Detection Tools for Disturbances and Protective Relay Operations Leading to Cascading Events

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***Abstract*-- The power system cascading outage is quite often a complex phenomenon, which may finally result in a large area blackout. Detecting and preventing cascading blackouts is crucial to maintaining the power system reliability and security. This paper discusses implementation of a method used to detect the cascading events by coordinating the system-wide and substation-wide monitoring and control tools. The framework of the implementation is given first. The data requirements for the proposed system-wide and local substation algorithms are investigated in detail. Obtaining and handling data through integration of traditional Supervisory Control and Data Acquisition (SCADA) system and modern Intelligent Electronic Devices (IEDs) is outlined. Case studies based on a real power system model shows the proposed algorithms are feasible.. These detection tools could work as decision-making support for system operators to deal with cascading event situations.**

***Index Terms*--Cascading events, blackout, operator tools, substation automation, SCADA, IEDs**

I. Introduction

MODERN power systems face many challenges in providing the reliable and stable power energy to society while maintaining the sustained load growth and economic prosperity. Under a flexible electricity markets operation under the deregulation rules, power systems became more stressed and power network security and reliability criteria became more complex than before. Since power systems are exposed to all kinds of disturbances, which may come from animal contacts, human errors, equipment malfunction, natural disasters, etc., some of these disturbances may cause major power service interruption [1]. Among the disturbances, cascading outage, especially the large-scale cascading outage, draws special attention since it can cause great economic loss to utility companies and other businesses and devastating impact on people's life. For example, the Northwestern America Blackout in 1996 disconnected 30.39 GW of power to 7.5 million customers [2]; Northeastern System Blackout in 2003 led to the load loss of 61.8GW, which influenced more than 50 million people [1].

It is apparent that large-size blackouts are less frequent than small-size blackouts. But researchers found that the large blackouts are much more likely that might be expected [3-5]. Hence focusing on the large area cascading blackouts and trying to understand the cause-effect relationships of the cascade steps remains a topic of paramount importance.

Many researchers have put lots of efforts on analyzing and finding solutions to detect, classify, mitigate or prevent cascading outages. Various solutions have been proposed, which include dynamic and probabilistic study of the cascade model, application of dynamic decision-event tree analysis, use of expert systems for wide area back-up protection, inclusion of relay hidden failure analysis, application of special protection schemes, implementation of controlled islanding, generalized line outage distribution factors calculation, etc. [6-12] According to the analysis results, it is obvious that relaying problems and inadequate understanding of unfolding events are two major contributing factors in inability to predict or prevent cascading events. Relay failure or unintended operation contributes the most to the inadequate handling of power system disturbances. According to historical data, relaying problems were the contributing factor in almost 70% of the US disturbances from 1984 to 1991 [13]. Another problem is that power system operators lack sufficient analysis and decision support tools to take quick corrective actions needed to mitigate unfolding events.

Aiming at resolving the above problems, a novel interactive scheme of system/local monitoring and control tools for detection, prevention and mitigation of cascading events is recently proposed [14-20]. This scheme is aimed at identifying the disturbance leading to cascading events and providing control means for preventing further unfolding of the cascading events while keeping the stability of the power system. Based on the proposed method, this paper will focus on developing the implementation framework for system-wide and substation-wide monitoring and control tools and investigating the data requirements for implementation of the proposed algorithms using a model of a real power system.

After an introduction, this paper reviews the overall scheme of the proposed method in Section II. The implementation framework and related data handling issues are discussed in Section III. Section IV demonstrates cases for the implementation and testing of system- and substation-wide algorithms. Conclusions are given in Section V followed by a list of references.

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II. REVIEW OF THE PROPOSED APPROACH

The proposed monitoring and control scheme for detection, prevention and mitigation of cascading events coordinates the system-wide side and substation-wide algorithms. The overall interaction is conceptually shown in Fig. 1.

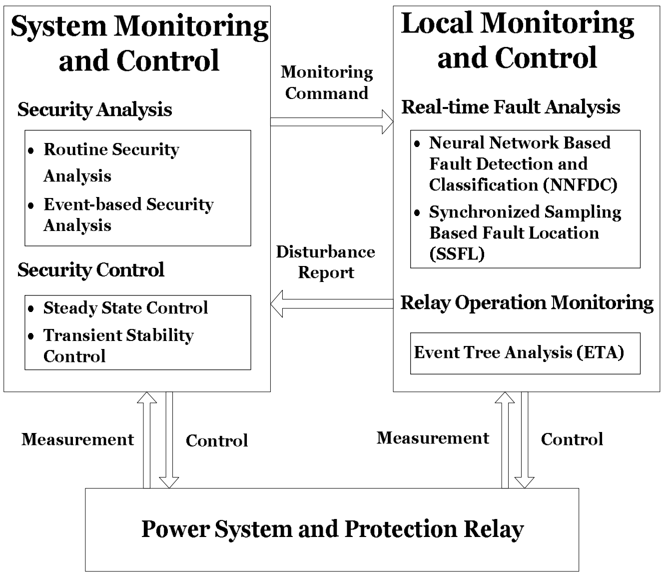

Fig. 1. Overall interactive monitoring and control scheme

The proposed system-wide monitoring and control tool is intended for installation at the control center. The system tool consists of the routine and event-based security analyses based on the power flow method and topology processing method, along with the security control schemes for expected and unexpected events. Vulnerable elements are identified using Vulnerability Index and Margin Index [14] calculated while related relays are closely monitored. The event-based security analysis is triggered when an unexpected disturbance occurs. It indicates whether the emergency control is needed to mitigate the transient stability problem or not. Steady state control tools are based on Network Contribution Factor (NCF) [15], Generator Distribution Factor (GDF) [21], Load Distribution Factor (LDF) [21], and Selected Minimum Load Shedding (SMLS) used for early detection and prevention of cascading outages as analyzed utilizing steady state method. Transient stability control tools are based on Potential Energy Boundary Surface (PEBS) method [22], Admittance-based Control (ABC) and Generator-input-based Control (GIBC).

The local monitoring and control tools intended for installation at local substations consists of an advanced real time fault analysis tool and a relay operation monitoring tool utilizing neural network based fault detection and classification algorithm (NNFDC), synchronized sampling based fault location algorithm (SSFL), and event tree analysis (ETA) [17, 18, 23, 24]. The advanced on-line fault analysis tool will detect the disturbance by analyzing local measurements. Once the disturbance is detected and classified, event tree analysis process will be invoked to validate relay operations. The combination of the two algorithms performs a more accurate fault analysis than conventional relays do. This provides a reference for monitoring and verification of the distance relay operations. The substation-based solution can provide the system-wide tool with local disturbance information and diagnostic support so that the system-wide tool can utilize local information to take better control action to ensure the secure operation.

III. THE IMPLEMENTATION OF PROPOSED ALGORITHMS

A. The Implementation Framework

System-wide tool uses wide-area information to generate a comprehensive view of the system security and vulnerability conditions. It can notify the substation-wide tool to engage in careful monitoring of vulnerable elements during abnormal conditions. The substation-wide tool collects the exact real-time local disturbance information. It has the ability of detecting, classifying and locating the fault with high accuracy and providing good reference for evaluating relay operation. Both the system-wide and substation-wide tools work together to fulfill the major task: detecting and classify cascading outages. The implementation framework is shown in Fig. 2.

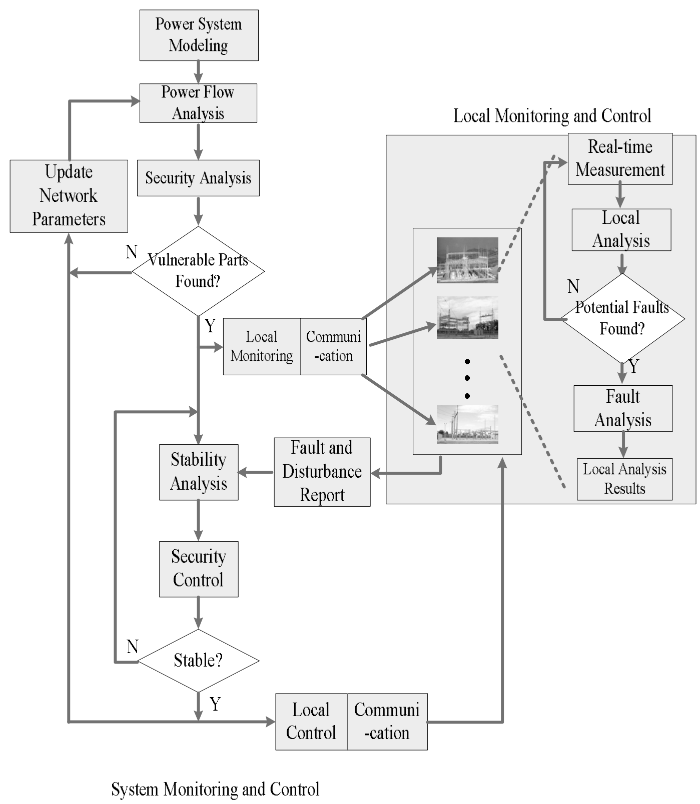

Fig.2 The implementation framework

B. Data Requirements

Data availability is the key factor in making the automatic monitoring and control feasible. Different types of data from various sources are needed to implement the proposed algorithms at system/substation level, which are naturally divided into two classes: system- level and substation level data.

The data required for system level analysis helps getting the power system network topology and establishing the steady state status. Information about changes in the power system model and real time network topology is also needed. Different utilities may use various commercial programs for power system analysis, which will cover the main functions for the system analysis needed for the proposed scheme. To meet the data requirement for system analysis and control tools, Table I shows the necessary data in detail.

TABLE I
DATA REQUIREMENTS FOR SYSTEM LEVEL ANALYSIS

Detailed Data	***Description***
Power Flow Analysis Data	This data contains the basic power system network topology. It is used to run the power flow analysis to establish the steady state status of the whole system.
Short Circuit Analysis Data	This data is needed to run short circuit calculation. It will be updated whenever the system topology changes.
Dynamic Analysis Data	This data contains all the dynamic models for generators, exciters, compensators, stabilizers, etc, which is used to perform dynamic analysis to check system dynamic stability under various disturbances.

The data required for substation level analysis allows getting detailed configuration for each substation, as well as measured data for any disturbance. To meet the data requirement for local fault analysis and control tool, Table II shows the necessary data in detail.

TABLE II
DATA REQUIREMENTS FOR SUBSTATION LEVEL ANALYSIS

Detailed Data	***Description***
Relay Setting and Event Reporting Data	Data for relay setting contains the relay configuration information. Data for relay event reporting contains the results of relay operation under disturbances. This data is used for reconstructing relay operation by simulating relay behavior under given disturbances.
Fault Record Data	Fault record data contains analog and digital sample values for all input channels for a specific fault or disturbance. It is used for the training set and testing set of fault scenarios for Neural Network based Fault Detection and Classification (NNFDC) Algorithm.
Synchronized Samples of Fault Voltages and Currents	The synchronized samples data of fault voltages and currents contains time stamps from the Global Positioning System (GPS) of satellites on all the pre- and during-fault sample signals. This data is used to verify the results of the Synchronized Sampling based Fault Location (SSFL) Algorithm.

C. Obtaining and Handling Data

This section will discuss how to obtain the needed data to meet the data requirements and how to handle those acquired data. Different utilities may adopt different software from various vendors. No matter what kind of programs the utilities used in dispatch center, they will definitely cover the power flow analysis, short circuit analysis and dynamic analysis. The only differences are coming from the data formats, which depend on the adopted programs. Table III shows an example of obtained data for system level analysis based on Siemens' PTI PSS/E program.

For the substation level, the integration and use of IED data and traditional Supervisory Control and Data Acquisition (SCADA) data are adopted. The data recording equipments may be very versatile, since they came from various vendors and were installed in different time periods [25]. Table IV shows the data obtained from the substation level considering the data integration from SCADA system and IEDs. [19]

TABLE III
OBTAINED DATA AND RELATED SOURCE FOR SYSTEM LEVEL

Function Module	***Detailed Data***	***Related Source***	***File Description***
Security Analysis	Power Flow Raw Data	Input Data Files for PSS/E (*.raw)	Contains power flow system specification data for the establishment of an initial case. This data is used by PSS/E to get the initialization values to be utilized for security analysis.
	Slider Binary Data or Drawing Coordinate Data	Input Data Files for PSS/E (*.sld for V30 or *.drw for V2x)	This file is used to create and modify one-line diagrams and to display a variety of results.
Stability Analysis	Sequence Impedance Data	Input Data Files for PSS/E (*.seq)	Contains the negative and zero sequence impedance data needed for unbalanced fault analysis. It is used by PSS/E to add the impedance data to the case of interest.
	Dynamics Data	Input Data Files for PSS/E (*.dyr)	It is used by the PSS/E Dynamics program. It contains synchronous machines and other system components data for input to the PSS/E dynamic simulation working memory.

IV. CASE STUDY

A. System Model for Case Studies

A real power system, which includes more than 2,100 buses, is modeled to demonstrate the implementation of the proposed approach. There are about 50 buses at 500kV as the part of Extra High Voltage (EHV) system. As shown in Table III, the static power system is modeled based on PSS/E program, which is an integrated program for simulating analyzing, and optimizing power system transmission network and generation, performance [26]. Power flow raw data files of PSS/E are used to build the system model. The network topology, load level, generators, buses, and transmission lines are include in the raw data files. The system steady state can be extracted from the basic power flow analysis. Data conversion may be needed according to the different versions of those raw data files.

TABLE IV
OBTAINED DATA AND RELATED SOURCE FOR SUBSTATION LEVEL

Function Module	*Detailed Data*	*Related Source*	*File Description*
Neural Network based Fault Detection and Classification (NNFDC)	Event File	Event File from Relays	Used to get the report of relay operations.
	Data Recorded During Faults	DFR and DPR files	Used to check the results of relay operations using NNFDC
Synchronized Sampling based Fault Location (SSFL)	Synchronized Samples of Voltage and Current Data during Faults	GPS-Synchronized DFR data	Used for evaluation of SSFL

For substation-wide study, NNFDC algorithm needs large number of fault and non-fault cases to complete the process of training and testing for neural network tuning. Those training and testing cases are quite different for various transmission lines due to the selection of different simulation parameters and settings. To perform comprehensive tests, it may not be possible to acquire enough fault cases from the field. Regarding to transmission line, a simulation model is built based on ATP/ATPDraw [27] and Matlab [28] as the alternative solution. The fault and non-fault scenarios can be generated by this model with provision for initializing the simulation setting parameters by the user.

B. Implementation and Testing of System-wide Algorithm

Steady state analysis and dynamic stability analysis are implemented to test the system-wide algorithm based on the modeled system.

Using vulnerability analysis, the vulnerability of individual elements and whole system can be assigned values. For this case, all the weight factors for different vulnerability indices are assigned value of one for a general case. The weight factor values can be assigned based on the importance of corresponding equipment. Large value of a weight factor shows the need for more concern for that part of the system than the others. For the loadability of the bus vulnerability index calculation, Thevenin equivalent impedance method is used. The bus voltage angle difference limit of a transmission line is assigned as 40^{o}. The base power is assigned as 100MVA. The results of the vulnerability analysis can be utilized as supplemental criteria for performance index analysis. Those most vulnerable elements need to be monitored to detect the sign of cascading outages, especially the elements in Extra High Voltage (EHV) system. The detailed results for the vulnerability analysis can be found in the detailed report of this study [29].

System dynamic analysis is based on the model built from power flow raw data files. It is used to determine the response of the system to the prescribed stimuli and will tell whether the system can lose the stability before it moves to a new steady state operation point. In PSS/E, the dynamic analysis is a straightforward simulation for an increasing time step. The dynamic simulation is advanced and finished step by step based on the present value of each state variable and its time derivative [26]. For the model power system, N-1 contingency analysis is performance requirement for the entire EHV system. None of the N-1 contingency cases has a stability problem, which satisfies the NERC requirement. Thus one N-2 contingency analysis is chosen as the case study.

For this case, two 500 kV transmission lines are tripped, which are both the ties connecting different power system regions. The dynamic analysis began to run from -0.167s to 0.1s, which shows the system being in steady state. Then one 500 kV transmission line is taken out of service. After 0.4s, a fault is introduced on another 500 kV transmission line. The whole dynamic analysis lasts 4.5second. Various states can be set for monitoring, including machine rotor angle, machine/bus real and reactive power, machine/bus terminal voltage, machine field voltage, machine speed deviation, frequency deviation, branch flow, real and reactive power load, etc. The dynamic analysis is based on step-by-step method. Fig. 3 shows part of the machine rotor angles to demonstrate dynamic stability performance.

C. Implementation and Testing of Substation-wide Algorithm

Case studies for substation-wide analysis demonstrate the performance of advanced fault analysis tools, which includes NNFDC and SSFL. When relays at the substation fail to detect the fault within its operating zones, the advanced fault analysis tool will serves as a backup on-line fault analysis tool. In order to implement the substation-wide algorithms, different fault scenarios are generated to test the algorithms. One 500 kV transmission line from studied power system is chosen as the base model for data generation, which is a tie line connecting the two regions in the system.

For NNFDC algorithm, a large number of fault and non-fault cases has been generated, which includes different fault types, fault locations, fault resistance, and fault angles. The fault is initiated at 0.02s into the simulation process, and cleared at 0.45s. The proposed neural network is trained by using the simulated fault and non-fault cases. There are 209 clusters altogether marked with labels of different fault types. Then 5000 cases are tested for the trained neural network. Two classification algorithms are used when performing the test procedures: the nearest neighbor algorithm and fuzzy k-nearest neighbor algorithm. Fig. 4 shows the errors for the fault classification for basic nearest neighbor algorithm and fuzzy 4-nearest neighbor algorithm. From Fig. 4, we can see that the error for fuzzy 4-NN is stable at about 1.5%.

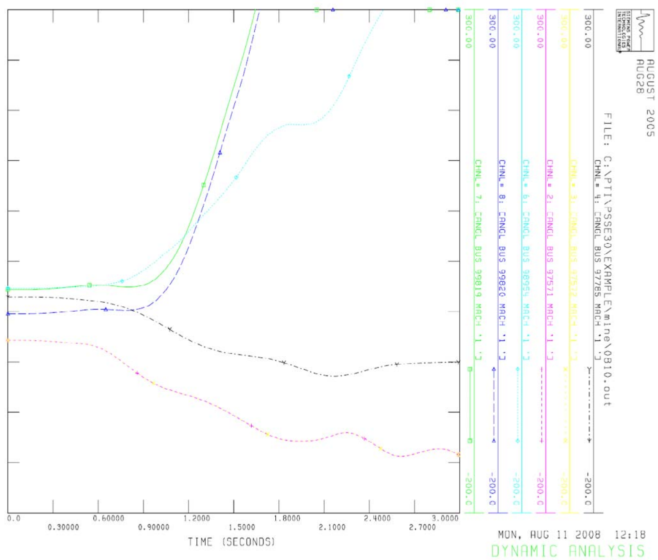

Fig. 3 System dynamic analysis result

For SSFL algorithm, the same simulated transmission line is used for tests. 140 fault cases are generated by random setting of parameters. The generated data includes the fault voltages and currents from two sides of the transmission lines, which covers different cases of fault types, fault angles, fault resistance, and fault locations. Table V shows 10 cases of the results for SSFL algorithm. For all the tests, the maximum error for fault classification is 3.6992%; the minimum error is 0.0234%.

From above results, we can see both NNFDC and SSFL algorithms can detect and locate the fault efficiently with high accuracy. The advanced fault analysis tools in substation combine these two different approaches to get the best analysis results, which can provide the exact disturbance information and make correction of relay operation if needed.

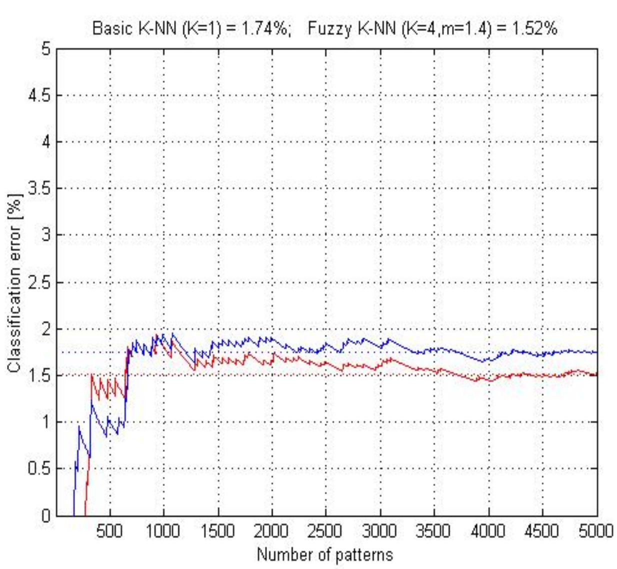

Fig. 4 Error results of neural network fault classification tools

TABLE V
RESULTS OF SSFL ALGORITHM

	Fault Type	Fault Distance (mile)	Fault Resistance (Ω)	Fault Angle (degree)	Fault Location (mile)	Error (%)
1	CAG	85.2	3.1	199.9	85.25	0.0234
2	ABG	151.1	11.9	121.6	150.19	0.4706
3	ABCG	23.1	13.1	38.2	22.51	0.2870
4	AG	135.2	11.7	49.8	136.30	0.5693
5	CAG	116.2	1.3	217.0	115.61	0.3037
6	AB	38.3	15.1	3.8	37.48	0.3933
7	BCG	19.6	2.5	239.7	21.57	1.0016
8	CG	120.0	4.3	110.0	122.14	1.0656
9	AG	176.4	9.2	98.5	174.60	0.8917
10	ABCG	68.0	2.3	102.8	66.60	3.6992

V. Conclusion

Based on the discussions presented in this paper, the following conclusions can be drawn:

- The implementation framework of the proposed algorithms is presented by coordinating the system and local level monitoring and analysis tools. This framework applies the theoretical research results into practical application.
- The data requirements discussed in detail in order to carry out the implementation issue.
- Data obtaining and handling for covering the data requirements are discussed based on the integration of data from SCADA system and substation IEDs, as well as data from simulations is needed.
- Case studies are used to demonstrate the feasibilities of the proposed algorithms. Different cases of system-wide and local level analysis tool application to a real system are tested.

VI. Acknowledgment

The contributions to the developments reported in this paper that came from earlier work of former graduate students Drs. S. Vasilic, N. Zhang, and H. Song are gratefully acknowledged.

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VIII. Biographies

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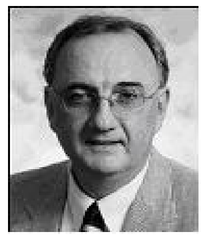

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