PSERC 97-13

"An Importance Sampling Application: 179 Bus WSCC System under Voltage Based Hidden Failures and Relay Misoperations"

Koeunyi Bae
James S. Thorp

An Importance Sampling Application: 179 Bus WSCC System under Voltage Based Hidden Failures and Relay Misoperations

Koeunyi Bae
kbae@ee.cornell.edu

James S. Thorp
thorp@ee.cornell.edu

School of Electrical Engineering

Cornell University
Ithaca, NY 14853

Abstract

Recent studies have shown that power systems protection mechanisms have played a major role in propagating disturbances. Out of the last five major Western Systems Coordinating Council (WSCC) events (the North Ridge earthquake, December 14th 1994, July 2nd & 3rd 1996, and August 10th 1996), the latter three involved false trips with line protection relays and generators. Using an importance sampling based algorithm on the 179 bus WSCC equivalent system, we modeled the sequence of rare events under generator trips and zone 3 relay misoperations. The resulting sequence of rare events and its corresponding probability are used to detect weak links in the system.

Introduction

According to recent studies, the power protection systems have played significant roles in the birth and propagation of major power disturbances. In the deregulated system of the future, the ability to transfer power reliably through a network becomes a necessity when monetary values are attached to its reliability. Hence there exists a need to study the hidden failures imbedded within the protection system.

A five year study by the North America Reliability Council [1] reports that protection systems have played a huge role in the sequence of events that lead to power system disturbances. In 1996 alone, the WSCC which services 59 million people suffered two blackouts. The WSCC Final Report [2] states that on July 2, parts of the WSCC system were not operating in conditions in compliance with the WSCC Minimum Operating Reliability Criteria. Although initiated by a flashover near the Jim Bridger-Kinport 345,000 Volt line, a protective device misoperation in the Jim Bridger-Goshen 345,000Volt line de-energized the line, triggered the remedial action scheme, and led to tripping of two units near the Jim Bridger generating station. In the WSCC Final Report dated October 1996[3], the August 10th event, which affected a loss of power to 7.5 million customers, involved a false tripping of the phase imbalance relay on the exciter system and a zone 1 KD relay malfunction. In both the July 2 and August 10th, 1996 cases, hidden failures have been blamed for promoting the initial disturbance.

In spite of its importance, the impact of protection system malfunction on overall system reliability has not been well studied. The existing protection system with its multiple zones of protection is biased toward dependability and is designed to be dependable even at the cost of global system security. Hence, a vast majority of relay miss-operations are unwanted trips and have been shown to propagate major disturbances. Again the obvious problem arises from the fact that such rare cases are difficult to capture in large but limited databases. Even though thousands of load flows or transient stability cases can be involved in a database, the probability of major disturbances are so small that they cannot reasonably be included by conventional techniques. The North American Electric Reliability Council reports make it obvious that major disturbances typically involve a string of 6 to 7 unlikely events. Since simulation studies which capture a number of low probability events are difficult to perform, and the exact probability of the various unlikely events are not known, almost no attempt has been made to model the temporal spreading of the disturbance.

There has been very little analytic or simulation work in the area of cascading disturbances of the bulk power system. Horowitz, Phadke, Tamronglak, and Thorp [4], [5], [6], [7], [8] propose the use of importance sampling to alleviate the difficulty of simulating rare events. The simulations are performed with altered probabilities, which make the unlikely events more likely and processing the simulation results so that the correct answers are obtained. An importance sampling-based algorithm can be used to investigate where in the system changes in the protection

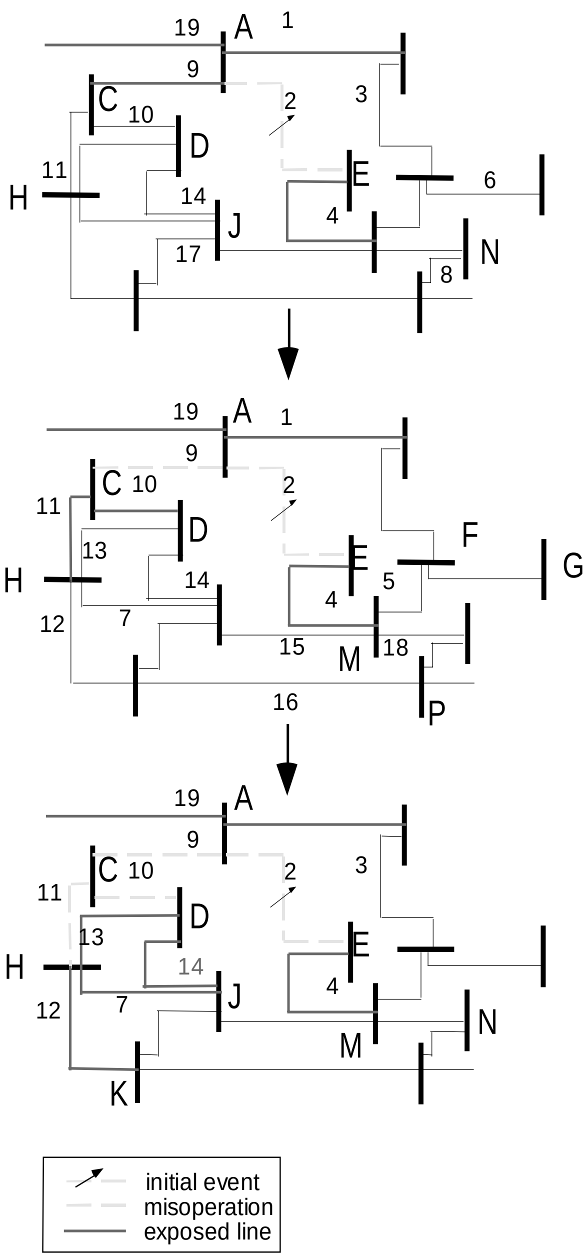

Figure 1: Sequence of Cascading Events

mechanism would be most effective, and then evaluate the increase in reliability obtained from monitoring the protection system.

Hence, importance sampling is critical to the success. In the wake of the summer of 1996, reliability of the protection system is an issue. It is our contention that study of hidden failures using importance sampling would determine the place in the bulk power system most sensitive to misoperations.

Methodology

Line Protection Hidden Failures

The assumption by [4] and [5] is that if any line sharing a bus with a transmission line *L* trips, then hidden failures in line *L* are exposed. That is, if one line trips correctly, then all the lines connected to its ends are exposed to the incorrect tripping. The probability of such occurrence is small but not negligible as seen by the WSCC events in1996.

Consider the following fictitious model in figure 1. If line 2 trips legitimately, then lines 1, 4, 9, and 19 are now exposed to hidden failures in the relays. The rest are not effected since they are not connected to bus A or E. There are 16 possible outcomes at this step:

- One possible way of misoperation
- Four possible ways of a single line misoperation
- Six possible ways of two line misoperation
- Four possible ways for a three line misoperation
- One possible way for all four lines to misoperate

For illustration purposes, if the probability of an exposed line tripping is taken as p then probability of it not tripping is $q = 1 - p$. Hence, there is a probability p^4 that all four lines succumb to the hidden failure and trip incorrectly, $4pq^3$ that a single line trips incorrectly, $6p^2q^2$ that two lines misoperate, $4p^3q$ that three lines trip, and q^4 that all four relays operate correctly.

Now suppose line 9 misoperates and exposes lines 1, 10, 11, and 19. Suppose lines 10 and 11 trip, then additional lines 7, 12, 13, and 14 are exposed plus bus C is isolated. These types of long sequences of events are what lead to major system disturbances.

Voltage Based Hidden Failures

In the July 2nd, 3rd and August 10th, 1996 events, low voltage conditions led the exciter to believe in the existence of an imbalance in the SCR bridge circuit.

The relay then misoperated and took action to avoid damage. Hence, the generator tripped unnecessarily.

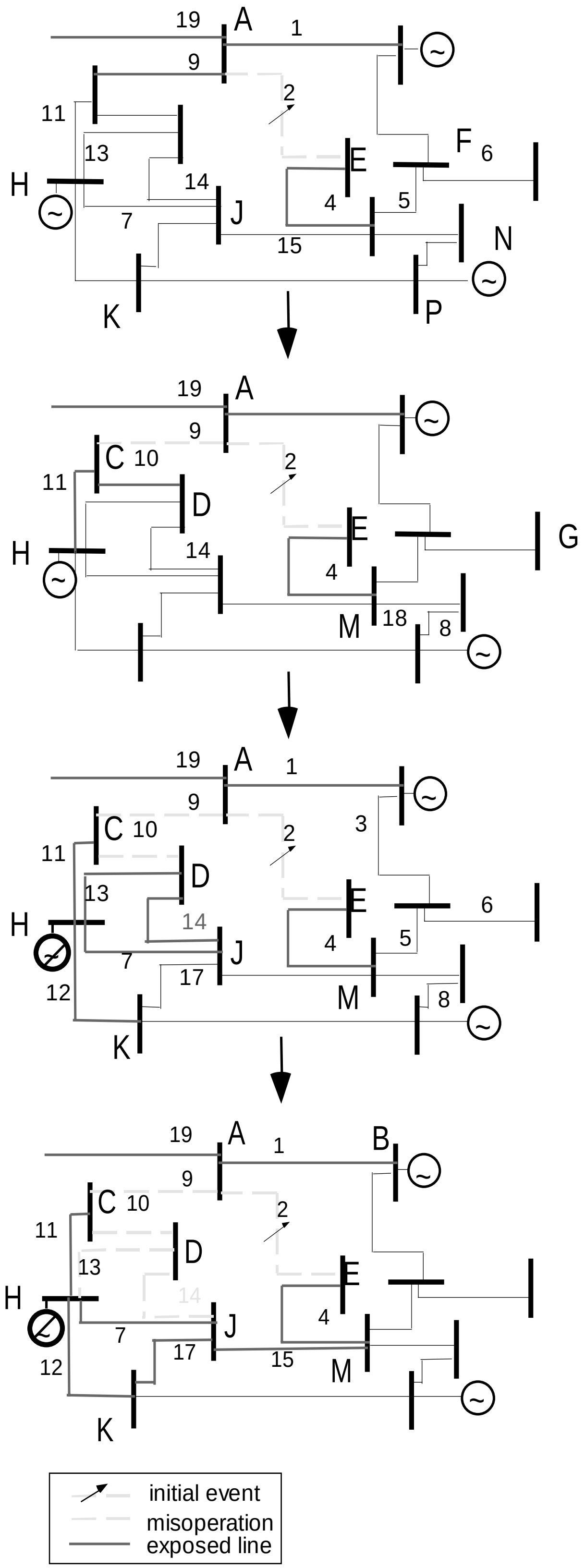

Figure 2: Sequence of Cascading Events

Therefore, we include the rare voltage based hidden failures in our study.

If the generator bus voltage violates

$$|V_{\min}| \leq |V| \leq |V_{\max}| \quad (1)$$

and there exists inadequate VAR support, then the protection system is exposed to hidden failures. If the relay misoperates and the generator trips, then all lines connected to that bus would also be exposed to hidden failures.

Figure 2 is another fictitious model and we will follow a similar sequence of events as shown in figure 1. Start with a legitimate relay operation on line 2 which exposes lines 1, 4, 9, and 19. Line 9 misoperates leaving hidden failures in lines 1, 10, 11, and 19. Line 10 trips and at the same time the generator at bus H trips. This exposes lines 7, 11, 12, 13, and 14. Then lines 13 and 14 trip exposing 7, 11, 12, and 17. The voltage based hidden failure gives another point for an initial disturbance perhaps even accelerating the cascading behavior.

Importance Sampling

Given $\{x_i\}$ are identically distributed Bernoulli random variables with

$$P\{x_i = 1\} = \rho = 1 - P\{x_i = 0\} \quad (2)$$

where $P\{x_i = 1\}$ is the probability of the event occurring and $P\{x_i = 0\}$ is the probability of an event not occurring, we will estimate ρ with at most 20% error with 95% confidence. We want to estimate $\hat{\rho}$

$$\hat{\rho} = \frac{1}{N}\sum_{1}^{N} x_i \quad \textbf{(3)}$$

to be such that

$$P\{|\rho - \hat{\rho}| \leq 0.2\rho\} \geq 0.95 \quad (4)$$

where N is the number of observations of the random variable x_i. For example, $x_i = 1$ could correspond to a line being in operation while $x_i = 0$ could refer to the line being tripped. In [2], the estimate of N is found to be

$$N = \frac{100}{\rho} \quad (5)$$

Hence if ρ is on the order of 10^{-6}, we would need 10^{8} number of samples to simulate the cascading outages.

Each simulation requires a random number draw putting the long-term behavior of the random number generator under scrutiny. It is clear that such long term simulation would require an unrealistically large amount of computation time and demands the impossible for the random number generator.

Importance sampling enables the simulation to be run with altered probabilities so that the rare events occur more frequently. If we re-examine the sequence of events in figure 1, after the original flashover of line 2, misoperation at line 9, and another misoperation at lines 10 and 11, bus C becomes isolated. This bus then would be recorded by the conventional method as a 1. The number of 1s in N simulations divided by N is the estimate of the probability of a cascading failure. In importance sampling rather than using the actual probabilities p and q, the simulations use the altered probabilities pp and qq. Rather than recording the number of 1's, we record a number t, a ratio of actual probability of the event divided by the probabilities used in the simulation, computed as the simulation progresses. For the event described,

$$t = \left(\frac{p}{pp}\right)\left(\frac{q}{qq}\right)^3\left(\frac{p}{pp}\right)^2\left(\frac{q}{qq}\right)^2 \qquad (6)$$

The actual probability of the event is p^3q^4 while the probability that the event occurs in the simulation is pp^3qq^4. The following forms the estimate of the probability:

$$\hat{\rho} = \frac{1}{N}\sum_{1}^{N} t_i \qquad (7)$$

and will have the correct mean even if N is smaller than the $\frac{100}{\rho}$ estimate.

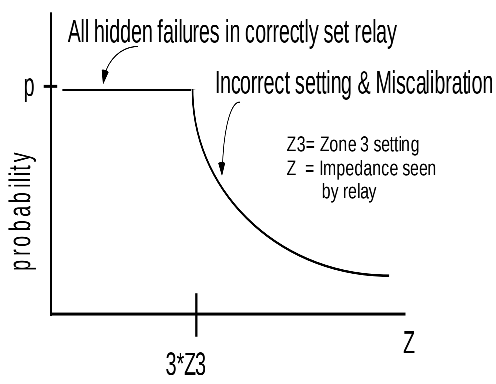

Figure 3: Probability of Exposed Line Tripping Incorrectly

More generally, each line will have a different probability of tripping incorrectly as shown in figure (3). The model shows the probability of the exposed line tripping incorrectly as a function of impedance seen by the relay. The value of three times the zone impedance setting is chosen. We will calculate the zone three impedance as 250% of the line impedance. Dependence on the current system condition implies that impedance must be calculated after each computation.

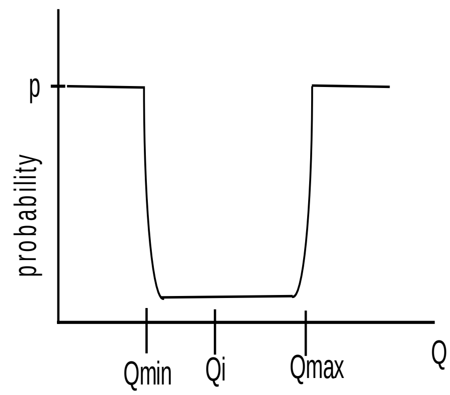

Figure 4: Probability of Generator Tripping Incorrectly

Figure (4) shows the probability of incorrect generator tripping as a function of reactive power. When the voltage is maintained within operating range, the probability of false trip is negligible. However, once outside that range, misoperations can occur. For our calculation purposes, we will gauge the misoperation using VAR support. If

$$|Q_{\min}| \le |Q| \le |Q_{\max}| \qquad (8)$$

is violated for any generator bus then operating voltage conditions cannot be met. Hence, the generators are exposed to false trips. Again, the voltage must be recomputed at each stage.

Importance Sampling Variation

As explained by [5], the following variation on importance sampling was incorporated into the algorithm. The numerator in equation (6) is the actual probability of the sample path of sequences of line outages. Rather than accumulate the weighted probabilities as in equation (7), we can record the distinct sample paths exposed in the simulation using pp probabilities along with the actual probabilities and then sum the probabilities. If the number of simulations is large enough to produce the significant sample paths, then the sum is a tight lower bound to the actual probability of failure. Although the choice of the simulation probabilities is less critical than the direct importance sampling, some variation in the typical sample paths are observed as the rule for generating the pp's is changed. If all exposed lines are given the same probability(say ½) then the resulting sample paths are somewhat different than those obtained when the exposed probabilities are simply scaled so the largest is ½. A solution is to randomize the rule for generating the simulation probabilities. If p_j represents the actual probability among the exposed lines, then

$$pp_j = 0.5\left(\frac{p_j}{p_{\max}}\right)^{\mu_j} \tag{9}$$

where μ_j are uniform random variables in the interval 0 to 1. The value $\mu_j = 1$ corresponds to uniform scaling while a value of 0 corresponds to setting all the values to ½. Since the μ_j are chosen at each step, all combinations are exposed.

Algorithm

For the following simulations, we use the definition of major disturbance given by [3], [4], and [5], as in relay operations which isolates a bus. In the future, we will use the NERC definition of a blackout.

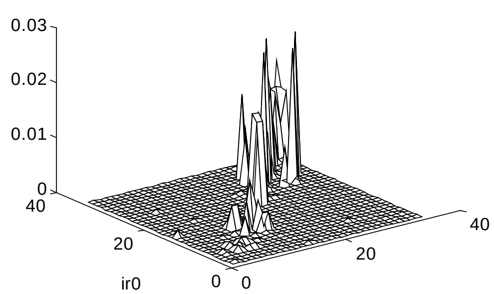

Figure 5 The New England 39 bus system. Ir0 denotes the initial line out numbers. The y-axis denotes the subsequent tripped lines. The z-axis denote the probability

Initially the simulation begins from a base load flow. A line is then selected as the triggering event and the following algorithm is repeated N times.

1. Determine all the lines that tripped in the last iteration.
2. Determine all lines connected to the buses of step 1. These are the exposed lines.
3. Check for violations in VAR constraints and find the probability of generator tripping using figure (4).
4. If generator protection misoperation occurs, add all lines connected to the bus to the list of exposed lines.
5. Compute the load flow. Recompute the impedance seen by relays for exposed lines.
6. Find the probability of tripping for each exposed line using figure(3).
7. For the exposed line record, $t_i = \prod_j p_j \prod_k (1 - p_k)$ where j are all lines that tripped and k all lines that did not trip.
8. Record all the lines that tripped.
9. Go to step 1 if any lines tripped and all buses are still connected. Continue until no lines are lost or all lines connected to a bus tripped.
10. If system failure, determine if $t = \prod_i t_i$ is a new number or a new sequence of line outages. If so record it.

179 Bus WSCC Equivalent System

The 179 bus WSCC system has 29 generators and 203 transmission lines. The initial load flow data is based on the December 12th, 1994 conditions. We chose this particular system rather than a fictional one (i.e. New England 39 bus) for the sole purpose of testing if the algorithm can pinpoint any weaknesses in a real system.

Simulation Results

For each initial line out, we obtain a table of sequence of line outages and the probability associated with that sequence. Table 1 shows that for an initial event, l^o, we generate M different sequences. Note however, that events involving the same lines but tripping in a different order will have distinct probabilities. Out of these M lines, only $\hat{M}$ contribute significantly to the total probability (i.e. sum of probability of all sequences). The other $M - \hat{M}$ sequences contain one of the $\hat{M}$ sequences as its subset. Therefore, we can justify using only the $\hat{M}$ sequences in evaluating the weaknesses in the system. Note that by the current definition of a major disturbance (the isolation of a node during relay misoperations), the sequence of lines tend to be short. Table 1 reflects this in its less abundance of the longer line outages in its $\hat{M}$ set. By using the NERC definition of a blackout, $\hat{M}$ should contain longer strings of events.

If total probability of sequence of events for initial line outage of l^o is

$$p^{l^o} = \sum_{\forall i} p_i^{l^o} \tag{10}$$

where i is the ith sample path of total M, then the probability of line k's contribution to the major disturbance for l^o is

$$p^{(k|l^o)} = \sum_{k \in i} p_i^{l^o} \approx \sum_{k \in m} p_i^{l^o} \qquad (11)$$

where $m \in \hat{M}$ is the list of sequences that contribute significantly to the total probability.

When the initial line outage, l^o, is plotted versus probability of subsequent tripped lines (i.e. line k given l^o), few lines stand out. For explanation purposes, we will first observe the New England 39 bus system with 34 transmission lines in figure 5.

If the system has a narrow banded adjacency matrix, then most of the activity occurs along the diagonal. For our New England 39 bus system, its adjacency matrix is almost narrow banded with the exception of few strays. In figure 5, the concentration of activity exists for l^o (or ir0) between lines 20 to 34. With those initial faults, the propagation of events with most significance remained within lines 20 to 34. The rest of the surface looks unvaried except for several lower peaks. The large off diagonal peaks are considered the weak lines.

For the 179 bus WSCC system in figure 6, again we see the cluster of high peaks around the diagonal with several off diagonal sharp peaks. These are the "weak" lines in the system. This figure shows that the 179 bus system contains single contingency cases with high probability and lengthy chains of misoperations (see l^o between 150 and 170). Also viewing the graph from the tripped lines' perspective, lines 150 to 170 cover a large area. This implies that it effects a large number of the initiating lines. For those reasons and along with large probability peaks around the initial faulted lines, the WSCC system contains several weak links that tend to propagate the initial disturbance.

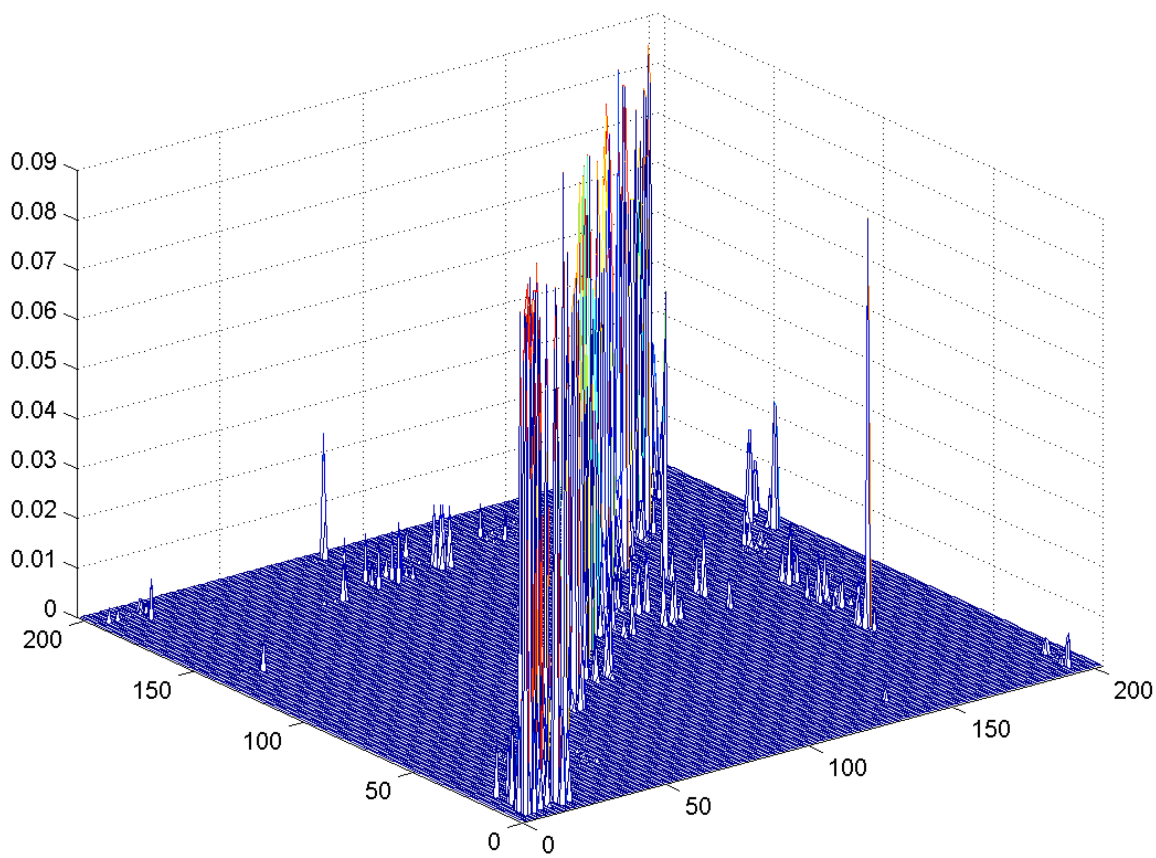

Figure 6 179 bus WSCC system. The right hand axis denotes the initial line out number. The left hand axis marks the subsequent tripped lines. The z-axis denotes the corresponding probability.

<table>
<tr><th colspan="7">Line out</th><th>Probability</th></tr>
<tr><td rowspan="8">– Initial line out is 200
– Probability of hidden failure is p=0.09 and N=1000
– Only 7 out of the 163 sequences contribute to the total probability.
– Total probability = 0.0104</td><td>154</td><td>155</td><td>200</td><td></td><td></td><td></td><td>0.0081</td></tr>
<tr><td>154</td><td>155</td><td>156</td><td>200</td><td></td><td></td><td>0.0009</td></tr>
<tr><td>154</td><td>155</td><td>156</td><td>200</td><td></td><td></td><td>0.0006</td></tr>
<tr><td>154</td><td>155</td><td>156</td><td>200</td><td></td><td></td><td>0.0005</td></tr>
<tr><td>154</td><td>155</td><td>156</td><td>161</td><td>200</td><td></td><td>0.0001</td></tr>
<tr><td>154</td><td>155</td><td>156</td><td>158</td><td>200</td><td></td><td>0.0001</td></tr>
<tr><td>154</td><td>155</td><td>156</td><td>162</td><td>200</td><td></td><td>0.0001</td></tr>
<tr><td>154</td><td>155</td><td>156</td><td>158</td><td>161</td><td>200</td><td>7.29e-6</td></tr>
<tr><td colspan="8">.
.
.</td></tr>
<tr><td colspan="8">1 | 154 | 155 | 156 | 157 | 158 | 159 | 160 | 161 | … | 166 | 168 | 200 | 201 | 202 | 9.847e-16</td></tr>
</table>

Table 1 `sequence of events for initial failure at line 200`

Future Work

As the definition of what constitutes a major disturbance changes to the NERC's standard of a blackout, the topology of figure 6 will change. The sequence of line outages will be longer and not dependent on isolation of one bus. Currently, an algorithm depicting a more "realistic" system scenario is in progress. Future works will contain the voltage based hidden failures, line hidden failures, and the NERC blackout criterion coupled with line constraints, frequency deviation monitoring for load shedding, and generator shedding.

Acknowledgements

This work was conducted under the NSF grant number ECS-9634823.

References

1. NERC Disturbance Reports, North American Electric Reliability Council, New Jersey, 1984-1988.

2. Western Systems Coordinating Council Final Report, *August 10th 1996 event*, October 1996.

3. Western Systems Coordinating Council Final Report, *July 2nd and 3rd event,* September 19th 1996

4. C. Tamronglak, A.G. Phadke, S.H. Horowitz, and J.S. Thorp, ``Anatomy of Power System Blackouts: Preventive Relaying Strategies", 95 WM 032-3-PWRD, IEEE Winter Meeting, Feb. 1995.

5. J. S. Thorp, A.G. Phadke, S.H. Horowitz, C. Tamronglak, ``Anatomy of Power System Disturbances: Importance Sampling", PSCC, Dresden, Aug 1996.

6. S. H. Horowitz, A.G. Phadke, J.S. Thorp, ``The Role of Adaptive Protection in Mitigating System Blackouts", 1995 CIGRE SC 34 Colloquium, Stockholm, June 11-17, 1995.

7. J. S. Thorp and A. G. Phadke, "Expose Hidden Failures to Prevent Cascading Outages", IEEE Computer Applications in Power, Vol 9, Number 3, July 1996, pp 20-23.

8. C. Tamronglak, S.H. Horowitz, A.G. Phadke, and J.S. Thorp, "Anatomy of Power System Blackouts: Preventive Relaying Strategies", IEEE Transactions on Power Delivery, Vol 11, No.2 April 1996, pp 708-715

9. S. H. Horowitz and A. G. Phadke, *Power System Relaying*, Research Studies Press, Somerset England 1992.

10. S.H. Horowitz, A.G. Phadke, J.S. Thorp, "Adaptive Transmission System Relaying", IEEE Transactions on Power Delivery, Vol. 3, No. 4, October 1988, pp 1436-1445.

11. J. C. Fort and G. Malgouyres, "Large Deviations and Rare Events in Study of Stochastic Algorithms", IEEE Transactions on Automatic Control, Vol AC-28, No. 9, pp907-920.

12. James A. Bucklew, Large Deviation Techniques in Decision, Simulation, and Education, John Wiley and Son, New York, 1990.

Biography

Koeunyi Bae is currently enrolled in the Ph.D. program in electrical engineering at Cornell University in Ithaca, New York. She received her B.S.EE and M.Eng.EE in 1994 and 1995 from Cornell. Her research interests include power systems protection and nonlinear dynamical systems.

James S. Thorp (F,1989) received the B.E.E, M.S., and Ph.D. degrees from Cornell University, Ithaca, New York. He joined the faculty of Cornell in 1962, where he currently is a Professor and Director of the School of Electrical Engineering. In 1976, he was the Faculty Intern at the American Electric Power Service Corporation. He was an associate editor for the IEEE Transactions on Circuits and Systems from 1985 to 1987. In 1988, he was an Overseas Fellow at the Churchill College, Cambridge, England. He is a member of the IEEE Power Systems Relaying Committee, CIGRE, Eta Kappa Nu, Tau Beta Pi, and Sigma Xi..