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Analysis on Reliability and Security of ZPW-2000A Track Circuit System Based on FMEDA and FTA

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Abstract: To aim at the reliability and security issues of ZPW-2000A Jointless Audio Frequency-shift Modulated Track Circuit System, Failure Modes Effects and Diagnositcs Analysis (FMEDA) and Fault Tree Analysis (FTA) were proposed for reliability and security analysis of system. The system was analyzed and defined, the FMEDA table was completed, and the fault tree was built, then the qualitative and quantitative analyses of the fault tree were conducted. The minimal cut sets of the fault tree were got by qualitative analysis, and the weak links of the system were located. The fail probability of roof events, important degree of each minimal cut sets and the indicators of reliability and security were gained through the quantitative analysis. The paper provides a practical method and theoretical basis for the reliability and security analysis of ZPW-2000A track circuit system. *Copyright © 2013 IFSA.*

Keywords: Track circuit, FMEDA, FTA, Reliability, Security.

1. Introduction

The track circuit is one of the key equipments of railway signaling systems, ZPW-2000A Jointless Audio Frequency-shift Modulated Track Circuit was based on introduction and localization of France UM71 jointless track circuit technology, researchers made it meet China's conditions requires by improving its security, the transmission performance and reliability [1]. At present, the track circuit is widely used in China's railway. In recent years, with the development of railway's high-speed, heavy-duty and high-density, the track circuit equipments become more and more important for ensuring train's high-speed and security, whose reliability and security have a direct impact on the safety and efficiency of rail transport. Therefore, in order to guarantee the level of reliability and security of the railway signaling systems, we need to analyze the reliability and security of ZPW-2000A Jointless Audio Frequency-shift Modulated Track Circuit System.

Signal equipments as a key component of the railway transportation, its reliability and security have become an important index to measure the performance of the railway equipments. In recent years, Fault Tree Analysis (FTA), Failure Mode and Effects Analysis (FMEA), Reliability Block Diagram (RBD) and Markov Model had been widely used in the analysis on the reliability and security of railway rolling stock. However, it is just getting started for research on the reliability and security of the railway signaling system [2]. Existing research had focused on the reliability index of Transmitter and Receiver of ZPW-2000A track circuit system, but it lacked for analyzing on the reliability and security of the whole ZPW-2000A track circuit system [3].

In this paper, Failure Modes and Effects and Diagnostic Analysis (FMEDA) and Fault Tree Analysis (FTA) were used to analyze the reliability and security of ZPW-2000A track circuit system. Firstly, in order to facilitate the analysis, the reliability model was established according to the structure characteristics of ZPW-2000A track circuit system, then FMEDA was used to analyze ZPW-2000A track circuit system. Finally, the qualitative and quantitative analyses of the fault trees of ZPW-2000A track circuit system were conducted on the basis of the FMEDA table.

2. ZPW-2000A Track Circuit Model

ZPW-2000A Jointless Audio Frequency-shift Modulated Track Circuit is composed of the equipment of indoor and outdoor. The indoor equipment includes Transmitter, Receiver, Attenuator and Cable Analog Network. The outdoor equipment includes Tuner Unit, Hollow Coil, Mechanical Insulation Joint Hollow Coil, Matching Transformer, Compensation Capacitor and SPT Cable. There are two kinds of structure of ZPW-2000A Jointless Audio Frequency-shift Modulated Track Circuit, one is the electrical-mechanical insulated joint, the other is electric-electric insulated joint, and the performance of two structures is the same. The former structure as a sample to be analyzed in this paper, as shown in Fig. 1.

ZPW-2000A Jointless Audio Frequency-shift Modulated Track Circuit is divided into two parts, one is the main track circuit, the other is a short track circuit of the tuning region. The transmitter of main track circuit is controlled by the encoding condition that generated different frequency-shift signals of low frequency modulation which indicate different information. The frequency-shift signal is sent to matching transformer and tuner unit through the cable channel. The frequency-shift signal is sent to the main track circuit, also to the tuning region's small track circuit. The main track's signal is sent to the receiving end of track circuit through rail, then through the tuner unit, matching transformer and cable channel, the signal is transmitted to the receiver in this section. Tuning region's signal is received and processed by receiver of the front of the adjacent track circuit, and the processing results is converted into the small track circuit relay's execution command that is sent to receiver of the section. Receiver of the section receives the main track frequency-shift signal and the small track circuit relay's execution command at the same time, this information will be judged, if it is correct, then driving the track circuit's relay and making it energize, to determine the section is cleared or occupied.

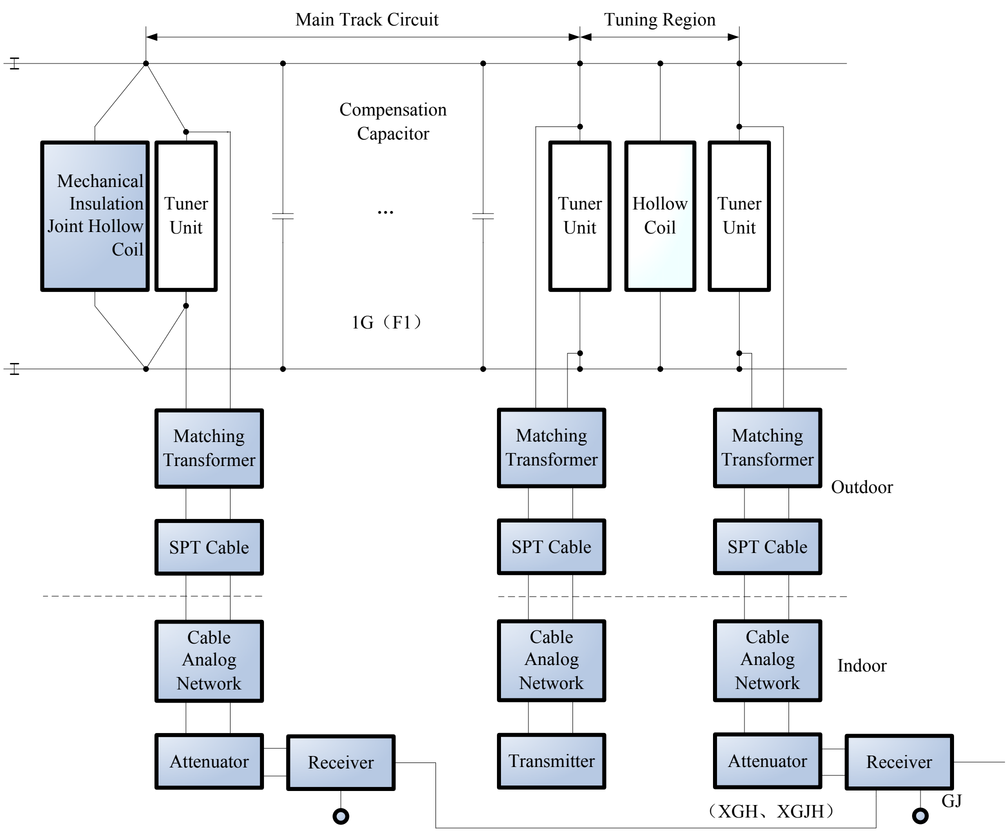

Fig. 1. ZPW-2000A track circuit model.

3. FMEDA Method

The FMEDA method was based on the report of a seminar which held in 1984 and then developed [4-5]. FMEDA is on the basis of the FMEA, then the online diagnosis technology is introduced into the standard FMEA. FMEDA is a technology used to identify equipment failure. At the same time, it is also the basis of FTA method [6].

3.1. System Description

As can be seen from Fig. 1, ZPW-2000A Jointless Audio Frequency-shift Modulated Track Circuit System is a complex series system, and it is an organic combination of the whole, whose important subsystem includes Transmitter, Cable Analog Network, SPT Cable, Matching Transformer, Tuner Unit, Compensation Capacitor, Hollow Coil, Attenuator, Receiver, Mechanical Insulation Joint Hollow Coil, and so on. Because the working states of these subsystems are independent each other, and the whole system is composed of these subsystems which were connected in series, therefore any one subsystem fails, it will result in system failure.

Prior to the FMEDA of ZPW-2000A track circuit system, the structure of the various subsystems of the system need to be divided, and as the basis of the established FMEDA table. Considering the structured hierarchical relationships of ZPW-2000A track circuit system, then the system is modeled. In order to simplify the system and make the system can be approximately expressed, in the process of modeling, ignoring the secondary factors, such as the rail, and so on, as shown in Fig. 2. Transmitter for N+1 redundancy, Receiver for the dual parallel hot standby, Mechanical Insulation Joint is composed by Mechanical Insulation Joint Hollow Coil and Tuner Unit.

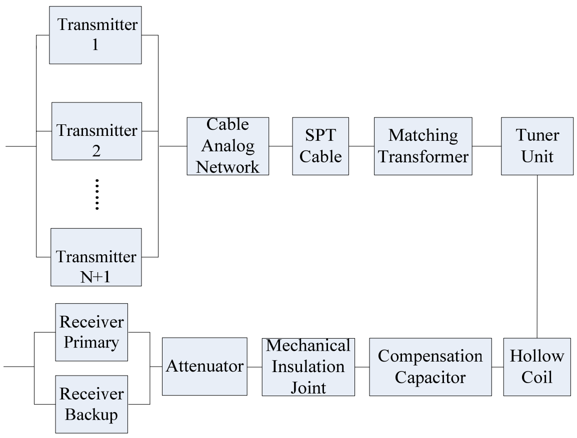

Fig. 2. RBD of ZPW-2000A track circuit.

3.2. FMEDA of System

Through the analysis of the breakdown maintenance data of railway operation unit and the data of the equipment manufacturers, the FMEDA table of ZPW-2000A track circuit system was established, as shown in Table 1.

Table 1. The FMEDA of ZPW-2000A track circuit system.

Name	Failure mode	Failure effects	λ	Detectability	Diagnostic capability	λ_{SD}	λ_{SU}	λ_{DD}	λ_{DU}
Transmitter	Frequency-shift signal cannot be generated	Go to the backup machine	2.003	1	Transmitter's indicator lamp is red, centralized monitoring alarm	2.003	0	0	0
	Frequency-shift signal is downgraded	Degraded running, fail-safe	0.501	1	Centralized monitoring alarm	0.501	0	0	0
	Frequency-shift signal is upgraded	It may cause train working failure	0.501	1	Centralized monitoring alarm	0	0	0.501	0
	Power of frequency-shift signal is too low	Frequency-shift signal can not be sent, console display for the red band	1.502	1	Centralized monitoring alarm	1.502	0	0	0
	Power of frequency-shift signal is slightly lower	No effect	2.003	1	Centralized monitoring alarm	2.003	0	0	0
Matching Transformer	Matching and connection can not be achieved	Information can not be transmitted	1.801	1	Console display for the red band	1.801	0	0	0

Table 1. The FMEDA of ZPW-2000A track circuit system (Cont).

Name	Failure mode	Failure effects	λ	Detectability	Diagnostic capability	λ_{SD}	λ_{SU}	λ_{DD}	λ_{DU}
Receiver	Main track's frequency-shift signal cannot be normally received	Go to the backup machine	1.354	1	Receiver's indicator lamp is red centralized monitoring alarm	1.354	0	0	0
	Main rail's upgraded frequency-shift signal is incorrectly demodulated	Affect train's safety	0.338	1	Receiver's indicator lamp is red, centralized monitoring alarm	0	0	0.338	0
	Main rail's downgraded frequency-shift signal is incorrectly demodulated	No effect	1.354	1	Receiver's indicator lamp is red, centralized monitoring alarm	1.354	0	0	0
	Small track's frequency-shift signal cannot be normally received	No effect	1.354	1	Receiver's indicator lamp is red, centralized monitoring alarm	1.354	0	0	0
	Small track's frequency-shift signal is incorrectly demodulated	No effect	1.354	1	Receiver's indicator lamp is red, centralized monitoring alarm	1.354	0	0	0
	Failed to move the track relay	Relay is in the down state, The fault section shown in red band	0.338	1	Receiver's indicator lamp is red, centralized monitoring alarm	0.338	0	0	0
	Error action of track relay	Relay's error action, it may affect train's safety	0.338	1	Receiver's indicator lamp is red, centralized monitoring alarm	0	0	0.338	0
Compensation Capacitor	Compensation effect disappeared, rail is inductive	The transmission performance of signal becomes poor	1.800	1	Track vacancy, console display for the red band	1.800	0	0	0
SPT Cable	Connection and signal transmission are failure	Equipment's work is interrupted	0.247	1	Console display for the red band centralized monitoring alarm	0.247	0	0	0

Table 1. The FMEDA of ZPW-2000A track circuit system (Cont).

Name	Failure mode	Failure effects	λ	Detectability	Diagnostic capability	λ_{SD}	λ_{SU}	λ_{DD}	λ_{DU}
Cable Analog Network	Cannot compensate for cable	Equipment's work is interrupted	0.484	1	Console display for the red band	0.484	0	0	0
Mechanical Insulation Joint Hollow Coil	Transmission parameters and transmission length are different	The working state of equipment is not stable	0.031	0	——	0	0	0	0.031
Tuner Unit	Electrical insulation is failure	Voltage of transmitting end track surface and indoor reception decrease	1.801	1	Voltage measurement	1.801	0	0	0
Hollow Coil	Balance traction return current is failure	Failed to balance traction return current	0.010	0	——	0	0.010	0	0
	Failure to maintain tuning region impedance function	Impedance of tuning region is unstable	0.010	0	——	0	0.010	0	0
	Choke is failure	Current is too large, burning equipment	0.010	0	——	0	0	0	0.010
Attenuator	The level adjustment of receiving end is invalid	Equipment's work is interrupted	0.175	1	Track vacancy, console display for the red band	0.175	0	0	0
	Failed to give each testing condition	Affect the detection work	0.262	0	——	0	0.262	0	0
	Track occupancy status is failure	Unable to determine the state of track	0.262	0	——	0	0	0	0.262
	Host failure, unable to turn the backup machine timely	Equipment's work is interrupted	0.175	1	Track vacancy, console display for the red band	0.175	0	0	0

The detectability column: number "1" represents the failure mode can be detected, "0" represents the failure mode can not be detected; λ represents failure rate; λ_{SD} represents that the security failure rate can be detected; λ_{SU} represents that the security failure rate can not be detected; λ_{DD} represents that the dangerous failure rate can be detected; λ_{DU} represents that the dangerous failure rate can not be detected; The diagnostic capability column: "——" represents no diagnostic capabilities; λ, λ_{SD}, λ_{SU}, λ_{DD} and λ_{DU} have the same unit:10^{-6}/h.

4. FTA Method

The FTA method was first proposed in 1961 by H. A. Watson and D. F. Hansl who were working at U.S. Bell Labs. At present, the FTA method is recognized as an equally important method for the analysis on reliability and security of complex system, and it had been widely used in many important fields[8].

4.1. System Fault Tree

Fault Tree makes result events, basic events and intermediate events linked mainly through two logic gates "OR door" and "AND door". "OR door" for the series system, indicating that output event occurs when there is at least one input event occurs. "AND door" for the parallel system, indicating that output events must occur when all input events occur.

On the basis of FMEDA table, FTA was used to analyze the ZPW-2000A track circuit system, the fault tree of ZPW-2000A track circuit system which can be shown in Fig. 3 to Fig. 5.

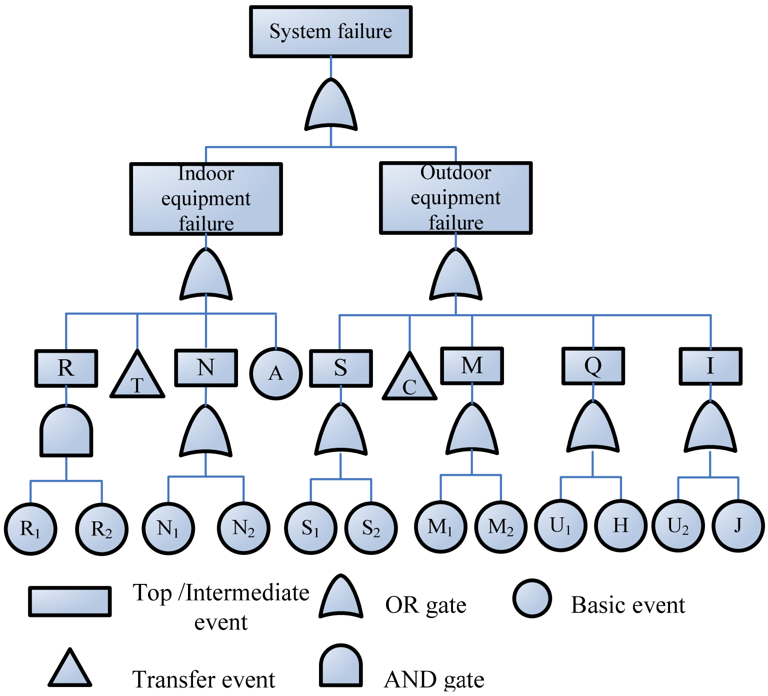

Fig. 3. ZPW-2000A track circuit system fault tree.

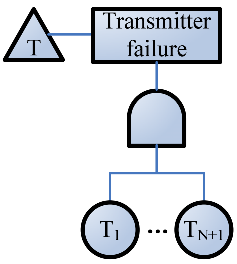

Fig. 4. Transmitter fault tree.

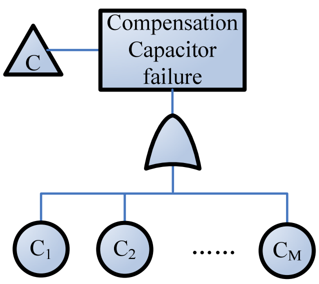

Fig. 5. Compensation Capacitor fault tree.

The fault tree of ZPW-2000A Jointless Audio Frequency-shift Modulated Track Circuit System includes two parts such as the indoor equipments and the outdoor equipments failure. The indoor equipments failure is constituted by Receiver failure $R(R_1,R_2)$, Transmitter failure $T(T_1{\sim}T_N)$, Cable Analog Network failure $N(N_1,N_2)$ and Attenuator failure A. The outdoor equipments failure is constituted by SPT cable failure $S(S_1,S_2)$, Compensation Capacitor failure $C(C_1{\sim}C_M)$, Matching Transformer failure $M(M_1,M_2)$, Tuning region failure $Q(U_1,H)$, Mechanical Insulated Joint failure $I(U_2,J)$, U_1 and U_2 represent the Tuner Unit, J represents the Mechanical Insulation Joint Hollow Coil, H represents the Hollow Coil.

4.2. FTA of System

The FTA method is used to study the system failure reasons, and establish a logical relationship between these reasons which expressed by fault tree. After the Fault Tree of ZPW-2000A Jointless Audio Frequency-shift Modulated Track Circuit System is established, the qualitative and quantitative analyses of system will be conducted.

1) Qualitative Analysis.

We used the minimal cut set method for qualitative analysis of fault tree, the weak links of the system can be judged according to the minimal cut sets obtained[11]. Descending method is used to solve the minimal cut sets of the fault tree of ZPW-2000A Jointless Audio Frequency-shift Modulated Track Circuit System.

According to the fault tree, the minimal cut sets of ZPW-2000A Jointless Audio Frequency-shift Modulated Track Circuit System includes: $\{R_1,R_2\}$, $\{T_1,\ldots,T_N\}$, $\{N_1\}$, $\{N_2\}$, $\{A\}$, $\{S_1\}$, $\{S_2\}$, $\{M_1\}$, $\{M_2\}$, $\{U_1\}$, $\{U_2\}$, $\{H\}$, $\{J\}$, $\{C_1\}$, $\{C_2\}$, …, $\{C_M\}$.

From the results of minimal cut sets can be seen, Matching Transformer, Compensation Capacitor and Tuner Unit of the outdoor equipment have a relatively large impact on the failure of system. So it is necessary to apply higher reliability and higher security outdoor equipment for ZPW-2000A Jointless Audio Frequency-shift Modulated Track Circuit System, and as far as possible to reduce the number of basic events in the system design process that can reduce the number of minimal cut sets.

2) Quantitative Analysis.

The minimal cut sets are obtained through qualitative analysis, the failure rate of the minimal cut sets can be got according to Table 1. In order to simplify the calculation, we assume that the transmitter N+1 redundancy N=1, the length of segment is 600 meters, the number of required compensation capacitor M is 7[13]. The failure probability of the top event P_{top} can be obtained through (1).

$$P_{top} = P(x_1 \cap x_2 \cap \ldots \cap x_n), \quad (1)$$

where x_i is the minimum cut set, n is the number of minimal cut sets. According to the failure rate of the minimal cut sets, $P_{\text{top}}=22.2002\times10^{-6}$.

The E_i^{FV} (Fussell-Vesely importance, FV) of each minimal cut sets can be obtained through (2).

$$E_i^{FV} = \frac{P(x_i)}{P_{top}}, \quad (2)$$

The FV of the minimal cut sets as shown in Table 2.

ZPW-2000A track circuit system reliability degree R_S: $R_S = 1 - P_{top} = 99.9978\ \%$.

The mean time between failure (MTBF) of system: $MTBF = \int_0^{\infty} R_S(t)dt = 4.5\times10^4\ \text{h}$.

According to the assumed conditions and Table 1, the risk ratio δ of ZPW-2000A track circuit system: $\delta = \sum \lambda_D \big/ \sum \lambda = 0.0552667$.

Table 2. The FV of each cut sets.

Name	FV	Name	FV
R_1,R_2	1.862E-06	U_2	0.0811252
T_1,T_2	1.909E-06	H	0.0013784
N_1	0.0218016	J	0.0013784
N_2	0.0218016	C_1	0.0810802
A	0.0393239	C_2	0.0810802
S_1	0.011126	C_3	0.0810802
S_2	0.011126	C_4	0.0810802
M_1	0.0811254	C_5	0.0810802
M_2	0.0811254	C_6	0.0810802
U_1	1.862E-06	C_7	0.0811252

Similarly, ZPW-2000A track circuit system security degree S_S: $S_S = 1 - \delta[1 - R_S] = 99.9999\ \%$.

The dynamic reliability degree and security degree of ZPW-2000A track circuit system as shown in Fig. 6.

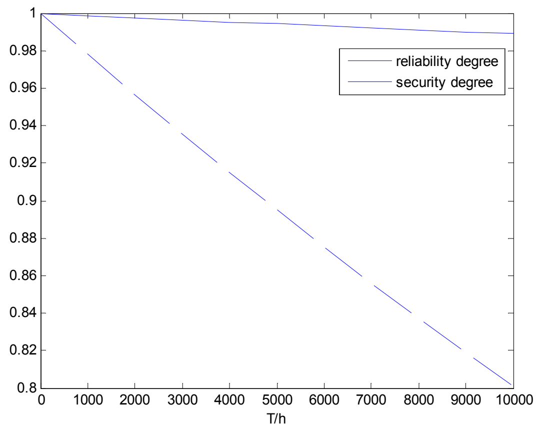

Fig. 6. The dynamic reliability degree and security degree of ZPW-2000A track circuit system.

Calculation results of MTBF, reliability indicators and security indicators of the system conformed to the technical conditions of ZPW-2000A track circuit[14].

5. Conclusions

The proposed method in this paper is based on FMEDA and FTA, to analyze the reliability and security of ZPW-2000A track circuit system. The system was analyzed and defined, reliability block diagram of system was established, each subsystem is analyzed one by one, and the FMEDA table was completed. On this basis, the system fault tree was built, the minimal cut sets of the fault tree were got, and the qualitative and quantitative analyses of the fault tree were conducted. The weak links of the system were located by qualitative analysis, the fail probability of roof events, important degree of each minimal cut sets and the indicators of reliability and security were gained through the quantitative analysis, the validity of the proposed method was verified by comparison with the relevant technical requirements.

Acknowledgements

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