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Modeling and Analysis of Incorrect Actions of Relay Protection Systems Based on Fault Trees

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ABSTRACT The safety of the power grid is threatened by incorrect action (IA) of relay protection system (RPS) resulting from defects, and even worsen a blackout. Currently, a large amount of data about IAs and defects in RPS are accumulated in operation. However, the relationship between the IAs and device defects is unclear. Recognizing the above problems, based on the 10-year field data, this paper proposes fault tree analysis for the IAs of RPS to discover relationship between the IAs and device defects. In detail, based on analysis of the field data, the defect sets which is related to IAs are built, after that, the method to construction of two fault trees for the incorrect actions, which taking the incorrect actions as the top event, and the defect locations and component factors as the bottom level respectively, is proposed. Furthermore, combined with the 10-year filed data, the different fault trees are established and presented, and the related analysis for different responsible entities is discussed, which show the feasibility and effectiveness of proposed method.

INDEX TERMS Fault tree, incorrect actions (IAs), relay protection system (RPS), relay protection device (RPD), relay protection defect.

NOMENCLATURE

incorrect actions (IAs), relay protection system (RPS), relay protection device (RPD), State Grid Corporation of China (SGCC), Energy Management System (EMS).

I. INTRODUCTION

Relay protection is the first line of defense to ensure the safety of the power grid, and its rapid and correct action can effectively prevent the deterioration of the power system and ensure the stable operation [1]. On the contrary, the incorrect actions of the relay protection system may seriously affect the operation of the power grid, and lead to more power outages and even blackout [2].

In general, the incorrect actions of relay protection system contains two consequence, i.e., the mis-operation and the rejections. The above two incorrect actions are mostly caused by relay protection defects, except for human factors [3]. Thus, understanding the relationship between the defects of RPS and IAs has become a concern of electrical power system, which is a prerequisite for improving the reliability of the RPS.

On the other hand, with the construction of smart grids and the widespread deployment of relay protection management systems, the relay protection management department in power system has accumulated a large amount of data on defects and incorrect actions of relay protection devices [4]. Based on the above defect data, a lot of research on the reliability analysis to the RPS or RPD failure and defect have been done [5]. Among which, the refs [6], [7] proposes the failure probability estimation and the refs [8]–[10] proposes optimal maintenance or replacement cycle, etc.

At the same time, with the philosophy of "from the results to the cause" [11], the fault tree analysis has been applied to analyze the failure models in power system. For example, refs [13]–[15] apply the fault tree method to the reliability analysis of the equipment in electric power system and their fault factors, the results show that the fault tree analysis

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is effective in power system. References [16], [17] apply the fault tree to failure analysis of digital substation, and it also provides optimization algorithm which could reduce the size of the fault tree clarity the factors spread relationship. References [18], [19] developed risk prevention for the on-site and system operation, with maintenance-oriented reliability model proposed by ref [20], which has good guiding significance for practical operation. References [21], [22] launched quantitative evaluation index construction for the reliability which optimized the quantitative analysis of fault tree. All above work extended the application of fault tree.

It is worth noting that most of the existing research are focused on the specific establishment of a certain type of equipment or system failure, and few of them considered the phenomenon of IAs. Furthermore, there is still a lack of systematically summarization for the relationship between defects and IAs with the field data, from the device level.

Recognizing the above problems, based on the 10-year incorrect actions data of the State Grid and the fault tree method, this paper proposes a method to construct the fault tree model for the RPS to discover relationship between the IAs and device defects. The defects set that causes incorrect actions is construct firstly, and then, two fault trees for the incorrect actions, which taking the incorrect actions as the top event, and the defect location and component factors as the bottom level respectively, is proposed. Furthermore, with the filed data, the proposed fault trees and the relationship with the different responsible entities is discussed.

The contribution of the paper are as follows.

(1) The fault tree model analysis method is proposed to analyze the relationship between the device defects and IAs. The proposed method can summarize the probability of device defects occurring under different influencing factors, analyze the responsible department for incorrect actions, and provide relevant suggestions in operation and maintenance management.

(2) The fault tree of IAs with the failed components of the relay protection system is established. It could express the structure of relationship between IAs and the defective parts.

(3) The fault tree of IAs with component factors of the relay protection system is established. It could refine the causes of various defective devices, and be applied to analyze the impact of production, operation and maintenance work of the different entities on incorrect actions.

The remainders of the paper are as follows. Section II analyzes characteristics of the field incorrect action data and explains the causes of the data, and then gives out the defect sets., Section III proposes the construction of two fault trees for the incorrect actions, which taking the incorrect actions as the top event, and the defect locations and component factors as the bottom level respectively. Section IV takes the incorrect actions in the SGCC from 2007 to 2016 as an example, and constructs the two IAs fault trees and presents the related analysis. Finally, section V gives out the conclusions and remarks.

II. FIELD DATA ANALYSIS AND DEFECTS SET CONSTRUCTION

This section analyzes characteristics of the field incorrect action data and explains the causes of the data, and then gives out the defects set.

A. CHARACTERISTICS OF FIELD INCORRECT ACTION DATA

The data of IAs of RPDs in 220kV and above AC system of SGCC from 2007 to 2016 is used by this paper. It contains 135 incorrect actions, including 122 misoperation cases and 13 rejection cases. Misoperation refers to that the relay protection devices give out wrong signal and act while it is not needed. Rejection means that the relay protection devices fail to act while it should be acted due to damage in device, or other cause.

First, based on the data, the statistical result of the cause of IAs can be obtained, as shown in Figure 1.

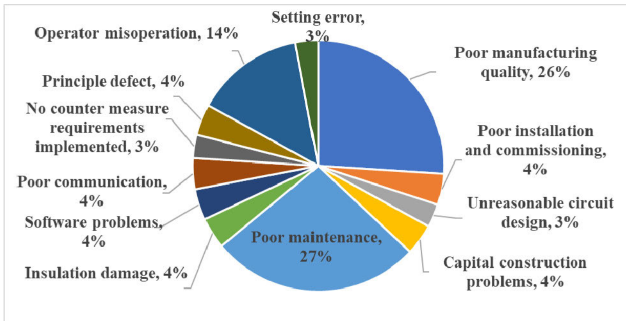

FIGURE 1. Statistical result of the cause of incorrect actions.

The Figure 1 shows that, the defective devices that can result in incorrect actions are as follows: the distributed in the protection device body, the secondary circuit, the fault recorder, the merge unit, the communication channel, the DC circuit and intelligent terminal and other aspects. However, the number of misoperation events (122 times) caused by defects is significantly larger than the number of rejection events (13 times).

The factors that lead to the above phenomena are as follows:

(1) When a device failure occurs within the protection scope of a RPD, at the same time, the RPD refuses to operate due to defects which are less likely to occur, such as device crash, component damage, wiring error and communication channel damage. The above two causes constitute the AND logic, thus the probability of rejection is small.

(2) When a failure occurs outside the protection scope of a RPD, it may cause a RPD to malfunction. And at the same time, the same fault generated by the system may cause multiple relay protection devices to malfunction. Therefore, the probability of misoperation is higher than that of rejection.

(3) As the rejection event may result in a more severe impact on the primary equipment, in operation, the staff may pay more attention to the rejection, thus, the corresponding anti- rejection measures are applied and lead to the probability of rejection is far less than the misoperation.

(4) The relay protection device has basically realized a dual configuration for 220kV or above power system, which further reduces the occurrence of missing functions of the devices, which is also one of the main reasons for less number of rejections.

B. CONSTRUCTION OF THE DEFECTS SET OF IAS

Based on the statistical analysis of the characteristics of IA data, this subsection analyzes the causes of IA from the device level and build the defects set.

The defects of relay protection devices from different manufacturers have different characteristics. This paper divides the devices into three categories according to the constitution of relay protection system when constructing the defects set, and pays attention to the defects that may result in incorrect actions. The principle and practical experience of RPS show that its defect analysis should cover many links such as the RPD, the secondary circuit and the related communication channel devices, etc. Furthermore, the statistical analysis of the historical actions information of the relay protection system, shows that the defects can result in IAs are mainly reflected in the following three aspects.

1) DEFECTS OF THE RPD

The main defects of RPD can be divided into two categories, one is the hardware defects and the other is software defects. The main causes of hardware defects are damage of the internal plug-in of the device, aging of equipment and components, etc., which may result the CPU to automatically shut down and even force the protection to quit operation. The causes of software defects mainly include software logic errors, program design defects, and protection setting errors. The statistical analysis of device failures and action information shows that the defects of RPD may mainly result in misoperation and device lock-up.

With the 10-year field data, the defects set of the relay protection device can be obtained, as shown in Table 1.

TABLE 1. The defects set about IAs caused by the rpd itselves.

Defective Part	Defect reason	TC	SC
A / D plugin	Poor manufacturing quality	M/R	M
CPU plugin	Principle defect Poor manufacturing quality	M/R	M/R
Abnormal CT sampling board	Poor maintenance	M/R	M
Acquisition board	Poor manufacturing quality	M/R	M
Sampling board	Null	M/R	M
Operation box	Poor maintenance	M/R	M
Other plug-in	Poor manufacturing quality	M/R	M
Knife gate auxiliary contact and circuit	Failure to implement countermeasures	M/R	M
Power plug	Poor manufacturing quality	M/R	M
Terminal block	Accidental touch	M/R	M
Input and output plug-ins	Principle defect Software principles	M/R	M
Switch	Poor operation and maintenance	M/R	M
	Poor maintenance		M
Software	Software problem	M/R	M
Data cable	Poor installation and debugging	M/R	M
Main module	Poor manufacturing quality	M/R	M
Device terminal	Poor maintenance	M/R	M

(M- MISOPERATION,R-REJECTION, TC- THEORETICAL CONSEQUENCES,SC- STATISTICAL CONSEQUENCE)

2) DEFECTS IN THE SECONDARY CIRCUIT

The secondary circuit is an important part of the relay protection of the power system, its defects is an important factor affecting the normal operation of the protection system. Among them, the AC circuit is responsible for collecting and reflecting the operating current and voltage of the primary equipment; the DC circuit is responsible for the power supply of the DC power supply of the protection device and the control operation of the protection system, so when the secondary circuit has a wiring error, insulation damage or poor contact, it may cause the protection system misoperation or rejection.

With the 10-year field data, the defects set of the secondary circuit can be obtained, as shown in Table 2.

TABLE 2. The defects set about IAs caused by secondary circuit.

Defective Part	Defect reason	TC	SC
CT secondary circuit	Accidental touch	M/R	M
Cable	Poor operation and maintenance	M/R	M
	Poor maintenance		M
Terminal block	Poor manufacturing quality	M/R	M
AC current, voltage circuit	Damaged insulation	M/R	M
AC current loop	Poor maintenance Miswiring	M/R	M M
AC voltage circuit	Failure to implement countermeasures	M/R	M
AC circuit	Unreasonable circuit wiring	M/R	M
Switch	Poor maintenance	M/R	M

(M- MISOPERATION,R-REJECTION, TC- THEORETICAL CONSEQUENCES,SC- STATISTICAL CONSEQUENCE)

3) DEFECTS IN THE COMMUNICATION SYSTEM

Communication systems for the protection are mainly divided into protection communication channels and information systems. In the microcomputer protection, the defects of the protection communication channel are mainly manifested as the failure of the communication devices and the damage of the cable. The information system is mainly used to record the voltage and current changes of the device. If the information upload or recording fails, the data information of the protection devices will be lost, affecting the correctness of the

TABLE 3. The defects set about IAs caused by communication system.

DDC	Defective Part	Defect reason	TC	SC
Fault recorder	Null	Poor manufacturing quality	M/R	M
Merge unit	CPU plugin	Poor manufacturing quality	M/R	M
	Abnormal CT sampling board	Poor manufacturing quality		M
	Communication interface plug-in	Communication reasons		M
	Null	Principle defect		M
	Carrier channel	Communication reasons		M/R
Channel transmission equipment	Carrier	Communication reasons	M/R	R
Channel processing equipment	Cable	Poor maintenance		M
Channel interface device	Null	Miswiring		M
DC circuit	Cable	Poor operation and maintenance	M/R	M
	Null	Poor manufacturing quality		M
	Null	Accidental touch		M
Intelligent Terminal	CPU plugin	Poor manufacturing quality	M/R	M
	Relay protection channel	Misadjusted		M
	Communication Carrier channel	Poor manufacturing quality		R

(DDC-Defective device category, M- misoperation, R-rejection, TC- Theoretical Consequences, SC- Statistical Consequence)

protection action and the judgment of the current state. With the 10-year field data, the defects set of the communication system can be obtained, as shown in Table 3.

Table 1 to Table 3 categorize and summarize the device defects set that result in the IAs of RPD, and present the information of the IAs that has occurred so far in combination with the field data.

III. CONSTRUCTION OF FAULT TREES OF INCORRECT ACTION OF RPS

In this section, based on the field incorrect action data and related defect sets, the relationship between the device defects and IAs could be analyzed by the fault tree model method. The construction of two fault trees for the incorrect actions, which taking the incorrect actions as the top event, and the defect location and component factors as the bottom respectively, is proposed. And the possible application of the two fault trees are discussed.

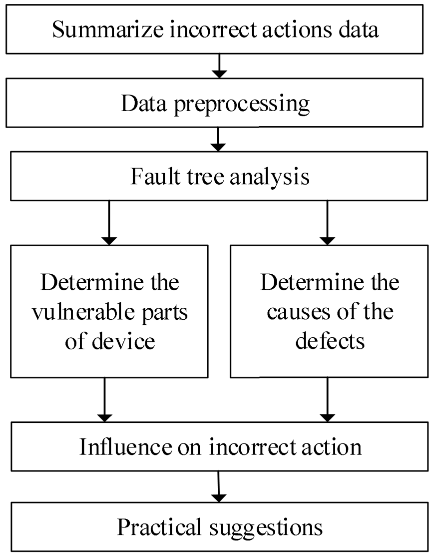

FIGURE 2. Flow chart of detecting the relationships between the IAs and device defects.

The relationship between the device defects and IAs reflects through fault tree model. Generally speaking, the number of device defects is far greater than the number of incorrect actions, not all defects lead to the occurrence of incorrect actions. However, each incorrect action could be analyzed from the perspective of device defects, some of which are caused by the device itself and some by human factors. Based on this, firstly, the fault tree of IAs with the failed components of the relay protection system is established. It could express the structure of relationship between IAs and the defective parts. Secondly, the fault tree of IAs with component factors of the relay protection system is established. It could refine the causes of various defective devices, and be applied to analyze the impact of production, operation and maintenance work of the different entities on incorrect actions. Specifically, the processes of detecting the relationships between the IAs and device defects are as follows:

Step1: Summarize incorrect actions data from EMS (Energy Management System);

Step2: Delete the incomplete data and wrong data, and divide data into piles according to equipment category;

Step3: Qualitative analysis of incorrect actions: analyze the defective parts corresponding to failure devices;

Step4: Quantitative analysis of incorrect actions: analyze the probability of incorrect action caused by various defect factors;

Step5: Based on the analysis of defect parts and defect factors, practical suggestions are put forward to prevent incorrect actions, including the improvement of device manufacturing quality and operation and maintenance department operation guidance.

A. GENERAL FAULT TREE CONSTRUCTION

The fault tree is an analysis method that takes the system failure state as the top event and finds out all possible direct factors and causes of this failure. Generally, the controlled events in the transition state are gradually analyzed in depth until the basic cause of the accident, which called the bottom event of the fault tree, is found. These bottom event data are known with statistical or experimental results.

In general, construction of a fault tree analysis contains following processes. As shown in Figure 3. In detail,

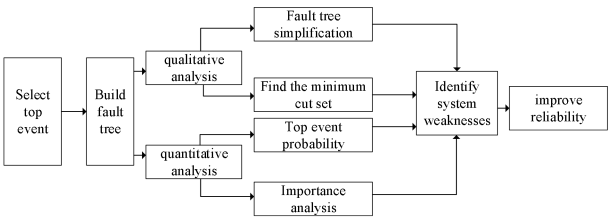

FIGURE 3. Fault tree analysis process.

1) Select a reasonable top event and determine the criteria for success and failure; 2) build a fault tree based on the technical data collected; 3) simplify or modularize the fault tree if necessary; 4) find the fault tree All minimum cut sets, that is, the non-repetitive sinks of intermediate events, are also called qualitative analysis; 5) Calculate the probability of top event occurrence, that is, quantitative analysis; 6) Determine the weak links of the system; 7) Take measures to improve system reliability and safety.

The qualitative analysis of the fault tree starts from whether the top event occurs and determines the combination of the bottom events that result in the event. The quantitative analysis mainly uses probability values to reflect the relative magnitude of each bottom event's impact on the top event.

B. FAULT TREE ANALYSIS MODEL FOR INCORRECT ACTION

With the above defect sets of the incorrect action of the relay protection devices, combined with the structure of the relay protection system, two fault trees can be established, taking the incorrect action as the top event.

One is the fault tree of IAs with the failed component of the relay protection system, this fault tree can express the system structure and show the defective parts. The other is fault tree of IAs with component factors, this fault tree could refine the causes of various defective devices, and be used to analyze the impact of production, operation and maintenance work of the different entities on incorrect actions.

In the process of building fault tree, this paper deals with the collected data as follows.

(1) Delete the incomplete and bad data.

(2) Relate the IAs to the defective devices. The device defects contained in the IAs information are searched from the device operation record.

(3) Divide the data to different sets according to the action behavior category, equipment category and defect cause.

The specific processes to construction the above two trees are shown in Figure 4.

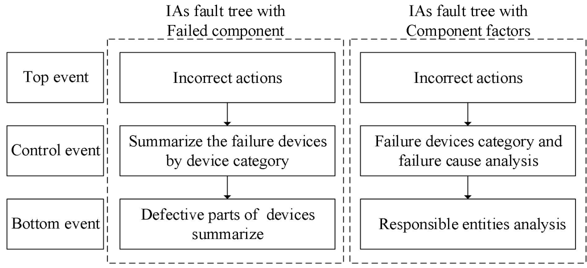

FIGURE 4. Flow chart of fault trees analysis model for incorrect actions.

Step1: Starting from the failure devices that cause the incorrect action of relay protection system;

Step2: Summarize the categories of failure devices according to the defect sets;

Step3: According to different device categories and structures, analyze the defective parts corresponding to failure devices;

Step4: Combined with the causes of defects in each part, summarize the specific factors that may cause failure of each part;

Step5: Based on the analysis of the defective location, the failure cause is introduced as the bottom event of the fault trees, the failure cause is corresponded to different failure devices, and then the responsible entities for the incorrect action of the relay protection are divided based on the failure cause.

Furthermore, combined with statistics of the collected field data, the quantitative fault trees analysis can be performed. That is, according to the system structure, using the statistics probability, the quantitative estimation of the occurrence probability of each background event can obtained, which is expressed by the proportion of fault factors (PF) and the occurrence probability of fault factors (OPF). The fault factors can be calculated as follows,

$$PF = \frac{F}{IA} \tag{1}$$

where F is the number of incorrect actions caused by a certain defect factor, IA is total number of incorrect actions. And the occurrence probability of fault factors (OPF) can be calculated as follows,

$$OPF = \frac{F}{AA} \tag{2}$$

where F is the number of incorrect actions caused by a certain defect factor, AA is total number of RPD actions, which include correct and incorrect actions.

IV. CASE STUDIES

Taking the incorrect actions in the SGCC from 2007 to 2016 as an example, the two IAs fault trees with the failed

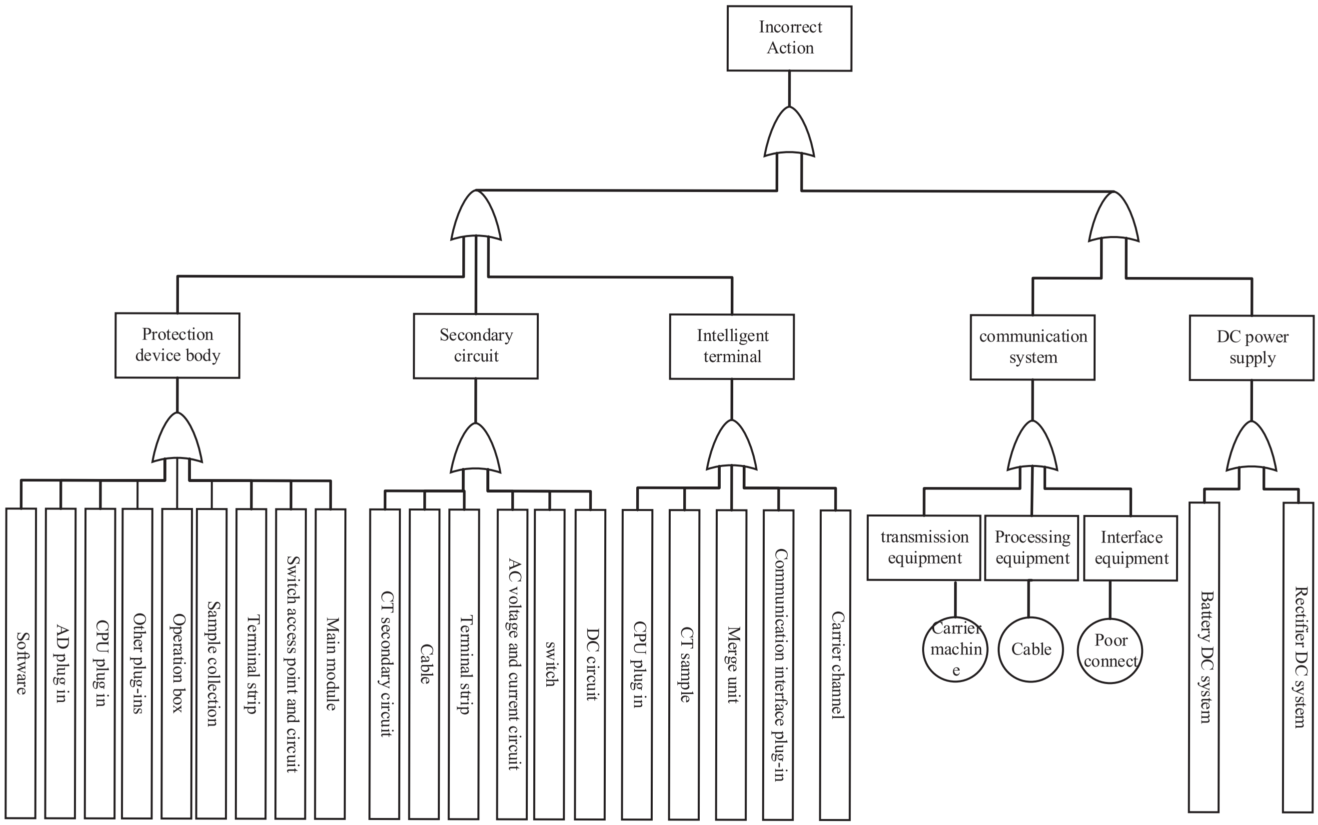

FIGURE 5. Fault tree of the failed component of the relay protection system.

component and component factors respective, are constructed and the related analysis is presented.

A. IAS FAULT TREE WITH FAILED COMPONENT

Based on the field data, the fault tree of IAs of the relay protection system due to failure components can be obtained, as shown in Figure 5.

Figure 5 shows that, in the control event layer, i.e. devices division, it includes five aspects: protection device body, secondary circuit, communication system, DC power supply and intelligent terminal. The merging unit is treated as the bottom event of the intelligent terminal. In the fault tree, DC power supply devices is divided separately to reflect its importance for relay protection system.

In the bottom event layer, i.e. defect location division, it takes the actual structure of each device as reference for division. In detail, the protection device body is divided into 9 parts from the perspective of hardware and software, the secondary circuit includes 6 parts such as AC and DC circuits, the communication system is divided into three types, i.e. interface, transmission and processing, meanwhile, the intelligent terminal includes 5 parts such as merging unit, and the DC power supply is divided into battery and rectifier power system.

Particularly, the CPU plug-in, as the core plug-in of data processing, is involved in the protection device body and intelligent terminal. It is the key factor to realize the function of the device. Therefore, the reliability of the CPU plug-in is one of the key issues to prevent incorrect actions.

B. IAS FAULT TREE WITH COMPONENT FACTORS

Furthermore, based on the statistical information of incorrect actions, the bottom events are aggregated and the probability of occurrence can be calculated, and the fault tree of the component factors can be obtained, as shown in Figure 6.

Figure. 6 shows that, there are many base event branches with the RPD and secondary circuit which are controlled events whose probability of each bottom event can be directly calculated from the original data. In addition, there are many branches in the communication system, but only the total failure proportion of the communication system can be obtained due to the small number of events. The intelligent terminal also can get the total failure proportion. However, the current data of DC power supply is not enough to get specific results.

The above data analysis and fault tree show that the relay protection device and the secondary circuit are the key factor related to the incorrect action of relay protection system.

C. ANALYSIS FOR DIFFERENT RESPONSIBLE ENTITIES

Furthermore, based on the cause of failure and above fault trees, the responsibility of different entities for the IAs of the RPS, can be compared. Taking the ratio of the IAs caused

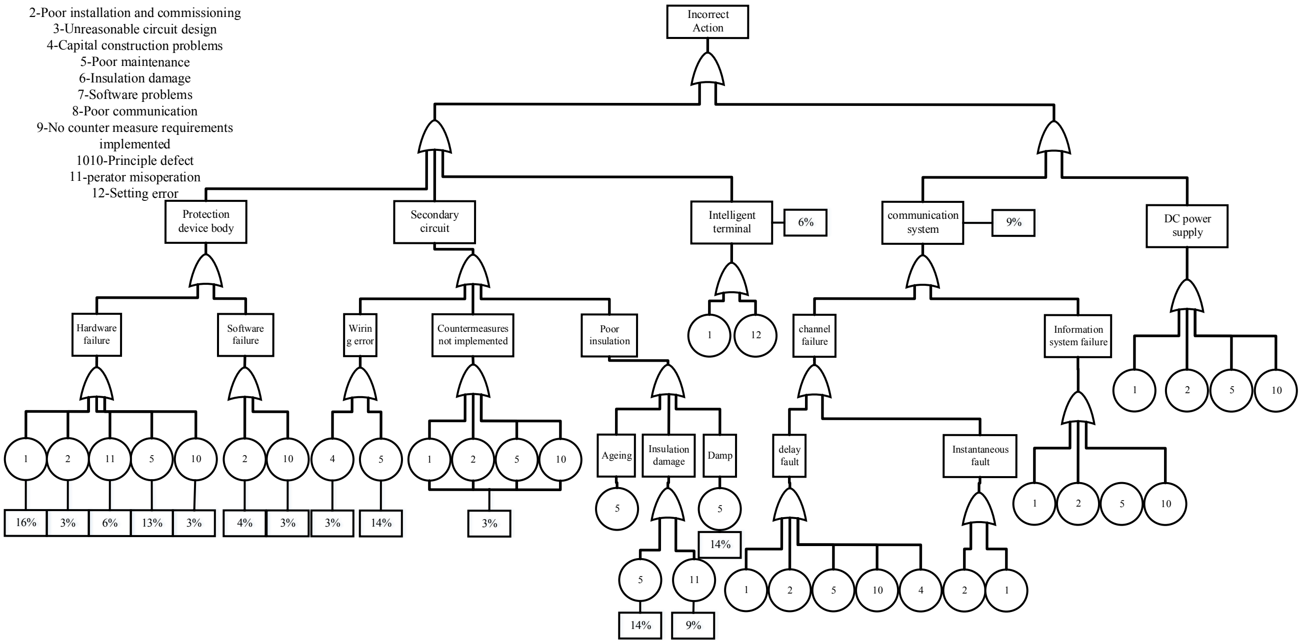

FIGURE 6. **Component factors fault tree of incorrect actions.**

TABLE 4. **Division of Responsibilities for IAs of RPS.**

Entities	Factors	Proportion (%)	Probability (×10-6)	Ratio (%)
ICC	Failure to implement countermeasures	0.8%	4.99	4.90%
	Insulation damage	1.4%	9.97	
	Infrastructure construction	2.6%	15	
PMC	Poor maintenance	26.9%	155	44.05%
	Personnel mis-operation	14.7%	84.8	
	Insulation damage	1.4%	9.97	
	Failure to implement countermeasures	0.8%	4.99	
RM	Unreasonable circuit design	2.6%	15	36.23%
	Insulation damage	1.4%	9.97	
	Poor manufacturing quality	20.0%	115	
	Software debugging issues	4.3%	24.9	
	Software principle defect	3.4%	19.9	
	Failure to implement countermeasures	0.8%	4.99	
	Poor installation	3.4%	19.9	

(ICC-Infrastructure Construction Company, PMC-Power Grid Maintenance Company, RM-Relay Manufacturer)

by the bottom event to the total IAs of RPS, the different probability of the bottom event, can be obtained, as shown in Table 4.

According to the ration of each entities in Table 4, the power grid maintenance companies and relay manufacturers are the main entities responsible for IAs, accounting for 44.05% and 36.23% respectively.

The ratios of failure according to different factors show that poor maintenance and manufacturing are the main factors of the PMC and RM, accounting for 26.9% and 20% respectively. Therefore, the power grid maintenance companies should further strengthen the standardized management to improve the operation quality, and the relay manufacturer should pay attention to improving the product quality. Among the other failure factors, the failure to implement countermeasures and insulation damage are involved in each entitie, and the ratio in each entity is the same. Thus, all entities should pay attention to such improvement.

Furthermore, the proportion and probability of each failure factor in Table 4 shows that, for the PMC, except for the poor operation and maintenance, the ratio and probability of personnel mis-operation are all at a high level, accounting for 14.7% and 84.8 × 10^(−6), respectively. Therefore, preventing the personnel mis-operation is also an effective way to improve the reliability of relay protection system.

For the relay manufacturers, in addition to poor manufacturing quality, software related detects, including principle design and debugging, has a high probability of problems, accounting for 7.7%, so improving software quality is conducive to ensuring reliability.

In addition, for the infrastructure construction companies, except for the counter measures not implemented and the insulation damage, the ratio of the infrastructure construction factors is relatively small, but the probability is relatively high. Therefore, improve the reliability in terms of construction safety and device protection during construction should be considered by the infrastructure construction companies.

V. DISCUSSION AND CONCLUSION

A. DISCUSSION

The field incorrect action data of PRDs includes 90.37% misoperation and 9.63% rejection, which are caused by the device defects. Meanwhile, the number of device defects is far greater than IAs. Thus, the device defects may not lead to the occurrence of incorrect actions, but the incorrect actions contain defects caused by the device itself or human factors.

In order to reduce the occurrence of incorrect actions, some practical suggestions are as follows:

(1) Improve the manufacturing quality of the vulnerable parts of the devices. The fault tree shows that, although the defect parts are divided into 25 categories, the incorrect actions caused by CPU and power plug-in accounts for 21%. In addition, the IAs caused by the defect of the cable accounts for 17.91%. Therefore, improve the quality of vulnerable devices may be an effective way to reduce IAS.

(2) Optimize the maintenance cycle and items to improve the maintenance level. From the field data, 44.05% of IAs are caused by power grid maintenance company. Among the various factors that cause IAs, the poor maintenance is the main factors which accounts for 26.9% and the ratio of personnel mis-operation is accounting for 14.7%. Thus, taking measures to avoid device defects caused by human factors, may be an effective way to reduce the IAs.

B. CONCLUSION

This paper proposed a method to construct the fault tree model for the RPS to discover relationship between the IAs and device defects.

The defects set that causes incorrect actions was construct firstly, and then, two fault trees for the incorrect actions, which taking the incorrect actions as the top event, and the defect location and component factors as the bottom level respectively, was proposed. Furthermore, with the filed data, the proposed fault trees and the relationship with the different responsible entities was discussed.

The proposed method could locate the fault location, and furthermore, based on the occurrence probability of related defects, provided reference for the improvement of the reliability of the relay protection device from two aspects, i.e., the equipment maintenance and the responsible entities implementation.

However, in this paper, the proposed fault trees model were static fault trees. The future work may be focused on the dynamic fault tree.

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