Verifying the Protection System Operation Using an Advanced Fault Analysis Tool Combined with the Event Tree Analysis

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***Abstract*—Relay misoperations play an important role in cascading events. This paper proposes a novel strategy to monitor and verify relay operations during disturbances. Neural network based fault detection (NNFD) algorithm and Synchronized sampling based fault location (SSFL) algorithm are combined as an advanced fault analysis tool to give the precise fault information. Event tree analysis (ETA) is used for comparing relay operations in the real system with expected relay actions. Corrective actions are introduced if relay operations are contributing to cascading events. A case study is given in this paper to help better understanding of the entire strategy.**

***Keywords*—event tree analysis, fault diagnosis, fault location, neural networks, power system faults, power system protection, protective relaying, synchronized sampling.**

I. Introduction

Major blackouts are rare but catastrophic events in power systems. The very recent northeast blackout on Aug 14, 2003, has affected 50 million people in eight states and two provinces of the United States and Canada.

The causes for blackouts are quite different and complex. One of the common conclusions based on the historical data is that 75 percent of the major disturbances in the United States involve relay operations directly or indirectly [1]. The hidden failures of protection relays, including the defective logic, incorrect settings and hardware failures, are contributing factors for initializing and propagating system instability even leading to large blackouts [2].

For conventional distance relays, settings are calculated based on short circuit studies. The relays take local measurements only and then make the decision about disconnecting the transmission line. When the system is closer to its transmission limits, the relays can easily misoperate because the settings may be improper. When a disturbance on the transmission line occurs, the system operator seldom gets the detailed information about the disturbance in a short time. Sometimes the operator will make a false decision because of the little information obtained. That may result in a loss of load, loss of stability or initiation of a blackout in the system.

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For those reasons, more stringent requirements are imposed on the protection systems. First of all, the selectivity of protective relay needs to be improved. The ideas of adaptive and wide-area protection are heading in this direction. Secondly, an automatic fault analysis tool is required to precisely analyze the fault in real-time, monitor and verify the protection system operation, and generate a disturbance report for the system operator instantly.

An expert system based fault analysis tool is developed in [3]. This tool is based on simple cases and crude assumptions about fault detection and fault location. Another strategy of wide-area backup protection expert system is proposed in [4]. This strategy is trying to locate the fault precisely and avoid unnecessary trips of backup protection. A detailed field performance of this method is not published yet.

This paper proposes a novel strategy for automatically implementing precise fault analysis as well as monitoring and verifying relay operations during fault contingencies. Neural network based fault detection (NNFD) algorithm and synchronized sampling based fault location (SSFL) algorithm are combined as an advanced fault analysis tool to give more reliable and accurate fault information than the traditional methods. Event tree analysis (ETA) is an efficient way for implementing contingency/response analysis and it is used in this paper for comparing relay operations in the real system with expected actions. Corrective actions are introduced if the relay operations are not as expected. By using the idea proposed in this paper, the protection system operation may significantly be improved. The occurrence of cascading events may be mitigated by this improvement.

The paper first introduces, in Section II, the ways of using the NNFD and SSFL techniques in a combined fashion to accomplish a new way of fault diagnosis. The event tree analysis and its relation to the proposed strategy are introduced in Section III. Section IV presents the entire strategy for monitoring and verifying distance relay operations. A case study for this strategy is given in Section V. At the end, conclusions and references are given.

II. Advanced Fault analysis tool

Conventional protective relaying and off-line fault analysis have their inherent shortcomings. When designing algorithms and selecting settings, the relay designer and user respectively must make trade-offs between accuracy and speed as well as dependability and security. If not done properly, this may results in less accurate decisions causing relay misoperation in certain occasions. In order to monitor and verify relay operations and perform more accurate fault analysis, we need some new techniques that have much better performances than the conventional relays.

A new technique developed for fault detection and classification is based on a specific Neural Network (NN) capable of providing the decision about the fault existence and fault type as discrete outputs [5]. By using this NN solution, the performance of the function is improved while the implementation is indeed straightforward. Most interestingly, this technique does not use the traditional settings and hence is not vulnerable to the inaccuracies in the settings.

The new fault location approach uses synchronized samples from two ends of the transmission line [6]. By doing so, the technique becomes transparent to many phenomena that make the traditional techniques to lose accuracy. This technique as well does not have any settings so it does not dependent on any inaccuracies associated with settings.

A. Neural Network Based Fault Detection and Classification

Neural network is an intelligent method to deal with nonlinear problems, especially in pattern recognition. Instead of comparing the computed impedance or phasor with thresholds (settings), which is the typical algorithm in most of the relays, the fault detection algorithm based on neural network is recognizing system's behavior by identifying natural groupings of data from large measurement sets. In this method, the sampled current and voltage measurements of the three phases of a transmission line are considered as patterns. The aim of the procedure is to allocate those patterns into groups called clusters such that each pattern is assigned to a unique cluster. Then the clusters are assigned to some classes, which are our expected fault events in power system, such as AB phase fault in zone 1, etc. The neural network algorithm is trained and tested off-line. After we get a well trained network that has a low and stable error, the neural network can be used online to detect faults.

The neural network based protection takes voltage and current measurements from one end of the line. This approach will have to reliably conclude, in a very short time, whether and which type of the fault occurs under a variety of time-varying operating conditions. The new relay algorithm does not have traditional settings, and hence will not be susceptible to the wrong or improper settings being present. Detailed explanation and implementation of the neural network based fault detection and classification algorithm can be found in [5], [7].

B. Synchronized Sampling Based Fault Location

Fault location techniques are used to accurately determine location of the fault on a transmission line. They are very important because the fault location can confirm whether a fault has indeed occurred on the line. If done in real-time, it can also serve as a verification tool for the fault detection algorithm in relays. When the fault is precisely located, one should know which breakers are responsible to clear that fault, and unnecessary trips should be avoided. Both the dependability and security of protection system operation will be improved by incorporating a precise real-time fault location function. Once the faulted spot is located accurately, repair crews can save the time of repairing and restoring the line.

Synchronized sampling based fault location algorithm uses raw samples of voltage and current data synchronously taken from the ends of the transmission line. This can be achieved using Global Positioning Satellite (GPS) receivers, which generate the time reference for data acquisition equipment. Such algorithm requires less than a cycle of the voltage and current data and can be used for real-time monitoring, control and protection applications [8].

Two versions of the time-domain algorithm were developed to handle the short transmission and long transmission line. Detailed derivation and testing of the algorithm can be found in [6], [8] and [9].

The main advantage of synchronized sampling based fault location algorithm is its rather simple implementation that only requires the line model and the samples at the two ends of a transmission line. The algorithm does not depend on any assumptions about system operating conditions, fault resistance, fault waveforms, etc. For this algorithm, model characteristics and operating conditions in the rest of the system are irrelevant.

A lot of scenarios are generated to evaluate the algorithm, and the results show that it is very accurate and robust [10].

C. Combination of Two Techniques as an Advanced Fault Analysis Tool

The neural network based fault detection and classification (NNFD) algorithm can be combined with synchronized sampling based fault location (SSFL) algorithm to form a powerful fault analysis tool. While the NNFD is working on-line to detect the fault, the SSFL can calculate the fault location right after the fault occurrence to confirm if the fault indeed exists. Both of the algorithms require samples of three phase voltage and current time domain signals. The implementation to combine those two algorithms is simple. A recent study shows that, when fault type is known, the accuracy of SSFL can be improved as well [10]. Since the NNFD will give the information on the fault type, the SSFL algorithm can utilize the classification result of the NNFD to improve its accuracy. The combination of the two algorithms is expected to perform a more accurate fault analysis than conventional relays. This may provides the reference to monitor and verify the distance relay operations.

III. Event Tree Analysis

The aim of the new strategy is to monitor the relay operation and provide event – response based reference indicating if the relay operation is going wrong. Here we utilize the event tree analysis (ETA), which is a commonly used technique for identifying the consequences that can result following an occurrence of the initial event [11]. It was first applied in the risk assessments for the nuclear industry but is now utilized by a lot of other industries such as chemical processing, gas production and transportation.

The Event Tree Analysis takes the structure of a forward (bottom-up) symbolic logic modeling technique. This technique explores system responses to an initial "challenge" and enables assessment of the probability of an unfavorable or favorable outcome [12].

Fig. 1 shows a very simple event tree for a gas leak protection system. The initiating event is the gas leak from an offshore platform. The branches then consider the success (S) and failure (F) of the gas protection system. The outcome determined by the end-point of each event tree branch identifies a different consequence following the initiating event. The probability of each outcome can be evaluated if we know the likelihood of each node passing along the branches.

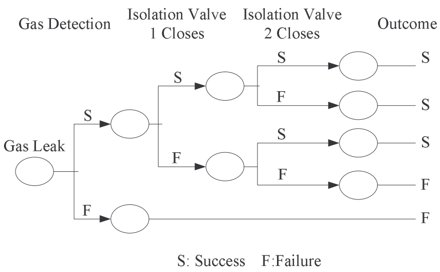

Fig. 1. A sample event tree for gas leak

There are not very many applications for the event tree analysis in the power systems so far. Reference [13] introduced a dynamic decision event tree (DDET) method to prevent system blackouts. The idea is very good but because of the randomness of the power system events, it is very difficult to predict all the initial events and its following contingencies. Therefore, it is still difficult to implement the idea in a real system.

To utilize the event tree analysis more efficiently, the initial event and the following events must be foreseen. By doing this, all of the possible events and actions can be covered by the event tree analysis. Considering the single protection system, consisting of a distance relay, its associated circuit breaker and communication equipment, the possible contingencies are finite and can be foreseen. In spite of randomness, it is still possible to predict all the events for each protection system module if its configuration is known. Therefore, the event tree analysis method can be used more efficiently in the fault analysis for the protection system. In the following sections, how to utilize the event tree analysis in our new strategy will be illustrated in detail.

IV. PROCEDURES OF THE ENTIRE STRATEGY

Having the tools including NNFD, SSFL, and ETA, we can integrate them into an automatic method to monitor and verify relay operations. The implementation steps of the new method are given as follows. A simple two machine five bus transmission system as shown in Fig. 2 is used for convenience. It should be noted that the strategy is not limited to this simple system.

A. Building the Event Tree for Each Protection System

The first step to implement the event analysis is building the event tree for each protection system in the transmission system. The protection system means a set of components that are in charge of certain type of protection function. Fig.3 shows an example of a distance relay function, including the relay, circuit breaker, communication equipment and other associated components. In this paper, we are just concern with the distance relay. Such kind of protection system is installed at each end of the transmission lines shown in Fig. 2. Event trees are built based on the configuration of each protection system. The purpose is to make the event trees as generic as possible. For a different configuration of protection systems, only a small change may be needed for building a new tree. For the case of Fig. 2, we just assume that all the distance relays have the same configuration. Therefore, we just need to build one set of event trees for each protection system.

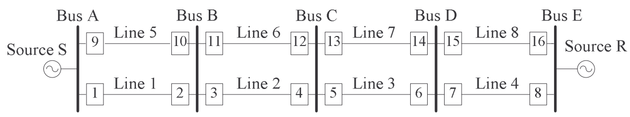

Fig. 2. A sample system for illustrating the strategy

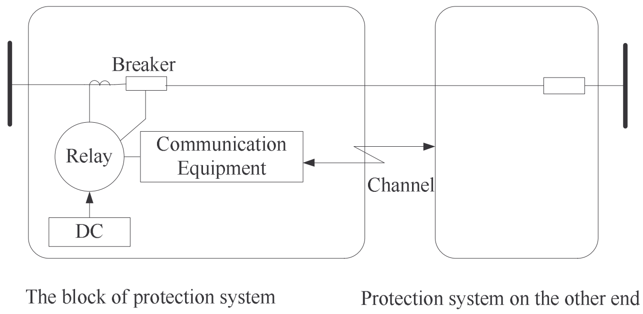

Fig. 3. The protection system for building event tree

Three event trees are built for each protection system based on three different initial events: (1) No fault in preset zones (2) Fault occurring in the primary zone (3) Fault occurring in backup zones. The third condition can be separated further into the zone 2, zone 3, and reverse zone if the logic has significant differences. In our case, we assume the backup zone protections have similar configuration and logic.

The event trees we built have been extended from the original one. The nodes in our event trees are categorized into different types, as seen in Fig. 4. The nodes stand for the events or actions, where the white ones represent correct actions and the black ones represent incorrect actions. In this event tree, we focus on the relay actions, breaker behavior and communication status. For the real system, the events may be more complicated. Following a set of events or actions from the root node, the protection system reaches an outcome that indicates whether the overall action is appropriate or not for reducing the impact of the disturbance. If the outcome reaches a “black” node, a corrective action must be taken. Depending on the elapsed time, the event tree can be used either for preventing or correcting the relay misoperations.

Fig. 4 gives the event tree 1 for the no fault condition, while the explanation of each node and its corresponding reference actions are given in Table I. The other two event trees are given in the appendix. In this case, each protection system has three event trees.

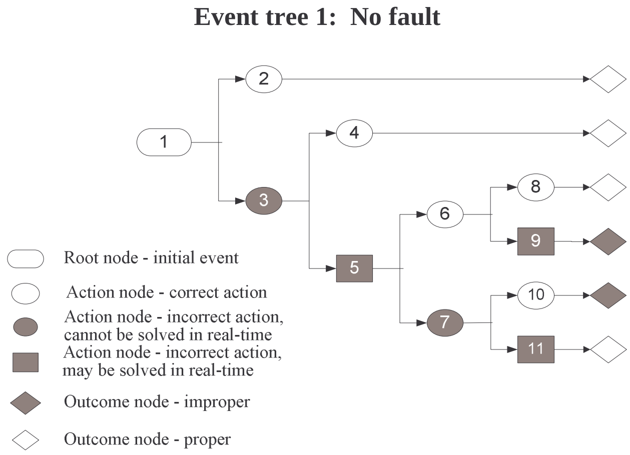

Fig. 4. Event tree for no fault condition

TABLE I
THE SCENARIOS AND REFERENCE ACTIONS FOR THE NODES OF THE EVENT TREE FOR NO FAULT CONDITIONS

Node	Scenarios	Reference Action
1	No fault in preset zones	Keep monitoring
2	Relay does not detect a fault	Stand by
3	Relay detects a fault and initiates a trip signal	Check the defects in relay algorithm and settings
4	Trip signal blocked by the other device in the system	
5	Trip signal failed to be blocked	Check communication channel Send blocking Signal if necessary
6	Circuit breaker opened by a trip signal	
7	Circuit breaker fails to open	Check the breaker circuit.
8	Autoreclosing succeeds to restore the line	
9	Autoreclosing fails to restore the line	Send reclosing signal to the breaker
10	Breaker failure protection trips all the breakers at the substation	
11	No Breaker failure protection or it doesn't work	Check the circuit of the breaker failure protection.

B. Implementing Relay Monitoring, Fault Detection and Fault Location

It is assumed that the fault analysis tool using NNFD and SSFL algorithms is provided for each protection system. That fault analysis tool is used for monitoring the protection system with the help of event tree analysis. We call that entire monitoring program the protection monitor, which has the structure shown in Fig. 5. For NNFD algorithm, the inputs are the sampled voltage and current signals seen from one end of the transmission line. The data acquisition requirement is the same as for the conventional relays except the sampling rate may be higher. For SSFL algorithm, synchronized sampling is needed at two ends of the transmission line. Communication equipments such as WAN are required to exchange the information between each protection monitor. That idea is feasible with today's wide area communication system or the system protection scheme. The open/close status of all the circuit breakers and the operational response of all the relays in the system should be sent into the protection monitor either via the communication interface or via the digital I/O equipment.

The protection monitor carries out the fault detection and fault location calculation online independently from the conventional relays. If any relay operates while there is no fault found by the monitoring program, or if there is a fault detected by the monitoring program, the event analysis process is triggered through the following steps.

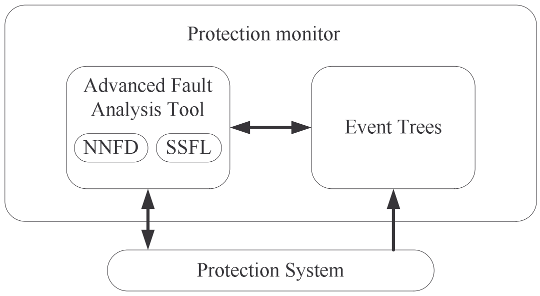

Fig. 5. Structure of protection monitor

C. Locating the Relays Responsible for Corresponding Scenarios

If there is no fault found anywhere in the system, but one or some of the relays detect a fault and initiate a trip signal, we should refer to the event tree 1 shown in Fig. 4. Either the trip signal should be blocked or the circuit breaker should be reclosed according to which node in the event tree that protection system is associated with.

If a fault is found by the monitoring program anywhere in the system, the information will be shared with other protection monitors in the system. Then we should locate and classify all of the relays in the system into the following categories according to the system and relay configurations:

(1) Relays that should stand by
(2) Relays that are responsible for main protection
(3) Relays that are responsible for backup protection

D. Tracing and Verifying the Operations for Each Protection System.

After each protection system is categorized, the protection monitor can find the right event tree for it. When the protection relay finds its appropriate event tree, the expected action chain is generated by selecting the all "white" node path. When there is a contingency, the path will be changed. If the relay action chain contains a "black" node, corrective action needs to be taken to reach the "white" outcome node. For the overall system, the analysis has two levels based on the priority. The relays matching the event tree 1 and event tree 2 are at the level 1 analysis, and the relays matching the event tree 3 are at the level 2 analysis. The goal of the protection monitor is to correct the improper actions of the protection system and avoid unnecessary trips in the whole system.

The detailed event analysis report of each protection monitor will be sent to the control center shortly so that it is more clear to system operator what happened in the system and more efficient control operation can be taken before the disturbance evolves into a cascading event.

V. Case Study

In order to illustrate the strategy of the event analysis more clearly, an example is given in this section based on the simple system shown in Fig. 2.

Assume the distance relay has four-zone protection scheme. For convenience, assume all the transmission lines in the system have the same zone length. For each relay, zone 1, zone 2 and zone 3 are set in the forward direction and the zone settings are 80 percent, 120 percent and 200 percent of its protected line respectively. Zone 4 protection is in the reverse direction and the setting is 20 percent of its “backward” line direction. Transfer trip scheme is used for the primary protection for all of the distance relays.

The fault scenario of this example is the A-to-ground fault on line 3, fault location is 15 percent of the line 3 from the end of bus D, shown as Fig 6.

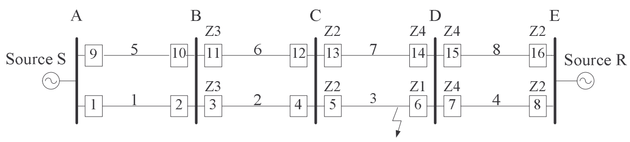

Fig. 6. A-to-ground fault at line 3

In this paper, we focus on illustrating the scheme only. We assume that the protection monitor program at both ends of line 3 can detect and locate the fault precisely. The two algorithms have been tested separately with the detailed and comprehensive fault scenarios and proved to be reliable. Considering the protection monitor programs installed in a redundant way in the system, the selectivity can be improved further.

After the protection monitors at both ends of line 3 have detected the fault, the information is shared with other protection monitors at every other substation. Then the eight protection systems can be classified into 3 categories shown in Table II:

Each protection monitor program will then compare its relay operation with the expected one by using the event tree. For example, for protection system 4, it matches event tree 1. In the ideal condition, the relay operation should match the route *1-2-white*.

We assume two contingencies in this scenario. (1) Relay at breaker 5 failed to detect the fault in line 3 because of the DC signal component impact on the relay. The transfer trip signal therefore fails to be obtained by this relay. (2) Relay at breaker 9 detects the fault as zone 3 fault.

TABLE II
CLASSIFICATION OF PROTECTION SYSTEMS IN THE EXAMPLE SYSTEM

Categories	Relay and Circuit breaker no.
Relays responsible for main protection	5(Z2) , 6(Z1)
Relays responsible for backup protection	13(Z2), 14(Z4), 7(Z4), 15(Z4), 3(Z3), 11(Z3), 8(Z2), 16(Z2)
Relays that should stand-by	4, 12, 1, 2, 9, 10

Because of these two contingencies, some relays changed their action from the expected one. The changes are shown in Table III.

TABLE III
THE CHANGES FOR THE RELAY OPERATIONS

Relay no.	Expected path	Real path
Relay 5 : event tree 2	*1-2-4-10-white*	*1-3-7-black*
Relay 9 : event tree 1	*1-2- white*	*1-3-5-6-9- black*
Relay 3, 11, 13 : event tree 3	*1-2-4-6-8- white*	*1-2-4-7-10-white*

Corrective actions are generated by the protection monitors if the relay actions are not appropiate. First of all, consider the level 1 analysis including relay 5 and relay 9. For relay 5, because it passed through a square node 7, the protection monitor will check the reference action at node 7. A trip signal is send from the protection monitor to open the breaker 5. Similarly for relay 9, the protection monitor will check the reference action at node 9. A reclosing signal is send from the protection monitor to reclose the breaker 9.

Then we go to the level 2 analysis. For relay 3, 11 and 13, although their relay action paths reach the “white” node finally to successfully clear the fault, there is still a “black” node 7 in their paths. We need to avoid the redundant trips after the prior relay actions have been corrected. Because the primary protection has been already corrected by its protection monitor, and this information will be sent to other protection monitors via WAN, then the protection monitors of backup protections will reclose their breakers to avoid unnecessary trips in the system.

VI. Conclusion

Based on the discussions given in the paper, the following conclusions may be drawn:

- Relay misoperation may contribute to cascading events. A more reliable program for monitoring and verifying protection system operation is needed to reduce this impact.
- The combination of NNFD and SSFL algorithms provides a more accurate approach for detecting and locating the fault than what is found in conventional relays.
- The event tree analysis method provides an efficient way for automatically preventing and mitigating the relay misoperation.

The future work will focus on the implementation of the overall strategy presented in this paper. The fault analysis algorithms and event tree analysis will be implemented in MATLAB. A model of a real power system and some corresponding scenarios will be built in EMTP/ATP to test the performance of the entire strategy.

VII. Appendix

Event tree 2: Fault occurring in the primary zone

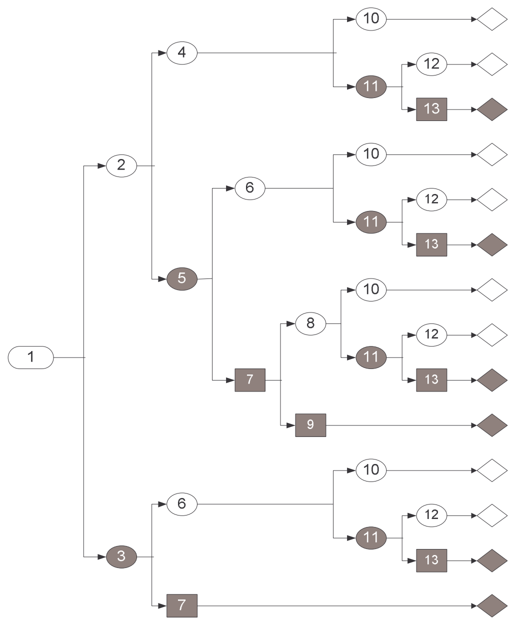

Fig. 7. Event tree for fault occurring in primary zone

TABLE IV
THE SCENARIOS AND REFERENCE ACTIONS FOR THE NODES OF EVENT TREE FOR FAULT OCCURRING IN THE PRIMARY ZONE

Node	Scenarios	Reference Action.
1	Fault occurs in a primary zone.	
2	Relay detects the fault	
3	Relay does not detect the fault	Check defects in relay algorithm and settings
4	Relay sees the fault in a correct zone	
5	Relay sees the fault in an incorrect zone	Check defects in relay algorithm and settings
6	Transfer trip signal is received	
7	Transfer trip signal is not received	Check communication channel Send Trip Signal if necessary
8	Relay trips the breaker	
9	Relay does not trip the breaker; Fault is cleared by other breakers	Try to open the breaker associated with this relay and correct other redundant trips
10	Circuit breaker opened by a trip signal	
11	Circuit breaker fails to open	Check the breaker circuit
12	Breaker failure protection trips all the breakers at the substation	
13	No breaker failure protection or it does not work	Check the circuit of the breaker failure protection

Event tree 3: Fault occurring in backup zones

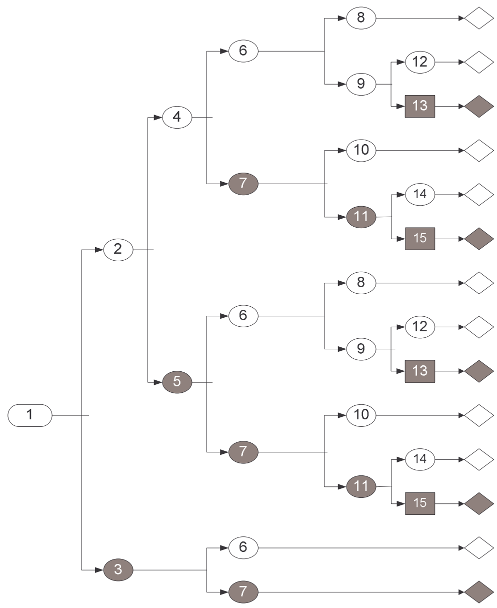

Fig.8. Event tree for fault occurring in backup zone

TABLE V
THE SCENARIOS AND REFERENCE ACTIONS FOR THE NODES OF EVENT TREE FOR FAULT OCCURRING IN BACKUP ZONES

Node	Scenarios	Reference Action.
1	Fault occurs in backup zone	
2	Relay detects the fault	
3	Relay does not detect the fault	Check defects in relay algorithm and settings
4	Relay sees the fault in a correct zone	
5	Relay sees the fault in a incorrect zone	Check defects in relay algorithm and settings
6	Other relays clear the fault successfully	
7	Other relays did not clear the fault successfully	
8	Back-up relay is reset or blocked	
9	Back-up relay is not reset or blocked	
10	Back-up relay trips the breaker	
11	Circuit breaker fails to open	Check the breaker circuit.
12	No unnecessary trips	
13	Unnecessary trip occurs	Try to restore the unnecessarily tripped lines
14	Breaker failure protection trips all the breakers at the substation	
15	No breaker failure protection or it does not work	Check the circuit of the breaker failure protection.

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IX. Biographies

Nan Zhang (S'04) received his B.E and M.E. degrees from Tsinghua University, Beijing, China all in electrical engineering, in 1999 and 2002 respectively. Since Jun. 2002, he has been with Texas A&M University pursuing his Ph.D. degree. His research interests are power system protection, power system stability, cascading events, and artificial intelligence applications in these areas.

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