tab.4 that the mean time between failure of the power supply system of the entire metro traction substation is about 4.69×10^3, which is about 6.5 months. Therefore, when formulating the maintenance plan, we should refer to and compare the steady-state availability and the average trouble-free operation time of each area to make a reasonable plan for the selection, maintenance, and replacement of key equipment. It provides a certain reference value for system maintenance management, avoiding "under-maintenance" or "over-maintenance" in inspection and maintenance.

V. CONCLUSION

For the three large areas of Area A, Area B and Area M of the Metro Traction Power Supply System, we can see from Tab. 3 and Tab. 4 that the reliability of area A is the lowest, and its value is about 99.9888%. So, area A, the step-down rectification zone is the weakest links in the whole system. The reason can be analyzed from the following two aspects. Firstly, from the electrical structure point of view, the entire area A contains more electrical equipment than the area B and the area M, the areas A1 and A2 are pure series structure and the number of series devices is large. It is available from the basic knowledge of reliability that the reliability of the series structure is low and the more series devices, the lower the reliability. Secondly, From the perspective of equipment failure rate data, in terms of A1 of area A, which includes the high-voltage breaker, the traction transformer, the rectifier and the middle-voltage breaker. It can be seen from Tab.2 that these devices have a higher failure rate rating.

The literature [15] establishes a fault tree model for the failure of metro traction power supply. According to the quantitative calculation by the fault tree down method, the reliability of the metro traction power supply system is about 0.99183, and the average operation time is about 122 days. From the actual statistics of the reliability evaluation project of the traction power supply system from Saudi Meghassa to Mugodasa Metro Project [16], the reliability of the subway traction power supply system is about 0.999828.Therefore, in summary, compared with the traditional fault tree solution, the method used in this paper is closer to the actual statistical results, and the error is smaller.

Based on the working characteristics of the subway traction substation, the reliability evaluation model of the traction substation is established by using the structure partitioning and fault tree principle. The sequential Monte Carlo simulation method is used to solve the system reliability indicators, and the reliability of the metro traction substation is quantitatively evaluated. The results obtained in the paper aim to find out the weak areas of the metro traction power supply system and figure out the best operation plan and maintenance cycle. It has guiding significance in the operation and maintenance of the traction power supply system of the subway and the coordination of reliability and economy.

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