Predictive Analytic to Supervise Zone 1 of Distance Relay using Synchrophasors

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Distance relays are the workhorses for transmission line protection system.

It can mal-operate on power swing and out-of-step condition.

This can trigger a collapse in the power system—e.g., 30-31st July 2012 blackout in India.

Existing power swing detection and out-of-step prediction methods are based on inference.

They use local information and hence may fail.

We propose verification strategies and more nuanced inferences for more secure and dependable protection.

Distance relay characteristic.
Managing Dependability vs. Security Conflict in Distance Relay

- OR-logic improves dependability.
- AND logic strengthens security.

We show that both dependability and security can be ascertained with OR logic using distance relay supervision by PMU data.
Alternative 1: Hybrid Scheme by Compounding Distance and Current Differential Relays

Now suppose that there is a severe power swing infringing into zone 1 of the distance relay. In case of a power swing infringing into zone 1, the proposed supervisory scheme anticipates this eventuality well in advance and moves the distance relay into the temporary block mode. Thus, in the absence of a fault, neither of the relays will pick up and we obtain security. In an extreme scenario of a line fault occurring subsequent to the distance relay entering the block state, CDR will always pick up and hence we ensure dependability.

**Figure 1:** Alternative 1.
Alternative 2: Main-1 and Main-2 both on Distance Relays and supervised by PMU

In case of a fault in the near vicinity of the distance relay under supervision, we use local override policy to remove the block signal.

Now OR configuration of distance relays provides both dependability and better security.

Figure 2: Alternative 2.
Zone 1’s default state is ‘No block’.

Only relays vulnerable to trip during out-of-step condition are moved to the block state during rare instances of out-of-step condition.

This should put to rest any concern on compromising dependability.

This ascertains that the protection system is not compromised.
If there is a fault in zone 1 during block then the relay should be unblocked.
We ensure that this is done using local substation input.
This ensures reliability.
We refer to it as local override policy.
Relay communication would be UDP based.

The block decision will be time stamped and stale decisions at relay end would be discarded.

Using P-type PMU, the PMU measurement time is 50 ms. Communication time to PDC is 40 ms if direct communication is used.

Total round communication time is 150 - 180 ms considering uncertainties.

Prediction of block should be this much early.
We first ascertain from synchrophasors of both ends of the line that there is no fault on the line.

We introduce a $\delta_{SR}(x \text{ axis}) - V_{\text{min}}(y \text{ axis})$ co-ordinate system where, $\delta_{SR} = \delta_S - \delta_R$ and define

$$V^2_{\text{min}} = \min_{0 \leq x \leq l} |V(x)|^2.$$ 

If an electrical center manifests on the transmission line, then, $V_{\text{min}} = 0$ and $\delta_{SR} \approx \pm 180^\circ$.

Therefore, for each synchrophasor sample, we can calculate $V_{\text{min}}$ and $\delta_{SR}$ and thereby monitor power swing trajectory in $\delta_{SR} - V_{\text{min}}$ plane.
Figure 5: Visualization of a 3-phase fault, power swings and electrical center formation in $\delta_{SR} - V_{min}$ plane. Coordinates of an electrical center have a strong separation from other events.
A Challenge in $\delta_{SR} - V_{\text{min}}$ Plane

- A problem with the simple $\delta_{SR} - V_{\text{min}}$ plane is that we just cannot map a distance relay characteristic e.g., of zone 1 from the R-X to the new plane.

- Hence, we cannot predict if and when the trajectory will enter zone 1.

- However, by a little modification of the new coordinate system, this difficulty can be circumvented.

- Without loss of generality, consider a distance relay at the receiving end of the line whose apparent impedance is given by

$$Z_{\text{app}}^R = R + jX = \frac{V_R}{-I_R}.$$  

$$\frac{V(x)}{V_R} = \cosh(\gamma x) - \frac{Z_c}{Z_{\text{app}}^R} \sinh(\gamma x)$$
Solution: Use $\delta_{SR} - V_{minpu} \text{ plane}$

- Thus, given $Z_{app}^R$ we can evaluate $V_{min}/|V_R|$. 
- Further, at $x = l$, $V(l) = V_S$

$$\frac{V_S}{V_R} = \cosh(\gamma l) - \frac{Z_c}{Z_{app}^R} \sinh(\gamma l).$$

- Thus, the boundary of a zone 1 can be mapped on to $\delta_{SR} - V_{minpu} \text{ plane}$
- $V_{minpu}$ can be estimated during power swing and $\delta_{SR}$ can be measured for each time snapshot.
Overlaying zone 1 characteristics (Illustration 1)

(a) Distance relay characteristic. A-B-C-D-E-F-A is the modified characteristic to avoid origin.
(b) Relay mapping using $|V_R|$ as a base.
(c) Relay mapping using $|V_S|$ as a base.
Also seen in the figures is the evolution of electrical center and infringement of zone 1.

Simulation done on IEEE 16 Machine system.
Curve fitting encodes various segments of the zone 1 characteristics in the $\delta_{SR} - V_{minpu}^R$ plane. i.e., $V_{minpu}^R = a_i \delta_{SR}^2 + b_i \delta_{SR} + c_i$, $i$ refers to line segment of the zone 1.

Extrapolate the power swing and check if it intersects the relay characteristic.

- Taylor series expansion of $\delta_{SR}$ and $V_{min}$ is used.

$$V_{minpu}^R (\delta_{SR}^0 + \Delta \delta_{SR}) = V_{minpu}^R (\delta_{SR}^0) + \frac{dV_{minpu}^R}{d\delta_{SR}} \Delta \delta_{SR} + \frac{1}{2} \frac{d^2V_{minpu}^R}{d\delta_{SR}^2} \Delta \delta_{SR}^2$$

If the extrapolated trajectory cuts the zone 1 locus then estimate time left before the encroachment happens.

Again a second order Taylor series expansion of $\delta_{SR}(t)$ is used.
The numerical derivatives with noisy data can be very inaccurate.

In fact, the prediction may go haywire.

First denoise the data and then compute the derivatives.

Consider that we are given a time series $y_t$, $t = 1 \ldots n$ of a signal $x_t$, $t = 1 \ldots n$. Signal $y_t$ could be equivalenced to either $\delta(t)$ or $V^R_{\text{min pu}}(t)$.

For this purpose, we use Hodrick-Prescott (HP) filtering. It consists of solving the following problem.

$$\min(1/2) \sum_{t=1}^{n} (y_t - \hat{x}_t)^2 + \lambda \sum_{t=2}^{n-1} (\hat{x}_{t-1} - 2\hat{x}_t + \hat{x}_{t+1})^2$$

Very Fast: Closed form expression available.
Illustration 2: Prediction algorithm with HP filtering

- \( \lambda \) plays the role of inertia in prediction.
- \( \lambda \) tending to infinity is just a LS fit and \( \lambda \) tending to zero, we just replicate noise.
- We have used \( \lambda \) equal to 200 in simulations.
Duration of the Block

- If a zone 1 encroachment is detected, it may be advisable to put the relay in the block mode for $T_{pr} + T_{bl}$ seconds.

- We observed that initial estimates of block time are conservative (860 milliseconds), but accuracy increases as we approach the relay characteristic (200 milliseconds).
If an absolute value of the residual \( r_t = y_t - x_t \) of magnitude of line current signal is above a threshold \( \epsilon > 0 \) for three consecutive samples then the relay can be moved into an unblock mode.

**Figure 6:** Event detection by residual of HP filter.
Extension to Zone 2 and Zone 3

Mapping of zone 2, zone 3 and blinders.

Block:

- The procedure of mapping is identical to that described for zone 1.
- The prediction should begin early, as infringement of zone 2 and zone 3, precedes infringement of zone 1.
- Early prediction would permit enough lead time to convey block decision to respective zones.
- A block decision once issued, should last for a specified time $T_{bl}$ e.g., 100 msec unless an override, rescind or unblock decision is made later on.
Unblock:

- However, if a 3 phase fault happens on any of the backed-up lines, we must rescind the block decision.
- If a fault is in zone 2 but on the primary line, differential logic using PMU data of the primary line itself will detect it and unblock the relay.
- Once unblocked, the state should be made to persist for at least TDS of the relay to provide relay an opportunity to trip.
- We enforce that if zone 2 or zone 3 of a relay has picked up before receipt of a block command then, we will ignore the block command.
- This will ensure that zones 2 and 3 are not blocked on
  1. stale data
  2. on a 3-phase fault that occurred between the dispatch and receipt of the block command.
### Table 1: Lead Time obtained by the Proposed Method

<table>
<thead>
<tr>
<th>Line (Bus)</th>
<th>Lead Time (ms.)</th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>$T_s$ (ms.)</td>
<td>10</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>4-machine System</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1 (9-10)</td>
<td>480</td>
<td>420</td>
<td>300 ✓</td>
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<tr>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>IEEE 16-machine System</strong></td>
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</tr>
<tr>
<td>64 (41-40)</td>
<td>440</td>
<td>380</td>
<td>360 ✓</td>
</tr>
<tr>
<td>59 (51-50)</td>
<td>150</td>
<td>140</td>
<td>120</td>
</tr>
<tr>
<td>61 (49-52)</td>
<td>360</td>
<td>350</td>
<td>320 ✓</td>
</tr>
<tr>
<td>58 (42-52)</td>
<td>390</td>
<td>330</td>
<td>300 ✓</td>
</tr>
<tr>
<td></td>
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<tr>
<td><strong>Indian Power Grid System</strong></td>
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<tr>
<td>1115</td>
<td>470</td>
<td>450</td>
<td>430 ✓</td>
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<tr>
<td>1140</td>
<td>420</td>
<td>410</td>
<td>400 ✓</td>
</tr>
<tr>
<td>2016</td>
<td>180</td>
<td>160</td>
<td>160</td>
</tr>
</tbody>
</table>
Comparison with $\Delta Z$ scheme

- A permanent 3-phase fault occurs close to and during occurrence of electrical center.
- $\Delta Z$ scheme fails to unblock the relay since variation in the impedance is not significant.
- Thus, relay compromises dependability. Even blinders (not shown) fail in such case.

A temporary 3-phase fault occurs on adjacent line during a power swing.
A large change in $\Delta Z$ will lead to unblock decision thereby compromising security.
Conclusion

- We have shown that, by using the standard voltage and current synchrophasors measurements from both the ends of a line, a supervisory scheme can be designed to predict zone encroachment.

- Then the zone 1 trip can be blocked prior to the infringement and thus prevent the uncontrolled system separation.

- We also suggest measures to guarantee that the dependability of the protection scheme is not compromised by the proposed enhancement.

- Even under the extremely rare scenario of an out-of-step condition, a PMU or a communication system failure and a 3-phase fault either on the line or in its close vicinity, we show that the relay block command can be discarded locally i.e., at the substation level itself.

- Hence, the line protection is never compromised, yet the probability of an incorrect line trip almost reduces to zero.

- The proposed scheme can also be applied to supervision of zones 2 and 3.
S. Lavand, S. Soman, “Predictive Analytic to Supervise Zone 1 of Distance Relay using Synchrophasors”, to appear in *IEEE Transactions on Power Delivery.*
Thanks

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