PSERC

Computer Simulation of Cascading Disturbances in Electric Power Systems

Impact of Protection Systems on Transmission System Reliability
Final Project Report

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Impact of Protection Systems on Transmission System Reliability
Final Report

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Executive Summary

Hidden failures in protection systems for electric power networks can play significant roles in propagating small disturbances into wide-area disturbances. Hidden failures are incorrect operations of protection device that usually remain undetected until abnormal operating conditions occur. The objective of this research project was to investigate and demonstrate a new approach to numerical assessment of the vulnerability of a power system to hidden failures of individual relays. By identifying the most vulnerable locations in a power system, the approach identifies the protection system relays that could be upgraded to provide the greatest improvement in reliability within a constrained capital investment budget. Using parallel processing, the research advances practical use of computing resources in applying numerical techniques to protection system assessment. We examine these techniques in a case study of the New York Power Pool's (NYPP) 3000-bus system.

Through computer simulations, we analyze the impact of consecutive relaying malfunctions, and define the protection system vulnerability and reliability to numerically characterize this impact. Protection system reliability and vulnerability can be reduced if upgraded relays with lower hidden failure probabilities are put into service. By sorting all the relays according to their vulnerabilities, we can locate the most vulnerable regions in the protection system. A heuristic random search algorithm is developed for fast, rare-event simulation of cascading outages. An optimal strategy for upgrading relays is proposed for the economical enhancement of protection system reliability under a limited capital budget.

Using a 256-Processor Intel cluster at Cornell Theory Center, we simulated 41,053 NYPP blackouts that have load losses greater than 10 MW. From the simulation results, the vulnerability of each relay and the global protection system reliability are computed. The twenty-five most vulnerable relays in NYPP are identified. By solving the economic optimization problem, we determine the ten relays whose replacement can best improve the global reliability.

Lack of computational resources and of efficient algorithms have been major obstacles in studying large blackouts. For large networks, the number of different disturbance paths would be quite large. It is difficult to simulate consecutive relay failures in large-scale power systems due to their inherently small failure probabilities and to their load-flow dependent nature. The heuristic random search algorithm presented in this report only simulates each important blackout once. It computes the probability afterwards based on the underlying hidden failure models. In addition, it is impossible to simulate all the paths on one single computer. Fortunately, the simulation of an individual path is relatively independent. Therefore, parallel computers can be used to speed up the simulation. As a result, the approach produces an attractive improvement in computational efficiency.

The major contributions of this research project are:

- demonstration of the use of parallel processing with an efficient heuristic for determining the vulnerability and reliability of a protection system to wide-scale outages due to hidden failures, and
- complimentary use of optimization techniques to identify relays that could be upgraded to yield the most economical improvement in power system reliability.

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Computer Simulation of Cascading Disturbances in Electric Power Systems

1 Introduction

The restructuring of electricity industry has renewed concerns about wide-area disturbances due to their high economic and social costs. Recent studies show that power protection systems can play significant roles in triggering and spreading these disturbances. The redundancy and over-protection in the current protection design, while preventing individual hardware damage, tends to promote hidden failures in relays, propagate long-chain disturbances and, as a result, compromise global reliability. Hidden failures, in this context, denote the incorrect operations that usually remain undetected until abnormal operating conditions are reached. The National Electric Reliability Council (NERC) has identified major electric disturbances involving six to seven of such unlikely events. In order to thoroughly understand power system disturbances, we need to study the hidden failures in the power protection systems and their impact on the global system reliability.

Current designs of protective relays have a bias toward dependability at the cost of global security. Hidden failures are the natural result of this design philosophy. Thorp et al. first analyzed the hidden failures in a variety of protective relays [1]. In this report, the vulnerability of each individual relay and the protection system reliability are defined to quantify the study of a hidden failure's impact on the global power system.

Lack of computational resources and of efficient algorithms have been major obstacles in studying large blackouts. It is difficult to simulate consecutive relay failures in large-scale power systems due to their inherently small failure probabilities and to their load-flow dependent nature. Bae et al. applied the technique of Importance Sampling to simulate the cascading outages leading to power system blackouts [2]. Importance Sampling, however, is not the most efficient algorithm for the simulation of hidden-failure chains because it needs to simulate each sample blackout more than once to estimate the blackout's probability. In contrast, a heuristic random search algorithm presented in this report only simulates each important blackout once. It computes the probability afterwards based on the underlying hidden failure models.

To appropriately manage the risk of wide-scale outages in a restructured power industry, it is crucial to review the current protection philosophy and investigate the feasibility of improving system reliability through partial protection system upgrades. Although the benefits of installing advanced relays are obvious, the question of where to put them cannot be easily answered without a detailed vulnerability analysis of the bulk power system. Bae et al. conducted the early simulation work on finding the most vulnerable locations and suggested that upgrading relays at these sites can significantly increase the global reliability [2]. The case study of the New York Power Pool (NYPP) presented in this report shows that a better solution exists. Under a limited capital expenditure budget, relays should be selected for upgrading to maximize global protection system reliability. Hence, the optimal solution can be found by solving an optimization problem.

The above techniques are applied to simulate cascading disturbances in the NYPP 3000-bus system. The objective is to pinpoint the most vulnerable locations in a real power system, numerically characterize the vulnerability, and find the most economical protection system upgrading solution.

Section 2 reviews the hidden failures, and defines the vulnerability and reliability. Section 3 presents the heuristic random search algorithm. Section 4 describes the method on how to find the optimal system upgrading solution. The case study of the NYPP system is then presented in Section 5.

2 Vulnerability and Reliability

While the modern relays operate securely during most of their lifetimes, they do occasionally experience hidden failures triggered by neighbor faults and may incorrectly remove equipment from the system. Such hidden failures have a great impact on the reliability of the protection system. Chains of consecutive relay failures may isolate buses, separate transmission networks, and lead to serious power system blackouts. As Bae reviewed in her research [3], there exists a strong correlation between major blackouts and relay failures in the United States. The six major power system blackouts that occurred in 1965, 1977, 1996 and 1998 notably involved incorrect relay operations.

To quantify the impact of hidden failures, we must first mathematically model them and then incorporate them into the simulation of electric blackouts. Bae el al. introduced stochastic models of two major types of hidden failures: line-protection hidden failures and voltage-based hidden failures [2].

Characteristic curves of line-protection hidden failures are plotted in Figure 1. The stereotypical curves illustrate the reduction in the probability of a hidden failure when a new or "upgraded" relay is installed. As noted later, the presumed reduction is 50% for the new relay curve. As shown in the figure, in line-protective relays, the probability of hidden failure P_{line} remains relatively constant as long as the impedance Z seen by the relay is less than three times the zone three setting Z_3. Beyond that boundary, however, it decreases exponentially as:

$$P_{line} = P_0 \cdot \exp(-Z / Z_3) \qquad (1)$$

Since the impedance Z seen by the relay depends on the load flow, P_{line} has to be recalculated each time after the system is changed. During the simulation, Z_3 is

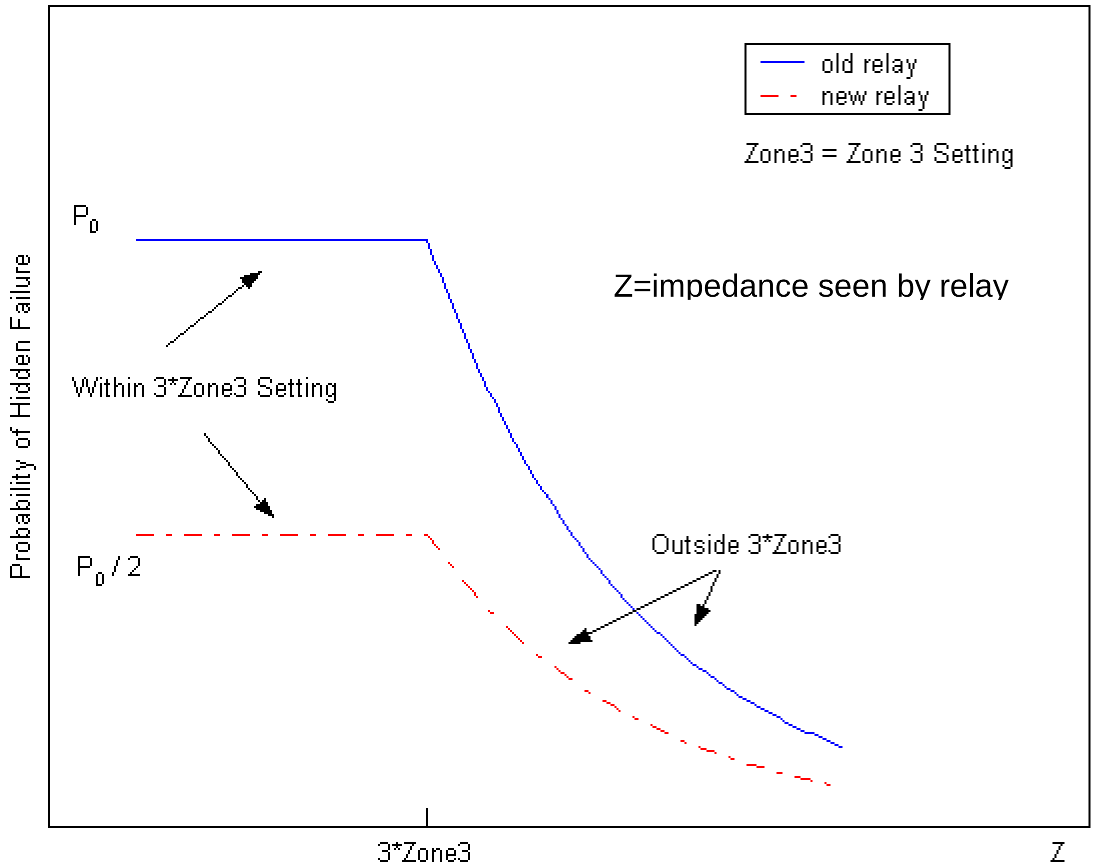

Figure 1: Hidden Failure Probability in a Line-Protective Relay

usually set to 80% of the local line's impedance plus 120% of the neighbor line's impedance.

At the generator bus, if the bus voltage violates

$$|V_{\min}| < |V| < |V_{\max}| \quad (2)$$

then a voltage-based hidden failure is exposed. Voltage-based hidden failures can trip generators and expose neighbor hidden failures. In simulations, it is more convenient to gauge the voltage-based hidden failure using VAR limits. As illustrated in Figure 2, the probability of incorrect generator tripping P_{gen} follows the following model:

$$P_{gen} = \begin{cases} P_{low} & Q_{\min} \le Q \le Q_{\max} \\ P_{high} & Q < Q_{\min} \text{ or } Q > Q_{\max} \end{cases} \quad (3)$$

Again, P_{gen} is load flow dependent and has to be recalculated whenever the load flow is changed.

Figure 3 illustrates how consecutive relay failures evolve to a system-scale blackout in a simple 5-bus network. At first, line-protective relays trip line 3 legitimately due to some natural disturbance. This relay operation exposes relays on lines 2 and 4 to line-protection hidden failures. At the same time, the generator-protective relay at bus 2 is exposed to voltage-based hidden failures due to the VAR limit violation. As in Figures 1 and 2, these exposed relays are subject to possible incorrect operations. Suppose the generator at bus 2 is tripped incorrectly. Then, relays on lines 1 and 2 are exposed in the next stage. Incorrect tripping of line 1 may further trigger the hidden failures of line-protective relays on line 4 and lead to a system-wide blackout as shown in the figure.

Consider a blackout B_i that involves a chain of N_i consecutive exposures of hidden failures. Among the N_i exposures, suppose n_i hidden failures lead to false relay operations. The overall probability P_{B_i} of this blackout B_i would be

$$P_{B_i} = \prod_{j=1}^{n_i} P_{ij} \prod_{j=n_i+1}^{N_i} (1 - P_{ij}) \tag{4}$$

where P_{ij} is the probability of each individual exposed hidden failure being triggered. Since P_{ij} is load flow dependent, the whole process of blackout B_i has to be simulated to compute P_{B_i}.

There also exist many other blackout paths in the simple 5-bus network. All the possible blackouts caused by hidden failures should be considered in evaluating the reliability of the protection system.

Bae adopted the following NERC definition of a blackout [3]:

1. For utilities with previous year's peak load greater than 3,000 MW, the loss of 300 MW of load for more than 15 minutes;
2. For utilities with previous year's peak load less than 3,000 MW, the loss of 200 MW or 50 % of load for more than 15 minutes;
3. Load shedding more than 100 MW;
4. Continuous interruption greater than 3 hours to 50,000 customers or more than 50% of total customers served;
5. Voltage reduction greater than 3%;
6. Public appeals to reduce consumption;
7. Sabotage or vandalism; or
8. Disturbances beyond the control of the utilities such as natural disasters are not included in the report.

Smaller disturbances, however, might be triggered more frequently and should not be neglected. Any disturbances with load loss will be considered as a blackout in this report. The expected load loss, which will be defined later, is a more appropriate indicator of the size of disturbances.

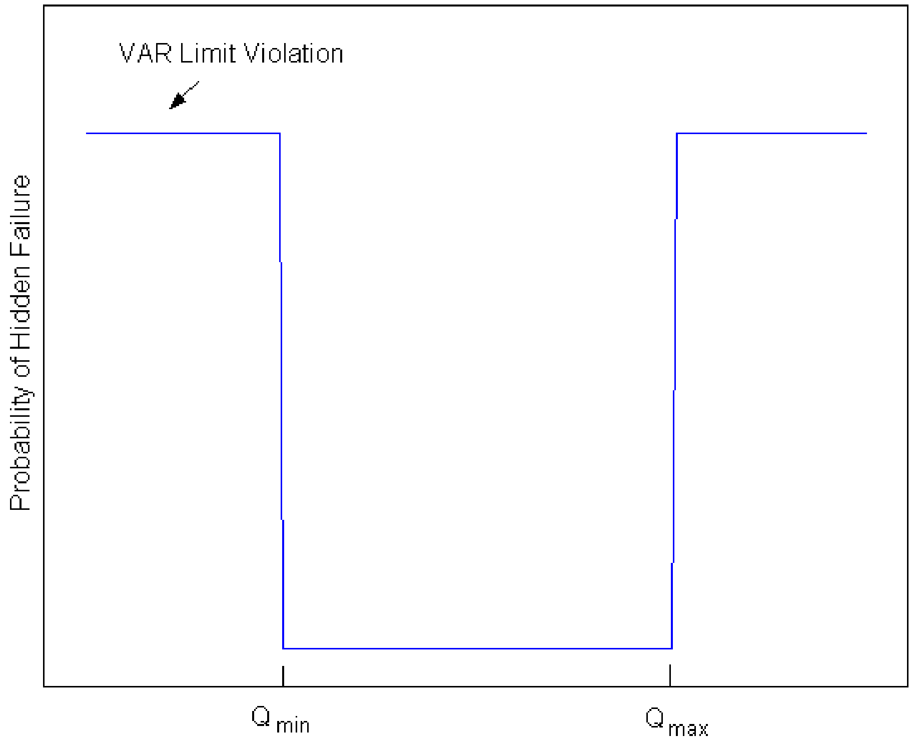

Figure 2: Characteristic of Voltage-Based Hidden Failures

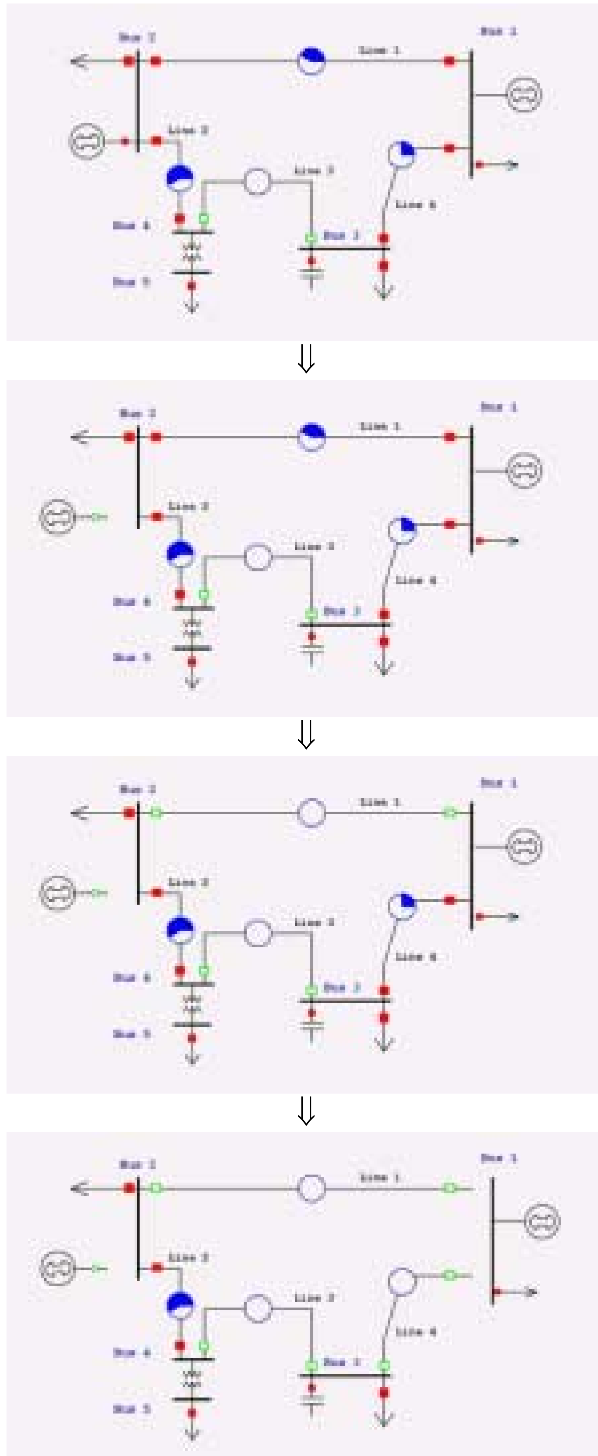

Figure 3: Evolution of Power System During Cascading Disturbances

We need some quantifiable parameters to evaluate each hidden failure's impact on the global system. Let $U = \{B_1, B_2, B_3, ..., B_M\}$ be the complete set of all blackout paths and C_i be the load loss associated with the blackout path B_i. The expected load loss of B_i is defined as:

$$E(L_i) = P_{B_i} \cdot C_i \tag{5}$$

Suppose all initiating events in the power system have the same frequency F^0. Then, the overall expected load loss per unit time $E(L)$ can be calculated as

$$E(L) = \sum_{i=1}^{M} (F^0 P_{B_i} C_i) = \sum_{i=1}^{M} \left(F^0 C_i \prod_{j=1}^{n_i} P_{ij} \prod_{j=n_i+1}^{N_i} (1 - P_{ij}) \right) \tag{6}$$

$1/E(L)$ reflects the global reliability of protection systems. However, since F^0 depends on external system conditions, it should not appear in the definition of global protection system reliability. In addition, C_i must be normalized to account for the difference among different power systems. Hence, the global protection system reliability η is defined as

$$\eta = G \Bigg/ \sum_{i=1}^{M} \left(C_i \prod_{j=1}^{n_i} P_{ij} \prod_{j=n_i+1}^{N_i} (1 - P_{ij}) \right) = F^0 G / E(L) \tag{7}$$

where G is the total system load.

Similarly, let V_k be the subset of U that contains all blackout paths involving relay R_k. We quantify the vulnerability υ_k of relay R_k as:

$$\upsilon_k = \sum_{V_k} \left(C_i \prod_{j=1}^{n_i} P_{ij} \prod_{j=n_i+1}^{N_i} (1 - P_{ij}) \right) \Bigg/ G \tag{8}$$

To calculate the reliability and vulnerability, all blackout paths in U have to be simulated. Since P_{ij} is load flow dependent, the system status must be recalculated after each system change during the simulation. For a large power system, the work of simulating all possible blackouts could be prohibitive. The size of U grows exponentially with the size of the network. In such cases, η and υ_k can be estimated by simulating the most significant subset of blackout paths.

The reliability and vulnerability are defined here to evaluate the effect of hidden failure chains. They may not fit in other contexts.

3 Simulation Algorithms

1. Island Detection and Isolation

Cascading disturbances sometimes create multiple islands in an electric transmission network. In real systems, an individual island usually continues to operate independently unless it is too small to sustain the disturbances. This section introduces an algorithm based on the BFS algorithm from graph theory for island detection and isolation.

Figure 4 illustrates the islanding problem. The loss of line B-F separates the graph A-B-C-D-E-F-G-H into two islands: A-B-E and C-D-F-G-H. Starting from B, only A and E are reachable. And similarly, starting from F, only C, D, G and H are reachable. Therefore, two separate breadth-first searches, starting from B and F respectively, can reveal what the two islands are.

Given a graph $G = (V, E)$ and two different source vertices S_1 and S_2, the algorithm tries to use the BFS-like algorithm to determine the connectivity between S_1 and S_2. It explores the edges of G to discover every vertex that is reachable from S_1 and every vertex reachable S_2. Two separate "breadth-first trees" that contain all reachable vertices are created on the fly in parallel. One root is at S_1, and the other root is at S_2. Nonempty intersection between the two trees implies that S_1 and S_2 are still connected to each other. Therefore, the algorithm should abort as soon as it finds out the nonempty intersection during the search.

The algorithm is given below. Ideas are borrowed from the BFS algorithm described in [4].

```
MARK S1 and S2
CREATE a queue Q1 ← {S1} and a set T1 ← {S1}
CREATE a queue Q2 ← {S2} and a set T2 ← {S2}
While Q1 ≠ ∅ and Q2 ≠ ∅
      Do u1 ← head[Q1]
          For each v1 ∈ Adj[u1]
             Do If v1 is not marked yet
                     Then MARK v1
                          ENQUEUE(Q1, v1)
                          INSERT(T1, v1)
      DEQUEUE(Q1)
      Do u2 ← head[Q2]
          For each v2 ∈ Adj[u2]
             Do If v2 is not marked yet
                     Then MARK v2
                          ENQUEUE(Q2, v2)
                          INSERT(T2, v2)
      DEQUEUE(Q2)
      If T1 ∩ T2 ≠ ∅
        Then RETURN S1 and S2 are connected
If T1 ∩ T2 ≡ ∅
Then RETURN G is separated into two islands: T1 and T2
```

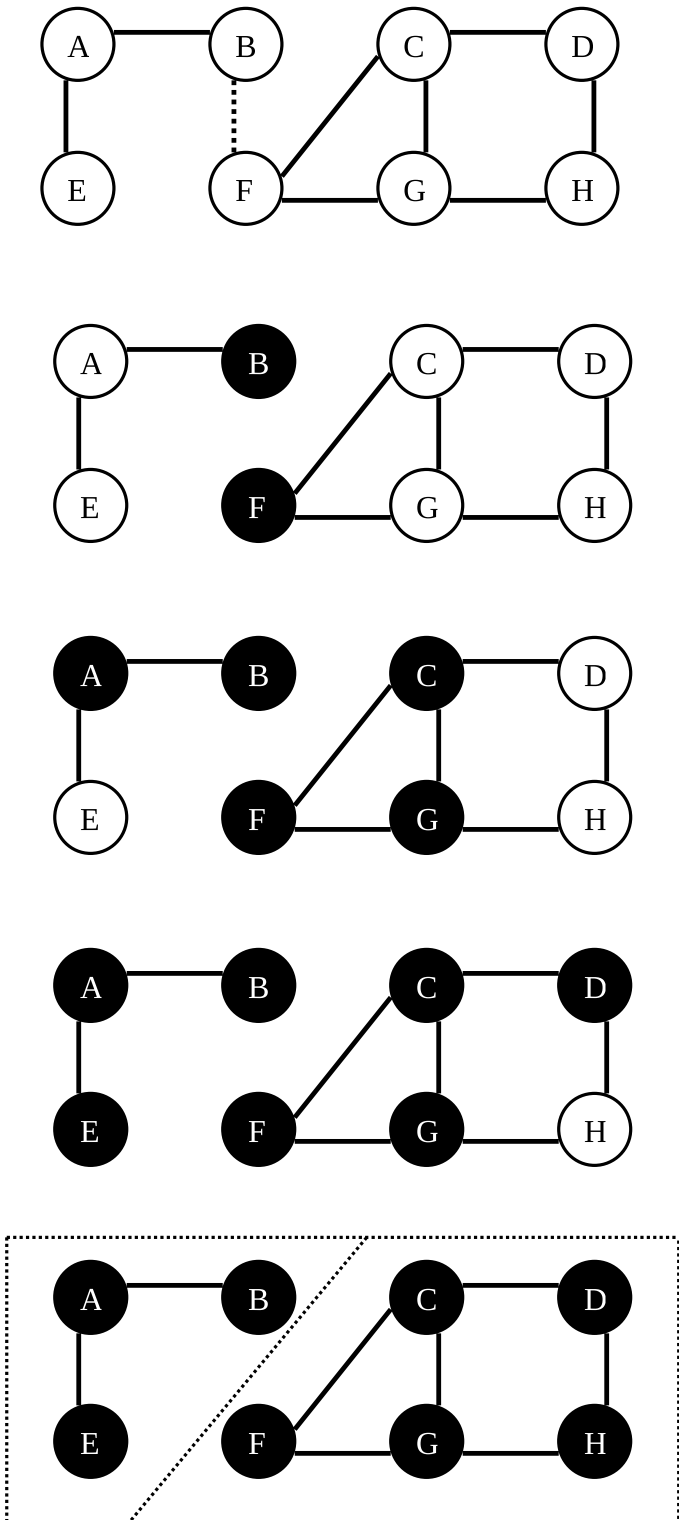

Figure 4: Two-Way BFS Search to Detect Islands

2. Simplified Load Shedding Method

In an ideal power system, total generation equals total load and the system runs at a fixed frequency (60 Hz in the U.S.). Cascading disturbances, however, can break this balance sometimes. For example, they might create multiple islands, isolate generators, or cut load. In these situations, actions must be taken to prevent frequency-related damage. Under-frequency relays are designed to maintain the frequency above the resonant frequency of generators. Usually when people study power system dynamics, they use a series of differential equations to simulate the frequency changes and take appropriate actions to bring frequency back to 60 Hz.

The simulation of cascading disturbances, however, focuses on studying the static behavior of power systems. The Newton-Raphson method is applied to solve the static load flow. Therefore, the process of load shedding is not important to us, as long as we can get a solution for the resulting system; i.e. load is reduced rationally and the system is brought back to balance. The algorithm used to simulate load shedding is:

- Calculate total load, total generation and their ratio;
- Simulate the changes on the system;
- Calculate the new total load, total generation and their ratio;
- Reduce load (or generation) homogeneously at each bus to maintain the old load/generation ratio;
- Solve the new load flow; and
- Update total load, total generation and load/generation ratio.

3. Parallel Simulation of Cascading Disturbances

For large networks, the number of different disturbance paths might be huge. In addition, it is impossible to simulate all the paths on one single computer. Fortunately, the simulation of an individual path is relatively independent. Therefore, parallel computers can be used to speed up the simulation.

As we will see in the Heuristic Random Search algorithm, different threads of simulations do need to share and update some common information. The following Master-Slave Model is adopted for parallel simulation of cascading disturbances:

Master:

1. Initialize common simulation parameters ($E_{\min}(L_i)$, $D_{\max}$, etc., see Heuristic Random Search Algorithm)
2. Broadcast parameters to all slaves;

3. **While** (*Heuristic Random Search IS NOT FINISHED*)
4. Listen to slaves:
    a. Create new thread to deal with slave request; Parent thread return to Step 4
    b. Process information from the slave, and update the shared parameters
    c. Kill this child thread

Slave:

1. Listen to the master and get the shared parameters
2. **While** (*Heuristic Random Search IS NOT FINISHED*)
3. Simulate individual disturbance
4. Send new path information to the master

4. Heuristic Random Search Algorithm

Bae et al. simulated the power system blackouts introduced by hidden failures using the technique of Importance Sampling [2]. Although Importance Sampling can significantly speed up the rare-event simulation, it still spends most of the computation resource in generating the same set of samples repeatedly to maintain its unbiased distribution. To calculate the vulnerability and reliability, however, we only need to simulate each important blackout path in U once. The probability of each path, instead, can be computed separately, as in Equations 1, 2 and 4, based on the underlying stochastic models of hidden failures. Therefore, the simulation should focus on searching new important blackout paths and try to eliminate the repetition of samples as much as possible. A random search approach is developed based on power system heuristics to accomplish this goal.

The transmission network can be studied as a graph. In the graph $G = (V, E)$, the vertex $u \in V$ corresponds to the bus in the power system and the edge $(u, v) \in E$ corresponds to the transmission line. Power system disturbances usually spread through the transmission network in one dimension. Therefore, a series of relay faults leading to blackouts is equivalent to a path between two vertices in G. The hidden failure chains and their relations are depicted in the blackout-tree shown in Figure 5. In the blackout-tree, each node denotes a false relay operation. Multiple nodes along the same path compose a hidden failure chain having probability P_{B_i} and associated loss C_i. Our task is to efficiently find the most significant paths in the blackout-tree that have both high probabilities and large amounts of load loss.

In the blackout-tree, hidden failures are simulated along every major blackout path starting from the root. A depth-first search algorithm is applied to walk through the tree because it does not need to store system information of other paths, while the breadth-first search algorithm requires hundreds of thousands of power system snapshots for the instant recovery of simulation along other paths. At each node, the new power flow and new hidden failures are recomputed. The subpath of a blackout path is also a blackout path. In other words, each intermediate node may also be the last event of another blackout path. Therefore, the cumulative path probability and overall load loss should be updated and recorded at each node along the blackout path. Next, the simulation either continues the search along the same path at further depth or restarts from the root. As mentioned earlier, the spread of disturbances is one-dimensional; i.e., only one event can happen each time. Hence, we uniformly rescale the probabilities of exposed hidden failures to let one and only one of them be triggered. The algorithm counts on the underlying stochastic process to choose the most promising search direction.

Still, the simulation must return to the root for a restart at the appropriate time. Bae et al. applied the definition of a NERC major disturbance as the terminating criterion for the simulation along any single blackout path [2]. However, blackouts at further depth in the tree have larger load losses. Our statistical analysis of blackout samples generated from the NYPP 3000-bus system simulation shows that load loss grows proportionally with the blackout's depth in the tree. Some of these larger blackouts may contribute significantly to global reliability and vulnerability, and therefore should appear in our simulation. On the other hand, Equation 4 implies that the paths sprawling deeper into the tree have smaller associated probabilities. In most cases, the path probability decreases with the depth faster than the loss increases. The expected load loss $E(L_i) = P_{B_i} \cdot C_i$ will get smaller in the long-run. Therefore, the favorite nodes locate in a range near the top of the tree. Blackout paths within this range play a dominant role in Equations 7 and 8. During the simulation, we can gauge the range by two empirical parameters: the minimal expected loss $E_{\min}(L_i)$ and the maximal depth of search $D_{\max}$. The simulation returns to the root whenever the depth is getting bigger than $D_{\max}$ or the expected loss becomes less than $E_{\min}(L_i)$. $D_{\max}$ is set to a large value to ensure that no important hidden failure chain will be missed. $E_{\min}(L_i)$ is initially set to zero. However, after each restart during the simulation, it is dynamically updated to one-half of the average expected loss of those significant blackouts already generated. Here, significant blackouts are defined as the blackouts having large expected load loss. By doing so, the simulation will eventually focus on searching paths in the interested range.

The algorithm is listed below in detail:

1. Set $E_{\min}(L_i)$ and $D_{\max}$ to 0 and 50 respectively. (The two values are empirical and might be different in other cases.)
2. Terminate the simulation if enough blackout sequences have been collected. (If significant portions of blackout paths have been simulated more than once, terminate the simulation.)
3. Update the minimal expected loss $E_{\min}(L_i)$ to one-half of the average expected loss of the significant blackouts already generated. (The definition of significant blackouts can be different from case to case. But in general, significant blackouts have large expected loss.)
4. Calculate the base load flow using Netwon-Raphson method before any change is made on the system.

5. Randomly select the initial transmission line to be tripped. (This event acts as the root of the blackout-tree.)
6. Determine all the exposed hidden failures and calculate their probabilities according to (Equations 1 and 2).
7. Check the transmission limits and generator VAR limits. Trip the overloaded transmission lines. Switch the working modes of generators that violate the VAR limits.
8. If there is no limit violation in step 7, proportionally rescale the probabilities of exposed hidden failures to trigger one and only one of them.
9. Check the connectivity of the network.
10. Fork the simulation if the system breaks into multiple islands and simulate each of them separately.
11. Determine all the exposed hidden failures and calculate their probabilities according to (Equations 1 and 2).
12. Check the transmission limits and generator VAR limits. Trip the overloaded transmission lines. Switch the working modes of generators that violate the VAR limits.
13. Determine all the exposed hidden failures and calculate their probabilities according to (Equations 1 and 2).
14. Check the transmission limits and generator VAR limits. Trip the overloaded transmission lines. Switch the working modes of generators that violate the VAR limits.
15. If there is no limit violation in step 7, proportionally rescale the probabilities of exposed hidden failures to trigger one and only one of them.
16. Check the connectivity of the network.
17. Fork the simulation if the system breaks into multiple islands and simulate each of them separately.
18. Track the frequency and shed the load if necessary.
19. Record the current node if its associated expected loss is nontrivial among the blackout paths already generated.
20. Return to step 2 to restart the search, if the current expected loss is decreasing and reaches the minimal expect loss $E_{\min}(L_i)$.
21. Return to step 2 to restart the search, if the current depth becomes larger than $D_{\max}$.
22. Compute the new load flow using Newton-Raphson method.
23. On success of step 15, return to step 6 to continue searching the nodes at greater depth.
24. Otherwise, the system is getting ill-conditioned. Return to step 2 to restart searching from the root.

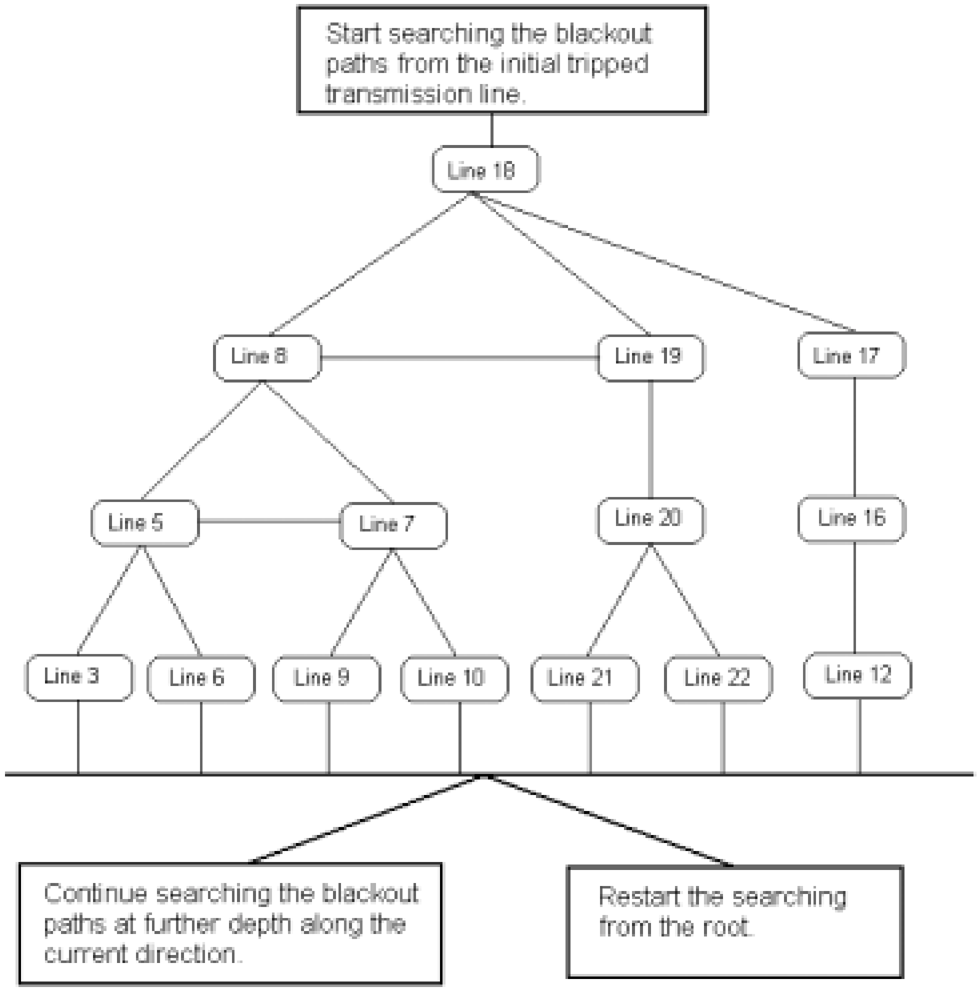

Figure 5: Illustration of Heuristic Random Search Algorithm

4 Optimal System Upgrading

In Section 2, we have defined the global protection system reliability η and the vulnerability υ_k for each protective relay. These parameters can be estimated from the blackout samples simulated using Heuristic Random Search algorithm presented in Section 3. υ_k reflects the vulnerability of each relay in the protection systems. By sorting all the relays according to their vulnerabilities, we can locate the most vulnerable regions in the protection system. Bae et al. devised a dual-mode relaying concept that allows each individual relay's hidden failure probability to be adaptively adjusted according to the system's operating condition [5]. The vulnerabilities may be reduced if such reliable relays with lower hidden failure probabilities are put into service.

The global reliability also benefits from the installation of more reliable relays. However, changing all relays in the system is economically prohibitive. Under a limited capital budget, only a small portion of relays can be upgraded. Replacing the relays that have the highest vulnerabilities can increase the global reliability, but may not be the best solution. Alternatively, we get the optimal solution by maximizing the global reliability η as

$$\max_{Cost \le H} \eta = \min_{Cost \le H} \sum_{i=1}^{M} \left(C_i \prod_{j=1}^{n_i} P_{ij} \prod_{j=n_i+1}^{N_i} \left(1 - P_{ij} \right) \right) \tag{9}$$

where H is the capital budget. The hidden failure probability P_{ij} is recorded during the blackout simulation. We assume that all P_{ij}'s associated with new relays will be reduced by one-half. If the budget only allows K relays to be put into service, solving the optimization equation Equation 9 will yield the ideal set of relays to be replaced.

5 A Case Study of NYPP 3000-Bus System

The NYPP 3000-bus equivalent system contains 2,935 buses, 1,304 generators, 6,571 transmission lines and 457 transformers. We modeled the following key elements in our simulation of hidden failure chains:

- Generators, loads and transmission lines;
- Line-protective relays;
- Generator-protective relays;
- Phase-shift transformers;
- Switch shunt elements;
- Transmission limits;
- Generator's VAR limit; and
- Under-frequency load-shedding relays.

Using a 256-Processor Intel cluster at Cornell Theory Center, we simulated 41,053 NYPP blackouts that have lost greater than 10 MW. From the simulation result, the vulnerability of each relay and the global protection system reliability are computed as in Equations 7 and 8. Figure 6 illustrates the distribution of the most vulnerable locations in NYPP. Relative vulnerability of relay R_k is defined as

$$\upsilon_k / \max_{\forall i}(\upsilon_i) \quad (10)$$

As we can see in Figure 6, the top three most vulnerable relays locate around the Indian Point Power Plant at Buchanan while the rest distribute around NYC, Oswego and Niagara regions respectively.

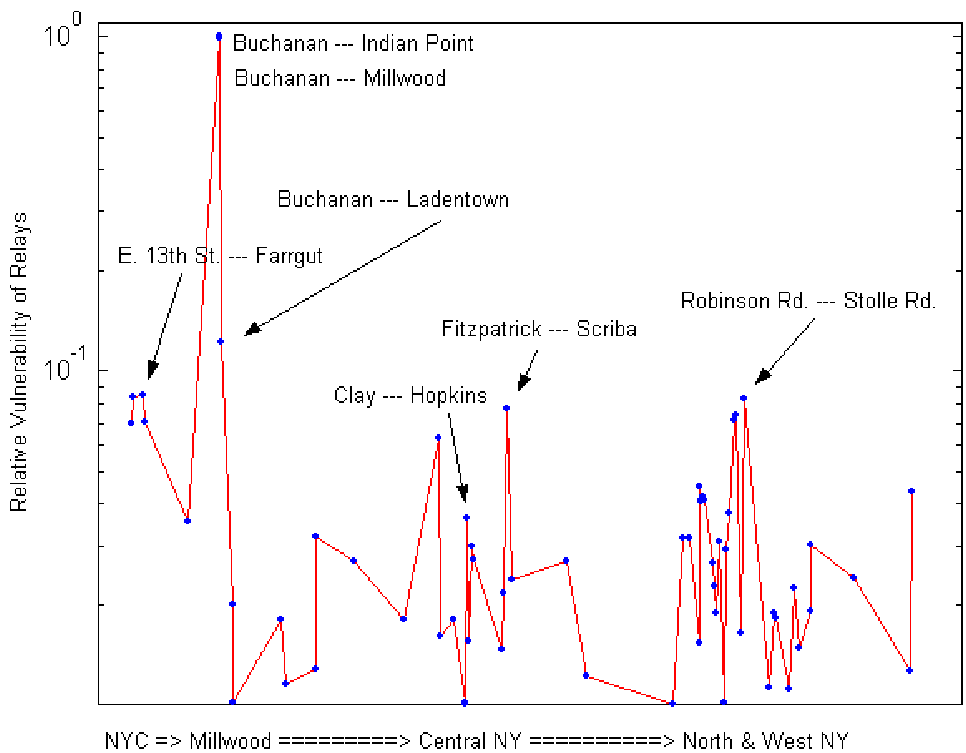

Figure 6: Locations of the Most Vulnerable Relays in NYPP

The NERC Disturbance Analysis Working Group (DAWG) Database indirectly supports our simulation and analysis [6]. For instance, the following documented disturbance is a typical one having hidden failures involved and matches well with our simulation result.

> "On Apr. 26, 1995, some shorting bars inadvertently left on a test block caused a relay to operate as if there was a breaker failure. The breaker failure scheme caused several breakers to open at the Volney Station (NYPP), and it sent a direct

> transfer trip signal to the Scriba Station to open other breakers at Scriba removing the line connecting the two stations. A phase-to-phase fault occurred at the Volney Station and it was seen correctly as a line fault by relays at Volney, and the relays opened breakers at Volney and Oswego Stations. Then a phase distance directional relay at the Clay Station misoperated and caused a breaker to open at Clay and a direct transfer trip signal was sent to Nine Mile Point No. 1 (NYPP) to open, removing the Clay-Nine Mile Point No. 1 line from service."

Figures 8a to 8h show a similar cascading disturbance generated by the simulation program. The simulated event starts from a line connected to Clay Station. Then a line to Fitzpatrick is tripped incorrectly due to hidden failure. Line between Scriba and Voley Station is then overloaded and removed. And another two lines around Scriba and Voley are tripped due to hidden failures. Finally, lines from Independence to Clay Station, from Independence to Scriba and from Clay to EDIC are overloaded. These events separate Fitzpatrick and Independence from the system. The lost generation adds up to 1,800 MW.

We shall keep in mind that this result does not necessarily reflect each relay's actual vulnerability since we have assumed that all relays exhibit the identical hidden failure characteristics and the frequency of initiating events (such as flashovers, human faults, etc.) does not change with locations.

Table 1 lists the twenty-five most vulnerable relays in NYPP and their relative vulnerabilities. They should gain more attention than other relays when planning a protection system upgrade. By solving the optimization problem in Section 4, we get the ten relays in Table 2 whose replacement can best improve the global reliability. They are quite different from the top ten in Table 1. Their improvements over the original system are compared in Figure 8. In both cases, the major improvement comes from the new relays at Indian Point. However, their difference is still significant. In general cases where many relays have similar vulnerabilities, the optimal solution is expected to yield a much better improvement.

An even better solution exists if the hidden failures can be reduced more than one-half by upgrading more relays. For example, in the NYPP system, the global reliability will be further increased if the hidden failures around Indian Point can be reduced to one-quarter or less.

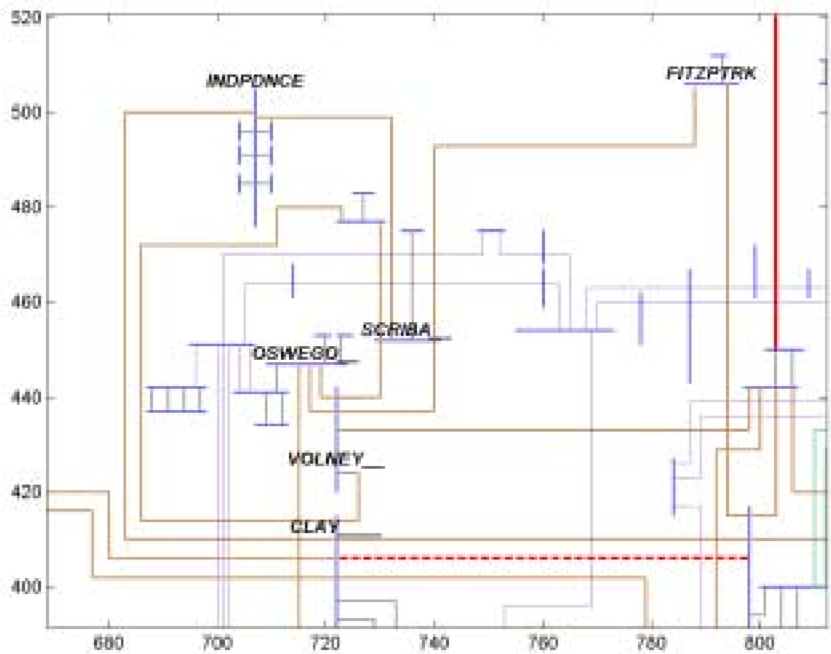

Figure 7a: A Simulated Cascading Disturbance in NYPP

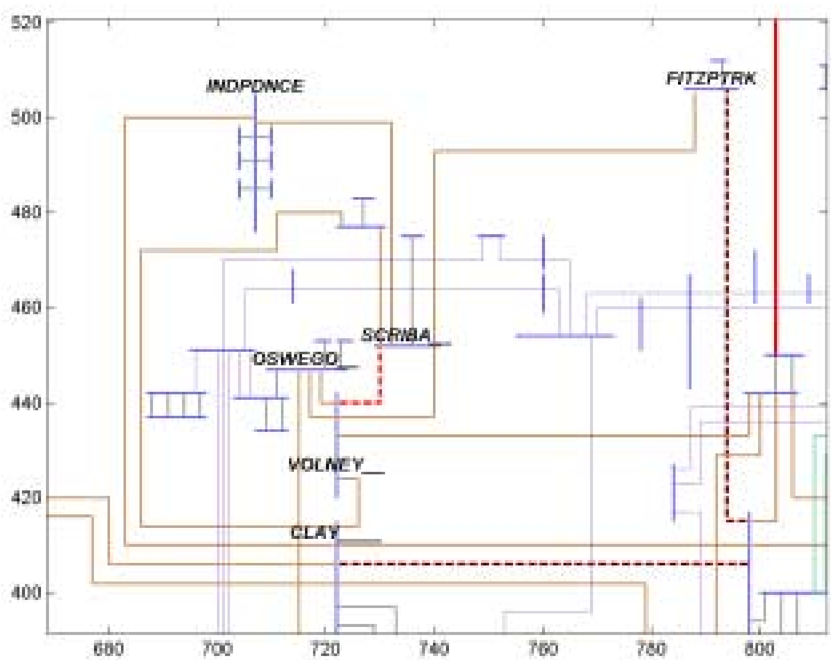

Figure 7b: A Simulated Cascading Disturbance in NYPP

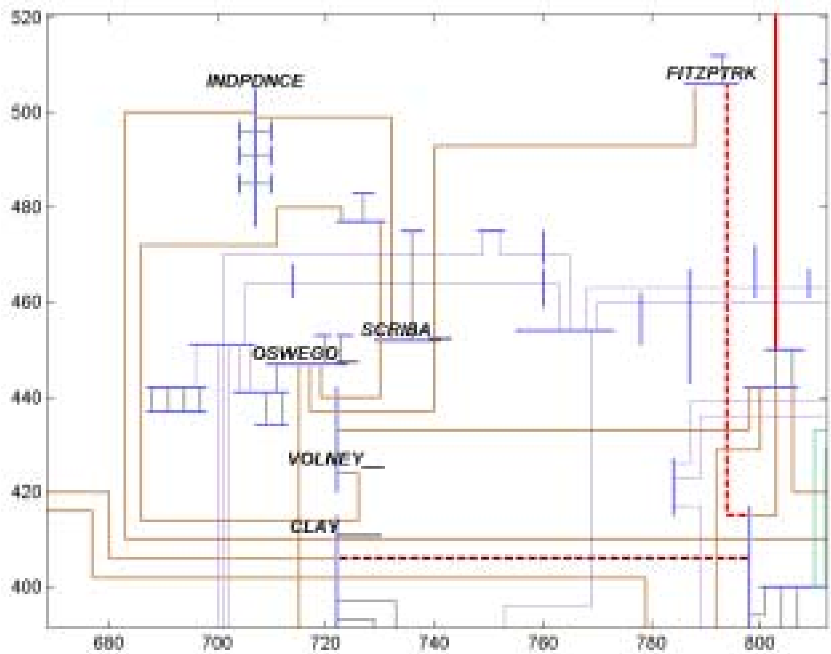

Figure 7c: A Simulated Cascading Disturbance in NYPP

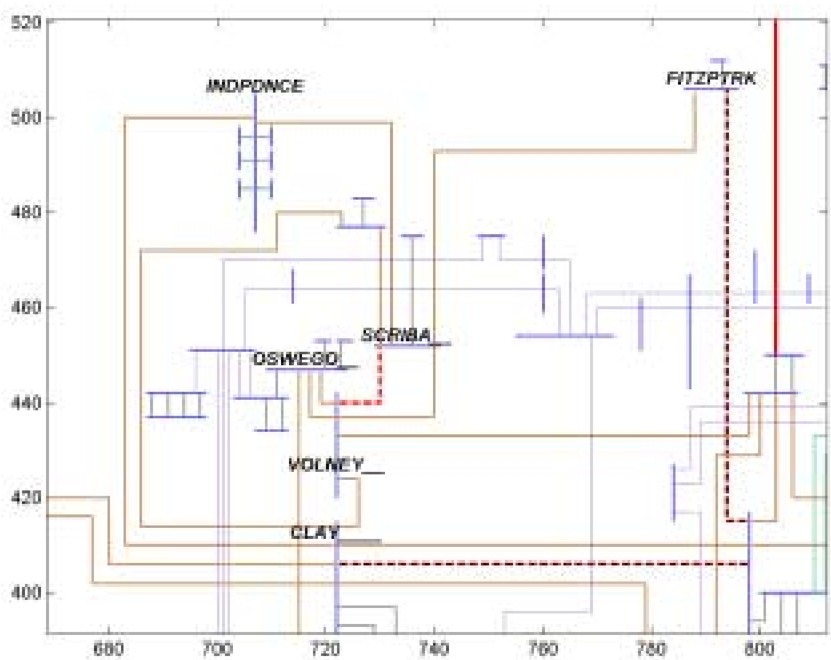

Figure 7d: A Simulated Cascading Disturbance in NYPP

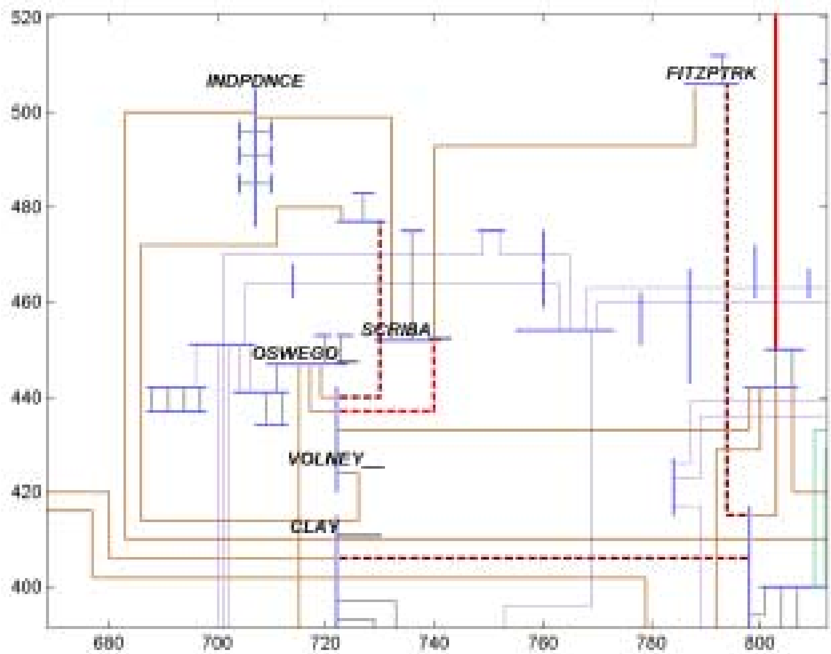

Figure 7e: A Simulated Cascading Disturbance in NYPP

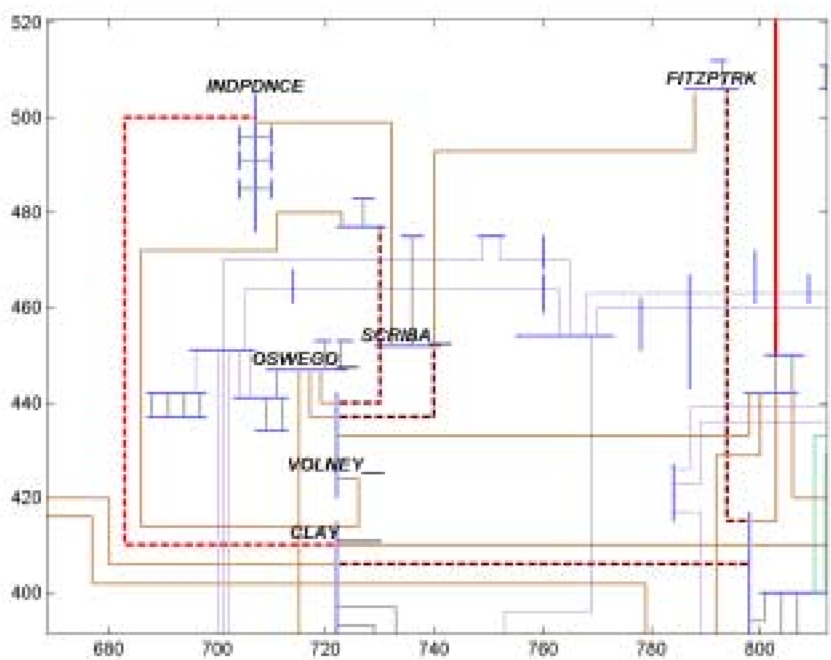

Figure 7f: A Simulated Cascading Disturbance in NYPP

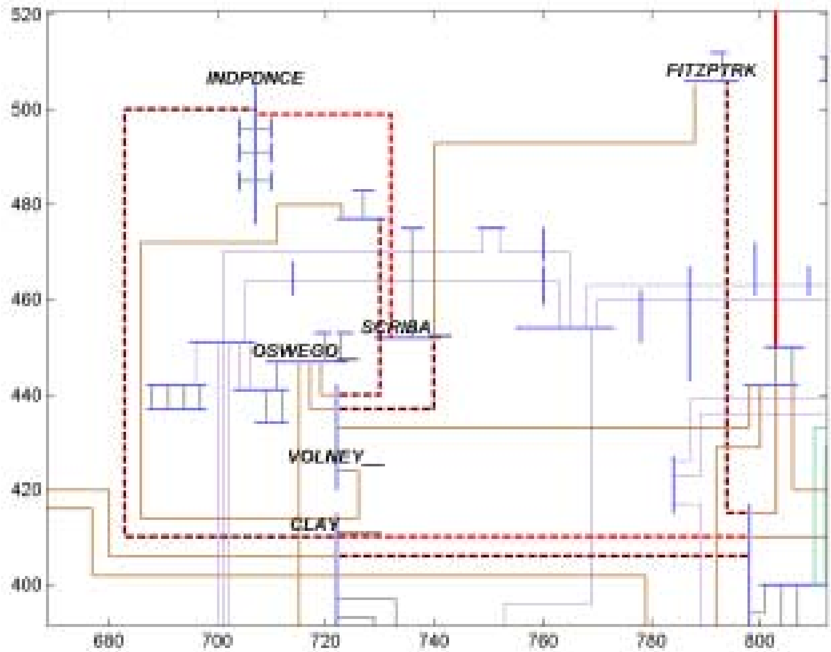

Figure 7g: A Simulated Cascading Disturbance in NYPP

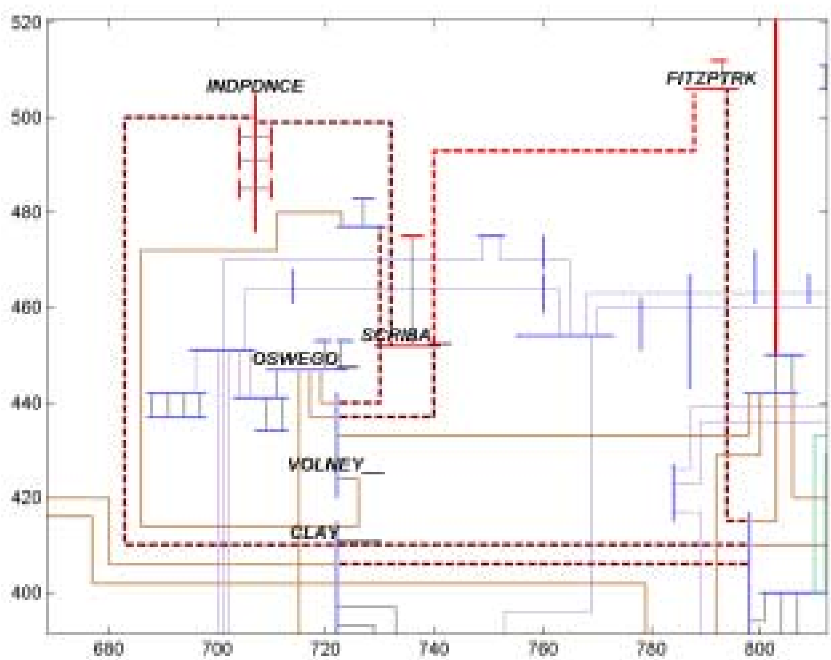

Figure 7h: A Simulated Cascading Disturbance in NYPP

Table 1: List of Most Vulnerable Relays in NYPP

Line No.	Bus from	Bus to	Zone	Relative Vulnerability
0127	BUCHANAN	INDIAN POINT	MILLWOOD	1.000
0126	BUCHANAN	MILLWOOD	MILLWOOD	0.993
0128	BUCHANAN	LADENTOWN	MILLWOOD	0.122
0047	E. 13TH ST.	FARRAGUT	N.Y.C.	0.084
0036	HELLGATE	W. 179TH ST.	N.Y.C.	0.084
0673	ROBINSON RD.	STOLLE RD.	WEST	0.082
0426	FITZPATRICK	SCRIBA	CENTRAL	0.078
0664	DAVIS RD.	STOLLE RD.	WEST	0.074
0663	HARRISON RADIATOR	HINMAN	WEST	0.071
0048	W. 179TH ST.	DUNWOODIE	N.Y.C.	0.070
0035	POLETTI	E. 13TH ST.	N.Y.C.	0.070
0354	MOUNTAIN	SWANN RD.	WEST	0.063
0627	CEDARS	ROSEMONT	NORTH	0.045
0848	BEEBEE	BEEBEE	GENESEE	0.043
0630	DENNISON	ROSEMONT	NORTH	0.042
0631	MALONE	WILLIS	NORTH	0.041
0628	CEDARS	ROSEMONT	NORTH	0.041
0629	DENNISON	ROSEMONT	NORTH	0.040
0658	PLATTSBURCH	ASHLEY RD.	NORTH	0.038
0384	CLAY	HOPKINS	CENTRAL	0.036
0094	PARKCHESTER	TRETMONT BRUCKNER	N.Y.C	0.035
0227	HOLBROOK	PORT JEFFERSON	LONG ISLAND	0.032
0616	MORTIMER	SWEDEN	GENESEE	0.032
0609	S. E. BATAVIA	BATAVIA	GENESEE	0.032
0648	ALCOA	S. ALCOA	NORTH	0.031

Table 2: List of Ten Relays in NYPP that should be Upgraded First

Line No.	Bus from	Bus to	Zone	Vulnerability Rank
0127	BUCHANAN	INDIAN POINT	MILLWOOD	1st
0126	BUCHANAN	MILLWOOD	MILLWOOD	2nd
0047	E. 13TH ST.	FARRAGUT	N.Y.C.	4th
0663	HARRISON RADIATOR	HINMAN	WEST	9th
0035	POLETTI	E. 13TH ST.	N.Y.C.	11th
0627	CEDARS	ROSEMONT	NORTH	13th
0630	DENNISON	ROSEMONT	NORTH	15th
0628	CEDARS	ROSEMONT	NORTH	17th
0629	DENNISON	ROSEMONT	NORTH	18th
0384	CLAY	HOPKINS	CENTRAL	20th

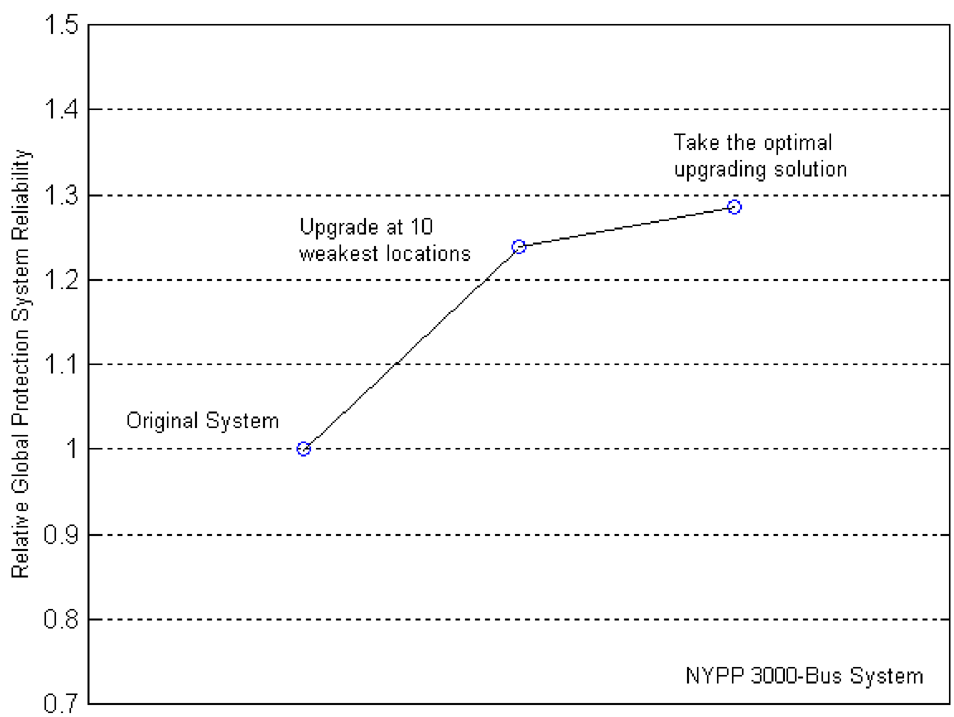

Figure 8: A Comparison Between Different Upgrading Solutions

6 Conclusion

This research focused on studying key elements relevant to transmission line protection, generator protection and system stabilities. The goal was to illustrate the basic methodology for planning system upgrades and to show the feasibility of studying rare events of power systems precisely using a modern powerful parallel computing facility.

System reliability and vulnerability are defined in this report. They are then used to pinpoint vulnerable relays. By solving the equivalent optimization problem based on blackout records collected in our simulation, we can find the optimal upgrading solution for the NYPP system.

The blackout simulation is characterized as a tree-search problem and a random search algorithm based on power system heuristics developed for faster rare-event simulation.

7 Future Research

It would be worthwhile applying the simulation technique to a system with more precise relay information. The NYPP relays were not actually modeled in the simulations, but only the effect of changing generic hidden failure probabilities. It would be desirable to begin with some relative ranking of the hidden failure probabilities for existing relays. For example, it is expected that most, if not all, the relays in Table 2 already have reduced hidden failure probabilities and that a search for the next set of ten relay locations is more appropriate.

The use of less formal clusters of PCs found in a typical engineering office could also be investigated along with techniques for speeding up the search for distinct sample paths.

Appendix: Notes On Some Practical Issues

1. Solving Linear Equations

Solving linear equations in the format of $\boldsymbol{AX = B}$ is the major task of simulating electric power flow using Newton-Raphson method. For power systems, $\boldsymbol{A}$ is a sparse matrix. Practically, *LU decomposition method* is the most efficient and robust way in solving these equations, although sometime *iterative methods* might be better.

There are a few C++ libraries available for the above type of matrix computations. On *MS-WINDOW* based platforms, *MATLAB C/C++ Math Library* is a pretty good choice. It offers almost all of *MATLAB*'s basic functionalities. User C/C++ programs can make a variety of matrix computations through simple function calls. Please refer *MATLAB* manual for details. The following installation procedures might be helpful for you when first using that package with *MS Visual C++ 6.0*:

- Install *MATLAB 5.3* with its *C/C++ Math Library* as written in the manual.
- Install *MS Visual C++ 6.0.*
- Get the following precompiled files (enclosed with this report) and put them in *\$matlab\extern\lib* where *$matlab* is your matlab home directory: *libmat.lib, libmatlb.lib, libmcc.lib, libmmfile.lib* and *libmx.lib*.
- Open your *MS Visual C++ 6.0* project file.
- Under the *Project→Settings* dialog window, Click the *C/C++* tab and choose *Preprocessor* in the *Category* list; Insert *\$matlab\extern\include* and *\$matlab\extern\include\cpp* as *additional include directories*; Enter *MSVC, IBMPC, MSWIND* to replace the original *Preprocessor Definitions*.
- Under the *Project→Settings* dialog window, Click the *Link* tab and choose *Input* in *Category* list; Input *\$matlab\extern\lib* as *additional library path* and add *libmatpm.lib libmat.lib libmatlb.lib libmmfile.lib libmx.lib* (in the exact order) into *Object/library modules*.
- Under the *Project→Settings* dialog window, Click the *C/C++* tab and choose *Code Generation* in the *Category* list; Select *Multithreaded DLL* or *Debug Multithreaded DLL* in *Use run-time library*.
- You may use *Matlab Function Calls* now.

2. Parallel Computation On Windows 2000 Clusters

The implementation of parallel simulations highly depends on the operating system and hardware. Our simulations are conducted on *Windows 2000 Clusters*. *MPI/Pro® for Windows NT®/2000®* is used to implement the parallel simulation algorithm in Section 3.3. Please refer http://www.mpi-softtech.com/ for further information.

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