Zero Sequence Line Parameter Estimation Using PMU Data Considering Uncertainty Factors

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INTRODUCTION

- Accurate zero-sequence impedance estimation is critical for ground fault protection in transmission systems.
- Traditional modeling methods may suffer from significant error due to environmental, construction, and human-related factors.
- Phasor Measurement Unit (PMU) measurements offer a data-driven alternative to refine these parameter.

Objectives

❖ Evaluate the impact of PMU measurement uncertainty and fault location inaccuracy to the zero-sequence line parameter estimation.

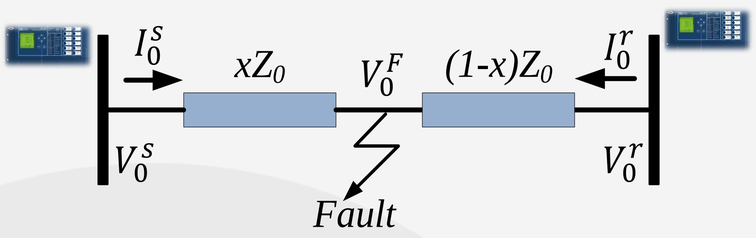
❖ Quantify the effect on distance protection relays.

ZERO-SEQUNECE PARAMETER ESTIMATION

- Two distinct cases can be explored during unbalanced ground faults:

A. Fault on the line of interest

SLG fault to the line that Z_0 will be estimated

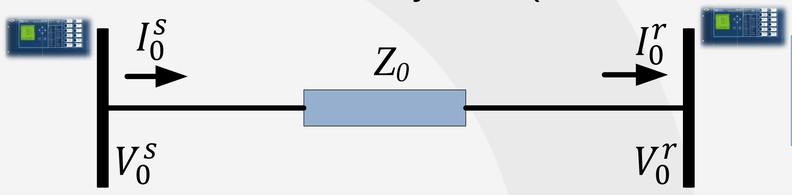


$$V_0^F = V_0^s - I_0^s x Z_0$$
$$V_0^F = V_0^r - I_0^r (1-x) Z_0$$

$$Z_0 = \frac{V_0^s - V_0^r}{I_0^s x - (1-x) I_0^r}$$

B. Fault elsewhere in the system

SLG elsewhere in the system (not in the line that Z_0 will be estimated)



$$Z_0 = \frac{V_0^s - V_0^r}{I_0^s}$$

UNCERTAINTY FACTORS

1. PMU measurement uncertainties

- PMU data during transients (e.g., faults) may include significant magnitude and angle errors.
- According to IEEE standards, dynamic PMU errors can reach:
  - **Voltage:** ±5.4%, ±3.3° ($\bar{e}_{PMU}^{V}$, $\bar{e}_{PMU}^{\varphi}$)
  - **Current:** ±1.6%, ±1.44° ($\bar{e}_{PMU}^{I}$, $\bar{e}_{PMU}^{\theta}$)
- PMU errors are modelled as uniformly distributed random variables:

$$V_{meas} = V_{act}\left(1 + unif(\bar{e}_{PMU}^{V})\right) \qquad \varphi_{meas} = \varphi_{act} + unif(\bar{e}_{PMU}^{\varphi})$$
$$I_{meas} = I_{act}\left(1 + unif(\bar{e}_{PMU}^{I})\right) \qquad \theta_{meas} = \theta_{act} + unif(\bar{e}_{PMU}^{\theta})$$

2. Fault location uncertainty

- When faults occur on the line of interest, location must be known to estimate Z_0 accurately
- Fault location is often expressed as a fraction x of the line length, but:
  - Fault resistance
  - Measurement noise
  - Assumptions in location algorithms

  introduce errors in estimating *x*
- Modeled as a random deviation around the true value:

$$x = x_{act}(1 + unif(\Delta x))$$

Δx denotes the error bounds for the fault location

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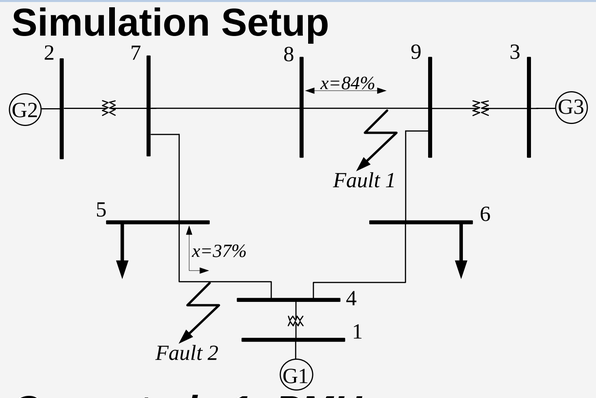
RESULTS

Simulation Setup

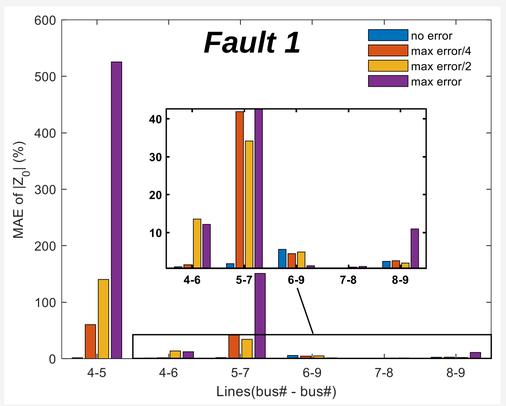


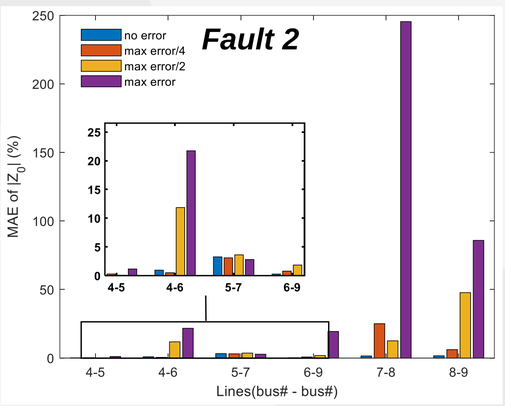
- Fault duration: 0.2 seconds, with PMU reporting at 50 phasors/sec
- PMU measurements assumed available at both ends of each line
- 500 Monte Carlo simulations (*M*) performed per scenario

Case study 1: PMU measurement uncertainty

- PMU data distorted with varying error levels (up to max limits).
- Estimation accuracy measured using MAE over the fault duration (*N*).

$$MAE_{|Z_0|} = \frac{1}{M}\sum_{m=1}^{M}\left(\frac{1}{N}\sum_{t=1}^{N}\left|\frac{|Z_{0,act}| - |Z_{0,est}^{t,m}|}{|Z_{0,act}|}\right|\right)$$



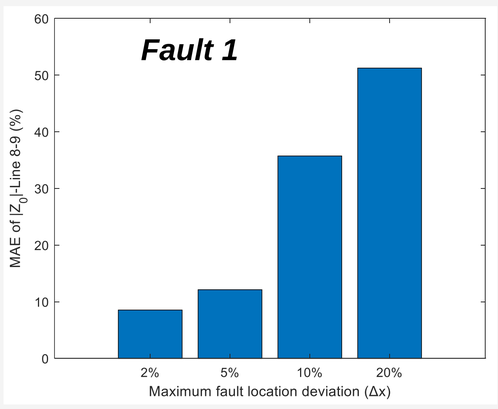


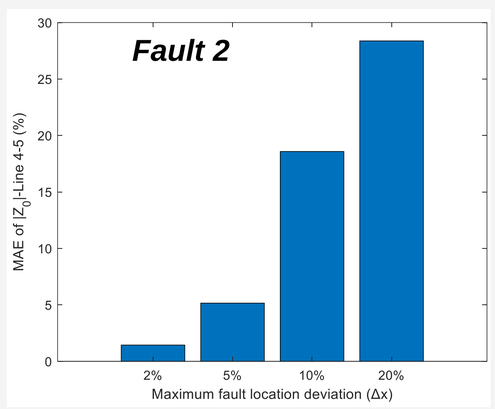
Key findings:

- Low PMU error→Accurate estimation of zero-sequence impedance
- As error increases, estimation accuracy degrades, especially in lines with low zero-sequence current during the fault→ 4–5, 5–7 (Fault 1); 7–8, 8–9 (Fault 2)

Case study 2: Fault location uncertainty

- PMU data is error-free
- Fault location deviations (Δx): 2%, 5%, 10%, 20%





Key Findings:

- MAE remains low when fault location error is less than 5%
- Estimation accuracy drops significantly when Δx exceeds 10%

Impact on Distance Protection Relays

- Distance relays rely on the zero-sequence compensation factor (K_0) to correctly interpret fault conditions.

$$K_0 = \frac{Z_0 - Z_1}{KZ_1} \Rightarrow Z_{comp} = \frac{V_A}{I_A + K_0 I_0}$$

Estimated Z_0 Measurement uncertainty	Relay operation
No error	Trip
Max error/4	Trip
Max error/2	No trip
Max error	No trip

Estimated Z_0 Fault location uncertainty	Relay operation
2%	Trip
5%	Trip
10%	No trip
20%	No trip

ACKNOWLEDGEMENTS

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