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A Reliability Evaluation of High Speed Railway Traction Substation Based on the GO-FLOW Methodology

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Abstract

In order to assure the uninterrupted power supply of high speed railway, the reliability assessment of traction substation is essential at the design stage. Based on the system reliability engineering theory, a new system reliability analysis method called the GO-FLOW methodology is applied in the reliability assessment of traction substation of high speed railway. Considering failure and dynamic characteristics over time of the components and shutdown correlation of electrical equipments in substation, on the analysis of the traction power supply system, the GO-FLOW chart of traction power supply system is established by taking the uninterrupted power supply as its target. Their operators signal flows and operation rules are analyzed. Then, the quantitative and qualitative assessment of reliability are realized, the weakness of system is determined. Thus, the reliability evaluation of high-speed railway traction power supply system is completed.

Keywords: *high speed railway, traction substation, GO-FLOW methodology, reliability assessment*

1. Introduction

Along with the large-scale construction and operation of high-speed railway, the problems of safety and reliability around people are concerned. As the transformation bridge of three-phase alternating current (AC) power supply system and single-phase electric system, traction substation is equipped with a large number of important electrical equipments. Once the equipments go wrong, they would directly affect the normal operation of the high-speed railway even cause great economic losses [1-2]. Traction substation must guarantee the good quality of power supply and high reliability, thus safety and stability of the running train could be ensured. The reliability evaluation of traction power supply system was conducted by Fault Tree Analysis (FTA) in 2006 [3]. The reliability and economy of traction substation were evaluated by the minimum cut set method based on adjacent terminal matrix in 2007 [4]. The reliability evaluation of main electrical wiring in traction substation was finished with the goal oriented (GO) method that is simple and clear in 2009 [5]. In 2012, a reliability evaluation of metro traction power supply system was conducted by failure mode and effects analysis (FMEA) and FTA met [6]. However, high-speed railway traction power supply system has an important feature, which is the obvious dynamic characteristic. In the above references, system risk analysis methods are the static analyses. They are traditional methods and are difficult to describe the system dynamic characteristic [7].

The paper applies a new reliability analysis method-GO-FLOW methodology to reliability analysis of the high-speed railway traction substation. Considering that the failure and complex dynamic characteristics of numerous electrical equipments; the reliability evaluation of the system is analyzed. *On the analysis of the traction power supply system, GO-FLOW chart of traction power supply system is established by taking the uninterrupted power supply as its target.* Quantitative calculation of the traction power supply system is realized, the steady-state characteristics of the system are achieved, and the probabilities of traction power supply system over all work time points have been achieved. Namely the dynamic reliability analysis and reliability evaluation of high speed railway traction power supply system are completed.

In this paper, it is shown that the GO-FLOW could complete these analyses in the traction substation system. And an example of analysis by the GO-FLOW methodology is presented.

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1.1. The Significant Features and Functions of GO-FLOW Methodology

In the mid of 1980's, two scholars, Japan's Mr. Matsuoka and Michiyuki Kobayashi Marine of research institute in Tokyo, developed the basic concept and algorithm on the basis of the research GO method, which is different from the GO method, named GO-FLOW methodology [8], it is a new method for system reliability analysis.

The GO-FLOW methodology possesses the following significant features [9]:

a) GO-FLOW chart corresponds to the physical layout of a system and is easy to construct and validate;

b) Alterations and updates of a GO-FLOW chart are easily made;

c) The GO-FLOW chart contains all possible systems operational states;

d) The analysis is performed by one GO-FLOW chart run by one computer.

The GO-FLOW methodology has the following functions:

a) Analysis of phased mission problem;

b) Identification of minimal cut sets;

c) Uncertainty analysis;

d) Aging and maintenance effects.

It is a kind of effective, intuitive and accurate method of system reliability analysis. The steps of analyzing the system by GO-FLOW methodology are as follows:

a) Establishing a system of GO-FLOW chart;

b) Inputting operator data by the GO-FLOW chart;

c) Finishing GO-FLOW calculation and the strength of a signal at all time points of the system;

d) According to the results of calculation, system needs to be analyzed.

For system modeling, fourteen different types of operators have been defined currently. The functions of the GO - FLOW operators are different from those of the GO operators. Because of the meaning of the signal in the GO-FLOW methodology is completely different from that in the GO methods. The principles of GO-FLOW operations can be referenced to reference [8]. The symbols of operators in the GO-FLOW chart are shown in Figure 1. The number of the figure in the symbol means the operator models. Type number is greater than 20, in order to show the difference operator with GO method.

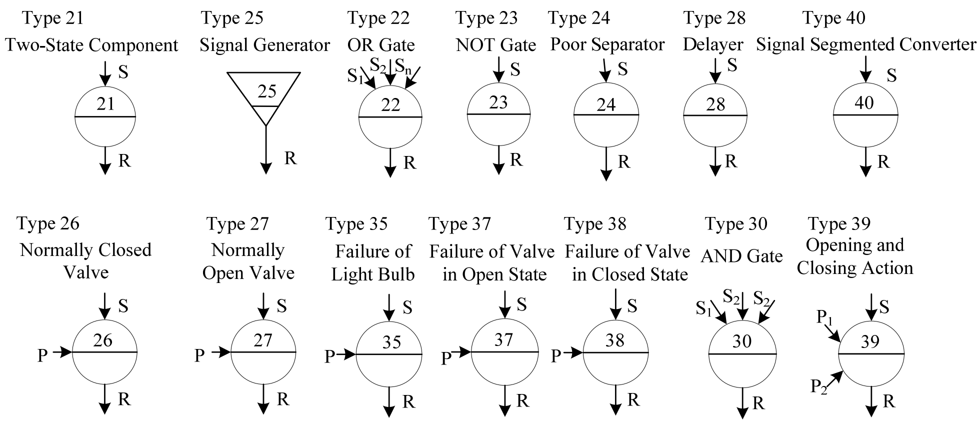

Figure 1. Operators in the GO - FLOW Methodology

2. Main Equipment Reliability Index of Traction Substation

From the viewpoint of reliability, assuming that all equipments and the components are exponentially distributed. At the same time, after continuous working, they already had stable characteristics. In addition, assume that the traction substation is a repairable system.

In an example of a high-speed railway traction substation, the external power supply of 220 kV level, it uses the AT power supply mode. The main electrical wiring of equipments is shown in figure 2. Visibly, the system is not a simple series-parallel structure, assuming that reliability parameters of main electrical equipments [10] are shown in Table 1.

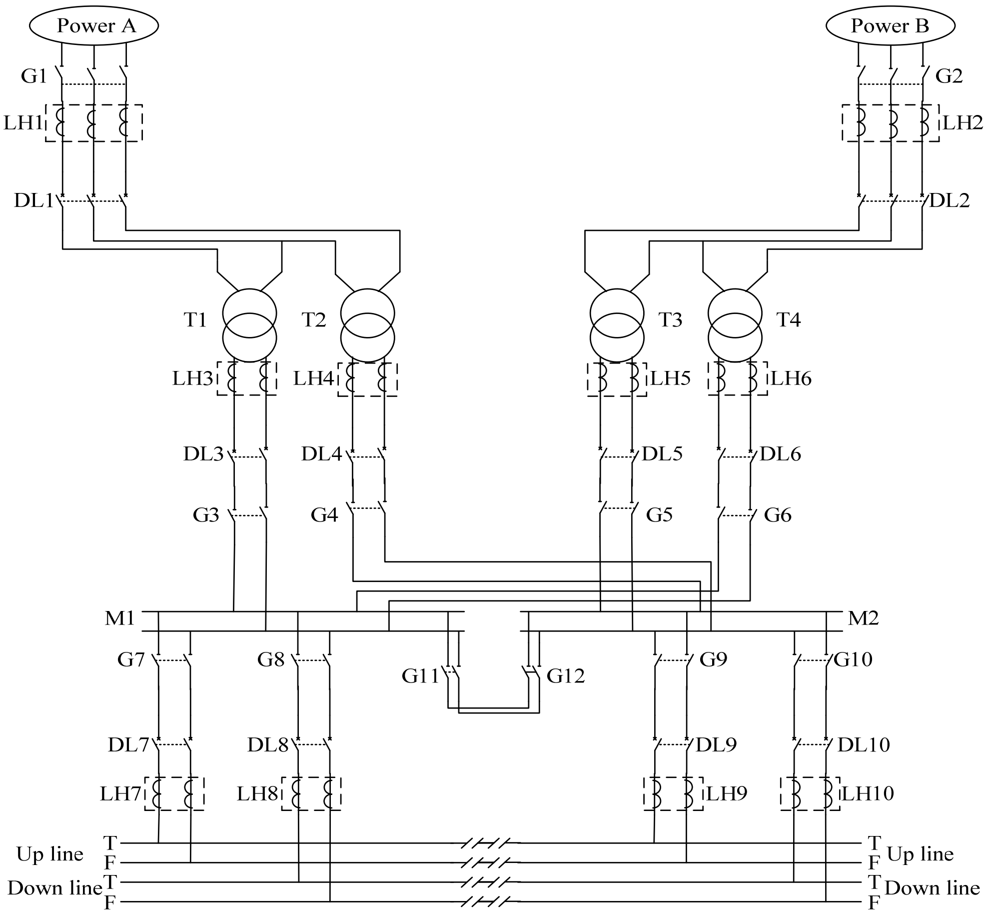

Figure 2. Schematic Diagram of Traction Power Supply System

Table 1. Reliability Parameters of Main Equipments in Traction Substation

Basic Components	Failure Rate γ /(Time/year)	Troubleshooting time/h
Local Power A	0.8	11
Local Power B	0.95	15
Bus	0.1	3
Isolating Switch	0.08	3
Circuit Breaker	0.12	3
Traction Transformer	0.03	90
Current Transformer	0.015	10

3. The Traction Substation Reliability Modeling Based on the GO-FLOW Methodology

3.1. System Analysis

Traction power supply system is mainly composed of external power supplies, isolating switches, current transformers, SF_6 circuit breakers, traction transformers, buses and other units (Figure 1). Traction substation is supplied by two external powers, which are independent and reliable power systems. The powers adopt 220kV voltage class and they are hot standby each other. In traction substation, the traction transformers use V/V connection forms (It is a mode of connection with two single-phase transformers linking three-phase power system in the way of V, each traction substation can be achieved power supply by the two-phase voltage in three-phase power supply system. The secondary windings of the transformer, one end linked to depicting two-phase bus of the traction substation, and the other end linked to the return lines with a common terminal connected to rail. At this time, the voltage of phase arms is 60). There are four single-phase traction transformers in traction substation, two of them are running, others are fixed and set aside. The bus 1, 2 provide power to up and down lines by four feeders.

3.2. Establish GO-FLOW Chart for Traction Substation

On the basis of the principles of the GO-FLOW methodology, in combination with Figure 1 and Figure 2, at the same time, considering that electrical equipments of traction substation have certain life, namely considering the change of the failure probability of components with time. The GO-FLOW chart of traction power supply system is established. The GO-FLOW chart is shown in Figure 3.

Because of various components of the system, the paper adopts that an operator represents the equivalent unit comprised of several series components. To simplify the structure of the GO-FLOW chart, each operator is represented by a compound number: The number above the horizontal line represents the type of operator, and the number below the line designates each operator. The numbers on the connecting lines identify the signals. The final signal is signal No.15. Each operator in Figure 3 is described detailed in Table 2.

Table 2. The Operators in GO - FLOW Chart

Serial Number	Type	Series Equipments
1	25	External Power A Isolating Switch G1 Current Transformer LH1 SF_6Circuit Breaker DL1
2	25	External Power B Isolating Switch G2 Current Transformer LH2 SF_6Circuit Breaker DL2
3	21	Traction Transformer T1 Current Transformer LH3 SF_6Circuit Breaker DL3 Isolating Switch G3
4	21	Traction Transformer T2 Current Transformer LH4 SF_6Circuit Breaker DL4 Isolating Switch G4
5	21	Traction Transformer T3 Current Transformer LH5 SF_6Circuit Breaker DL5 Isolating Switch G5
6	21	Traction Transformer T4 Current Transformer LH6 SF_6Circuit Breaker DL6 Isolating Switch G6
7	22	OR Gate
8	22	OR Gate
9	21	Bus 1
10	21	Bus 2
11	21	Isolating Switch G7 SF_6Circuit Breaker DL7 Current Transformer LH7
12	21	Isolating Switch G8 SF_6Circuit Breaker DL8 Current Transformer LH8
13	21	Isolating Switch G9 SF_6Circuit Breaker DL9 Current Transformer LH9
14	21	Isolating Switch G10 SF_6Circuit Breaker DL10 Current Transformer LH10
15	30	AND Gate
16	25	The time interval between two time points in succession
17/18/19/20/21/23/22/23/24/25/26	35	Component failure over time work

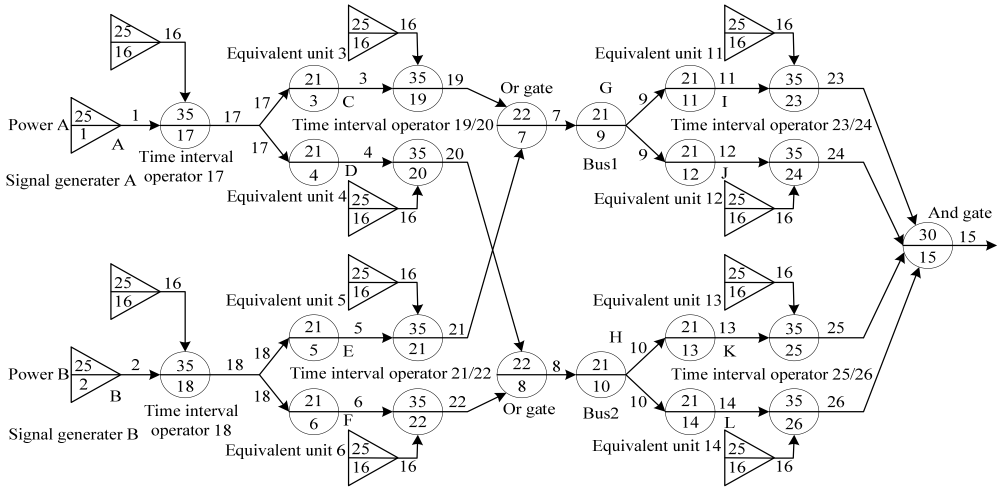

Figure 3. The Simplified GO - FLOW Chart for Traction Power Supply System

3.3. Model Analysis and Parameters Calculation

Traction power supply system is a repairable system. Since the failure of a component, the traction substation may stop working, or the operation of other components of system would be stopped. Namely, in a repairable system, the lockout features need to be considered. That is to say, some parts of equipments have shutdown correlation [8].

In Figure 3, when the operator represents equivalent unit that is comprised of several series parts, the calculation method of reliability parameters needs to be improved. Assuming that the operator corresponding to M related series parts, which the number of series structure's shutdown stoppage I is 1. Because of considering downtime association of components, tandem structure failure mode is only one component fails. There are not occurred that two or more components in failure at the same time. So the failure rate and repair rate ratio is the sum of all parts rate and repair rate ratio [8]. Setting τ_{Si} is mean repairing time, μ_{Si} is the mean repairing rate.

So failure rate of series equivalent unit λ_{R} and mean repairing time τ_{R} meet type (1), (2):

$$\lambda_{\mathrm{R}} = \sum_{i=1}^{M} \lambda_{Si} = \lambda_{S1} + \lambda_{S2} + \ldots + \lambda_{SM} \tag{1}$$

$$\lambda_{\mathrm{R}} \tau_{\mathrm{R}} = \sum_{i=1}^{M} \lambda_{Si} \tau_{Si} \tag{2}$$

Or $\lambda_{\mathrm{R}} / \mu_{\mathrm{R}} = \sum_{i=1}^{M} \lambda_{Si} \mu_{Si}$ among them, $\tau_{Si} = \dfrac{1}{\mu_{Si}}$

The output signal's success state probability value of series equivalent unit $P_{\mathrm{R}}(1)$ meets type (3):

$$P_{\mathrm{R}}(1) = \frac{1}{1 + \lambda_{\mathrm{R}} / \mu_{\mathrm{R}}} \tag{3}$$

The output signal failure state probability value $P_{\mathrm{R}}(2)$ meets type (4):

$$P_{\mathrm{R}}(2) = \frac{\lambda_{\mathrm{R}} / \mu_{\mathrm{R}}}{1 + \lambda_{\mathrm{R}} / \mu_{\mathrm{R}}} \tag{4}$$

The reliability parameters of series connection structure as shown in Table 3.

Table 3. The Tandem Structure Reliability Parameters of the Operator

Operator Number	Failure Rate/ (times/year)	Repair Rate/ h^{-1}	Normal Work of the Probability/%	Probability of Breakdown Maintenance
1	1.0150	1.062827e-1	99.89110	0.108900
2	1.1650	7.766667e-02	99.829060	0.170940
3/4/5/6	0.2450	7.101449e-02	99.960632	0.039368
11/12/13/14	0.2150	7.101449e-02	99.991439	0.008651

In this example, assuming that power A closed 10 hours later, power B is connected. In traction substation power supply system, we declare five time points. Time point 1 is an initial time point, the system has not started any action; at time point 2, the system began to work, remembered it is the actual time of zero moment. At this time, external power A is connected, two transformers are running. Time point 3 is 10 hours after time point 2; Point 4 is followed by a time point connected to external power B after point 3, at the point, external power B is connected, the other two standby transformers began to work; Time Point 5 is 10 hours after time point 4. We assume that invalid rate λ of electrical equipment in traction substation is constant. The operator types, parameters and meanings of traction power supply system are shown in Table 4.

Table 4 Operator data of the traction power supply system

Serial number	Type	Parameter	Meaning
1	25	R(2)=0.99891100,R(t)=0(t $\neq$ 2)	Connected to external power A generator
2	25	R(4)=0.99829060,R(t)=0(t $\neq$ 4)	Connected to external power B generator
3	21	Pg=0.99960632	Equivalent series unit of T1
4	21	Pg=0.99960632	Equivalent series unit of T2
5	21	Pg=0.99960632	Equivalent series unit of T3
6	21	Pg=0.99960632	Equivalent series unit of T4
7	22	—	Or gate
8	22	—	Or gate
9	21	Pg=0.999893	Bus 1
10	21	Pg=0.999683	Bus 2
11	21	Pg=0.99991439	Series equivalent switch unit 7
12	21	Pg=0.99991439	Series equivalent switch unit 8
13	21	Pg=0.99991439	Series equivalent switch unit 9
14	21	Pg=0.99991439	Series equivalent switch unit 10
15	30	—	And gate
16	25	R(3)=10h,R(5)=10h,R(t)=0(t $\neq$ 3,5)	Time interval signal generator
17	35	λ =0.001	Running external power A equivalent unit
18	35	λ =0.002	Running external power A equivalent unit
19	35	λ =0.003	Running T1 equivalent unit
20	35	λ =0.003	Running T2 equivalent unit
21	35	λ =0.003	Running T3 equivalent unit
22	35	λ =0.003	Running T4 equivalent unit
23	35	λ =0.001	Running 7 series equivalent switch unit
24	35	λ =0.001	Running 8 series equivalent switch unit
25	35	λ =0.001	Running 9 series equivalent switch unit
26	35	λ =0.001	Running 10 series equivalent switch unit

Note: T1, T2, T3, T4 means traction transformer symbols, Pg means normal probability in working of equivalent units.

4. Reliability Analysis of Traction Substation Based on the GO - FLOW Methodology

4.1. Quantitative Calculation of Substation Reliability Evaluation

Operation process of GO-FLOW methodology starts from the signal generator (operator 1 and operator 2 in figure 3), along with the signal line sequence. According to the operation rules [8], we calculate the output signal one by one for operator which is on all time points until the final signal. Setting R(t) is the strength of the output signal at time t, S(t) is given priority to the main input signal at time t, P(t) is the input signal of the intensity at time t. The operators 21, 22, 30, 35 are used in the paper. Their algorithms are shown in formula (5) to formula (8). In repairable system reliability analysis, trouble-free working time and repairing time of each component of system are both obey exponential distribution. Named failure rate γ and repair rate μ, they are constant. Reliability characteristics of system shown as formulas (9)~(14).

Operator algorithm of type 21:

$$R(t) = S(t) \cdot P_{\mathrm{g}} \tag{5}$$

Operator algorithm of type 22: Supposing you had M input signals and they were independent from each other.

$$R(t) = 1 - \prod_{j=1}^{M}[1 - S_j(t)] \tag{6}$$

Operator algorithm of type 30: Supposing you had M input signals, and they were independent from each other.

$$R(t) = \prod_{j=1}^{M} S_{\mathrm{j}}(t) \tag{7}$$

Operator algorithm of type 35: Input signal S(t_k) before the time t affects the output signal intensity R(t).

$$R(t) = S(t) \cdot \exp\{-\gamma \sum_{i} \sum_{k \le t} P_i(t_k) \times \min[1.0, S(t_k)/S(t)]\} \tag{8}$$

Among them, γ represents failure possibility over time work. As the element in the failure probability per unit time, named the failure rate.

The average trouble-free working hours:

$$\text{MTBF}=\frac{1}{\gamma} \tag{9}$$

Average repairing time:

$$\text{MTTR}=\frac{1}{\mu} \tag{10}$$

The average life cycle:

$$\text{MCT}=\text{MTBF}+\text{MTTR} \tag{11}$$

The average probability of work:

$$A = \frac{\text{MTBF}}{\text{MCT}} = \frac{\mu}{\gamma + \mu} \tag{12}$$

The average probability of shutdown:

$$\bar{A} = \frac{\text{MTTR}}{\text{MCT}} = \frac{\gamma}{\gamma + \mu} \tag{13}$$

The failure rate:

$$f = A\gamma = \bar{A}\mu = \frac{1}{\text{MCT}} \tag{14}$$

Formulas (5)-(14) are used to calculate the state probability and the probability of strength of the signal flow 15 (output signal) at all time points quantitatively. The quantitative assessment of the reliability of the traction substation could be completed. Here, duing to the limitation of space, we don't make it a tautology. The calculation results of traction substation reliability parameters are shown as Table 5, the calculation results of signal strength are shown as Table 6.

Table 6 shows that time point 1 as the initial time, the system does not take any action, so the signal flow intensity is zero; the signal flow strength of system sharply declines in the time point 2 to point 3, the increase of failure probability of system in point 2 to point 3 is faster than time point 4 to point 5.That is because the system launches another standby power supply branch of the external power supply B. The system becomes into a internal system that containing parallel redundant series-parallel relationships from a single series parallel relationship. Signal flow strength of the system reduces significantly. It is consistent with the actual situation.

Table 5. Calculation Reliability Parameters Results of Traction Substation

Reliability Parameters	Signal 15
Average probability of work /%	99.959376
Average probability of shutdown /%	0.040624
Average number of failure (f/ a-1)	1.263000
Failure Rate	1.263771
Repair Rate	0.354984
Average Working Time/h	6391.6356
Average Repairing Time /h	2.817
Average life cycle /h	6934.453

Table 6. Calculation Results of Signal Strength in Substation Power Supply System

Time Point	1	2	3	4	5
Actual Time/h	Initial	0	10	10	20
Strength of the signal 15	0.0	0.99279191	0.99089162	0.99043702	0.98992608

4.2. Reliability Qualitative Assessment of Substation

The principles of GO-FLOW are used in the process of qualitative calculation. Because of the probability of input operators and function operators are zero, we thought that they are not existed and not included in the state of the corresponding operator numbers. So they would not participate in operations of state combination, thereby the numbers of state combinations are reduced. Thus the operational process would be simplified. There are multiple components in series equivalent units of the system. Their minimum cuts are generated by qualitatively analyzing of equivalent units. Duing to the restraint of the paper, only six of them are given. First cut set of system as shown in Table 7. The corresponding operator of the symbol has been listed in the GO–FLOW chart.

Table 7. Qualitative Assessment in First Cut Set

Serial Number	Cut set order number	Inside the cut set operator symbols
1	1	G(Bus 1)
2	1	H(Bus 2)
3	1	I(Isolating Switch G7, SF_6Circuit Breaker DL7, Current Transformer LH7)
4	1	J(Isolating Switch G8, SF_6Circuit Breaker DL8, Current Transformer LH8)
5	1	K(Isolating Switch G9, SF_6Circuit Breaker DL9, Current Transformer LH9)
6	1	L(Isolating Switch G10, SF_6Circuit Breaker DL10, Current Transformer LH10)

5. Conclusion

In the paper, GO-FLOW methodology is applied to the reliability analysis and research of high speed railway traction substation. It enriches the methods of traction power supply system reliability studying and broadens the research train of thought. The main conclusions are as following several aspects:

(1) Considering the dynamic characteristic, the failure rate and downtime relation of many electrical equipments and taking uninterruptible power supply of traction as a goal, the simplified GO-FLOW chart is established. Quantitative calculation of the reliability of the system has been finished. The signal flow parameters, the strength of the output signal flow at various time points and the system of minimum cut sets have been achieved. The evaluation goals are clear and focused;

(2) The failure process of parts in working is simulated. The probability of the normal operating system in the whole operation process has been calculated. With the increase of system complexity, working probability is dropped. It is consistent with the actual situation.

(3) Quantitatively and qualitatively evaluating for the reliability of the traction substation had been achieved. Quantitatively reliability calculation of system in a given working conditions had been completed. Thus, the weaknesses of system had been found out. It would provide an optimal design scheme of the traction substation.

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