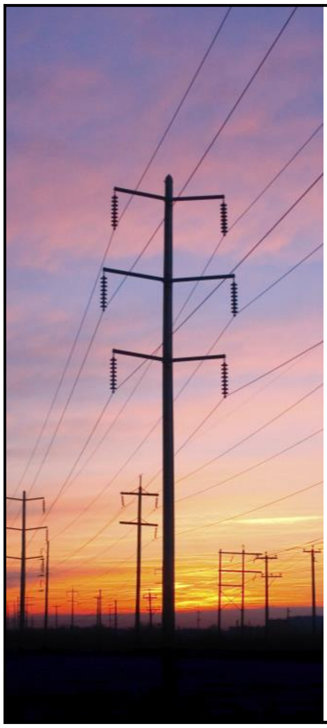

Transmission Line Parameter Estimation Using Traveling-Wave Fault Location Data

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Outline

- Necessity of accurate line parameters
- Available line parameter estimation methods
- Double-ended traveling-wave fault location
- Incremental quantities
- Proposed line parameter estimation method
- Simulation and field event results
- Phenomena that impacts accuracy
- Conclusion

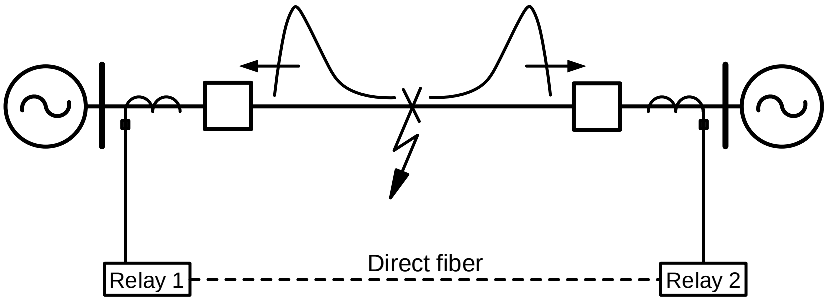
Necessity of accurate line parameters

- Phasor-based distance protection
- Impedance-based fault location
- Short circuit analysis
- Relay testing
- Power flow and stability studies

Available line parameter estimation methods

- Offline methods
  - Line constant tools
  - Signal injection methods
  - Event analysis using known fault location
- Online methods
  - Synchrophasor measurements
  - SPO method

Double-ended traveling-wave fault location



$$m = \frac{1}{2}\left[l + \left(t_L - t_R\right) \bullet v\right]$$

m = fault location estimation using DETWFL
l = line length setting
t_L = first TW arrival time at local relay
t_R = first TW arrival time at remote relay
v = TW propagation velocity

Double-ended traveling-wave fault location

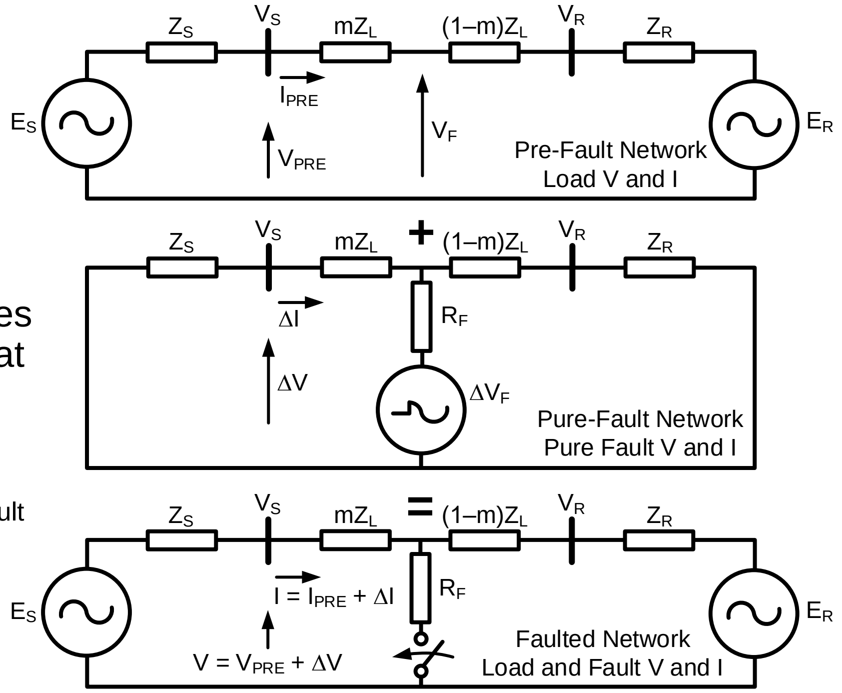
- DETWFL method does not use Z_1 and Z_0 parameters; errors in line parameter settings have no impact on fault location estimates
- DETWFL method provides accuracy as low as 300 m or close to one tower span in real-world fault events

Incremental quantities

- Superposition principle is applied
- Incremental quantities represent signals that appear in the pure-fault network

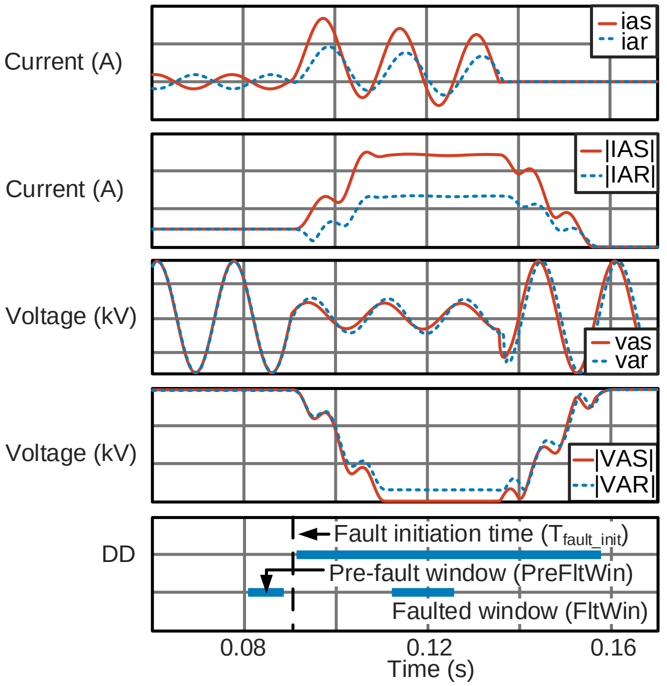
$$\Delta V = V_{Faulted} - V_{Pre\text{-}fault}$$

$$\Delta I = I_{Faulted} - I_{Pre\text{-}fault}$$



Proposed method

DD – disturbance detector is used to identify fault initiation time



Proposed method

- Z_1 is estimated using phasors from pre-fault window and solving positive-sequence network
- Incremental phasors (ΔV, ΔI) are computed by subtracting pre-fault phasors from faulted phasors
- Z_0 is estimated using incremental phasors and solving pure-fault zero-sequence network
- Only Z_0 estimation method uses TW fault location data

Proposed Z_1 estimation method

Time synchronized voltage and current phasors from pre-fault data window from both ends are used; PI equivalent model is used

$$I_{C1} = I_{1S} + I_{1R} \qquad |Y_{C1}| = \left|\frac{2 \bullet I_{C1}}{V_{1S} + V_{1R}}\right| \qquad |Y_{C0}| = \frac{|Y_{C1}|}{1.7} \qquad B_S = \frac{2 \bullet Y_{C1} + Y_{C0}}{3} \qquad B_M = \frac{Y_{C0} + Y_{C1}}{3}$$

Line charging current supplied from local end

$$\begin{bmatrix} I_{AS\_CC'} \\ I_{BS\_CC'} \\ I_{CS\_CC'} \end{bmatrix} = 0.5 \bullet \begin{bmatrix} B_S & B_M & B_M \\ B_M & B_S & B_M \\ B_M & B_M & B_S \end{bmatrix} \bullet \begin{bmatrix} V_{AS} \\ V_{BS} \\ V_{CS} \end{bmatrix}$$

Proposed Z_1 estimation method

Current flowing through local end

$$\begin{bmatrix} I_{AS'} \\ I_{BS'} \\ I_{CS'} \end{bmatrix} = \begin{bmatrix} I_{AS} \\ I_{BS} \\ I_{CS} \end{bmatrix} - \begin{bmatrix} I_{AS\_CC'} \\ I_{BS\_CC'} \\ I_{CS\_CC'} \end{bmatrix}$$

Positive-sequence current through line is calculated ($I_{1S'\_Pre\text{-}fault}$), and Z_1 is estimated

$$Z_1 = \frac{V_{1S\_Pre\text{-}fault} - V_{1R\_Pre\text{-}fault}}{I_{1S'\_Pre\text{-}fault}}$$

Proposed Z_0 estimation method

m_{TW} – TWFL data in per unit; B-susceptance matrix

Current flowing through local end

$$\begin{bmatrix} I_{AS\_CC''} \\ I_{BS\_CC''} \\ I_{CS\_CC''} \end{bmatrix} = m_{TW} \bullet \begin{bmatrix} B_S & B_M & B_M \\ B_M & B_S & B_M \\ B_M & B_M & B_S \end{bmatrix} \bullet \begin{bmatrix} V_{AS} \\ V_{BS} \\ V_{CS} \end{bmatrix}$$

$$\begin{bmatrix} I_{AS''} \\ I_{BS''} \\ I_{CS''} \end{bmatrix} = \begin{bmatrix} I_{AS} \\ I_{BS} \\ I_{CS} \end{bmatrix} - \begin{bmatrix} I_{AS\_CC''} \\ I_{BS\_CC''} \\ I_{CS\_CC''} \end{bmatrix}$$

Current flowing through remote end

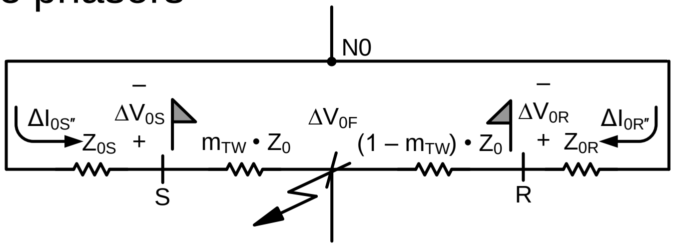
$$\begin{bmatrix} I_{AR\_CC''} \\ I_{BR\_CC''} \\ I_{RS\_CC''} \end{bmatrix} = \left(1 - m_{TW}\right) \bullet \begin{bmatrix} B_S & B_M & B_M \\ B_M & B_S & B_M \\ B_M & B_M & B_S \end{bmatrix} \bullet \begin{bmatrix} V_{AR} \\ V_{BR} \\ V_{CR} \end{bmatrix}$$

$$\begin{bmatrix} I_{AR''} \\ I_{BR''} \\ I_{CR''} \end{bmatrix} = \begin{bmatrix} I_{AR} \\ I_{BR} \\ I_{CR} \end{bmatrix} - \begin{bmatrix} I_{AR\_CC''} \\ I_{BR\_CC''} \\ I_{CR\_CC''} \end{bmatrix}$$

Proposed Z_0 estimation method

Incremental zero-sequence phasors

$$\Delta V_{0S} = V_{0S\_Faulted} - V_{0S\_Pre\text{-}fault}$$
$$\Delta I_{0S''} = I_{0S''\_Faulted} - I_{0S'\_Pre\text{-}fault}$$
$$\Delta V_{0R} = V_{0R\_Faulted} - V_{0R\_Pre\text{-}fault}$$
$$\Delta I_{0R''} = I_{0R''\_Faulted} - I_{0R'\_Pre\text{-}fault}$$

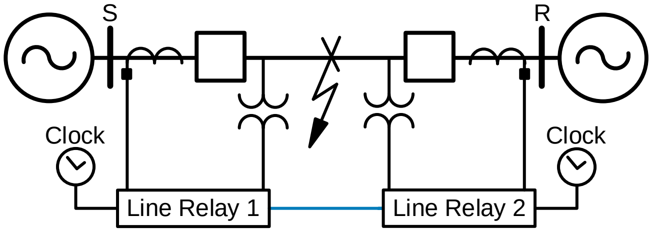


Pure-fault network is used to estimate Z_0

$$Z_0 = \frac{\Delta V_{0S} - \Delta V_{0R}}{m_{TW} \bullet \Delta I_{0S''} - (1 - m_{TW}) \bullet \Delta I_{0R''}}$$

Test setup

- System nominal voltage is 400 kV, and line length is 100 km
- Modeled with CT, CCVT, and 2-cycle circuit breakers
- 81 fault cases using following combinations
  - Load angle (δ): 20°, 1°, –20°
  - Fault resistance (R_f): 0, 10, 40 ohms
  - Fault type: AG, BC, CAG
  - Fault location (m_{TW}): 30, 50, 80 km



Faulted network method

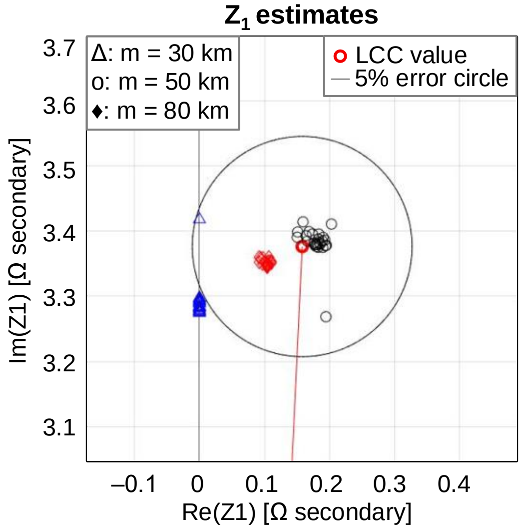
Faulted negative-sequence network is used to estimate Z_1

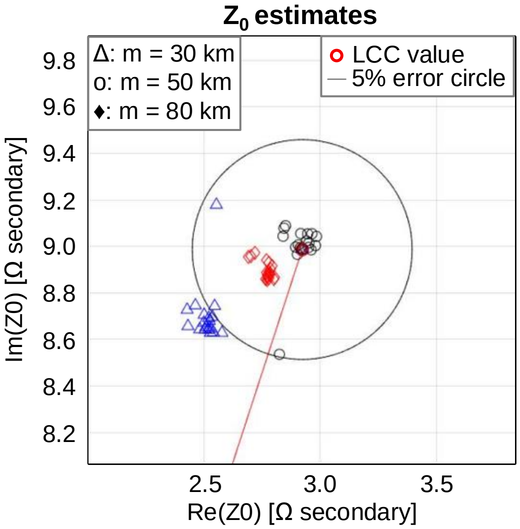
$$Z_1 = \frac{V_{2S} - V_{2R}}{m_{TW} \bullet I_{2S} - \left(1 - m_{TW}\right) \bullet I_{2R}}$$

Faulted zero-sequence network is used to estimate Z_0

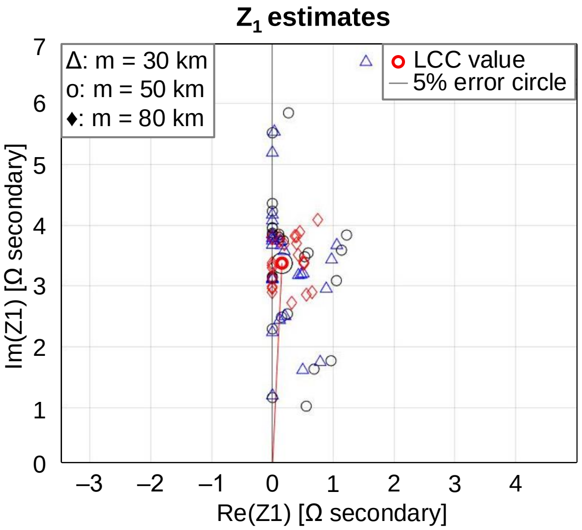
$$Z_0 = \frac{V_{0S} - V_{0R}}{m_{TW} \bullet I_{0S} - \left(1 - m_{TW}\right) \bullet I_{0R}}$$

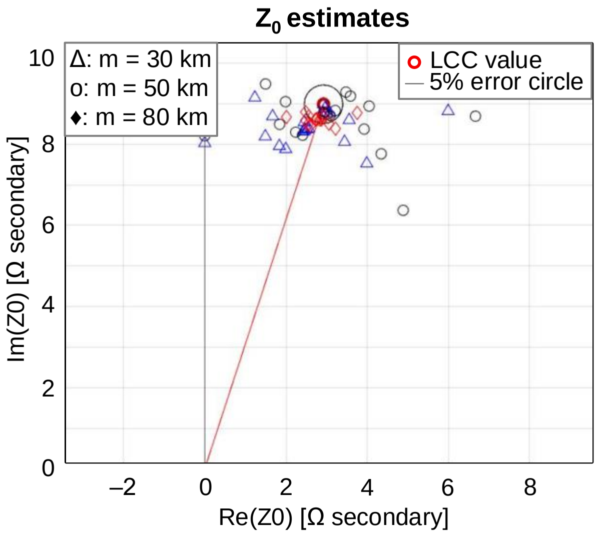
Transposed line model – faulted network method



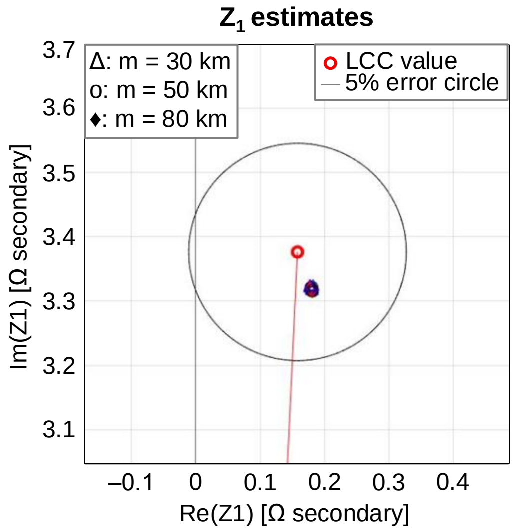


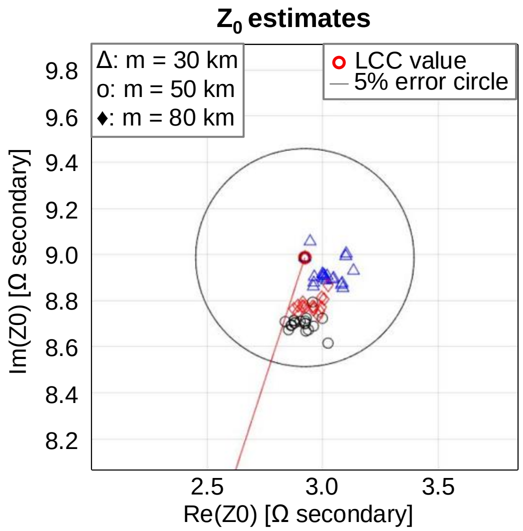
Untransposed line model – faulted network method


Z_1 estimates

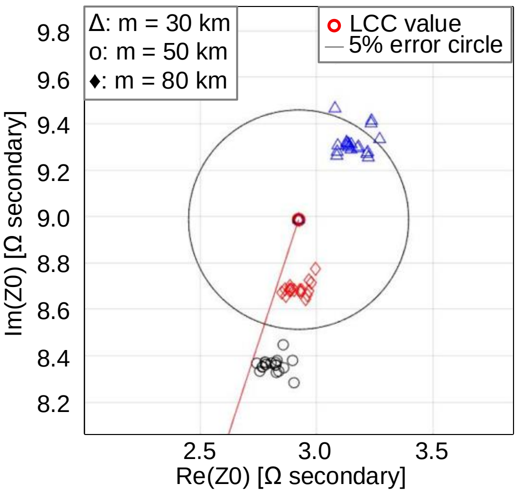

Z_0 estimates

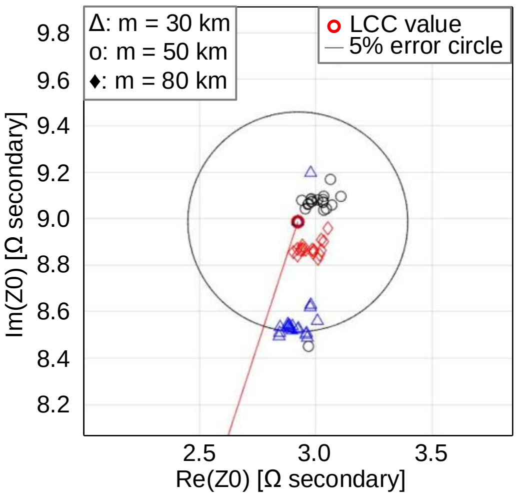
Untransposed line model – proposed method


Z_1 estimates


Z_0 estimates

Impact of TWFL inaccuracy


Z_0 estimates with +300 m TWFL inaccuracy


Z_0 estimates with –300 m TWFL inaccuracy

Field event results

Event	Line voltage (kV)	Fault type	Fault location (miles)		Z_1/Z_0 estimates	[Mag error, phase error]
			Actual	DETWFL		
1	230	CG	61.501 (local), 91.669 (remote)	60.995 (local), 92.175 (remote)	$Z_1 = 22.86\angle 80.75^\circ$ $Z_0 = 48.81\angle 73.78^\circ$	Z_1 = [2.82%, 0.96°] Z_0 = [4.75%, 7.35°]
2A	220	BG	33.867 (local), 28.085 (remote)	33.837 (local), 28.143 (remote)	$Z_1 = 5.70\angle 76.94^\circ$ $Z_0 = 12.32\angle 72.68^\circ$	Z_1 = [9.19%, 2.59°] Z_0 = [3.08%, 3.05°]
2B	220	BG	33.867 (local), 28.085 (remote)	33.908 (local), 28.072 (remote)	$Z_1 = 5.63\angle 80.09^\circ$ $Z_0 = 11.92\angle 73.17^\circ$	Z_1 = [7.99%, 0.55°] Z_0 = [6.29%, 2.57°]
3	115	AG	3.1 (local), 54.66 (remote)	3.199 (local), 54.504 (remote)	$Z_1 = 6.1488\angle 70.25^\circ$ $Z_0 = 17.52\angle 78.48^\circ$	Z_1 = [4.04%, 1.04°] Z_0 = [7.63%, 9.28°]
4	132	AB	32.593 (local), 26.443 (remote)	32.665 (local), 26.375 (remote)	$Z_1 = 2.72\angle 63.11^\circ$	Z_1 = [4.24%, 0.88°]

Phenomena that impacts accuracy

- Z_1 estimates are sensitive to CT and PT errors at low load angle conditions
- Evolving faults, CT saturation, CCVT transients, faults with time varying resistance, and fast breaker operation impact accuracy of Z_0 estimates
- Inaccuracies in TWFL have direct impact on accuracy of Z_0 estimates
- Proposed method does not account for coupling of positive-sequence and negative-sequence quantities on pure-fault zero-sequence networks, which in turn, impacts Z_0 accuracy
- Proposed method cannot be applied on mutually coupled lines

Conclusion

- Pre-fault positive-sequence quantities and PI equivalent line model are used for Z_1 estimates
- Incremental zero-sequence quantities and pure-fault zero-sequence network are used for Z_0 estimates
- Proposed method provides better Z_0 estimates for both transposed and untransposed lines

Questions?