Remote Backup Protection Systems Using Synchrophasors and NTP-based Frequency Measurement System

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Outline

Issues with Zone 3 protection

- A distance relay, zone-3 element, can maloperate on power swings. Power swings are electromechanical oscillations with 0.5- 2.0 Hz frequency
- It can maloperate under low voltage and high line loading conditions:

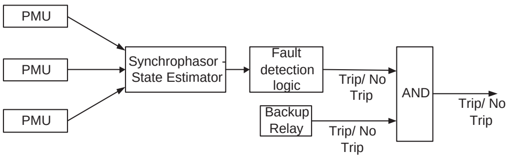
$$Z_{app} = \frac{|V_i|^2}{P_{ij}^2 + Q_{ij}^2}\left(P_{ij} + jQ_{ij}\right) \tag{1}$$

  - 10 % voltage drop implies a 19 % reduction in Z_{app}
  - 10 % increase in load implies 10 % reduction in Z_{app}
  - Simultaneous application of above leads to 24 % reduction in Z_{app}
- Specially an issue when a short line terminates into a long line and with lines having significant infeed

Can SynSE be used to improve *security* of distance relays?

Overview of Proposed Synchrophasor Supervisory System

- Yes because
  1. PMU reporting rate - 20ms -0.1 sec or 10-50 Hz; Nyquist criteria satisfied
  2. communication latency $\leq$ 100 ms;
  3. zone-3 operating time 90 cycles
- SynSE is a faster application while backup protection is a slower application



- AND logic improves security
- Dependability depends upon accuracy of fault detection logic
- In case of failure of communication system, the scheme degenerates to existing backup scheme

SynSE - A Review

- Synchrophasor Based State Estimator is a Linear State Estimator

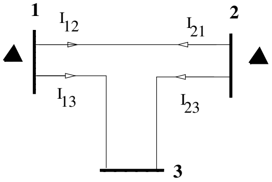
$$\vec{\mathbf{Z}}_t = \vec{\mathbf{M}}_t \vec{\mathbf{V}}_t + \vec{\mathbf{e}}_t \tag{2}$$

$$\vec{\mathbf{V}}_t^{est} = \vec{\mathbf{M}}_t^{+} \vec{\mathbf{Z}}_t \tag{3}$$

$$\vec{\mathbf{r}}_t = (\mathbf{I}_m - \vec{\mathbf{M}}_t \vec{\mathbf{M}}_t^{+}) \vec{\mathbf{Z}}_t \tag{4}$$

where, $\vec{\mathbf{M}}_t^{+} = [\vec{\mathbf{M}}_t^{H} \vec{\mathbf{M}}_t]^{-1} \vec{\mathbf{M}}_t^{H}$

- It creates time snapshots for the system at a rate of 10-50 Hz. In fact, it can be thought of as a dynamic SE

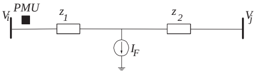


$$\begin{bmatrix} V_1^{pmu} \\ V_2^{pmu} \\ I_{12}^{pmu} \\ I_{13}^{pmu} \\ I_{23}^{pmu} \end{bmatrix} = \begin{bmatrix} 1 & & \\ & 1 & \\ y_{12} & -y_{12} & \\ y_{13} & & -y_{13} \\ & y_{23} & -y_{23} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \\ e_5 \end{bmatrix}$$

Notion of Fault Observability

- Under idealized conditions $\| \vec{\mathbf{r}} \|_{\infty} = 0$
  - Source of error is CT and VT, not time synchronization
- Hence, a fault is said to be observable by SynSE, if under fault $\| \vec{\mathbf{r}} \|_{\infty} > 0$
  - Fault observability is different from bus observability
- Not all transmission line faults can be detected by SynSE:
  - Lack of fault observability - inappropriate PMU placement
  - Low sensitivity of residual vector to a fault

Fault Model of transmission line:

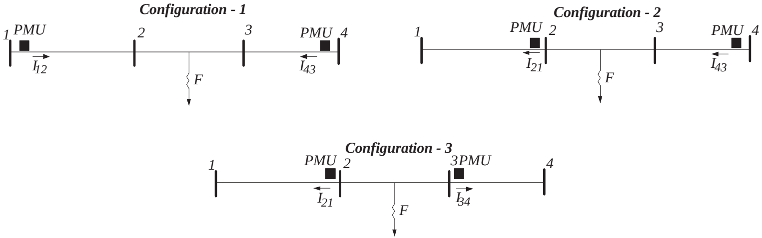


$$\vec{I}_{ijpmu} = \frac{\vec{V}_i - \vec{V}_j}{\vec{Z}_{ij}} + \frac{\vec{Z}_2}{\vec{Z}_{ij}} \vec{I}_F \quad (5)$$

Question: Will $\frac{\vec{Z}_2}{\vec{Z}_{ij}} \vec{I}_F$ reflect in residual vector?

PMU placement vis-a-vis Transmission Line

- For an observable system, PMU placement vis-a-vis a transmission line can happen in three configurations



- Depending upon CB status, this leads to five modes of operation in SynSE based backup protection system

Mode 0: When no PMU is present at either end of the transmission line, a fault on the line cannot be observed in SynSE residual vector

Fault observability Modes 1 and 2

Mode 1 condition:

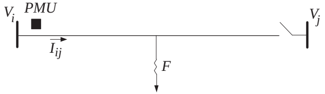
1. PMU is placed at only one end of transmission line
2. Primary protection at both ends of the line fail

Remark: Very low probability of occurance of this mode of failure

Mode 1: If both PMU end and remote end busses of a transmission line are observable without flow measurement $\vec{I}_{ij}$ and $\vec{I}_{ij}$ is also made available, then a shunt fault on the line will be observable in SynSE residual vector

Mode 2 condition:

1. PMU is placed at only one bus of transmission line
2. CB at PMU end fails to open
3. For an unfaulted system $I_{ij} = 0$

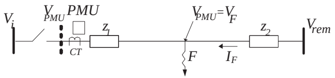


Mode 2: As $I_{pmu} = I_F$, fault can not only be detected but also located to a specific transmission line

Fault Observability Mode 3

Mode 3 condition:

1. PMU at one end of transmission line
2. CB at the remote bus fails to open



- After CB operation, line terminal voltage is different from station bus voltage
- Hence, line VT (not bus VT) should be used to give input to the PMU
- Makes an interesting case for using numerical relays as PMU

Mode 3: If PMU placement is such that remote end bus is observable irrespective of status of corresponding CB, then a fault on the line will lead to nonzero residual in SynSE

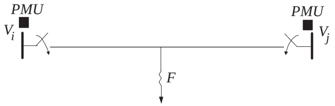
Remark: $V_{pmu} = V_F$ and hence $V_{rem} - V_F = z_2 I_F$

Fault observability Modes 4 and 5

Mode 4 conditions:

1. PMU is placed at both ends of transmission line
2. Circuit breaker at both ends fail to open

Remark: Probability of occurence of this mode is extremely low



Mode 4: Transmission line fault is always observable in mode 4 because $I_{ij_{pmu}} + I_{ji_{pmu}} = I_F$

Mode 5 conditions:

1. PMU is placed at both ends of transmission line
2. Circuit breaker at one end of the line fails to open

Mode 5: Transmission line fault is always observable in mode 5 because either $I_{ij_{pmu}} = I_F$ *&* $I_{ji_{pmu}} = 0$ *or* $I_{ji_{pmu}} = I_F$ *&* $I_{ij_{pmu}} = 0$

$$\therefore I_{ij_{pmu}} + I_{ji_{pmu}} = I_F$$

Case Studies

- Two area, 230 kV, 50 Hz, 4 generator, 10 bus system considered
- CT and VT models correspond to ANSI 1200:5, class C100 CT and 250:0.1 kV CVT
- Self clearing fault on L_3 of 0.5 seconds duration simulated
- Simple power swing simulated by tripping lines L_1 and L_2
- Different PMU placement configurations considered
- Simulations carried out using ATP/ EMTP

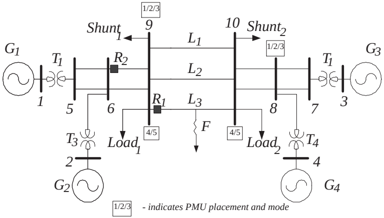
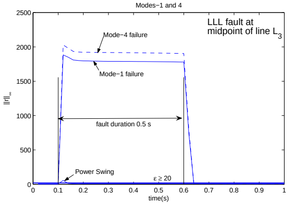
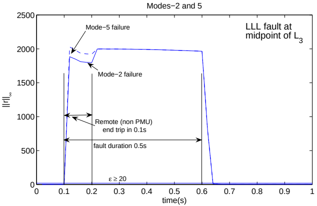


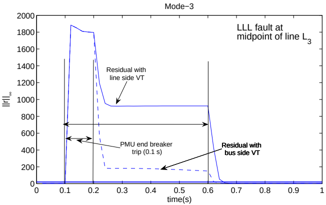
Table: Optimal PMU placement and failure modes for fault on L_3

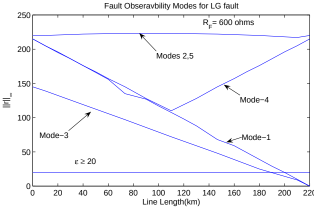
Sr. No.	PMU placement	Failure modes
1	5,6,7,8	0
2	5,9,7,8	1,2,3
3	5,6,7,10	1,2,3
4	5,9,7,10	4,5

Case Studies: Results









Sensitivity Issues

- SynSE cannot detect bus fault.
- Modes 1 and 3 are extremely unlikely
- In these modes, fault detection sensitivity is compromised when the fault is close to the remote bus i.e. $z_2 \approx 0$
- This can compromise dependability of the supervisory solution
- For mode 3, remote backup protection for the remote bus CB will operate in zone 2. Thus line is automatically deenergized.

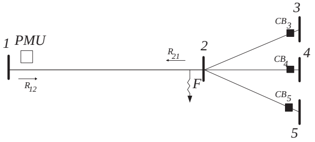
Solution for Mode 1:

- Consider SLG fault. Evaluate:

$$R_f = \frac{\vec{V}_{ag} - \vec{Z}_1(\vec{I}_a + \vec{m}\vec{I}_0)}{\vec{I}_a}$$

- If R_f less than threshold, allow trip
- Similar equations can be derived for other faults

Solution for Mode 3:

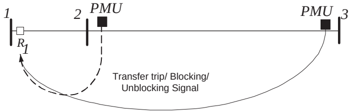


Discussion

Q: Is the work futuristic?

- SynSE is still a few years away

A: Yes and No. No because SynSE can be restricted to a sub system



Many simple schemes are in fact specializations the proposed scheme

Q: Given a critical transmission line, which PMU placement should be favoured?

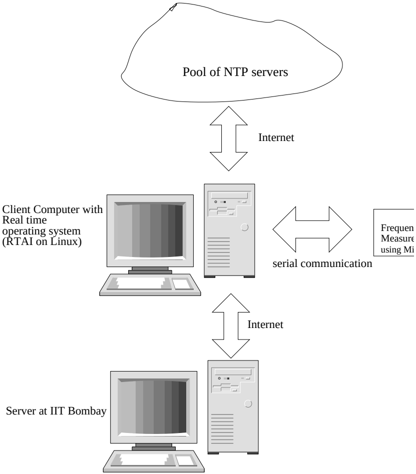
A: Place PMUs at both ends of transmission line leading to mode 4/ 5 operation. In case of a PMU failure, the other PMU can backup as a modified distance relay as in previous slide

References

1. S. H. Horowitz and A, G. Phadke, “Third zone revisited”, IEEE Transactions on Power Delivery, Volume: 21 , Issue: 1, 2006 , pp 23 - 29
2. P. V. Navalkar and S. A. Soman “Secure Remote Backup Protection of Transmission Lines using Synchrophasors”, submitted to IEEE Transactions on Power Delivery
3. S. A. Soman and P. V. Navalkar, “A system and method for detecting and locating a fault and controlling the tripping of a backup relay in a power transmission network using phasor measurement units”, Indian Patent Application No 1117/MUM/2010

NTP Synchronized Frequency Measurement System

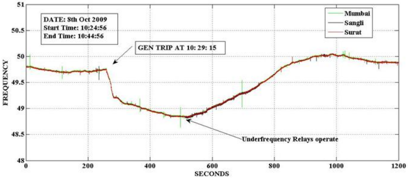
This is the work of my colleague Dr. A. M. Kulkarni

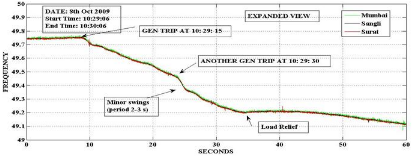


NTP Synchronized Frequency Measurement System (cont.)

- FNET in Virginia Tech uses GPS
- Frequency measurement is done by a microcontroller which counts the time period between two positive zero crossing of the 230 V AC supply
- This measured time period is send to a computer which has a real time operating system (RTAI) on it so that there is no delay between measurement and time stamping
- The computer which does the time stamping has NTP client software running on it. NTP client software uses UDP protocol to exchange packets between client and the NTP server NTP synchronizes the clocks of the computer with nearly 2ms to 10 ms accuracy. This is adequate to capture electromechanical transients
- The time stamped data from all places is continuously sent to server in IITB

Frequency Measurement Observations-1

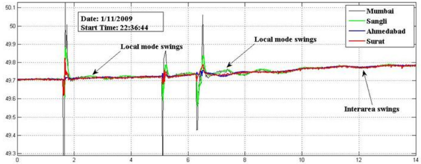


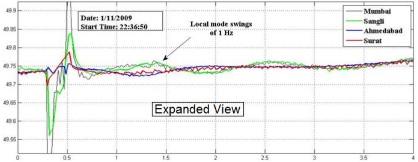


Frequency Measurement Observations-1 (cont.)

- This event is due to a major generator tripping in the grid
- Two generating stations Anpara(1400 MW) and Obra (400 MW) of about total generating capacity 1800 MW tripped
- Due to this event the frequency of the northern grid fell rapidly (0.023 Hz/sec)
- Govenors disabled in Indian System: Emergency frequency control using u/f and df/dt relays
- Minor swings of 2-3 secs are observed
- At about 49.2 Hz and 48.8 Hz under frequency relays provided some load relief Frequencies in the western part of the country move together

Frequency Measurement Observations-2





Frequency Measurement Observations-2 (cont.)

- This event is due to Bus Fault at the Padghe Bus which is near Mumbai
- Local mode swings of about 1 Hz are seen initially
- Just after the fault Mumbai and Sangli are swinging against Ahmedabad and Surat
- Later on all four are swinging together and an inter area swing of about 0.5 Hz is seen

Conclusion: NTP synchronization is adequate to observe electromechanical transients