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Nodal-Price Dependent, Dual-Mode Transmission Line Protection Strategy

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Abstract

It is argued that the Independent System Operator (ISO) should be able to adjust the security and dependability of the protection system in response to the system and market conditions. However, the existing protection philosophy's multiple, overlapping schemes tend to favor individual elements over the security of the wide-area. We revisit the rare-probability, hidden failures embedded within the individual relays but this time include the failure to trip when a fault needs to be cleared along with the unnecessary tripping of a transmission line. We devise a relaying concept to reduce the probability of cascading outages by decreasing incorrect relay operations through a dual-mode or the security-dependability mode (S-D Mode) scheme. It is our contention that during periods of high nodal prices which may even predict a cascading event, we can reduce the probability of a blackout by changing to a secure mode over the dependable region of operation.

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 "miss-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 thoroughly 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, 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. Updating in these areas with a S-D Mode-like relaying scheme would provide the good investment 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.

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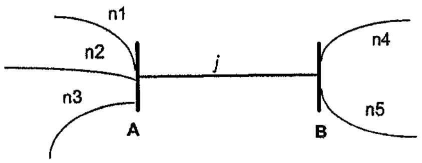

Figure 1: Example of line j and its antecedents

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. In [13] and [14] locate possible weak links in the New England 34 bus system and the WSCC 179 bus system using importance sampling-based techniques.

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.

3 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:

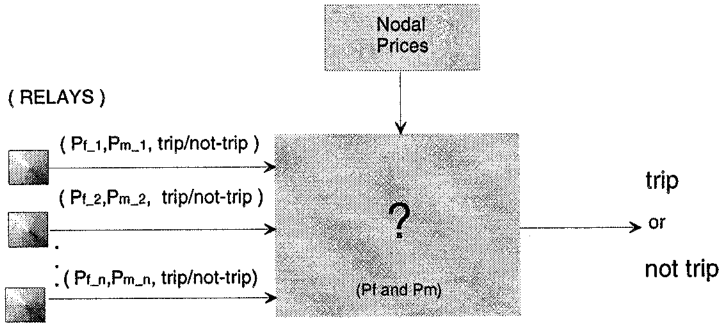

Figure 2 Block diagram of security-dependability mode relay design

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:

$$\begin{aligned} P^{l_o} &= \sum_i P_i^{l_o} \\ &= \sum_i A_i\, x_l + \sum_k C_k\, x_l\, (1 - x_l)^{n_k} + \\ &\quad \sum_j B_j\, (1 - x_l)^{m_j} + \sum_\gamma D_\gamma \end{aligned} \quad (1)$$

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,

$$A_i \equiv \prod_{r_a} p_{r_a} \prod_{s_a} (1 - p_{s_a}) > 0$$

$$B_j \equiv \prod_{r_b} p_{r_b} \prod_{s_b} (1 - p_{s_b}) > 0$$

$$C_k \equiv \prod_{r_c} p_{r_c} \prod_{s_c} (1 - p_{s_c}) > 0$$

$$D_\gamma \equiv \prod_{r_d} p_{r_d} \prod_{s_d} (1 - p_{s_d}) > 0$$

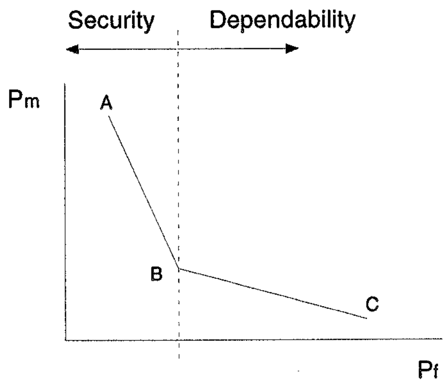

Figure 3 Probability of false trip vs. missed trip showing the two regions of operation

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,

$$[S^{l_o}] = \begin{bmatrix} S_1^{l_o} \\ S_2^{l_o} \\ \vdots \\ S_m^{l_o} \end{bmatrix} \tag{2}$$

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

$$A_j = [n_1 \; n_2 ... n_m] \tag{3}$$

where the $n's$ are the lines connected to the buses connecting line j. If any line in the set $A_j \in S_i^{l_o}$, 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

$$\Phi_{\hat{s}^{l_o}} = \zeta \; (1 \; - \; p_j) \tag{4}$$

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

$$\Phi_{\tilde{s}^{l_o}} = \Phi_{\hat{s}^{l_o}} \frac{p_j}{(1 - p_j)}(1 - p_{n_1})(1 - p_{n_2}) \; ... \; (1 - p_{n_m}) \tag{5}$$

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,

$$\Phi_{\tilde{s}^{l_o}} = \zeta \; p_j \; \Upsilon \tag{6}$$

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

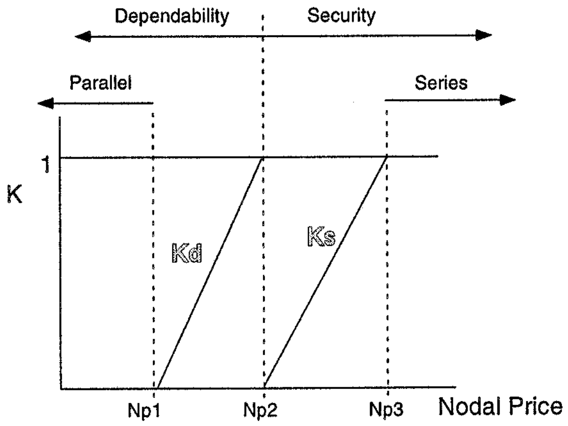

Figure 4 Relationship between nodal prices and modes of operation

$$\sum_{\gamma}(\Phi_{\hat{s}l_o} + \Phi^{\gamma}_{\tilde{s}l_o}) = \sum_{\gamma} \zeta\,(1 - p_j + \Upsilon_{\gamma} p_j) \quad (7)$$

$$\begin{aligned} \Phi_{\hat{s}l_o} + \sum_{\gamma} \Phi^{\gamma}_{\tilde{s}l_o} &= \zeta\,(1 - p_j + \sum_{\gamma} \Upsilon_{\gamma} p_j) \\ &= \zeta \end{aligned} \quad (8)$$

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,

$$\begin{aligned} P^{l_o} &= \sum_{\hat{i}} P^{l_o}_{\hat{i}} \\ &= \sum_{i} A_i\, x_l + \\ &\quad \sum_{k} C_k\, x_l\, (1 - x_l)^{n_k} + \sum_{\gamma} D_{\gamma} \end{aligned} \quad (9)$$

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

$$\begin{aligned} \Delta P^{l_o} &= \sum_{i} A_i + \sum_{k} C_k\, (1 - x_l)^{m_k} - \\ &\quad \sum_{k} C_k\, m_k\, x_l\, (1 - x_l)^{m_k - 1} \end{aligned} \quad (10)$$

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

$$\begin{aligned} \Delta P^{l_o} &\rightarrow \sum_{i} A_i + \sum_{k} C_k \\ &\geq 0 \end{aligned} \quad (11)$$

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

4 Security-Dependability Mode Relaying Philosophy

A method for reducing hidden failures associated with false tripping or failure to trip a line is to embed a tunable security-dependability mechanism within a new relay. The strategy is to design a S-D mode relay which gathers information from the various primary relays already in operation. The nodal price determines which mode of operation is in effect. For instance, high prices would force a tighter security mode. By combining the "trip/not-trip" signals from the individual relays and the current nodal prices (figure 2), the S-D mode relay makes its decision.

Fundamentally, we can define the following protection options:

1. *Series Protection:* All primary relays must agree to trip before S-D Mode relay signals for clearing of the transmission line.
2. *Voting Protection:* Majority of the relays must agree before S-D Mode signals to open the line.
3. *Parallel Protection:* At least one relay must signal the S-D M to clear the line. This is the current relaying philosophy.

Again, the implementation of a series protection or voting protection reduces the probability of a false trip. Hence it should not aide in the propagation of a disturbance. Define P_{f_i} as the false tripping probability of relay i and P_{m_i} be the failure to trip a line probability of relay i. Then we may say that for n independent relays protecting a single transmission line,

$$\begin{aligned} P_{f_{series}} &= \prod_{j=1}^{\zeta} P_{f_j} \\ &\ll P_{f_i} \\ P_{f_{voting}} &= P_{f_1} P_{f_2} \ldots P_{f_\zeta} \sum_{j=1}^{\zeta} P_{f_{\zeta+j}} \\ &+ P_{f_1} P_{f_2} \ldots P_{f_{\zeta-1}} \sum_{j=1}^{\zeta-1} P_{f_{\zeta+j}} P_{f_{\zeta+j+1}} \\ &+ P_{f_1} P_{f_2} \ldots P_{f_{\zeta-2}} \sum_{j=1}^{\zeta-2} P_{f_{\zeta+j}} P_{f_{\zeta+j+1}} P_{f_{\zeta+j+2}} \\ &+ P_{f_1} P_{f_{\zeta+1}} P_{f_{\zeta+2}} \ldots P_{f_{2\zeta-1}} \\ &+ P_{f_{\zeta+1}} P_{f_{\zeta+2}} \ldots P_{f_{2\zeta}} \\ &\ll P_{f_i} \\ P_{f_{parallel}} &= 1 - \prod_{j=1}^{n} (1 - P_{f_j}) \end{aligned} \quad (12)$$

and,

$$\begin{aligned} P_{m_{series}} &= 1 - \prod_{j=1}^{n} (1 - P_{m_j}) \\ P_{m_{voting}} &= P_{m_1} P_{m_2} \ldots P_{m_\zeta} \sum_{j=1}^{\zeta} P_{m\zeta+j} \\ &+ P_{m_1} P_{m_2} \ldots P_{m_{\zeta-1}} \sum_{j=1}^{\zeta-1} P_{m\zeta+j} P_{m\zeta+j+1} \\ &+ P_{m_1} P_{m_2} \ldots P_{m_{\zeta-2}} \sum_{j=1}^{\zeta-2} P_{m_{\zeta+j}} P_{m_{\zeta+j+1}} P_{m_{\zeta+j+2}} \\ &+ P_{m_1} P_{m_{\zeta+1}} P_{m_{\zeta+2}} \ldots P_{m_{2\zeta-1}} \\ &+ P_{m_{\zeta+1}} P_{m_{\zeta+2}} \ldots P_{m_{2\zeta}} \\ &\ll P_{m_i} \\ P_{m_{parallel}} &= \prod_{j=1}^{\zeta} P_{m_j} \end{aligned} \quad (13)$$

$$\ll \quad P_{m_i}$$

where $\zeta = trunc(\frac{n}{2})$, and $P_{f_{series}}$, $P_{f_{voting}} P_{f_{parallel}}$, $P_{m_{series}}$, $P_{m_{voting}}$, and $P_{m_{parallel}}$ denote the false tripping probability (series, voting, and parallel schemes) and the missed tripping probability (series, voting, and parallel schemes).

For illustration purposes, we can design P_f and P_m of the S-D Mode relay as

$$P_f = x_1 P_{f_{series}} + x_2 P_{f_{voting}} + x_3 P_{f_{parallel}} \tag{14}$$

$$P_m = x_1 P_{m_{series}} + x_2 P_{m_{voting}} + x_3 P_{m_{parallel}} \tag{15}$$

where x_1, x_2, x_3 are random numbers with constraint $x_1 + x_2 + x_3 = 1$.

Using equations (14) and (15), we can plot the false tripping versus failure to trip curve for the S-D Mode relay. Figure (3) shows the resulting minimum values of the two distinct regions. The area B-C is the dependability mode due to the low missed tripping probability. Currently, the industry operates in this area. Region A-B is the secure mode where the probability of false tripping is minimal, decreasing the likelihood of propagating a disturbance or failing to fulfill a contract. Points A, B, C reflect the series, voting, and parallel protection algorithms respectively.

Now to simplify equation (14) and (15), for the security mode

$$P_{f_s} = K_s P_{f_{series}} + (1 - K_s) P_{f_{voting}} \tag{16}$$

$$P_{m_s} = K_s P_{m_{series}} + (1 - K_s) P_{m_{voting}} \tag{17}$$

and the dependability mode,

$$P_{f_d} = K_d P_{f_{voting}} + (1 - K_d) P_{f_{parallel}} \tag{18}$$

$$P_{m_d} = K_d P_{m_{voting}} + (1 - K_d) P_{m_{parallel}} \tag{19}$$

where $0 \le K_s \le 1$ and $0 \le K_d \le 1$.

Figure (4) shows our selection method as a linear relationship with the nodal prices. The linearity of K_s and K_d with the cost were chosen for simplicity.

Given N_p is the nodal price at the current bidding,

1. $N_{p_3} < N_p$ Absolute secure mode nodal price. All relays must agree to trip.
2. $N_{p_1} \le N_p \le N_{p_3}$ Possible region for voting.
3. N_{p_2} One price always in the voting mode.
4. $N_p < N_{p_1}$ Absolute dependable mode. Only one relay needed to send the trip signal.

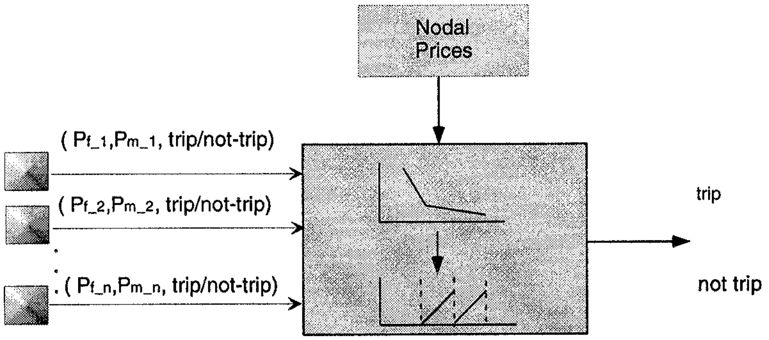

Figure 5 Security-Dependability Mode design

Only case 2 is ambiguous about the number of relays needed to make the final decision. For $N_{p_1} < N_p < N_{p_2}$ or $N_{p_2} < N_p < N_{p_3}$, draw a random number, Z. Then there exists according to figure 4, an associated K_d or K_s for the N_p such that

security mode	$Z \geq K_s$	Series
	$Z < K_s$	Voting
dependability mode	$Z \geq K_d$	Voting
	$Z < K_d$	Parallel

5 Conclusion

Two-thirds of the blackouts in the United States document involvement of relays in possibly propagating the initial event. During the highly stressed periods, the cost of the MWhr soar and ability to deliver power and fulfill the contract is more crucial. By incorporating economic factors such as nodal prices or cost of failing to deliver on a contract due to hidden failure related events into a relay scheme, the relay can work in two regions of operation to benefit individual elements in the power grid and protect the overall security of the network. The ability to adjust or dial in the degree of security or dependability will be a key in preventing unnecessary line clearings. Hence, essential in preventing blackouts.

6 Acknowledgments

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