2007

Identification of cascaded generator over-excitation tripping events

Juan Li
Iowa State University

Identification of cascaded generator over-excitation tripping events

by

Juan Li

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Electrical Engineering

Program of Study Committee:
Chen-Ching Liu, Major Professor
Venkataramana Ajjarapu
Manimaran Govindarasu

Iowa State University

Ames, Iowa

2007

UMI Number: 1447490

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Undesirable tripping of generators contributed to the 1996 and 2003 blackouts in the U.S. Tripping of these generators initiated by over-excitation protection can lead to a shortage of reactive power supply. An effective way to prevent cascaded events is to identify the anticipated operations of generator protective devices such as over-current relays. For a given contingency, the post-disturbance field currents can be obtained from the results of steady-state contingency evaluation in the on-line security assessment process. However, their accuracy is inadequate compared with the post-contingency field current obtained from off-line time-domain dynamic simulations. In this thesis, a Fuzzy Inference System (FIS) is proposed to correct discrepancies between post-contingency field currents obtained from steady state contingency evaluation and the corresponding values obtained from time-domain dynamic simulations. Post-contingency field currents obtained from steady-state security assessment can be corrected on-line using an FIS constructed off line. A 200-bus system model is used to validate the performance of the developed FIS.

CHAPTER1. INTRODUCTION

1.1 Background and Motivation

Cascaded events such as transmission line and generator outages have contributed to catastrophic power failures, such as the U.S. Northeast blackout of 1965 [1] [2], New York power failure in 1977 [3], July 2 and August 10, 1996, outages on the western interconnection [4], and the blackout in the eastern interconnection in Aug. 2003 [5]. The undesirable tripping of generators caused by over-excitation protection contributed to the cascaded events in Aug. 10, 1996, WECC disturbance, Aug. 22, 1987, Tennessee disturbance, and June 5, 1967, PJM Disturbance [11].

With the available technologies today, it is impossible to predict the cascaded events in real-time or ahead of time. However, it is possible to identify basic patterns leading to cascaded events based on the results of on-line steady state contingency evaluation that is performed every several minutes. Undesirable generator tripping by the over-excitation protection is one of the basic patterns leading to cascaded events. Identifying the existence of the relay operations ahead of time is an effective way to prevent cascaded generator tripping events. Once the undesirable cascaded generator tripping can be identified, the dispatchers will be able to take actions to reduce the armature and field currents of the generator(s) involved. These preventive actions may require several minutes.

The proposed approach in this thesis is to extend the on-line security assessment framework that is based on a list of next contingencies. The identification of cascaded events will enhance our ability to avoid catastrophic outages. A Fuzzy Inference System (FIS) is developed to identify contingencies that are likely to trigger cascaded generator tripping. Off-line time-domain simulation cases are performed for the construction of a rule base and verification of the performance. This thesis is concentrated on the cascaded generator tripping events due to over-excitation protection. A related task in this research is concerned with cascaded distance relay tripping events following line contingencies [16].

1.2 Contributions of the Work

This research leads to an innovative method to identify one of the basic patterns of cascaded events following a contingency, thereby reducing the possibility of large-scale blackouts. The proposed approach makes use of a fuzzy inference system to identify the generator tripping events due to over-excitation protection. The proposed system is expected to provide system operators with a vulnerability assessment report with warning signals on cascaded generator tripping events. This work is an extension of the on-line steady state security assessment framework that is the standard practice in industry.

1.3 Thesis Organization

Chapter 2 provides a review of past major blackouts in North America. It is shown that cascaded events such as transmission line and generator outages have contributed to catastrophic power failures. The chapter continues with a discussion of existing techniques for preventing wide area outages against cascaded events. Chapter 3 summarizes the basic patterns of cascaded events in blackouts and provides an explanation of the fuzzy inference system method. The chapter also gives an overview of the technical problem associated with cascaded events triggered by over-excitation protection. Chapter 4 provides a discussion of the proposed FIS based methodology that can be used to obtain the post-contingency field current. Chapter 5 includes the simulation results obtained from steady state and dynamic simulations on a 200 bus test system. Chapter 6 gives the conclusion and future work.

CHAPTER 2. PREVETING BLACKOUTS AGAINST CASCADED EVENTS

2.1 Review of Major Blackouts in North America

There have been a number of major power system blackouts in North America. In this research, 5 scenarios were analyzed; the first one is the 1965 blackout in the Northeast, and the most recent one occurred on the Eastern Interconnection in 2003. These 5 major blackouts in North America are summarized in Table 1. A detailed description of these catastrophic failures can be found in references [1] [2] [3] [4] [5] and NERC's website [6].

Table 1. Major Blackouts in North America

Date	Location	Scale in term of GW or Population	Time Span of Cascaded Events
9 November,1965 [2]	Northeast	20GW, 30M people	13 minutes
13 July, 1977 [3]	New York	6GW, 9M people	1 hour
2 July, 1996 [6]	Wyoming, Idaho	11.7GW, 1.5M people	36 seconds
10 August, 1996 [4]	Western Interconnection	30.5GW, 7.5M people	> 6 minutes
14 August, 2003 [5]	Northeast	62GW, 50M people	> 1 hour

Northeast, November 9, 1965

At 5:16 pm, November 9, 1965, a backup relay on one of five 230-KV transmission lines carrying power from the Niagara River north to the Toronto, Ontario, metropolitan area operated and disconnected the affected line. Within about 2.5 s, the remaining four 230-KV transmission lines became loaded and tripped out of service. Shortly after that, the Northeast area of the United States and a large part of Canada went dark. From Buffalo to the eastern border of New Hampshire and from New York City to Ontario, a massive power outage struck without warning. By 5:40 p.m. that evening, 80,000 square miles of the Northeast United States and Ontario, Canada, were without power, leaving 30 million people in the dark [2].

New York, July 13, 1977

At 8:37 pm, July 13, 1977, during a severe thunderstorm, lightning struck two extra-high-voltage lines in northern Westchester County, at the northern extreme of Con Edison's service area. At 8:56 p.m., two more lines were struck, and it led to the loss of a major generator and several other vital transmission lines. At 9:19 p.m. the final major interconnection to Upstate New York tripped due to a thermal overload. By 9:30 p.m., all tie lines to external sources were open. The customer load was too high for Con Edison's available in-city sources of power. At 9:36 p.m., the system was completely shut down. Electric service to more than 8 million people in the metropolitan area and to the commercial and industrial users of this area was interrupted for periods from 5 to 25 hours [3].

WECC, July 2, 1996

At 1:25 pm on July 2, 1996, a significant disturbance occurred on the interconnected transmission systems of the Western Electricity Coordinating Council (WECC). A short circuit occurred on the 345 kV transmission line between the Jim Bridger plant near Rock Springs and the Goshen substation near Idaho Falls, and it was tripped successfully. This disturbance caused a parallel line to be tripped. Loss of the lines initiated a protective action that shut down two generating units at the Jim Bridger plant. The under-voltage and inter-area oscillation problem developed quickly throughout the system and five islands were formed. At least 1.5 million customers were affected in this catastrophic blackout [6].

WECC, August 10, 1996

At 3:48 pm on August 10, 1996, hot weather throughout the West coast contributed to widespread high power demands. Random multiple transmission line outages occurred during a period of about one hour and weakened the system, leading to voltage oscillations. As a result, three 500 kV Pacific AC Inter-tie lines and the +/- 500 kV Pacific DC Inter-tie lines between Oregon and California were lost. The successive random outages over a short period of time pushed the system into an abnormal condition. Consequently, about 7.5 million customers in the Western Interconnection were interrupted [6].

US Midwest and Northeast/Canada, August 14, 2003

At 1:31 pm on August 14, 2003, the First Energy's Eastlake unit 5 was tripped in the Northern Ohio service area due to high reactive power output. After 3:05 pm, a sequence of lines tripped, causing heavy loadings on a number of other transmission lines. The critical event leading to widespread cascading in Ohio and beyond was the tripping of the Sammis-Star 345-kV line at 4:05 pm. After that, more than 508 generation units at 265 power plants were lost in less than ten minutes. The northern part of the Eastern Interconnection was broken into five islands. About 50 million people lost power in this blackout and 61,800 megawatts of load were lost in most of New York state as well as parts of Pennsylvania, Ohio, Michigan, and Ontario, Canada [5].

2.2 Characteristics of Cascaded Events in Major Blackouts

An analysis of the five major blackouts summarized above shows that all these major blackouts involve complex sequences of cascaded events. In general, these cascaded events were initiated by a single event or a combination of events, such as the misoperation of a backup zone-3 relay in the 1965 blackout, two lightening strokes in the 1977 blackout, the line outages in the July and August 1996 blackouts and the generator tripping in the 2003 blackout. Following the initiating contingencies, the cascaded events occurred in a sequence.

The general sequence of the events in major blackouts is illustrated in Figure 1. The causes of cascaded events in the past five major blackouts are summarized in Table 2.

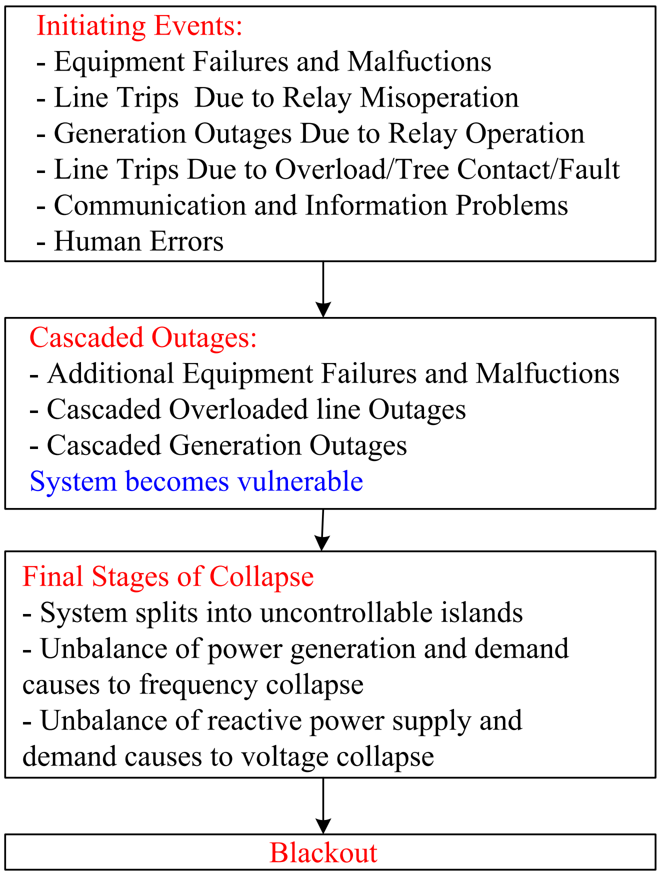


Figure 1. Sequence of Events Leading to Blackout

As it is shown in Table 2, the causes of cascaded events leading to catastrophic outages are usually complex. They may involve faults, equipment failures, malfunctions, communication and information problems, misoperation of protection equipments, and human errors, etc. The external factors can also contribute to the events, e.g., tree contacts, lightening, and excessive line sagging in summer.

Table 2. Major Causes of Cascaded Events in Major Blackouts

	Nov,1965	July,1977	July,1996	Aug ,1996	Aug ,2003
Environment Reasons (Tree contact, lighting, etc)		√	√	√	√
Equipment Failures and Malfunctions	√	√	√	√	√
Communication and Information Problems					√
Misoperation of Protection Equipments	√		√	√	√
Human errors		√			

It is also observed that four out of the five past blackouts occurred in summer when the power system was heavily stressed. The reason is that the higher load brings more pressure for the system to maintain the voltage profile. Thus, a single event is more likely to trigger other events that can cause a large blackout. If proper planning criteria are followed, most power systems are designated to be able to operate safely such that a single initial event will not cause further cascaded failures [14]. However, if the system is operating under the peak load condition, depending on the severity of the event, the system may enter an emergency state following the disturbance. If proper control actions or operator intervention are not taken in a timely manner, the system may be susceptible to further failures and subsequent cascading.

2.3 Undesirable Relay Tripping in Cascaded Events

As mentioned in Section 1.2, events that contribute to the cascaded sequences are probabilistic in nature. Therefore, it is not feasible to predict the cascaded events that will occur in the future. However, it is useful to determine the basic patterns of cascading, i.e., which event may trigger other event(s).

The undesirable zone 3 relay operations and undesirable generator tripping by over-excitation protection are two of the basic patterns. As shown in Table 2, undesirable zone 3 relay and other generation and transmission backup relay operations have contributed to the 1965, 1996 and 2003 blackouts [11]. A study by the North American Electric Reliability Corporation (NERC) indicates that protective relays are involved in about 75 percent of major disturbances [4]. Given the importance of undesirable relay operations, recognition of these two basic patterns becomes a critical step toward the understanding of cascaded events.

2.3.1 Undesirable Zone 3 Relay Operation

One of the basic patterns of cascaded events is the undesirable zone 3 relay operations that do not involve a fault. Undesirable zone 3 relay operations can lead to unnecessary loss of transmission lines [15]. These zone 3 relay operations can be caused by power flows transferred to the lines due to a fault at different line. See Figure 2. Due to removal of Line 1, the heavy power flow on Line 2 causes a low voltage and high current condition. As a result, the apparent impedance viewed by the zone 3 relay on Line 2 is more likely to enter the zone 3 reach.

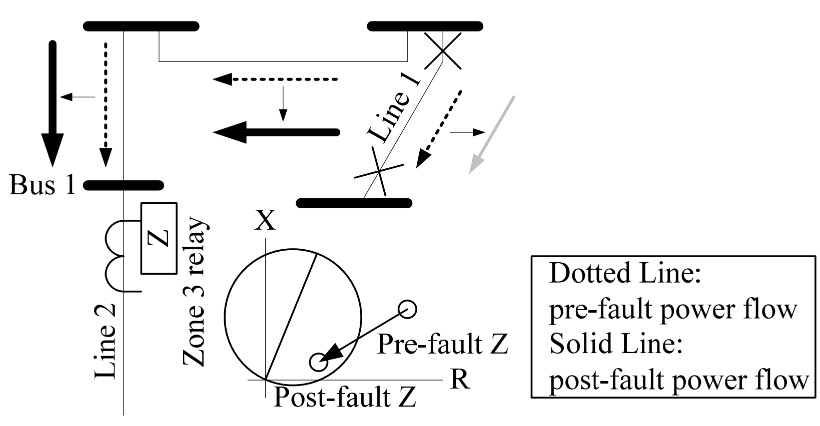


Figure 2. Relationship between A Line Fault and Cascaded Zone 3 Relay Operation(s)

The critical event for the 1965 Northeast Blackout was a false operation of an impedance relay initiated by load current [1]. The critical event for the Aug 14, 2003 Eastern blackout was also an inappropriate zone 3 relay operation caused by high real and reactive load current and depressed system voltage [5].

2.3.2 Undesirable Generator Tripping by Over-Excitation Protection

Undesirable generator tripping by over-excitation is another basic pattern of cascaded events. Generator tripping by over-excitation protection can reduce the reactive power supply in the system, causing the system voltage profile to decline. One generator tripping may trigger another generator to trip, leading to cascaded events.

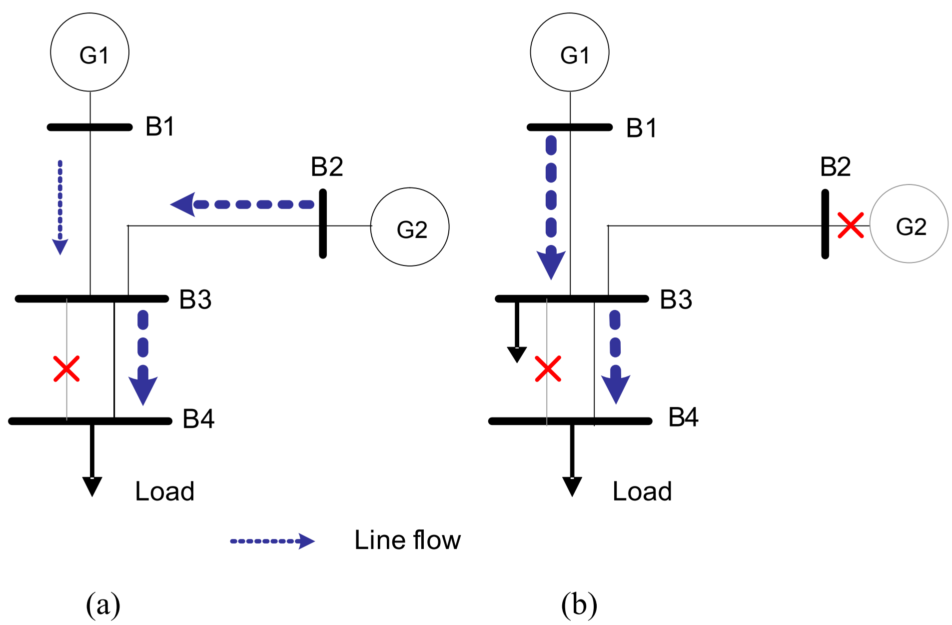


Figure 3. Example of Cascaded Generator Tripping

Figure 3 shows an example of cascaded generator tripping caused by over-excitation protection. In Figure 3 (a), due to a fault on line B3-B4, the bus voltage at B3 falls and the field current of G2 increases. If line B3-B4 is heavily loaded and MW output of G2 is also at a high level before the contingency, the line outage can cause a heavy loading condition of G2, and therefore the unit may be tripped by its over-excitation protection. Tripping of G2 can cause further reduction of the reactive power supply in the system. As shown in Figure 3 (b), generator G1 becomes overloaded after G2 is lost and G1 may also be tripped by its own over-excitation protection.

Undesirable tripping of generators initiated by over-excitation protection contributed to the 1996 and 2003 blackouts in the U.S. The first event in the Aug. 14, 2003, blackout is the Eastlake 5 generator tripping. It was an excitation system failure—as voltage fell at the generator bus, the generator tried to increase its voltage on the AC winding of the machine quickly. This caused excessive armature and field currents on the generators and finally led the generator's excitation protection scheme to trip the plant [5]. Furthermore, between 16:05 and 16:10 at that day, 29 generators tripped, which triggered the first major power swing. These trips were caused by the generators' protective relays that are responding to overloaded transmission lines. Many of these trips were reported as under-voltage and over-current [5].

In the Aug.10, 1996, blackout, over-voltage during the disturbance caused relay operations due to the manual excitation control. However, even if automatic excitation control is in service, it is possible that the post-contingency power system requires a significant amount of VARs. The consequence may be excessive armature and field currents on the generators that increase the risks of voltage instability.

2.4 State-of-the-Art on Prevention of Cascaded Events

Some studies concerning blackouts have centered on the goal of preventing cascaded events from starting, or at least, reducing their rate of occurrence. This section provides a survey of the state-of-the-art on the prevention of cascaded events.

The conceptual design of the Strategic Power Infrastructure Defense (SPID) system that is aimed at prevention of the wide area grid outages against cascaded events has been developed [7]. By incorporating multi-agent system technologies, the SPID system is intended to assess the power system vulnerability, monitor hidden failures of protective devices and provide adaptive control actions to prevent catastrophic failures and cascading sequences of events.

The Special Protection Scheme (SPS) is used as an event-based emergency control for mitigating conditions that can cause unusual stress on the power system [8]. SPS is based on direct detection of predefined outages, with high-speed binary signals to control centers for logic decisions, and then to power plants and substations for generator tripping and capacitor/reactor bank switching. Disadvantages of SPSs include their control capability only for predefined events, complexity, and high costs [8].

A response-based Wide-Area stability and voltage Control System (WACS) has been developed [9]. WACS is a technology to use system-wide information together with distributed local intelligence and communication of selected information between separate locations to counteract propagation of major disturbances in the power system [10]. This technique is aimed at better management of the system condition during the disturbances and more reliable system performance under high power transfers.

A concept of Wide Area Monitoring and Control (WAMC) to mitigate cascaded events using a steady state approach is reported in [11]. WAMC could act in the early stage of the cascading failures and prevent it from spreading. A WAMC based approach is established to determine the boundary between the initiating event and its subsequent cascaded spreading. The WAMC long-term impact on the network is studied in [11].

The hidden failures in protection systems have been identified as key contributors of the cascaded events. A technique to catalog and analyze the possible hidden failures in the protection systems is presented in [12]. The basic idea of this method is to identify the modes in which the protection systems may fail to operate correctly and the consequences of these failure modes.

A tripping of the generator by an armature over-current relay or the activation of an armature current limiter will severely cripple the power system which often causes the breakdown of the system voltages [17]. In [17], a MW rescheduling strategy that alleviates the over-current condition on the armature is proposed. This method is to make small changes in the active power production of the generator, thereby fully utilizing the capability of the generator.

CHAPTER 3. TECHNICAL PROBLEMS

3.1 Problem Formulation

The purpose of this research is to estimate the post-contingency field currents in order to identify cascaded events triggered by over-excitation protection. To obtain accurate field currents, time-domain simulations are performed off line. Figure 4 shows a simplified over-current relay characteristic curve [17]. Once the post-contingency field current is obtained, which is illustrated by the red line in Figure 4, the relay operating time can be estimated using the relay characteristic curve in Figure 4. Note that there is a threshold pick-up value (indicated by vertical dotted line) for over-current relay to operate.

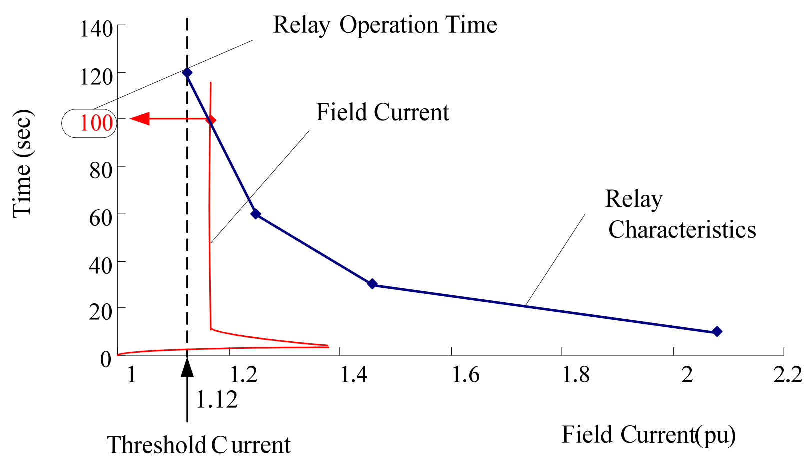


Figure 4. Time/Current Characteristics for Field Over-Current Relay Model

To obtain accurate field currents, time-domain simulations need to be performed off line. Magnetic saturation and controllers of generators, load characteristics, and other control devices need to be modeled in the time-domain simulations.

To illustrate the computation time of time-domain simulations for a large system, it is noted that it takes approximately 5 minutes for PSS/E to perform a 10 second simulation on a

15,000 bus system based on 3 GHz Pentium CPU and 1GB RAM, Clearly, it is infeasible to conduct many time-domain simulations for different contingency scenarios in operational environment. The proposed time-domain simulations are performed off line.

On-line steady state security assessment is commonly performed in the Energy Management System (EMS) environment. Contingency analysis is an important part of security assessment. The post-contingency field current can be obtained from contingency analysis results. However, steady state power flow calculations do not incorporate dynamic models of the power system such as generator controllers, voltage controls, and load characteristics. As a result, the post-contingency field current obtained from steady state power flow results usually do not match the value obtained from time-domain dynamic simulations. As the dynamics of a power system become more significant, the discrepancy is also wider.

In this thesis work, a fuzzy rule based method is proposed to determine the post-contingency field current. The post-contingency field current obtained by steady state power flow calculation is corrected using fuzzy rules constructed from off-line time-domain simulation results.

3.2 Fuzzy Inference System Approach

3.2.1 What is fuzzy logic?

Fuzzy logic is used to handle the concept of partial truth instead of absolute truth. The concept of fuzzy logic was established by Dr. Lotfi Zadeh at UC-Berkeley in the 1960's [16]. It was introduced as a method to handle the uncertainty of verbal terms. Basically, Fuzzy Logic is a multivalued logic, which allows intermediate values to be defined between conventional evaluations like high/median/low.

In fuzzy logic, membership functions are used to define a degree of membership of a particular term. Several fuzzy sets are assigned to each variable to cover its domain and it is common for these sets to overlap so that the entire domain will be covered. In general, symmetric membership functions that peak at a value of one such as triangular, trapezoidal, Gaussian, or bell-shaped are used. Intermediate membership functions may be added to the decision alternatives as well as the inputs to increase the accuracy of the network. These values can be reduced to more specific membership functions (e.g. very low, median high) if necessary. An example membership plot for input variable voltage in per unit is given in Figure 5.

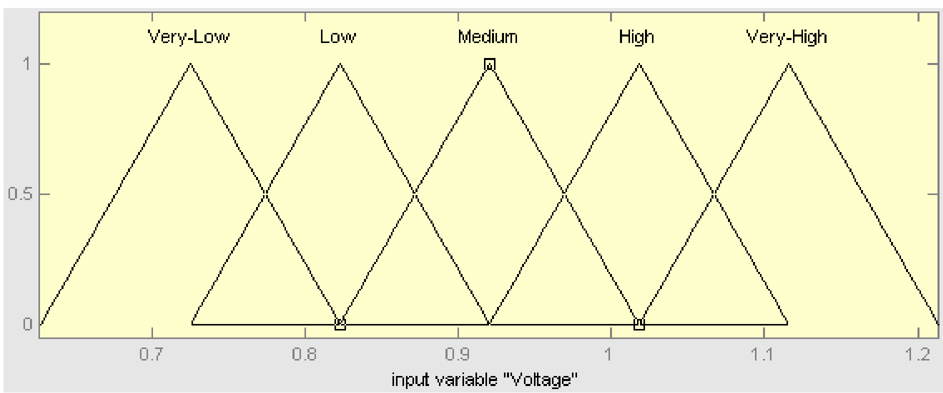


Figure 5. Membership Functions for Input Variable Voltage (Per Unit)

Fuzzy sets and fuzzy operators are the subjects and verbs of fuzzy logic. Once fuzzy sets are established, the if-then rule statements are used to formulate the conditional statements that comprise fuzzy logic. Rules may be specified by an expert as well as learned from training data automatically.

For example, for a generator, a rule could be:

If Post-Contingency Reactive Power Output is ***High*** and Terminal Voltage is ***Low***, then Post-Contingency Terminal Current is ***High***.

Here, the fuzzy variables are per unit Post-Contingency Reactive Power Output, Terminal Voltage and Post-Contingency Terminal Current of a generator. Other logical operators such as NOT and OR may be used as well. Methods for implementing the operators must be selected for the system. Some examples are shown in Table 3.

Table 3. Fuzzy Logic Operators

Method	Not A	A AND B	A OR B
Product/Sum	1-A	A * B	A + B
Max/Min	1-A	Max(A,B)	Min(A,B)

3.2.2 What is Fuzzy Inference System?

Fuzzy inference is the process of formulating the mapping from given inputs to an output using fuzzy logic. The mapping provides a basis from which decisions can be reached, or patterns discerned. The process of fuzzy inference involves all elements that are described in the previous sections: Membership Functions, Logical Operations, and If-Then Rules.

Once a fuzzy system has been specified, a defuzzification method must be selected. In this research, a commonly used centroid defuzzification method is applied. The first step in this method is the aggregation of memberships of the fuzzy sets in the output variable given the firing level of each rule. The firing level is calculated by the total membership of each antecedent in the rule base using the appropriate operator method. Then, the rule firing level (product of degree of certainty) is applied to each consequent fuzzy set. The final crisp output value is the centroid of all fuzzy output sets.

3.2.3 Why Fuzzy Inference System is applied?

Fuzzy inference systems have been widely applied in control systems, data classification, decision analysis, expert systems, and other rule based systems. The main reasons why fuzzy inference systems are successfully used could be described as follows:

1. Fuzzy inference system is suitable for uncertain (include fuzziness, inaccurate, or incomplete data) or approximate reasoning (incomplete or inaccurate formulas or inference rules).

2. Fuzzy inference system is suitable for the system with a mathematical model that is difficult to derive.

3. Fuzzy inference system can make decision with estimated values under incomplete information.

4. Fuzzy inference system allows representation of descriptive or qualitative expressions, which are more natural than mathematical.

5. In a fuzzy inference system, describing the rules is usually simpler and easier, and thus the systems can execute faster than conventional systems.

In this research, it is intended to determine the post-contingency field current. It is difficult to establish a precise mathematical model that describes the detailed and complex dynamic behaviors of the system. However, with fuzzy rules constructed from off-line time-domain simulation results, a fuzzy inference system can help to find the relationship between the time-domain simulation results and the steady state power flow results. The detailed methodology and procedure is introduced in the following sections.

CHAPTER 4. METHODOLOGY AND PROCEDURES

4.1 Calculation of Field Current Using Steady State Power Flow Solution

In the proposed approach, the post-contingency field current is calculated using steady state power flow solution that provides MWs, MVARs, and bus voltages. The field current i_{fd} can be obtained by Eq. (4-1)

$$i_{fd} = \frac{e_q + r_a i_q + x_d i_d}{x_{ad}} \tag{4-1}$$

where, e_q is the internal voltage, r_a is the armature resistance, x_d is the direct-axis synchronous reactance, x_{ad} is the mutual inductance, and i_d and i_q are the dq components of the armature current. Figure 6 shows the steady state phasor diagram of synchronous machines. The current components i_d and i_q are calculated using armature current I_t, the internal angle δ, and power factor angle φ as shown in Eq. (4-2) and Eq. (4-3).

$$i_d = I_t \sin(\delta + \varphi) \tag{4-2}$$

$$i_q = I_t \cos(\delta + \varphi) \tag{4-3}$$

As shown in Eq. (4-4) and Eq. (4-5), the terminal current I_t and power angle φ are calculated using active power P_t, reactive power Q_t, and terminal voltage E_t .

As shown in Eq. (4-6), the internal angle δ is calculated using the terminal voltage E_t, quadrature-axis synchronous reactance x_q and Eq. (4-4) and Eq. (4-5).

As shown in Eq. (4-7), the internal voltage e_q is calculated using terminal voltage E_t and Eq. (4-6).

$$I_t = \frac{\sqrt{P_t^2 + Q_t^2}}{E_t} \tag{4-4}$$

$$\varphi = \cos^{-1}\left(\frac{P_t}{I_t E_t}\right) = \cos^{-1}\left(\frac{P_t}{\sqrt{P_t^2 + Q_t^2}}\right) \tag{4-5}$$

$$\delta = \tan^{-1}\left(\frac{x_q I_t \cos\varphi}{E_t + x_q I_t \sin\varphi}\right) \tag{4-6}$$

$$e_q = E_t \cos\delta \tag{4-7}$$

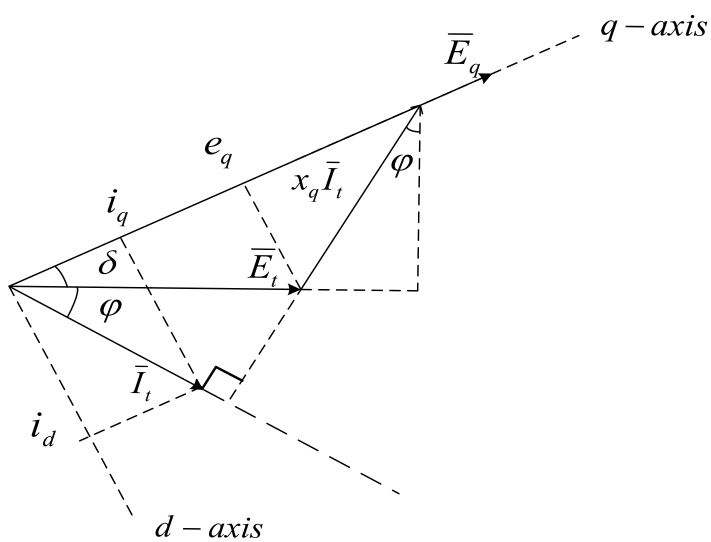


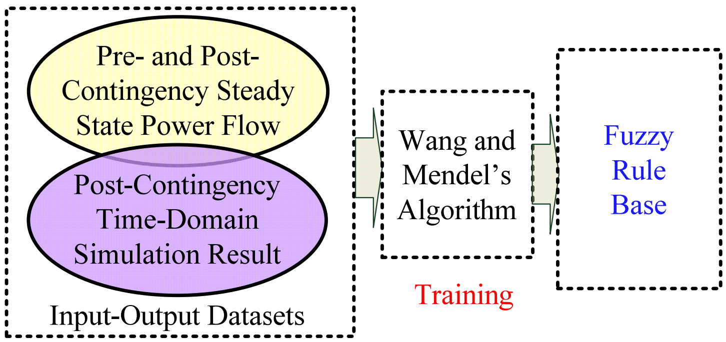
Figure 6. Steady-State Phasor Diagram

Since generator constants in Eq (1) are pre-designated data obtained through the factory test and active power, reactive power, and terminal voltage are obtained by steady state power flow, the steady state post-contingency field current can be calculated using power flow results of the contingency evaluation process.

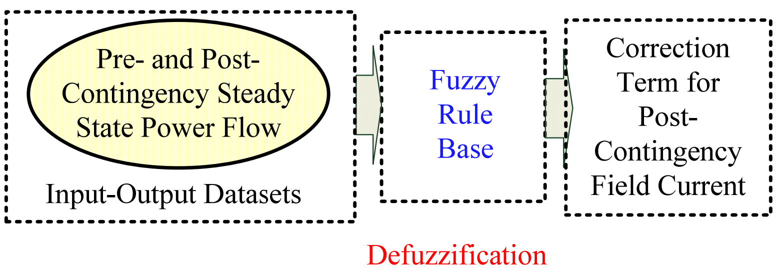
4.2 Correction of Post-Contingency Field Current

As shown in Figure 7, the proposed approach is to correct the post-contingency field current in two steps. 1) Developing a Fuzzy Inference System (FIS) using off-line time-domain dynamic simulated data, 2) Obtaining a correction term to be added to the post-contingency field current calculated using the steady state power flow. As illustrated in

Figure 7 a), a fuzzy rule base is automatically generated with specified fuzzy logic variables and membership functions. The fuzzy rule base is constructed by an adaptive learning algorithm developed by Wang and Mendel. Pre- and post-contingency steady state power flow and power flow snapshots obtained by time-domain simulations are used for the training and development of the fuzzy rule base.



a) Off-Line Approach for Constructing of the Fuzzy Rule Base



b) On-Line Environment for Application of FIS

Figure 7. FIS for Correction of the Post-Contingency Field Current

It is noted that a post-contingency power flow snapshot obtained from time-domain simulation is necessary for the development of FIS. Once FIS is developed, only pre- and post-contingency steady state power flow and post-contingency field current from steady state contingency evaluation are needed to obtain the corrected post-contingency field current.

4.3 Input and Output of FIS

The proposed FIS method is to correct the post-contingency field current based on the steady state power flow result. Hence, the output of FIS is the estimated value of the discrepancy between the post-contingency field currents obtained using time-domain simulation and steady state power flow, respectively.

The loss of heavily loaded transmission lines can cause voltage degradation at the load buses and increases the reactive power demand on the generators. A simple two-machine-one-load system shown in Figure 8 is used to illustrate the change in system conditions. Table 4 shows the pre- and post-contingency steady state power flow and the power flow snapshot obtained by time-domain simulation following a line tripping.

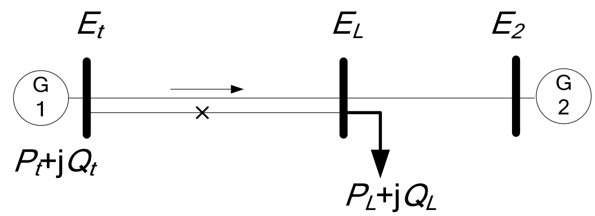


Figure 8. Two-Machine-One-Load System

Table 4. One Contingency Simulation Result

	Pt	Qt	Et	EL	PL	QL
Pre-pf	2.21	0.50	1.03	1.00	2.20	0.20
Post-pf	2.22	1.21	1.03	0.88	2.20	0.20
Post-td	2.05	0.88	1.03	0.93	2.04	0.17

All of the values are in per unit

Pre-pf: Pre-Contingency Power Flow Solution
Post-pf: Post-Contingency Power Flow Solution
Post-td: Post-Contingency Power Flow Snapshot Obtained by Time-domain Simulation

As shown in Table 4, the post-contingency terminal voltage Et and active power Pt obtained by power flow solutions are almost the same as the pre-contingency values. However, the post-contingency reactive power output of G1, Qt, is clearly higher than the pre-contingency value. The table also shows that post-contingency load bus voltage EL obtained by steady state power flow is lower than that obtained by time-domain simulation. The discrepancy can be caused by the load voltage characteristics, as shown in Eq. (4-8).

$$Q = Q_o \times \left(\frac{V}{V_o} \right)^2 \tag{4-8}$$

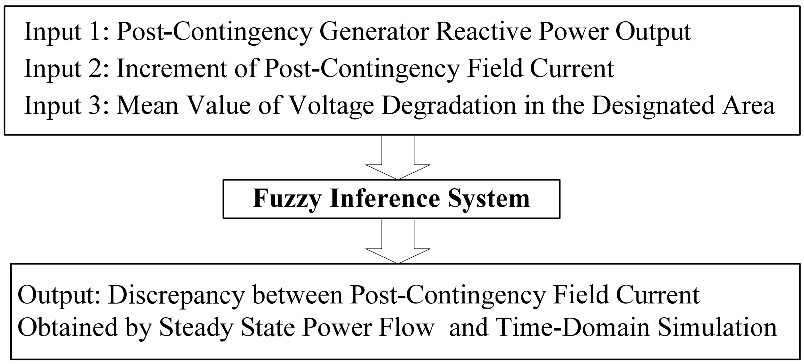
In time-domain simulation, when the load bus voltage declines due to a contingency such as a line tripping, the bus voltage degradation is mitigated by a reduction of reactive power loads, which can be seen by the load voltage characteristics. In contrast, for the steady state power flow, there is no reduction of the reactive power load as a load bus is modeled as a PQ bus. The reduction of reactive power loads can be significant at load buses near the contingency location.

The discrepancy of the reactive power models results in a difference between the generator reactive power output obtained by steady state power flow and time-domain simulation. As mentioned previously, the reactive power demand obtained by steady state power flow is not mitigated by load characteristics. The generator reactive power output obtained by steady state power flow is expected to be higher than that the value obtained by time-domain simulation. Note that the overestimated reactive power load may lead to "false alarm" when the field currents are used to identify the relays that will trip.

The discrepancies of the steady state power flow results and the time-domain simulation results exist in the generator reactive power and load bus voltages. Hence, the post-contingency generator reactive power output and the mean value of voltage degradation in the designated area are used as inputs for the FIS, i.e., input 1 and input 3 in Figure 9.

The post-contingency field current can increase from the pre-contingency value. When the increment between the pre- and post-contingency field currents obtained from power flow solutions is high, the difference of post-contingency field currents obtained from time-domain simulation and steady state power flow is also significant. Therefore, the increment of the post-contingency field current obtained by steady state power flow is used as an input, Input 2. All three inputs can be obtained from the results of on-line steady state contingency evaluation.

Figure 9. Input and output of FIS



4.4 Wang and Mendel's Algorithm

The adaptive learning algorithm proposed by Wang and Mendel provides an efficient technique for fuzzy inference systems. By Wang and Mendel's algorithm, the basic procedure to generate an FIS consists of following steps [18]:

1) Dividing the input and output spaces of the given numerical data into regions of the fuzzy variable,

2) Generating fuzzy rules from the given data,

3) Assigning a degree to each of the generated rules,

4) Combining the generated rules with linguistic rules of human experts, and

5) Determining a mapping from input space to output space using a defuzzification procedure.

The above procedure only passes through the dataset one time. Hence, time-consuming iterative training is avoided. Moreover, the membership functions are pre-defined in this algorithm. Therefore, it provides users with a higher level of flexibility.

An example of the FIS using Wang-Mendel's algorithm is given in Figure 10. In the input-output dataset, input1 Q=0.65 has a degree of 0.75 on membership function M and a degree of 0.25 on H. The input2 V_{drop}=15 has a degree of 1 on H. The output I=0.375 has a degree of 0.75 on H and a degree of 0.25 on L. As shown in Figure 10, two rules are generated from the input-output dataset. However, these two rules have the same IF part but a different Then part and therefore they are "in conflict." In this case, the rule that has a higher degree value is adopted. In this example, rule1 is adopted in the rule base because rule1 has a higher degree than rule2. By this conflict resolution procedure, the number of rules is reduced.

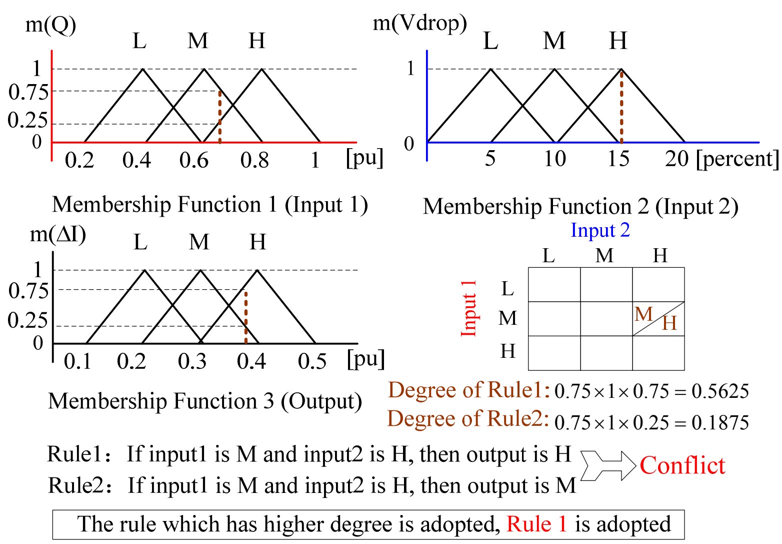
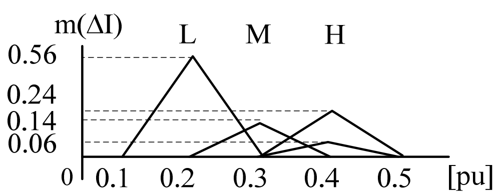


Figure 10. Example Procedure of Generating Fuzzy Rules

The centroid defuzzication method is applied to obtain the output of FIS. The output becomes a single number by calculating the center of gravity or center of area. Figure 11 shows an example of the centroid calculation procedure. In the upper right table in Figure 11, it is assumed that input1 has a degree of 0.8 on membership function M and degree of 0.2 on H. Input2 has a degree of 0.7 on M and degree of 0.3 on H. Figure 11 shows four rules that are satisfied. The degree of output mo is derived using product operation for the degree of each input. For example, for the rule: "IF input 1 is M and input2 is M, Then output is L," the degree of the rule mo is 0.56 that is derived from the product of 0.7 and 0.8. See the upper left table in Figure 11. Note that D in Figure 11 denotes the center value of the output region. (The center of a fuzzy region is defined as the point that has the smallest absolute value among all the points at which the membership function for this region has membership value equal to one.) D of membership function L equals to 0.2, D of M equals to 0.3 and D of H equals to 0.4. Consequently, the output value is 0.27 which is derived from the equation in Figure 11 which determines the center of gravity of the fuzzy sets.

Input 1 \ Input 2	L	M	H
L	L	L	L
M	L	L	H
H	M	M	H

Input 1 \ Input 2	L	M/0.7	H/0.3
L			
M/0.8		0.56	0.24
H/0.2		0.14	0.06



The Degree of the Output m_o = the Product of the Degree of Each Input

$$\text{Final Output} = \frac{\sum m_o \times D}{\sum m_o} = \frac{\begin{pmatrix} 0.56 \times 0.2 + 0.24 \times 0.4 \\ + 0.14 \times 0.3 + 0.06 \times 0.4 \end{pmatrix}}{0.56 + 0.24 + 0.14 + 0.06} = 0.2740$$

Figure 11. Example Procedure of Centroid Defuzzification

CHAPTER 5. SIMULATION RESULTS

In order to evaluate the performance of the developed FIS, a case study is performed using a 200-bus test system. This test system is a variation of the simplified model of the western inter-connection in the U.S. The demonstration in this section is based on PSS/E power flow solutions and PSS/E time-domain simulations. Four different load levels, shown in Table 5, are created by changing generation and loads. FIS is developed for correction of its post-contingency field current and is applied to the generator G43 in Figure 12.

In this research, line outages such as single line and multiple line tripping are considered. A total of 36 different line contingencies are included in the training datasets. Also, 15 load buses in the dotted square area shown in Figure 12 are selected for calculation of the mean value of voltage degradation following the contingency. Note that the line contingencies close to G43 result in a relatively high level of voltage degradation around those 15 load buses. The degradation is around 3 times higher than the average voltage degradation of the entire system.

Table 5. Training Datasets

Load Condition	V-G43(pu)	P-G43(MW)	Number of Datasets
100%Peak Load	1.05	486.0, 437.3, 388.8, 340.2 291.6, 194.4, 97.2	79
95%Peak Load	1.05		32
90%Peak Load	1.02		9
75%Peak Load	1.05		27

V: Terminal Voltage, P: Generator Active Power Output

5.1 Description of Test System

Figure 12 shows the simplified diagram of test system. Table 6 shows the specification of the system model.

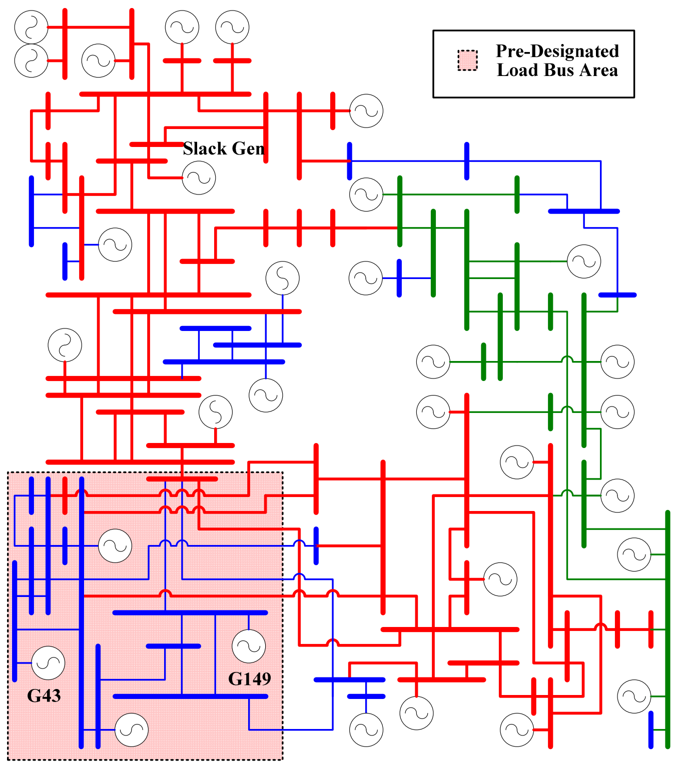


Figure 12. One-Line Diagram of The 200-Bus System

Table 6. Specification of 200 Bus System Model

Item	
Number of Buses	199
Number of Machines	31
Number of branches	229
Static Load	19816 MW
Generation	50671 MW
Reactors	8087.5 Mvar
Capacitors	4070 Mvar
Generator Control Models	AVR, PSS, GOV

5.2 Training Datasets

A total of 7 active power output levels of G43, ranging from 97.2 to 486 MW, are used to vary the field current. Note that the rated capacity of G43 is 540MVA and the rated MW output is 486MW. As shown in Table 6, the total number of the training datasets is 147. Although various MW output levels and line contingencies are used, the output values tend to be small. To enhance the performance of FIS by spreading the data points in a wider range, the logarithm function is applied to the output on the basis of Eq. (5-1).

$$LN_{Output} = -\log_e(Output + 0.05) \quad (5\text{-}1)$$

The number of membership functions of input1 is 3, the numbers of membership functions of input2, input3 and output are 7, respectively. A FIS rule base is shown in Table 7.

Table 7. Fuzzy Rule Base

Num	Input1	Input2	Input3	LN_{Output}	Output
1	L	VL	H	2.83	-0.00901
2	L	VL	VH	2.83	-0.00901
3	L	L	M-H	1.94	-0.0937
4	L	L	H	2.38	-0.0426
5	L	L-M	L-M	1.50	-0.173
6	L	L-M	M	1.50	-0.173
7	M	L	M-H	2.38	-0.0426
8	M	L	H	2.38	-0.0426
9	M	L-M	M	1.50	-0.173
10	M	L-M	M-H	1.94	-0.0937
11	M	L-M	H	2.38	-0.0426
12	M	M	L-M	1.06	-0.296
13	M	M	M	1.50	-0.173
14	M	M-H	L	1.06	-0.296
15	M	M-H	L-M	1.06	-0.296
16	H	M-H	L-M	1.06	-0.296
17	H	H	L	0.616	-0.490

LNOutput = - $\log_e$ (output+0.05), VL: Very low, L: Low, M: Medium, H: High, VH: Very high

4.2 Validation of Proposed Fuzzy Inference System

In order to verify the developed FIS, 10 contingency scenarios that are not included in the training datasets are developed. From Figure 13 and Table 8, it can be seen that the corrected post-contingency field currents by FIS are close to the post-contingency field currents obtained by time-domain simulation. The maximum mismatch between the two field currents is 4.73%.

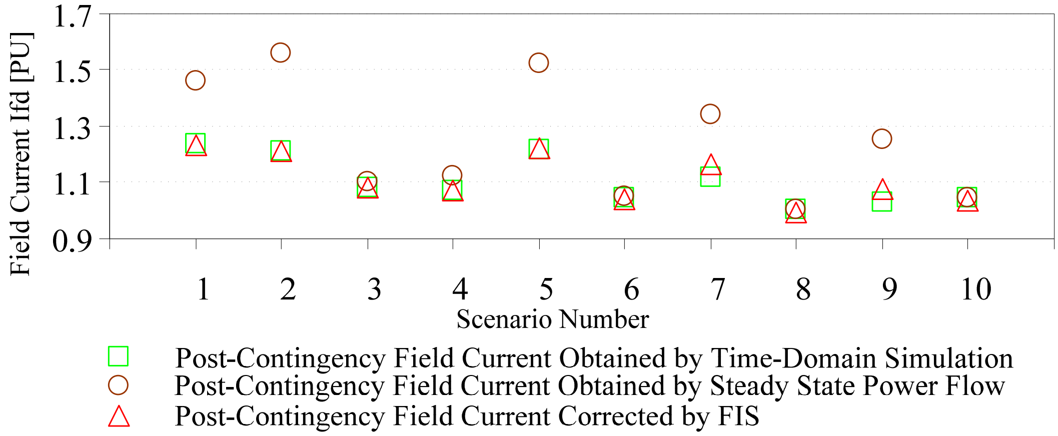


Figure 13. Corrected Post-Contingency Field Current for 10 Validation Scenarios

Table 8. Corrected Post-Contingency Field Current for Testing Scenarios

N	Input1	Input2	Input3	Output	I_{fd}-fis	I_{fd}-pf	I_{fd}-tds	ROT-fis	ROT-pf	ROT-tds	Error
1	692.0	0.46	-10.73	-0.229	1.233	1.462	1.240	67.88	29.94	64.57	-0.007
2	807.6	0.62	-13.77	-0.351	1.210	1.561	1.213	78.04	26.75	77.01	-0.003
3	351.2	0.06	-1.997	-0.024	1.080	1.104	1.080	N/A	N/A	N/A	0.000
4	424.2	0.15	-4.259	-0.052	1.069	1.121	1.073	N/A	119.6	N/A	-0.004
5	778.0	0.59	-12.84	-0.301	1.223	1.524	1.214	72.61	27.93	76.43	0.008
6	302.1	0.01	-0.284	-0.009	1.043	1.052	1.046	N/A	N/A	N/A	-0.003
7	565.3	0.30	-8.913	-0.173	1.167	1.341	1.120	98.11	47.04	120	0.049
8	292.2	0.00	-0.073	-0.009	0.996	1.005	1.005	N/A	N/A	N/A	-0.009
9	556.3	0.32	-8.810	-0.173	1.079	1.252	1.032	N/A	59.66	N/A	0.047
10	295.1	0.00	-0.070	-0.009	1.036	1.045	1.045	N/A	N/A	N/A	-0.009

N: Scenario Nunber, I_{fd}: Post-Contingency Field Current, pf: Steady State Power Flow, fis: Fuzzy Inference System, tds: Time-Domain Simulation, ROT: Relay Operation Time (in seconds), Error: The Difference of Post-Contingency Field Current Obtained by FIS and Time-Domain Simulation

Figure 14 shows the post-contingency field current and the corresponding field over-current relay operating time for the first validation scenario. Note that the relay operating time obtained by time-domain simulation is 64.6 seconds after the line contingency, while the relay operating time obtained by steady state power flow is 29.9 seconds after the line contingency. The relay operating time corrected by FIS is 67.9 seconds after the line contingency. Thus, the relay operating time can be corrected properly through the proposed FIS.

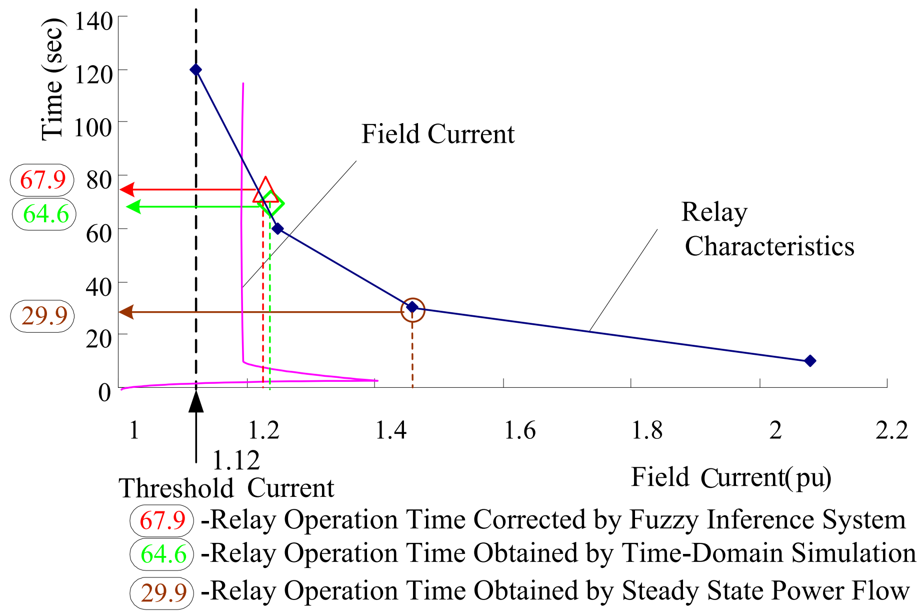


Figure 14. Validation Scenario 1

Figure 15 shows the post-contingency field current and the corresponding field over-current relay operating time for the ninth validation scenario. It can be seen that the relay operating time obtained by steady state power flow is 59.7 seconds after the contingency. On the other hand, the relay operating time obtained by time-domain simulation cannot be specified because the field current did not exceed the threshold current. The ninth scenario is critical. Without the FIS, the steady state power flow would have incorrectly predicted that this field current relay will trip.

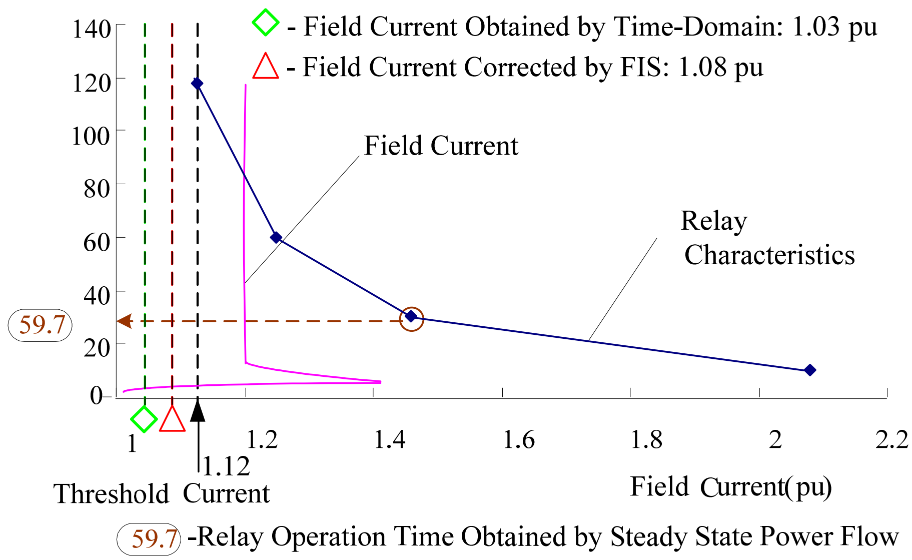


Figure 15. Validation Scenario 9

Figure 16 shows the time-domain simulation results for scenario 7. The contingency, which is a three phase to ground fault, occurs at 0 seconds in Figure 16. Following the contingency, the faulted lines are tripped after 60 ms.

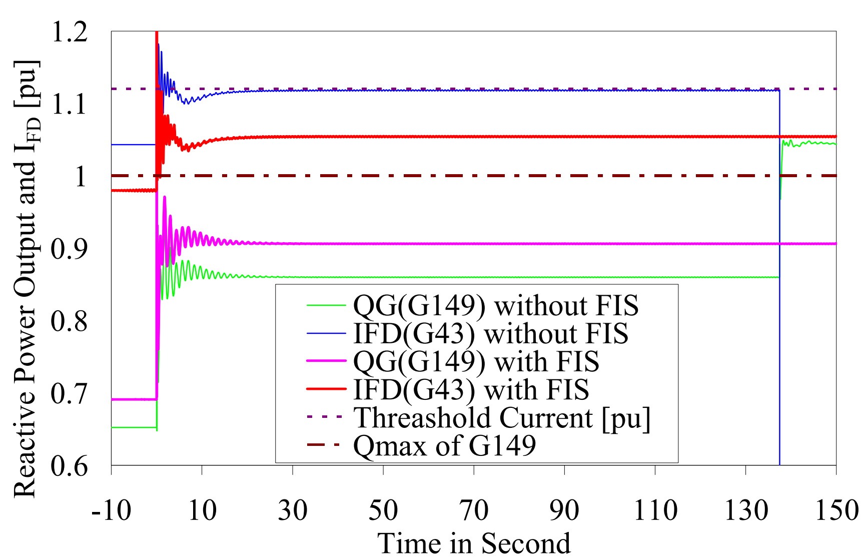


Figure 16. Simulation Results with or without FIS for Validation Scenario 7

Without the FIS, G43 is tripped at 137 seconds because the field current IFD continuously exceeds the threshold (1.12 per unit) for 120 seconds, which results in an excessive reactive power output from G149 after 137 seconds. The maximum reactive power of G149 is 1 per unit. See the alternate long and short dash line in Figure 16. If one considers the change of power system conditions such as load increases, it is highly possible that another generator (G149) would trip by the over-excitation protection.

With the FIS, the undesired G43 tripping can be prevented by reducing the terminal voltage from 1.05 per unit to 1.02 per unit. As shown in Figure 16, the field current IFD is lower than the threshold after the contingency. The reactive power output of G149 is also within the allowable range. Thus, the proposed FIS can serve as the basis for determination of the remedial actions needed to prevent undesirable generator tripping.

CHAPTER 6. CONCLUSIONS AND FUTURE WORK

In this research, the FIS technique is proposed for the identification of cascaded generator tripping events caused by field over-current relays. The proposed method is developed in the framework of on-line steady state security assessment. For a given list of next contingencies, the proposed method is developed to identify the contingencies that will be followed by cascaded generator tripping events. The FIS is based on fuzzy rules constructed automatically using off line time-domain simulation results. The FIS categorizes the detailed simulation cases into rules and allow uncertainties through fuzzy logic. The proposed FIS performs well as the rules used for correction are derived from detailed time-domain simulations.

The proposed method is based on an on-line security assessment framework. The list of next contingencies is hypothetical, i.e., they have not occurred. As a result, if appropriate, system operators have the time needed to take remedial actions to reduce the field current. Remedial actions may include generator re-dispatch or reduction of terminal voltages.

The developed FIS can easily be applied for another over-excitation protection such as armature over-current relay, because the relay characteristic of armature current is the same as the characteristics of field current relay.

Although significant progress has been made in this research, the following important issues remain to be addressed in the future work:

1. The field or armature current limiter should be examined.
2. Magnetic Saturation should be incorporated.

REFERENCE

[1] G. S. Vassell, "Northeast Blackout of 1965," IEEE Power Engineering Review, Vol. 11, Issue: 1, January 1991, pp. 4-8.

[2] "Northeast Power Failure, a Report to the President by the Federal Power Commission," Federal Power Commission, Washington, DC, Dec. 6, 1965.

[3] "The Con Edison Power Failure of July 13 and 14, 1977 (June 1978)," Available: http://chnm.gmu.edu/blackout/archive/a_1977.html.

[4] WSCC, "Western Systems Coordinating Council (WSCC) Disturbance Report for the Power System Outage that Occurred on the Western Interconnection, August 10, 1996," approved by the WSCC Operations Committee on October 18, 1996.

[5] U.S.Canada Power System Outage Task Force, Final Report on the August 14th blackout in the United States and Canada. United States Department of Energy and National Resources Canada, April 2004.

[6] NERC (North American Reliability Council) Disturbance Analysis Working Group Database, http://www.nerc.com/~dawg/database.html, 1984-2002. (Date accessed: Nov.1, 2007).

[7] C. C. Liu, J. Jung, G. T. Heydt, V. Vittal, and A. G. Phadke, "Conceptual Design of the Strategic Power Infrastructure Defense (SPID) System," IEEE Control System Magazine, Aug. 2000, pp.40-52.

[8] C. Taylor, D. Erickson, K. Martin, R. Wilson, and V. Venkatasubramanian, "WACS – Wide Area Stability and Voltage Control System: R&D and Online Demonstration," Proceedings of the IEEE, Vol. 93, No. 5, May 2005, pp. 892-906.

[9] M. G. Adamiak, A. P. Apostolov, M. M. Begovic, C. F. Henville, K. E. Martin, G. L. Michel, A. G. Phadke, and J. S. Thorp, "Wide Area Protection—Technology and

Infrastructures," IEEE Transactions on Power Delivery, Vol 22, No.2, April 2006, pp. 601-609.

[10] M. Begovic, D. Novosel, D. Karlsson, C. Henville, and G. Michel, "Wide Area Protection and Emergency Control," Proceedings of the IEEE, Vol. 93, No. 5, May 2005, pp. 876-891.

[11] M. Zima and G. Andersson, "Wide Area Monitoring and Control as a Tool for Mitigation of Cascading Failures," Probabilistic Methods Applied to Power Systems, Sept. 2004, pp. 663-669.

[12] D. C. Elizondo, J. de La Ree, A. G. Phadke, and S. Horowitz, "Hidden Failures in Protection Systems and Their Impact on Wide-area Disturbances," IEEE Power Engineering Society Winter Meeting, 2001, Vol. 2, pp. 710-714.

[13] Working Group J6 of the Rotating Machinery Protection Subcommittee, Power System Relaying Committee, "Performance of Generator Protection During Major System Disturbances," IEEE Transactions on Power Delivery, Vol 19, No.4, October 2004, pp. 1650-1662.

[14] P.Pourbeik, P.S.Kundur, and C.W.Taylor, "The Anatomy of a Power Grid Blackout - Root Causes and Dynamics of Recent Major Blackouts," IEEE Power and Energy Magazine, Sep.-Oct.2006, pp.22-29.

[15] G. Andersson, P. Donalek, R. Farmer, N. Hatziargyriou, I. Kamwa, P. Kundur, N. Martins, J. Paserba, P. Pourbeik,J. Sanchez Gasca, R. Schulz, A. Stankovic, C. Taylor, and V. Vittal, "Causes of the 2003 Major Grid Blackouts in North America and Europe, and Recommended Means to Improve System Dynamic Performance," IEEE Transactions on Power Systems, Vol 20, No.4, November 2005, pp. 1922-1928.

[16] K.Yamashita, J.Li, C.C.Liu, P.Zhang, and M.Hofmann, "Learning to Recognize Vulnerable Patterns Due to Undesirable Zone 3 Relay Operations," submitted to IEEE Transactions on Power Systems, Oct 2007.

[17] S. G. Johansson, “Mitigation of Voltage Collapse Caused by Armature Current Protection,” IEEE Transactions on Power Systems, Vol 14, No.2, May 1999, pp. 591-599.

[18] “American National Standard Requirements for Cylindrical Rotor Synchronous Generators”, C50.13-1977, p.6, 1977.

[19] L. Wang and J. M. Mendel, “Generating Fuzzy Rules by Learning From Examples,” IEEE Transactions on Systems, Man, and Cybernetics, Vol. 22, No.6, pp. 1414-1427.

ACKNOWLEDGMENT

My foremost thanks go to my major professor, Dr. Chen-Ching Liu, who provided me with his continuous support and encouragement during my research work. His high-level, insightful and technical advice was essential to the completion of this work. I am very grateful to him for giving me an opportunity to work under his great guidance.

I am also like to express my thanks to Mr. Koji Yamashita who supported me throughout my thesis work with his knowledge and patience. He is an excellent researcher and instructor to me. His guidance and suggestions were essential for the completion of this thesis.

I would like to thank Drs. Ajjarapu Venkataramana and Govindarasu Manimaran for serving on my committee. Their valuable feedback was helpful in improving the thesis.

This research is supported by Electric Power Research Institute (EPRI). Special thanks go to Dr. Pei Zhang for his valuable comments on this project. The contributions from the project team members at Bonneville Power Administration, including Mike Hofmann, Ken Martin, Anders Johnson, and Alan Courts, are acknowledged.

I also want to thank all the dear friends in the power group at Iowa State University for their friendship, encouragement and help.