Improving Real-time Fault Analysis and Validating Relay Operations to Prevent or Mitigate Cascading Blackouts

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***Abstract*—This paper proposes a new strategy at the local (substation) level, aimed at preventing or mitigating the cascading blackouts that involve relay misoperations or inadequate local diagnostic support. The strategy consists of an advanced real-time tool that combines neural network based fault detection and classification (NNFDC) algorithm and synchronized sampling based fault location (SSFL) algorithm with a relay monitoring tool using event tree analysis (ETA). The fault analysis tool provides a reference for conventional distance relay with its better performance and the relay monitoring tool provides detailed local information about the disturbances. The idea of the entire strategy is to meet several NERC recommendations to prevent blackouts using wide area protection and control.**

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

I. Introduction

System-wide disturbances become a major concern in the power industry again recently as a result of the northeast blackout on Aug 14, 2003. The causes for large-scale blackouts are quite unique due to the complexity of power system operations. According to the historical data [1], relay misoperation is one of the contributing factors of 70 percent of the major disturbances in the United States. The major problem of conventional relays is that they make the decisions based on local measurements. In certain situations, the conclusion made by a local relay may not be suitable from a global stand point. In addition, the relay hidden failures may be another factor to cause relay misoperations [2]. Inadequate local level diagnostic support is another factor that may contribute the blackouts. When disturbances occur, if the detailed local information can not be delivered from the substations to the centralized system in an effective way, the system operator may not be able to make an informed decision and issue corrective controls on time.

As shown in Table I, NERC proposed several related recommendations in the final report about the August 14, 2003 blackout [3] to solve above problems.

TABLE I
SEVERAL NERC RECOMMANDATIONS TO PREVENT CASCADING EVENTS [3]

21	*"Make more effective and wider use of system protection measures."*
22	*"Evaluate and adopt better real-time tools for operators and reliability coordinators."*
28	*"Require use of time-synchronized data recorders."*

Obviously, the system protection schemes, synchronized measurements, and better real-time analysis tools are very helpful to prevent the blackouts. In [4], the idea of wide area protection and emergency control was proposed similarly as a guide to prevent the system-wide disturbances.

With the availability of advanced computer, communication and measurement technologies, new real-time analysis tools can be developed at the local substation level today to help the implementation of a wide area protection and control system. The system disturbances may be very random and unfold very quickly. The system based approaches, although better in global view, may not have sufficient time to deal with all the tasks to prevent the blackouts. If some tasks are distributed to the substation level, those approaches may be more effective.

We propose a new strategy at the substation level to help prevent or mitigate the cascading blackouts that involve relay misoperations or inadequate local diagnostic support. The strategy includes two parts: a) Improving real-time fault analysis by more "intelligent" fault analysis approaches. The Neural Network based Fault Detection and Classification (NNFDC) algorithm [5] and Synchronized Sampling based Fault Location (SSFL) algorithm [7] are combined as a real-time fault analysis tool to provide more reliable and accurate fault information than provided by the traditional distance relays. b) Validating relay operations by event analysis tools. The event tree analysis (ETA) is used for monitoring actual relay operations and providing the event diagnostic support.

The algorithms of NNFDC and SSFL were originally aimed at applying new techniques in fault diagnosis. They are developed using MATLAB and validated using Alternative Transients Program (ATP) [5-8]. This paper further explores the basic idea of both algorithms and proposes the way to incorporate them along with ETA into the new solution for preventing and mitigating blackouts. The implementation of

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the entire strategy to a practical system will be studied in the future.

II. Improving real-time fault analysis

Conventional protection systems are concerned more about the dependability by introducing many backup strategies [9]. In this sense, the selectivity and security of the protection systems are hard to coordinate because the trade-off must be made in relay settings. For distance relay located at one end of the transmission line, the settings are made to protect the line from most of the fault cases in predefined system condition. When the fault with unexpected properties occurs or when the system is experiencing overload and oscillation, unnecessary trip or false trip of distance relays may happen. Those activities may worsen the system stability and even initiate cascading events leading to blackouts.

To improve the real-time fault analysis, new techniques for transmission line protection need to be applied. In this paper, a new real-time fault analysis tool using two techniques is proposed.

A. Neural Network Based Fault Detection and Classification

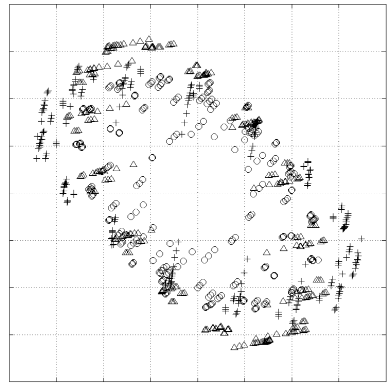
Neural network based fault detection and classification algorithms are extensively studied in recent years because of its intelligence and adaptability. Instead of phasor calculations, the time domain measurements from transmission lines are formed as patterns. The fault detection and classification task then becomes a pattern recognition issue.

An ART neural network based fault detection and classification algorithm is developed earlier [5]. The aim of the algorithm is to allocate the training patterns into homogeneous clusters by some grouping technique. Then the clusters are assigned to the classes, which are our expected fault events in power system, such as “ABG_zone_I”, etc. Finally, the prototype and position of each cluster are stored and used for recognizing and classifying unknown patterns. The process is demonstrated using a 2-D demo shown in Fig. 1.

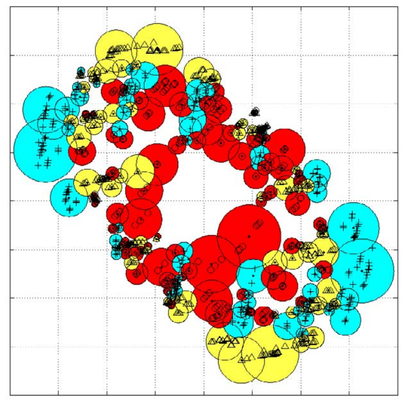
The detailed algorithm and implementation of ART neural network based fault classification can be found in [5]. The improvement of the original algorithm to solve the application issues is proposed in [6]. The advantage of the improved algorithm is that the neural network can form its knowledge by learning as many fault scenarios as it can “see”, and does not need to rely on the compromise settings used in conventional distance relays. With this approach, the accuracy of fault detection will be improved under all circumstances.

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. When the fault is precisely located, we could know which breakers are responsible to clear that fault, and unnecessary trips would be avoided.



(a) The raw training patterns from three classes



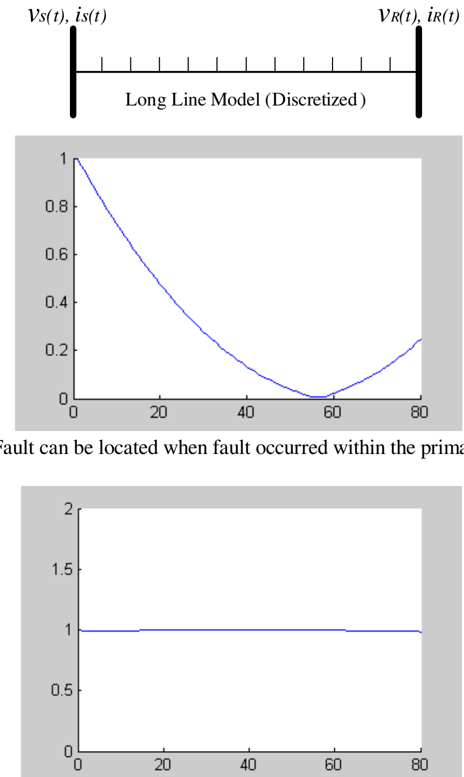
(b) The patterns are allocated to the clusters after a training process

Fig. 1. A 2-D demo of ART neural network training

Synchronized sampling based fault location algorithm is developed in [7] to implement the precise fault location. This algorithm requires raw samples of voltage and current data synchronously taken from both ends of a transmission line. It is more attractive now because the use of GPS time-synchronized data acquisition units is an emerging trend in the utility industry.

The principle of this algorithm relies on the fact that the voltage and current at the faulted point can be represented by both sending data and receiving data using certain linear relationship. If there is no fault within the primary line, such a point can not be found. For short transmission lines, the fault location can be calculated directly by an explicit equation if the fault has indeed occurred [7]. For long transmission lines, the line is discretized first. Using traveling wave method, the voltages at each point are calculated using the data from both the sending end and receiving end. The fault location is then calculated by finding the point that has minimum voltage difference calculated using data from the two ends. As shown in Fig.2, the square of the difference is plotted for each discretized point on a transmission line. Figure (a) and (b) show the obvious differences for faulted and unfaulted line.

The main advantage of synchronized sampling based fault location algorithm is that it confirms whether a fault indeed occurred on the transmission line of interest. The algorithm



(a) Fault can be located when fault occurred within the primary line

(b) Fault can not be located for a healthy line

Fig. 2. An example of fault location calculated by SSFL

does not depend on any assumptions about system operating conditions, fault resistance, fault waveforms, etc. Using this approach, the protection system can be kept from tripping on overload, power swing and other no-fault abnormal situations [8], which may otherwise initialize or facilitate cascading blackouts.

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

The performance studies of both two algorithms indicate their advantages respectively in fault diagnosis than conventional distance relay [5-8]. The combination of those two algorithms as an integrated real-time fault analysis tool can provide more satisfied solution because each algorithm has its focus. For NNFDC, it only takes local data at the sampling rate similar to distance relays. It has the capability to quickly detect the fault and provide the exact fault type. Since only data from one end of a transmission line are used, NNFDC can not have as good of a performance in distinguishing the faults occurring around the zone boundaries. The SSFL can take over this job more precisely by using the fault type information concluded by NNFDC. A software package incorporating the two algorithms is developed using MATLAB [10].

Ideally, the fault analysis tool will be installed at each EHV substations. Concerning the hardware costs, it can be first installed at the important lines and vulnerable regions according to the system analysis [2]. The required field configuration of the proposed algorithm is shown in Fig. 3. For NNFDC, it does not require extra equipment. The input

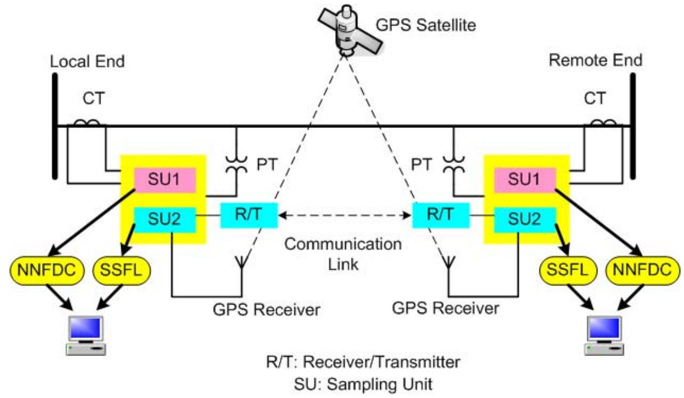


Fig. 3. Field configuration of combined fault analysis tool

data can be sampled by regular AD converter, which is commonly used in distance relays. For SSFL, it requires synchronized data from both ends and high sampling rate usually in the order of 10-100 kHz is preferred. High frequency sampling unit, such as digital fault recorder (DFR), is required for higher accuracy of fault location. Both of algorithms require one cycle post fault data and they are capable for real-time analysis.

III. VALIDATING RELAY OPERATIONS

Two main causes of the August 14, 2003 blackout are [3]: i) Inadequate situational awareness, and ii) Inadequate diagnostic support. When disturbances occur in the system, the system operator usually can not get the detailed information about what is going on in the substations in a short time. A relay monitoring tool at local level is needed to provide the event analysis about the disturbances. Event tree analysis (ETA) is a commonly used event/response technique in industry for identifying the consequences following an occurrence of the initial event [11,12]. We can use it on the relay monitoring purpose.

In the example shown in Fig.4, ETA takes the structure of a forward (bottom-up) symbolic logic modeling technique. This technique links system responses to an initial "challenge" and enables assessment of the probability of an unfavorable or favorable outcome [12].

The general design of the event trees may not be able to deal with different types of relaying systems. Each event tree must be implemented carefully taking into account the detailed relay system design and specific protection settings. Usually, at least three types of event trees need to be built for a single relay system based on three types of initial events: (1) No fault detected in either primary zone or backup zones, (2) Fault detected in the primary zone, and (3) Fault detected in backup zones. Fig. 4 demonstrates an example of the event tree that matches the first case. In that event tree, the nodes stand for the events or actions, where the white ones represent correct actions and the black ones represent incorrect actions. Following a set of events or actions from the root node (initial event), the protection system reaches an outcome that indicates if the entire actions are appropriate for a corresponding disturbance. If the event sequence is heading to or already reached a "black" node, a corrective action must be taken either at local level or at system level.

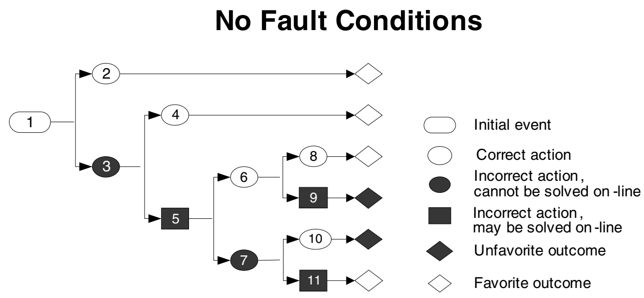


Fig. 4. Event tree for non-fault conditions

TABLE II
SCENARIOS AND REFERENCE ACTIONS FOR THE NODES OF THE EVENT TREE

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	Check the defects in relay algorithm and settings
4	Trip signal is blocked	
5	Trip signal is not blocked	Send block Signal if necessary
6	Circuit breaker opened by the 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.

The explanation of each node in the event tree from Fig.4 and its corresponding reference actions are given in Table I. The table is set up along with the design of the event tree. The other two example event trees matching the case (2) and case (3) are described in [13] for a typical relay system.

IV. IMPLEMENTATION OF REAL-TIME FAULT ANALYSIS AND RELAY MONITORING

A. *Setup of the Fault Analysis Tool and Event Analysis Tool*

Before the above techniques are used for on-line analysis, each distance relay system needs to have the analysis tools installed.

For NNFDC, the neural networks need to be trained offline first by a variety of scenarios covering the different combinations of fault parameters, including fault type, location, resistance, and inception angle. The training process should also take into account the system-wide disturbances, especially the fault and switching events in the surrounding lines. The input for training can be waveforms obtained by power system simulation or combined with the substation field recorded data. The detailed training process is described in [5,6].

For SSFL, the important issue is finding the appropriate line parameters for each transmission line. For the short transmission line, usually shorter than 50 miles, the lumped line parameters can be used. For long transmission lines, the distributed line parameters should be used because the capacitance of the line can not be neglected.

For ETA, the event trees for each distance relay system should be built in advance. The design of each event tree should reflect the system configuration and relay settings and be able to explore all the required relay activities useful for system view. After the event trees at local level are built, they should be stored at the system level as an event tree database, as the example shown in Fig. 5. During the disturbances, the system can collect the local diagnostic information for a graphic view of the event analysis by activating the related event trees.

B. *Scheme of On-line Analysis and Monitoring*

The real-time fault analysis tool and event tree analysis may be formed as a local event analysis system (LEAS) to monitor system disturbances and the relay operations in substations. The proposed structure is shown in Fig.6. The real-time fault analysis could be a continuous process. When there is a suspect disturbance detected, event tree analysis process will be triggered. The first step is to determine which event tree (no fault? primary zone? backup zone?) should be selected according to the result of real-time fault analysis. Then by obtaining the relay output signals and breaker status, the actual relay system activities is monitored in that event tree. The diagnostic information about the local activities will be sent to a central event analysis system (CEAS) and other

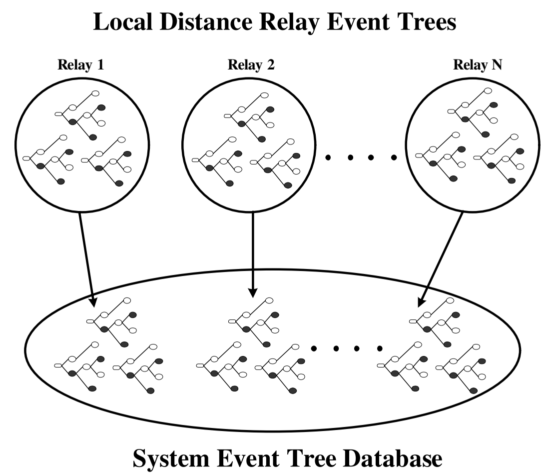


Fig. 5 The structure of local and system event tree coordination

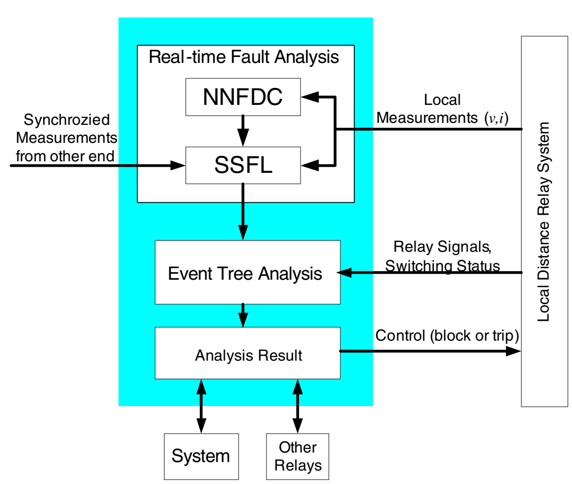


Fig. 6. Block diagram of local event analysis system (LEAS)

LEASs to confirm and issue corrective controls. An example of field installation of LEAS and CEAS is given in Fig. 7.

As mentioned earlier, the large-scale blackouts are quite complex. It is impossible yet to give a complete solution to deal with them. The strategy proposed here intends to give some preventive and corrective approaches for those blackouts that may involve relay misoperations and inadequate local event analysis support. A typical cascading blackout process usually has two stages: i) The initiating stage. In that period, some components are removed from the system but the stability issue is not so severe yet. That period may last from minutes to hours. If that period includes relay misoperations (e.g. tripping on overload or redundant trips for a certain fault), the real-time fault analysis tool in LEAS will make the different conclusions from relays and inform the CEAS with the event analysis result. The system knows what was wrong and make the corrections quickly. The blackouts may be prevented from the starting points. ii) The fast evolving stage. If the disturbances keep unfolding, the system reaches the emergency state. The system should give LEAS the priority to intervene the false operations because there may not be enough time to coordinate the system and local activities. In this period, due to the system oscillation, the distance relays may be affected by overloading and power swings. They may trip the healthy lines as Zone 3 or even Zone 2 fault and cause the cascading blackouts. The studies of NNFDC and SSFL indicate that they have less influence by overloading or power swings [6,8]. Both of the algorithms take one cycle post fault data for calculation, therefore they can reach the correct fault analysis and block the relays tripping on power swing and overloading situations before the relay Zone 2 or Zone 3 timers expires. Therefore, it can hold the uncontrolled trips and leave the time to island the system at expected separating locations. The blackout loss can also be mitigated.

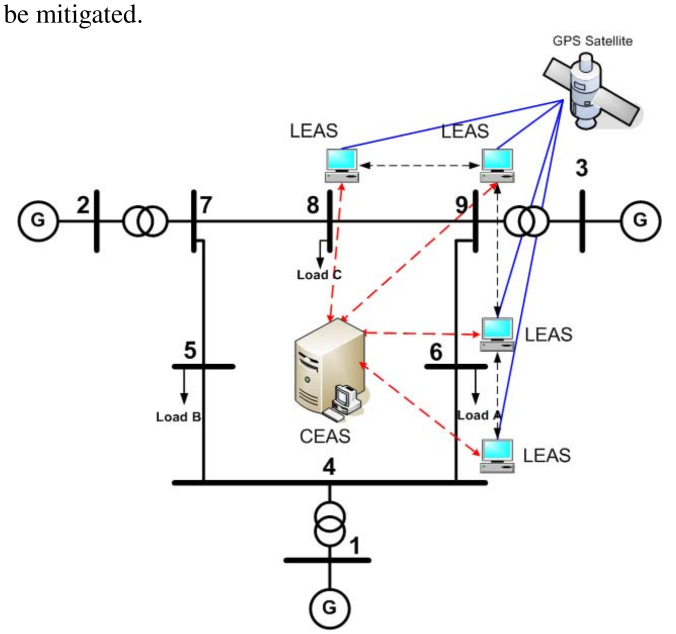


Fig. 7. Coordination between local event analysis system (LEAS) and central event analysis system (CEAS)

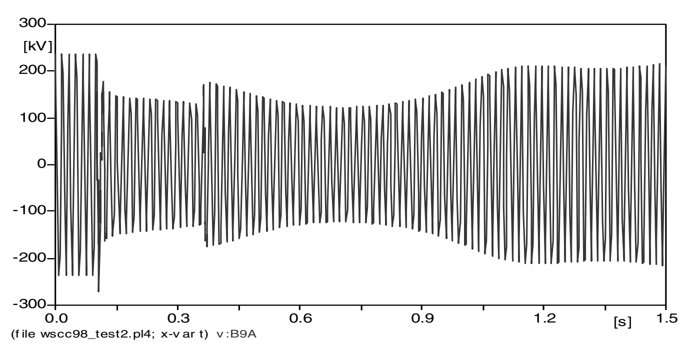
V. Case Study

In order to demonstrate the entire process of the proposed strategy, a case study is given based on the 9-bus system shown in Fig. 7. This system is modeled in ATP using dynamic generator parameters [14]. The detailed performance evaluations for NNFDC and SSFL are implemented in [5-8]. The accuracy of both algorithms is confirmed under a variety of fault scenarios, system-wide disturbances and power swing conditions.

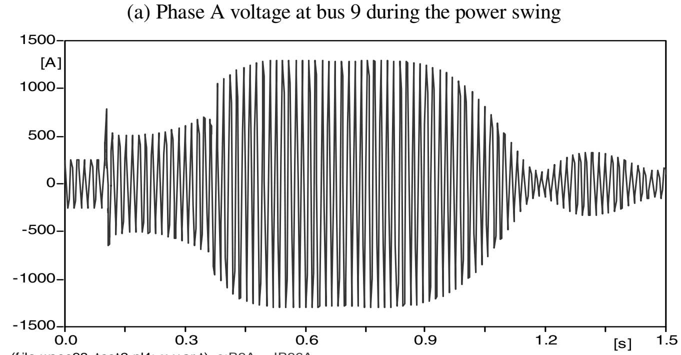
The demonstration in this section is based on the simulation result using ATP. In the 9-bus system, assume there is a three-phase fault that occurred at middle of line 4-5. Assume that for some reason, the trip signal is delayed and the circuit breakers at line 4-5 have opened very close to its critical clearing time (CCT). After the fault is cleared, the system experienced a power swing. As shown in Fig. 8, the voltage and current for line 9-6 at bus 9 have the profile with an oscillation.

At a certain time, low voltage and high current are observed by this relay. The impedance calculated by this relay will float into the relay setting areas, as shown in Fig. 9. The relay will detect the event as the Zone 3 fault. If the timer of Zone 3 expires, the relay will trip the healthy line 9-6. That will further worsen system stability. If such a scenario happens in a large system, a probable blackout may be initialized.

For this scenario, the conclusions of both NNFDC and SSFL indicate that there is no fault either in the primary zone or backup zones. In this case, the event tree shown in Fig. 4 should be activated for the LEAS at bus 9 to monitor its relay system activities.



(a) Phase A voltage at bus 9 during the power swing



(b) Phase A current in line 9-6 during the power swing

Fig. 8. Oscillation of voltage and current at bus 9 and line 9-6

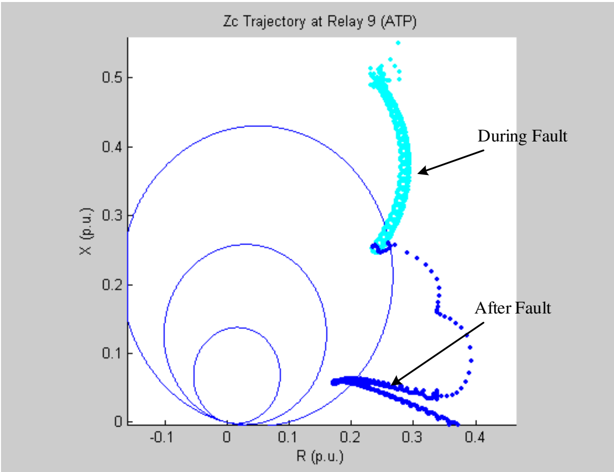


Fig. 9. Trajectory of computed impedance for distance relay of line 9-6 at bus 9

Depending on the priority of the LEAS to intervene relay operations, two probable event sequence trails may be obtained from that event tree, shown in Table III. For the former case, since the final outcome is a "black" node, the CEAS is informed that it should try to reclose the line 9-6 when it confirms there is no fault on that line. For the latter case, the trip signal is blocked by the LEAS at the local level. By either case, the relay misoperation can be prevented or mitigated and the local diagnostic support is provided for the CEAS as a reference for further studies.

TABLE III
TWO PROBABLE EVENT ANALYSIS RESULTS

Relay#: Event Tree#	W/O Priority	W/ Priority
Relay 9 : event tree 1	*1-3-5-6-9-black*	*1-3-4-white*

VI. CONCLUSION

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

- There are two ways to reduce the probability of cascading blackouts at the local substation level: i) Improving real-time fault analysis using better techniques than conventional distance relays. ii) Improving the communications between system and local level to obtain more comprehensive monitoring methods.
- NNFDC and SSFL are basically derived from two different approaches. The combination of the two algorithms provides a more accurate fault analysis and can double-check the analysis result of the relays.
- The event tree analysis is easy to realize and it can provide an understanding of the event sequences happening at local sites. That can help system operators make an effective corrective decision quickly.
- The proposed methods are in accordance with several NERC recommendations and fit well in the trend of the wide area protection and control.
- Further developments aimed at implementing a practical system to incorporate the proposed strategy are needed.

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VIII. BIOGRAPHIES

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