Tracking Three Phase Untransposed Transmission Line Parameters Using Synchronized Measurements

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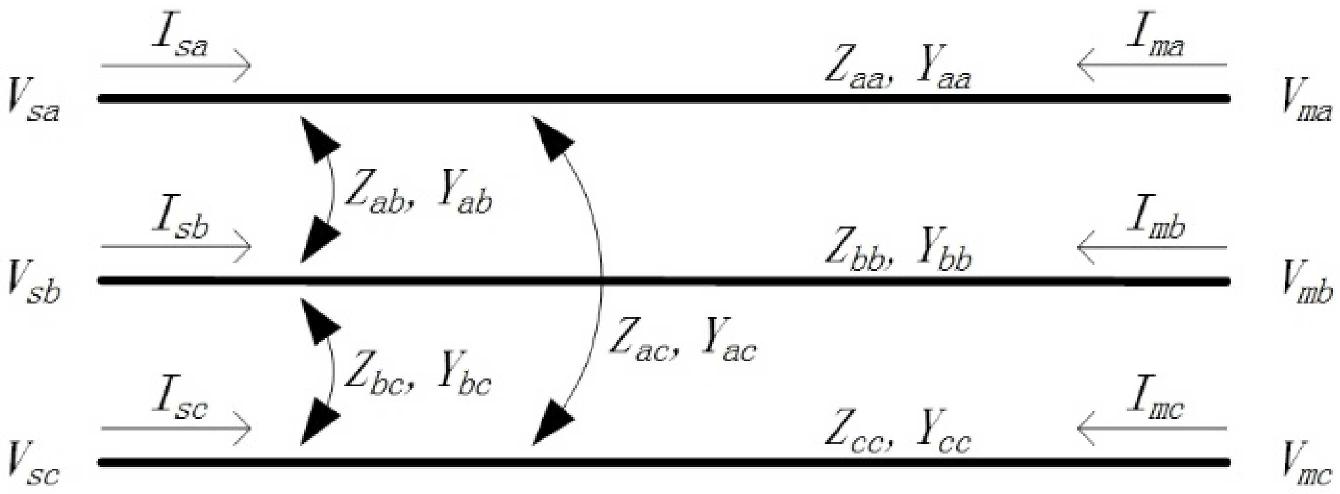
Motivation

- Transmission line parameters may not all be accurate in the existing data base.
- Only positive and zero sequence parameters may be available, yet not all lines are fully transposed.
- Parameters may change due to changes in ambient temperature, wind, loading etc.

A method to track the parameters of the fully coupled three-phase line model is needed !

Three Phase Transmission Line Model

- Consider the following untransposed three-phase transmission line with mutual coupling between phases:



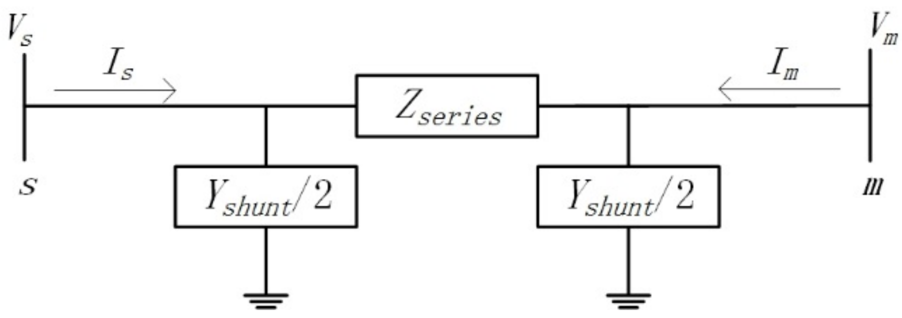
- Assume PMU measurements at both terminals of the line.

Equation: I = YV

- Nodal equations for the line can be written as:

$$\tilde{I} = Y\,\tilde{V}$$

- Considering the pi-model for the line:



$$V_s = \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix}, \qquad I_s = \begin{bmatrix} I_{sa} \\ I_{sb} \\ I_{sc} \end{bmatrix},$$

$$V_m = \begin{bmatrix} V_{ma} \\ V_{mb} \\ V_{mc} \end{bmatrix}, \qquad I_m = \begin{bmatrix} I_{ma} \\ I_{mb} \\ I_{mc} \end{bmatrix},$$

$$\tilde{V} = \begin{bmatrix} V_s \\ V_m \end{bmatrix}, \qquad \tilde{I} = \begin{bmatrix} I_s \\ I_m \end{bmatrix}.$$

Y will then be a 6-by-6 matrix (complex entries) given below:

$$Y = \begin{bmatrix} Y_{shunt}/2 + Z_{series}^{-1} & -Z_{series}^{-1} \\ -Z_{series}^{-1} & Y_{shunt}/2 + Z_{series}^{-1} \end{bmatrix}$$

Parameters in Untransposed Line

- How many independent parameters will be in an untransposed transmission line model?

$$Z_{series} = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ab} & Z_{bb} & Z_{bc} \\ Z_{ac} & Z_{bc} & Z_{cc} \end{bmatrix} \qquad Y_{shunt} = \begin{bmatrix} Y_{aa} & Y_{ab} & Y_{ac} \\ Y_{ab} & Y_{bb} & Y_{bc} \\ Y_{ac} & Y_{bc} & Y_{cc} \end{bmatrix}$$

  - Impedance Z_{series} consists of line resistance and inductance.
  - Admittance Y_{shunt} consists of shunt capacitance and conductance.
  - For an overhead line, conductance is commonly ignored, i.e. Y_{shunt} will just have an imaginary part.
- 6 complex unknowns in Z_{series} , 6 imaginary unknowns in Y_{shunt}
- Total: 2 * 6 + 6 = **18 real unknowns**, make up the unknown vector p

Measurement Equation Formulation

- Using rectangular coordinates:

$$\tilde{I}_{\text{(6-by-1 complex vector)}} = Y_{\text{(6-by-6 complex matrix)}} \tilde{V}_{\text{(6-by-1 complex vector)}}$$

$$\Downarrow$$

$$I_{\text{(12-by-1 real vector)}} = H_{p\ \text{(12-by-12 real matrix)}} V_{\text{(12-by 1 real vector)}}$$

- Equation $I = H_p V$ can be rearranged as $I = H_V\, p$ where:
  - I is a 12-by-1 vector that contains the current measurements in rectangular coordinates from both terminals of the line.
  - p is the 18-by-1 unknown parameter vector.
  - H_V is the 12-by-18 rearranged coefficient matrix consisting of measured voltages at the line terminals.

Measurement Equation Limitations

Regarding the newly formulated equation $I = H_V\, p$:

- Good news: This is a linear equation !
- Bad news: More unknowns p (18) than measurements I (12)

QUESTIONS

- Can we use multiple measurement snapshots ? **NO**
  - H_V will still have low rank because voltages will not change much between measurement scans
- Can we model parameter dynamics ? **YES**
  - Assumed dynamics : $p_{k+1} = p_k + w_{p,k}$ (process noise)

Parameter Tracking Formulation

- Parameter dynamics : $p_{k+1} = p_k + w_{p,k}$
- Measurement equation: $I_k = H_{V,k}\, p_k + v_k$
  - k is the time instant
  - Current measurement noise is modeled as v_k
- Use Kalman filter to solve the parameter tracking problem

ONE MORE QUESTION:

- Can we use the measured voltages directly in $H_{V,k}$? **NO**
  - Measurements always contain error or noise.

Three phase phasor-only SE

- Therefore, we introduce a three phase static state estimator using PMU measurements to estimate the states x

$$\begin{bmatrix} V \\ I \end{bmatrix} = \begin{bmatrix} Identity\ matrix \\ H_p \end{bmatrix} x + e$$

  - V is voltage measurement in rectangular form, it is a 12-by-1 vector.
  - I is current measurement in rectangular form, it is a 12-by-1 vector.
  - x is the state in rectangular form, it is still a 12-by-1 vector.
  - H_p is the coefficient matrix consists of parameters, 12-by-12 matrix.
  - e is the measurement noise.

- Use Least-Squares to solve this state estimation problem.

- But the parameters in H_p are not known !

Chicken-and-egg conundrum?

- We want to estimate states from parameters and current measurements
- We also want to estimate parameters from states and current measurements

Solution:

- Iterative between state estimation and parameter tracking problems

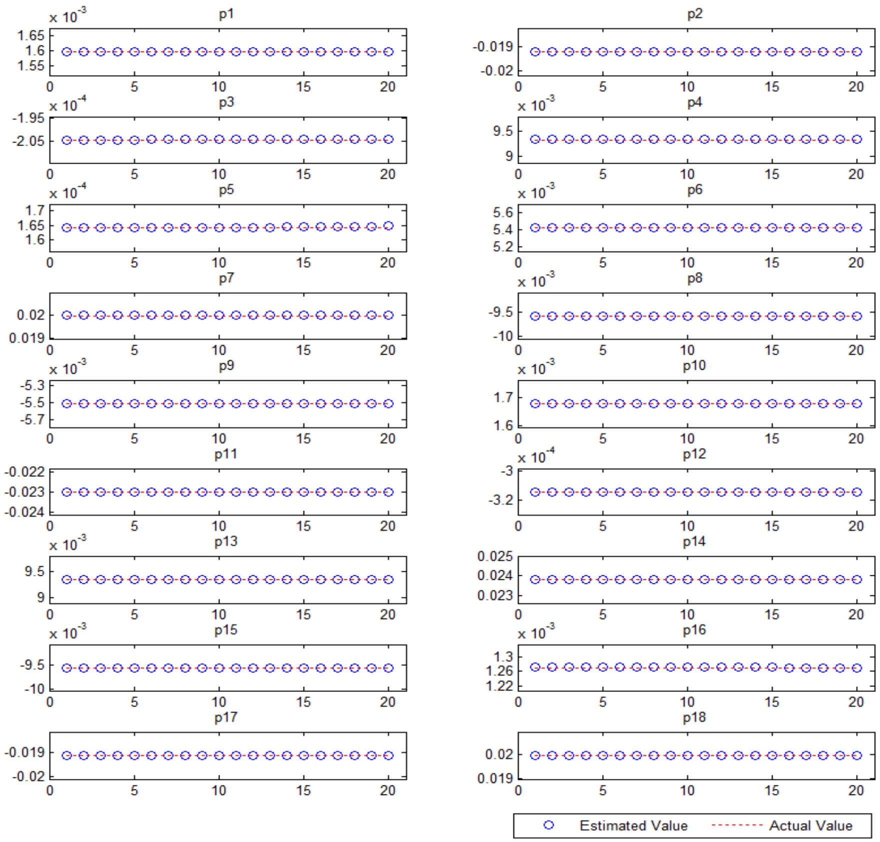
Convergence of the iterations

- It is important to ensure that iterations always converge!
- When two successive iterations yield close enough solutions, iterations can be terminated and results will be trusted.
- Trace of the error covariance of parameters will be used to monitor the "health" of iterations:
  - Error covariance is one of the major measures of estimation accuracy
    - The smaller, the better
  - Trace of error covariance for this problem is always convex, so when it begins to increase, iterations can be terminated.

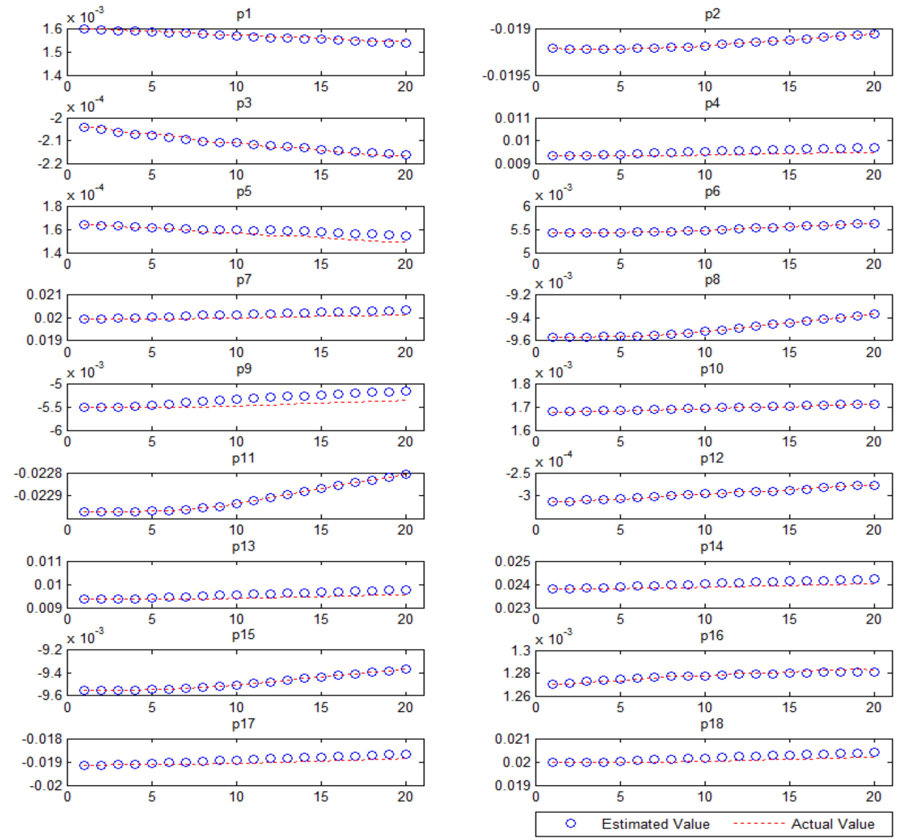
Simulations 1

- We have tested the algorithm on several simulated cases

Constant parameter

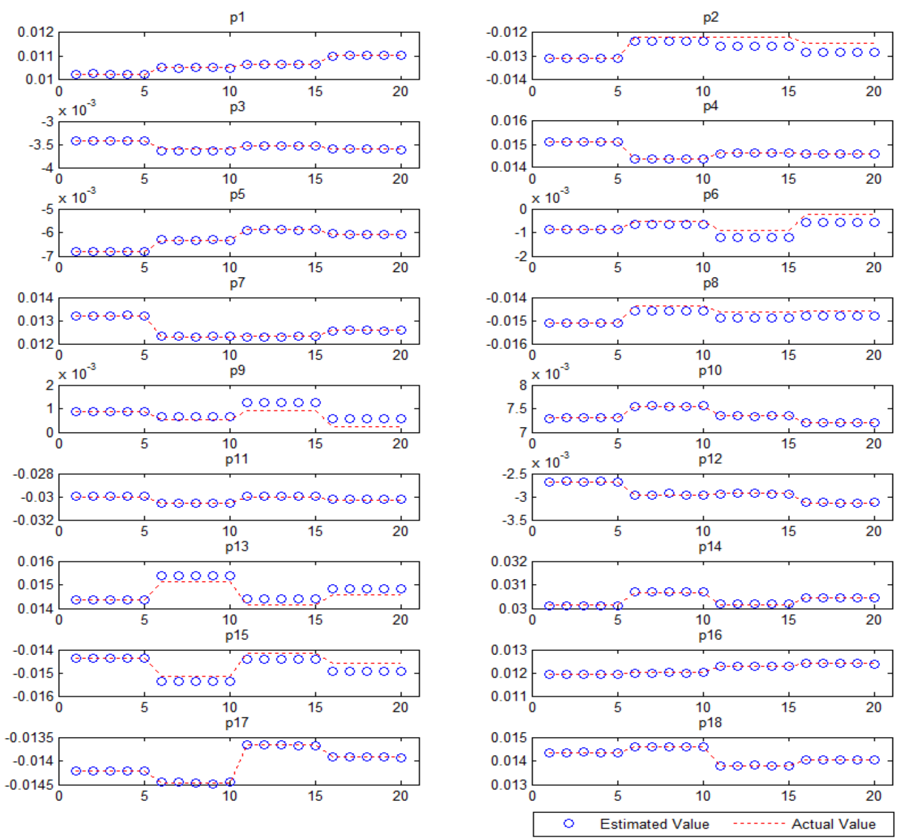


Varying parameter



Simulations 2

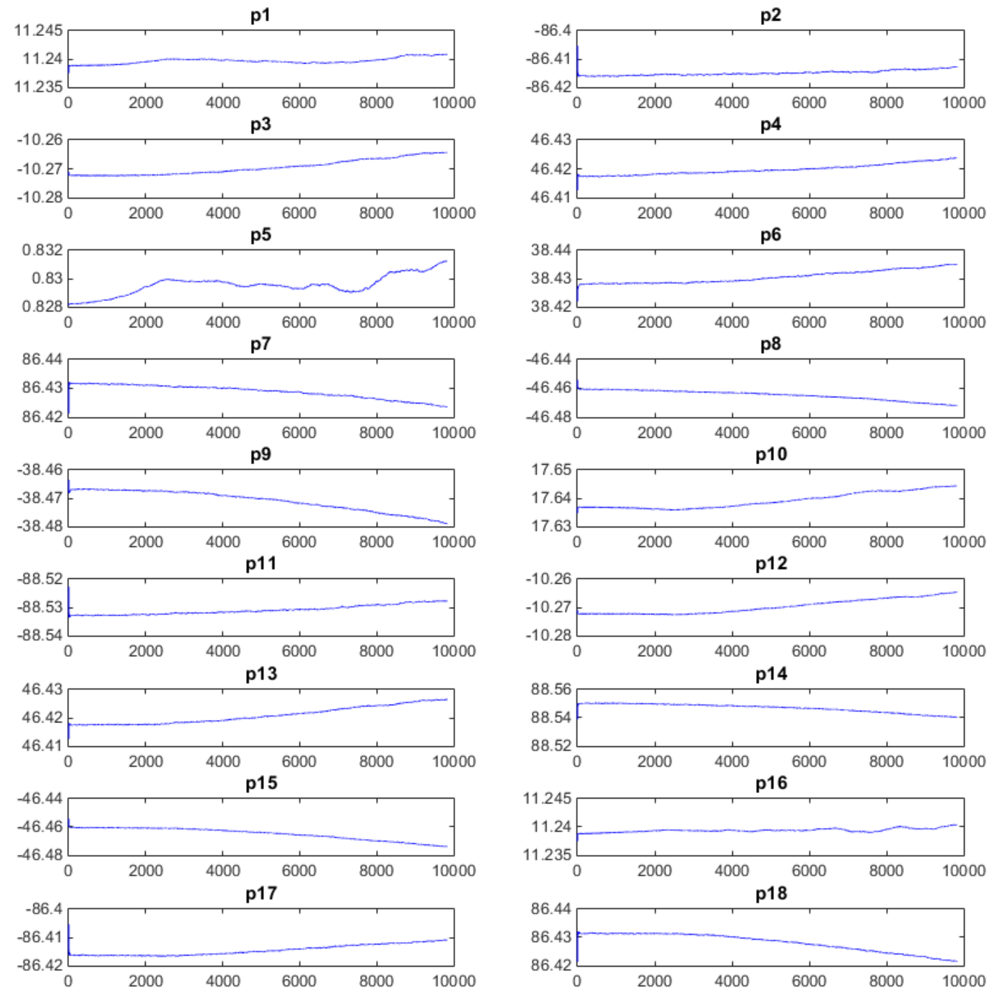
Varying parameters with abrupt changes



- Although some simulated cases are not realistic in practice, they justify the algorithm since the actual values of parameters are available and the estimates can track them almost perfectly

A real case

- Test our algorithm on a real transmission line with two PMUs on both sides.
- Duration is 5.5 minutes, have about 9800 data points.
- CPU running time < 2ms per data point.
- The estimated parameters are close to values in data base.
- Even small variations of the parameters can be tracked accurately.



Advantages

- Can obtain all the parameters of a three phase (untransposed) transmission line
  - Not only positive sequence, but also negative and zero sequence data
- Can track line parameters dynamically using limited information
- Can be implemented for large scale systems with sparsely installed PMUs.

Applications

- Validate database for transmission line parameters
- Track changes of line parameters dynamically
- Support state estimator, especially for three phase phasor only state estimator, dynamic state estimator etc.
- Accurate operation/setting of protective relays and dynamic relays
- Monitoring line corona loss under different weather conditions

THANK YOU !