Detecting and Improving the Vulnerable Links in the Power Network:Part I

Koeunyi Bae
Student Member
Cornell University

James S. Thorp
Fellow IEEE
Cornell University

Abstract

We simulate, via a variance reduction scheme called importance sampling, rare events involving generator trips and incorrect zone three relay operations while monitoring the frequency, generation, and load deviation. We have studied the significance of reducing the probability of a false relay operations in the weak links to determine its effect on the rest of the network and prove that reducing the probability of hidden failures does not pose negative side effects on the system security. Given a system and economic conditions, it is useful to know where investments such as microprocessor relays will be most effective. It is our contention that the improvements in protection in these weak links will allow the ISO to make better future financial investments.

Keywords
Power system protection, power system reliability, power system dependability, power system security, importance sampling, power system relaying.

1 Introduction

The five major Western Systems Coordinating Council (WSCC) events, involved incorrect operations in the generator protection equipment or the line protection relays. As shown by these WSCC events, the initial act may be a fault clearing device working properly to prevent real damage to the equipment. However, history also shows that after the initial correct course of action, a series of unnecessary protection operations only served to propagate the initial disturbance and damage the security of the whole power system. These "mis-operations" are noted as the hidden failures embedded in the protection schemes which reveal themselves when the power system deviates toward an abnormal state. The current protection system's multiple overlapping mechanisms incline heavily toward dependability and promote hidden failures. Although the redundancy and over-protection in this design prevents any hardware damage, these "sympathy" trips of lines and generators presents a danger to global power system security.

Due to the rarity of these types of cascading outages, the compounded effects of a series of unlikely protection operations have not been throughly studied. However, recent events necessitate further exploration into the protection system's hidden failures. These simulations, though computationally intensive, can be aided by a variance reduction method called importance sampling.

As we embark on an era of restructuring in the power industry, the reliable transfer of power through a network is necessary when contracts must be fulfilled. Hence, reliability, security, and dependability are commodities. Since *dependability* and *security* are tied together, meaning one improves at the expense of the other, the ability to adjust the two criterion to maintain system integrity becomes crucial. It is our contention that study of hidden failures would determine the place in the bulk power system most sensitive to incorrect operations and determination which areas would provide the best ventures for the ISO.

2 Background

The current industry standard of heavy bias toward dependability in the protection system deteriorates under a strained network. A Special Protection System study by [1] show that in some regions unnecessary operations are more frequent than predicted. This particular survey showed 30% were unnecessary trips. Most of this number were contributed by the generator protection mechanisms. This nevertheless indicates that the power protection system's heavy bias needs reviewing.

According to Thorp, Phadke, and Horowitz, [2] and [3], security and dependability are intertwined in a protection system. Hence we must re-examine the redundancies present in the protection schemes to allow for countermeasures against hidden failures exposed in a stressed state. In [4], the list of hidden failures are well documented. The WSCC events, [5] and [6], illustrate that we should remain focused on the backup system and the special protection schemes not the primary protection devices.

The study of cascading rare events are computationally intensive. Phadke, Thorp, Horowitz, and Tamronglak, [7],[8], [9], [10], and [11], suggest implementing an importance sampling based algorithm to reduce the simulation time. In [12], importance sampling was used in the power systems model for planning purposes.

As the power industry goes through restructuring, studies in cascading events are more crucial than ever. The increase in number of operators controlling smaller pieces of the network necessitates teamwork and coordination to protect the bulk power system as a whole. Therefore, the ISO needs to locate the areas within their own network prone to propagating disasters and invest to decrease this type of malfunctions. It is our intension to locate regions of vested interest for the ISO and perhaps through better maintenance and calibration scheduling, microprocessor relays, or a new scheme(i.e. voting) improve the reliability and the dependability of the system.

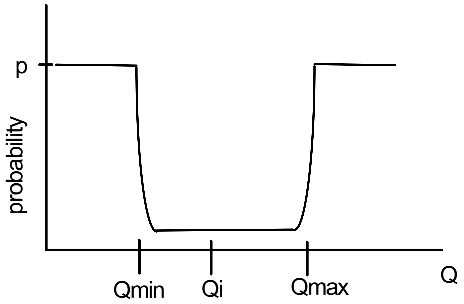

Figure 1: Voltage Based Hidden Failures

3 Problem Formulation

Given any power system, we must attend to the following four criterion to gain more knowledge of the system and to provide a better model for the simulations.

1. *List of non-primary measures in the protection system:* Protection schemes include equipment and algorithm used to protect the product. It includes relays and special protection systems such as remedial action schemes, devices for generator tripping and frequency monitoring. It has been noted that incorrect operations in backup systems, not primary seem to promote the cascading effect.
2. *List of hidden failures found in the system in 1:* Using [4] as a guide, gain knowledge of existence of different types of hidden failures within the system.
3. *List of what constitutes a "blackout":* The NERC blackout criterion might be adequate for a simulation such as the WSCC 179-bus, but each ISO may have different costs to consider.
4. *List of high probability candidates for faults:* This is the list of high probability initial events. For instance, certain transmission lines have more occurrence of faults than others, be it fast growing trees or unfriendly weather conditions.

In our models, we simulate based on the following:

<u>Protection System:</u> Voltage-based generator protection relays and third zone relays.

<u>Associated Hidden Failures:</u> According to [4], third zone relays are subject to hidden failures when the timer contact fails close and then the relay contact closes, resulting in loss of coordination. Generator protection is subject to breakdown during low voltage situations.

<u>Blackout Criterion:</u> In the 179-bus system , 300 MW loss is one type of a blackout. For the New England 39-bus system, an isolation of a bus constitutes a blackout.

<u>Initial Event:</u> All lines are equally likely to start an event.

Using these four criterion, we also applied the importance sampling in our algorithm to make calculations more manageable and used Newton-Raphson and DC load-flow for load flow calculations.

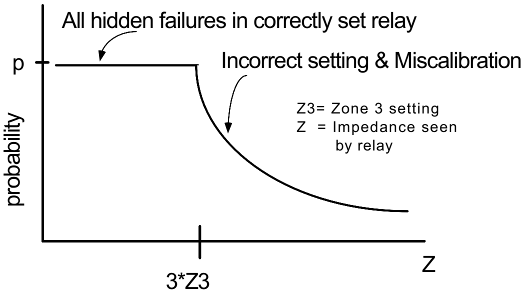

Figure 2: Hidden failures in Third Zone Relaying Protection Scheme

Algorithm :

Step 0 l_o trips. This is the initial legitimate fault clearing event.

Step 1 Make the changes in the line data to reflect the trip.

Step 2 l_e contains the antecedent transmission lines to the buses connected to the previously tripped line. These are now exposed to hidden failures.

Step 3 Check for voltage-based hidden failures in generator protection by checking for violations in VAR support using figure 1.

Step 4 Add the lines connected to the tripped generator bus to l_e.

Step 5 Check for frequency deviations.

Step 6 Compute load flow.

Step 7 Compute impedance seen by the relay.

Step 8 Record the probability of a hidden failure using figure 2.

Step 9 Record $t_\alpha = \prod_j \; p_j \;\; \prod_k \; (1 \; - \; p_k)$ where j denote the tripped exposed lines and k reflect those still intact.

Step 10 Check for violations in "blackout".
If no violation occurs then return to Step 2.

Step 11 Record $P_i^{l_o} = \prod_\alpha \; t_\alpha$, the probability of the i^{th} new sequence in a blackout given l_o.

Step 12 Update the list of blackout sequence $S_i^{l_o} = [l_o \;\; l_{i_1} \; ... \, l_{i_n}]$ This is the i^{th} new sequence leading to a blackout.

Repeat until a complete set of $S_i^{l_o}$ for l_o is obtained.

Step 13 Record $P^{l_o} = \sum_i P_i^{l_o}$ which is the total probability that initial event, l_o , starts a chain reaction that leads to blackouts.

Step 14 Record the set $\{S^{l_o}\}$ which contains all $S_i^{l_o}$. Truncate and only keep the highest probability subset of S^{l_o}. This set constitutes a 6 or 7 core lines which make up the subset of longer string of low probability events. Hence, part of the lower probability is always contained in the set $\{S^{\hat{l}_o}\}$ made of $\hat{S_i^{l_o}}$.

Step 15 Extract the probability of line $k's$ likelihood to be involved in a blackout. Whenever $l_k \in \{\hat{S_i^{l_o}}\}$, add the corresponding $P_i^{l_o}$ together. Hence,

$$p^{(l_k|l_o)} = \sum_{l_k \epsilon \hat{S}_i{}^{l_o}} P_i^{l_o} \tag{1}$$

Step 16 Let J_k be

$$J_k = \sum_j \;\; C_{l_k} \; w_{l_j} \; p^{(l_k|l_j)} \tag{2}$$

where C_{l_k} denote the cost of losing a transmission line, w_{l_j} is the likelihood of line j initiating an event, $p^{(l_k|l_j)}$ is the probability of line k being involved in a blackout event initiated by line j.
Then we want to minimize J such that

$$J = \sum_k \; J_k \tag{3}$$

The cost, C_{l_k}, of transmission line is in most part an estimate in comparison to other lines in the system. The simulation uses a sliding scale between [0 1]. The weighting factor, w_{l_j} represents line $j's$ likelihood of starting an event. There exists instances where the company can improve this number. For example, active tree trimming in heavily vegetated areas would reduce w_{l_j} for particular lines or perhaps consistent maintenance will reduce certain flash-overs during a lightening storm. However, for the most part, natural phenomenon tend to be less than certain. Hence a change by reducing the hidden failure in the protection system makes the system more robust.

4 Locations for Improvement

Before discussing the effects of improvements on a system, we will show that decreasing the hidden failure in a line does not increase the probability of another line being involved in a blackout scenario.

Let l_o be the initial event.
Let x_l be the probability of hidden failure in line l.
Let p_i be the likelihood of hidden failure in all other lines.

Since this is a study of rare events, all probabilities x_l and $p_i \ll 1$. As shown previously, the total probability of a blackout event initiated by line l_o is $P^{l_o} = \sum_{\forall r} \; P_r^{l_o}$. This can be broken down into four categories:

1. Sequence of events which exposes line l and trips line l immediately.
2. Sequence of events which exposes line l at least once and never trips it.
3. Sequence of events which exposes line l at least once and trips it eventually.
4. Sequence of events which never exposes line l.

Hence, the total probability of a blackout started by line l_o is the following:

$$\begin{aligned} P^{l_o} &= \sum_{\hat{i}} P_{\hat{i}}^{l_o} \\ &= \sum_i A_i \; x_l \; + \sum_k C_k \; x_l \; (1 \; - \; x_l)^{n_k} \; + \\ & \quad \sum_j B_j \; (1 \; - \; x_l)^{m_j} + \sum_\gamma \; D_\gamma \end{aligned} \tag{4}$$

where $i \neq j \neq k \neq \gamma$ and

- $A_i x_l$ denote the i^{th} sequence leading to a blackout with line l tripping immediate after the exposure.
- $C_k \; x_l \; (1 \; - \; x_l)^{n_k}$ denotes the k^{th} sequence leading to a blackout with line l being exposed at least once and eventually tripping.
- $B_j \; (1 \; - \; x_l)^{m_j}$ denotes the j^{th} sequence leading to a blackout with line l exposed at least once but never tripping.

- D_γ denotes γ^{th} sequence never exposing line l

The coefficients A_i, B_j, C_k, and D_γ reflect the contribution of the other transmission lines in the network,

$$\begin{aligned} A_i &\equiv \prod_{r_a} p_{r_a} \prod_{s_a} (1 - p_{s_a}) > 0 \\ B_j &\equiv \prod_{r_b} p_{r_b} \prod_{s_b} (1 - p_{s_b}) > 0 \\ C_k &\equiv \prod_{r_c} p_{r_c} \prod_{s_c} (1 - p_{s_c}) > 0 \\ D_\gamma &\equiv \prod_{r_d} p_{r_d} \prod_{s_d} (1 - p_{s_d}) > 0 \end{aligned}$$

where $r, s \neq l$ and $r =$ exposed lines that tripped, $s =$ are the exposed lines that did not trip, and p_r and p_s are the associated probabilities.

We want to show that as x_l decreases, P^{l_o} never increases and prove that improvement in one line does not have any adverse effects on the system.

Suppose,

$$[S^{l_o}] = \begin{bmatrix} S_1^{l_o} \\ S_2^{l_o} \\ \vdots \\ S_m^{l_o} \end{bmatrix} \tag{5}$$

contains all the cascading transmission lines involved in a blackout event initiated by l_o. If line j is not in $[S^{l_o}]$ then line j never tripped. To find if line j was ever exposed, let

$$A_j = [n_1 \ n_2 ... n_m] \tag{6}$$

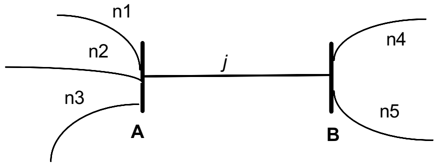

Figure 3: Example of line j and its antecedents

where the $n's$ are the lines connected to the buses connecting line j. If any line in the set $A_j \in S_{\hat{i}}^{l_o}$, then line j was exposed but never tripped. Looking at equation (3), we find that if line j is exposed and never trips, there exist a possibility that reducing the probability of line j increases the risk in the system. Now we will proceed to prove that this cannot happen.

Let $\hat{s}^{l_o} = [l_1 \ ... \ l_n]$ to be a blackout sequence which exposes j but never trips. Let $\tilde{s}^{l_o} = [l_1 \ ... \ l_n \ j]$ be the same sequence as $\hat{s}^{l_o}$ but with line j added to it. Nothing has changed between the two except for the addition of j in the $\tilde{s}^{l_o}$ and hence, $\tilde{s}^{l_o}$ is a new sequence. If

$$\Phi_{\hat{s}^{l_o}} = \zeta \ (1 - p_j) \tag{7}$$

denotes the probability of $\hat{s}^{l_o}$, where ζ is the product of probability of events without the contribution by line j. Then there exists a $\Phi_{\tilde{s}^{l_o}}$ such that

$$\Phi_{\tilde{s}^{l_o}} = \Phi_{\hat{s}^{l_o}} \frac{p_j}{(1-p_j)} (1-p_{n_1})(1-p_{n_2}) \ ... \ (1-p_{n_m}) \tag{8}$$

where j trips but the lines exposed by j did not trip. Now $\tilde{s}^{l_o}$ has an associated probability and is in the list of sample paths. Simplifying equation (7) further,

$$\Phi_{\tilde{s}^{l_o}} = \zeta \ p_j \ \Upsilon \tag{9}$$

Notice that $\tilde{s}^{l_o}$ is just one of many sequences using line j as a initial event! Now we extend $\tilde{s}^{l_o}$ to include all events initiated by j. Since $\sum_\gamma \Upsilon_\gamma = 1$ for all events initiated by j, then we can show

$$\sum_\gamma (\Phi_{\hat{s}^{l_o}} + \Phi_{\tilde{s}^{l_o}}^\gamma) = \sum_\gamma \ \zeta \ (1 - p_j + \Upsilon_\gamma p_j) \tag{10}$$

$$\begin{aligned} \Phi_{\hat{s}^{l_o}} + \sum_\gamma \Phi_{\tilde{s}^{l_o}}^\gamma &= \zeta \ (1 - p_j + \sum_\gamma \Upsilon_\gamma p_j) \\ &= \zeta \end{aligned} \tag{11}$$

and the sum is independent of probability of line j, p_j. Therefore, any j that has been exposed and has contributed toward P^{l_o} is also in S^{l_o}. Returning to equation (3), this implies that there are no $B_j \ (1 - x_l)^{m_j}$ terms. Hence,

$$\begin{aligned} P^{l_o} &= \sum_{\hat{i}} P_{\hat{i}}^{l_o} \\ &= \sum_i A_i \ x_l + \zeta + \\ & \quad \sum_{k'} C_{k'} \ x_l \ (1 - x_l)^{n_{k'}} + \sum_\gamma D_\gamma \end{aligned} \tag{12}$$

Then the changes in P^{l_o} with respect to x_l is,

$$\begin{aligned} \Delta P^{l_o} &= \sum_i A_i + \sum_{k'} C_{k'} \ (1 - x_l)^{m_{k'}} - \\ & \quad \sum_{k'} C_{k'} \ m_{k'} \ x_l \ (1 - x_l)^{m_{k'}-1} \end{aligned} \tag{13}$$

As $(x_l \ll 1) \rightarrow 0^+$,

$$\begin{aligned} \Delta P^{l_o} &\rightarrow \sum_i A_i + \sum_{k'} C_{k'} \\ &\geq 0 \end{aligned} \tag{14}$$

Therefore, decreasing x_l will not increase the overall security of the system.

5 Improving the New England 39-Bus System

We tested this theory and applied our algorithm and software to the New England 39-bus system.

Let i is the line with 50% reduction in hidden failures.
x_i is probability of line i.
p_t is the probability of line $t \neq i$ in the network.
$C_{l_k} = 1$
$w_{l_j} = 1$
$p^{(l_k|l_j)}$ is obtained through conditions mentioned in section 3. This is the probability of line k being involved in a blackout event given line j as the initiating fault trip.

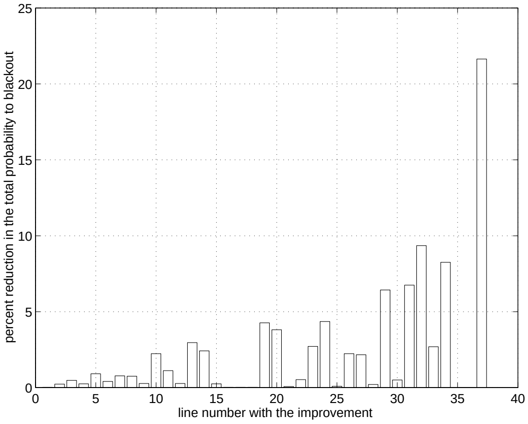

Figure 4: Results of reduction in probability of hidden failure in transmission

Then in the 34 transmission line, 39-bus New England system, thirty-five simulations based on the algorithm previously stated were conducted. Each simulation curtails reduction of probability of hidden failure. For instance, this reduction can be due to improved monitoring of the system.The first 34 are single line reductions and the last simulation is a multiple line reduction. For each of these simulations, the blackout probability for every initial line trips (all 34 lines) have to be recalculated. Since each triggering event has approximately $10,000$ load flow computations, it is safe to say that each bar in figure 4 is the result of $34,000$ load flow calculations. Again, the first 34 were for single line improvements in lines 1 to 34 and the last case simulates the multiple line improvement involving the highest $p^{(l_k|l_j)}$ valued lines [step 23 (a)]. In the 39-bus system, these same three lines, 31, 32, and 34, were also in a cluster [step 23 (b)].

The objective function for the simulation is the following:

$$J_i = \sum_{\forall l_j} p^{(l_k|l_j)} \tag{15}$$

where l_j denotes the j^{th} line.

Figure 4 supports our claim that reducing the hidden failure rate improves the overall quality of the system. Notice that there are no negative reductions shown in figure 4. The most improvements by a single line enhancement were shown by decreasing the false operation rate of lines 31, 32, and 34. They corresponds to the highest $p^{(l_k|l_j)}$ values. The multiple line improvement is plotted as line "36" in figure 4 and shows that ventures in several key areas further increases protection against blackouts. For this particular system, it is our recommendation to invest, improve, and maintain key the lines 31, 32, and 34.

6 Conclusion

This type of analysis based on our algorithm and software should be implemented by the utilities. The simulation can be part of a regular periodic check when changes in load flow and system conditions occur or as part of special studies to gain insight into the consequences of lines being temporarily taken out of service. In either case, any foresight will greatly reduce the probability of a system blackout.

This report illustrates through computer simulations a method which can depict weaknesses in the protection system. By incorporating economic factors such as cost of failing to deliver on a contract due to hidden failure related events, this type of analysis will provide means by which utilities can continually test and maintain their network for better investment in their protection system.

7 Acknowledgments

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8 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.