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Three-phase Instrument Transformer Calibration with Synchronized Phasor Measurements

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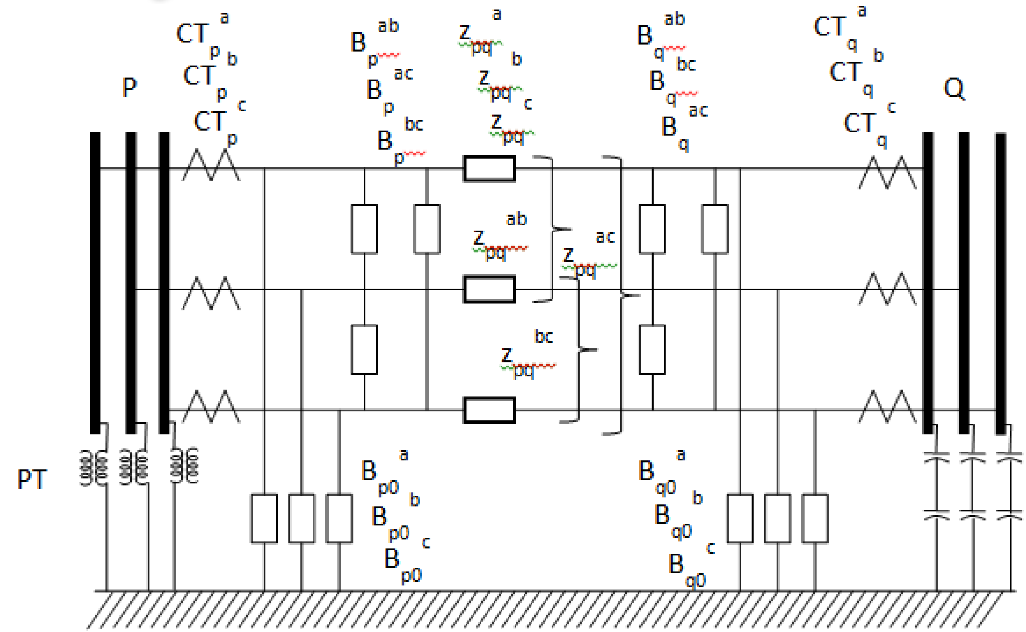
Dominion
It all starts here.

Two-bus system

- Voltages: PT CVT
- Currents: CT



- PMUs are installed at two substation

$$\begin{bmatrix} E_{q0}^{a} \\ E_{q0}^{b} \\ E_{q0}^{c} \end{bmatrix} = \begin{bmatrix} E_{p0}^{a} \\ E_{p0}^{b} \\ E_{p0}^{c} \end{bmatrix} - \begin{bmatrix} Z_{pq}^{a} & Z_{pq}^{ab} & Z_{pq}^{ac} \\ Z_{pq}^{ab} & Z_{pq}^{b} & Z_{pq}^{bc} \\ Z_{pq}^{ac} & Z_{pq}^{bc} & Z_{pq}^{c} \end{bmatrix} \left(\begin{bmatrix} I_{pq0}^{a} \\ I_{pq0}^{b} \\ I_{pq0}^{c} \end{bmatrix} - \begin{bmatrix} B_{p}^{a} & B_{p}^{ab} & B_{p}^{ac} \\ B_{p}^{ab} & B_{p}^{b} & B_{p}^{bc} \\ B_{p}^{ac} & B_{p}^{bc} & B_{p}^{c} \end{bmatrix} \begin{bmatrix} E_{p0}^{a} \\ E_{p0}^{b} \\ E_{p0}^{c} \end{bmatrix} \right)$$

Measurement Errors

- **Relaying instrument transformers have 3% to 10% Ratio Magnitude Error and 0.5 to 3 degrees Phase angle Error.**

Limits of ratio error relay class	@ rated current	@ 20 times
C and T classification	3%	10%
X classification	1%	user defined

- **High accuracy voltage transformers for extra-high voltage (500KV in Dominion Power System) have ≤0.15% Ratio Magnitude Error and ≤ 0.1degrees Phase angle Error.**
- **Synchronous Phasor Measurements have two parts of error:**
  - quantization of the A/D converter (12 bits -> 10-5)
  - GPS synchronization uncertainties (1μs -> 0.021 degress)

Error Models

- **Error model of CVTs and CTs:**

$$\begin{bmatrix} E^a \\ E^b \\ E^c \end{bmatrix} = \begin{bmatrix} e^a & 0 & 0 \\ 0 & e^b & 0 \\ 0 & 0 & e^c \end{bmatrix} \begin{bmatrix} E_m^a \\ E_m^b \\ E_m^c \end{bmatrix} \qquad \begin{bmatrix} I^a \\ I^b \\ I^c \end{bmatrix} = \begin{bmatrix} i^a & 0 & 0 \\ 0 & i^b & 0 \\ 0 & 0 & i^c \end{bmatrix} \begin{bmatrix} I_m^a \\ I_m^b \\ I_m^c \end{bmatrix}$$

Here, e and i are the ratio correction factor (RCF),

$|e|,|i| \sim$ Uniform(0.96,1.04),

angle(e), angle(i) ~ Uniform(-3,3) degree

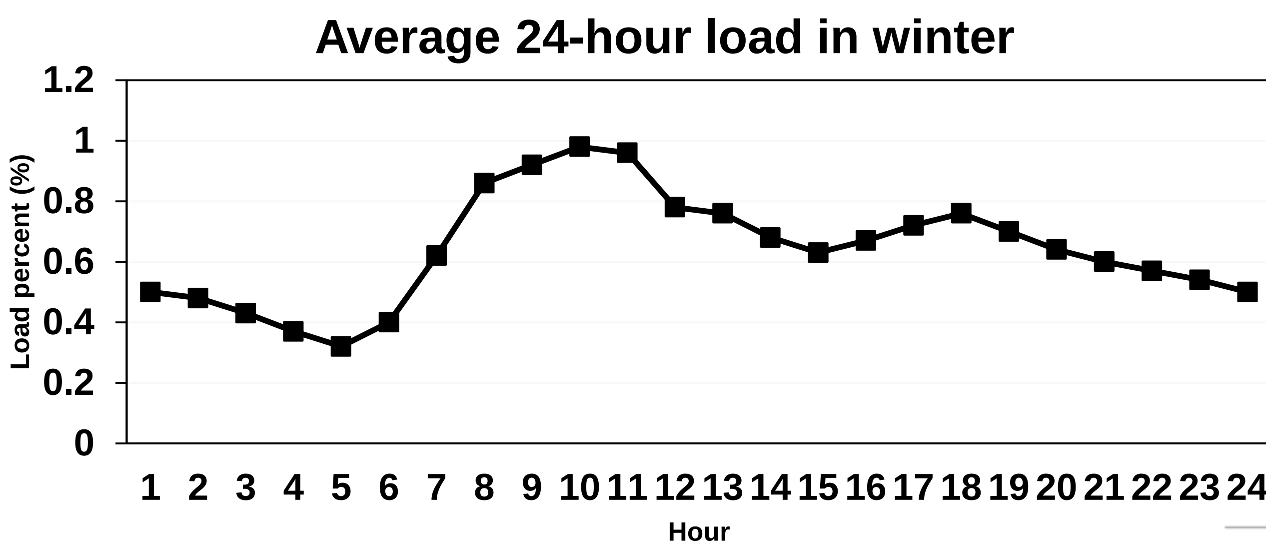
Assumption:

1. The transformer ratio correction factors are assumed to be constant over the simulation period
2. The system model (network impedance matrix) is accurate.

24-hour load cases

- **At each point, the load condition changes. PMUs can measure three-phase voltages and currents under each condition. And all of these set satisfy OHM law.**

$$\begin{bmatrix} e^a & 0 & 0 \\ 0 & e^b & 0 \\ 0 & 0 & e^c \end{bmatrix}\begin{bmatrix} E^a_{qm} \\ E^b_{qm} \\ E^c_{qm} \end{bmatrix} = \begin{bmatrix} E^a_p \\ E^b_p \\ E^c_p \end{bmatrix} - \begin{bmatrix} Z^a_{pq} & Z^{ab}_{pq} & Z^{ac}_{pq} \\ Z^{ab}_{pq} & Z^b_{pq} & Z^{bc}_{pq} \\ Z^{ac}_{pq} & Z^{bc}_{pq} & Z^c_{pq} \end{bmatrix}\left(\begin{bmatrix} i^a & 0 & 0 \\ 0 & i^b & 0 \\ 0 & 0 & i^c \end{bmatrix}\begin{bmatrix} I_m^a \\ I_m^b \\ I_m^c \end{bmatrix} - \begin{bmatrix} B^a_p & B^{ab}_p & B^{ac}_p \\ B^{ab}_p & B^b_p & B^{bc}_p \\ B^{ac}_p & B^{bc}_p & B^c_p \end{bmatrix}\begin{bmatrix} E^a_{p0} \\ E^b_{p0} \\ E^c_{p0} \end{bmatrix}\right)$$



Linear Method

- Get linear equations

Branch with perfect PT

$$(Y_{12}+B_{12})E_1 = i_{12}I_{12} + Y_{12}e_2E_2$$

$$Y_{12}E_1 = -i_{21}I_{21} + (Y_{12}+B_{12})e_2E_2$$

Branch with two buses to be calibrated

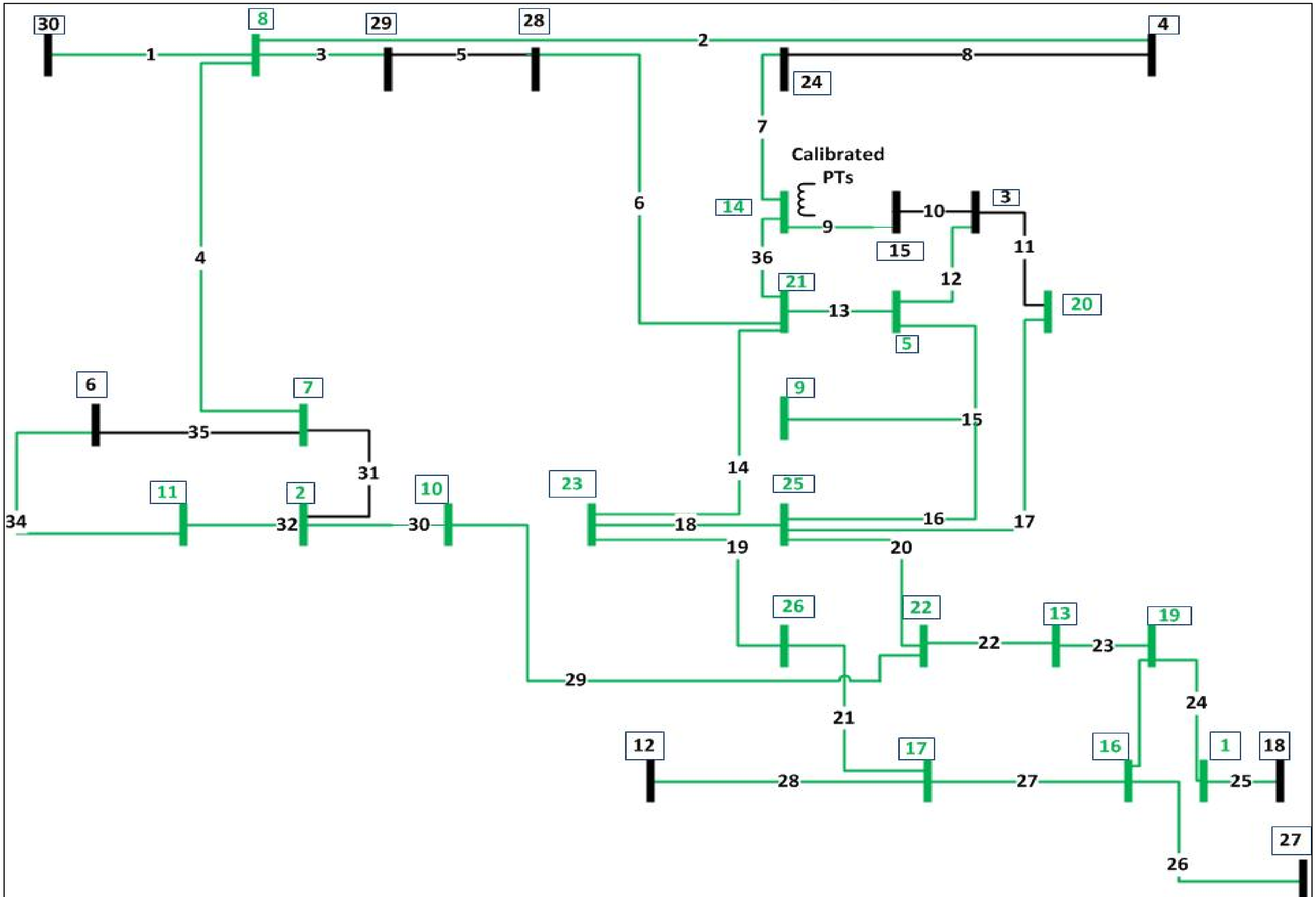
$$0 = -i_{rs}I_{rs} + (Y_{rs}+B_{rs})e_rE_r - Y_{rs}e_sE_s$$

$$0 = -i_{sr}I_{sr} + (Y_{rs}+B_{rs})e_sE_s - Y_{rs}e_rE_r$$

$$\begin{bmatrix} D(I) & \cdots & Y_A E \\ \vdots & \vdots & \vdots \end{bmatrix} \begin{bmatrix} i_{12} \\ i_{21} \\ i_{rs} \\ i_{sr} \\ \vdots \\ e_2 \\ e_r \\ e_s \\ \vdots \end{bmatrix} = \begin{bmatrix} E_{ref} \end{bmatrix}$$

$$X = ([D(I)\ Y_A E])^{-1} E_{ref}$$

DVP 500kv system



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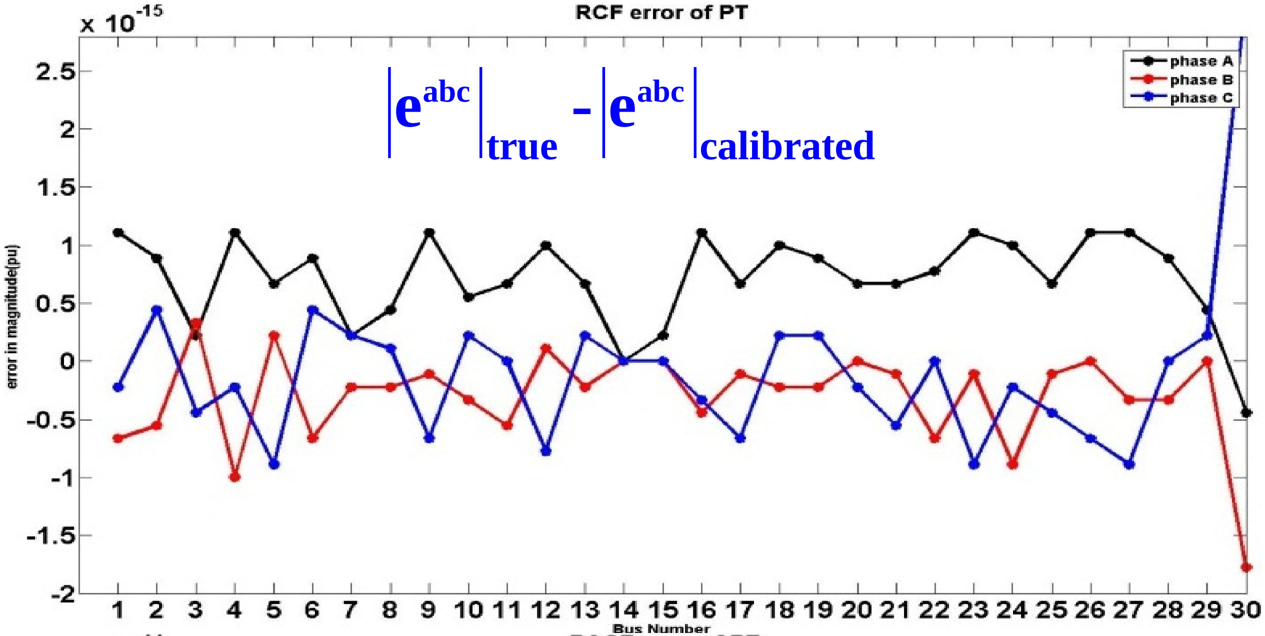
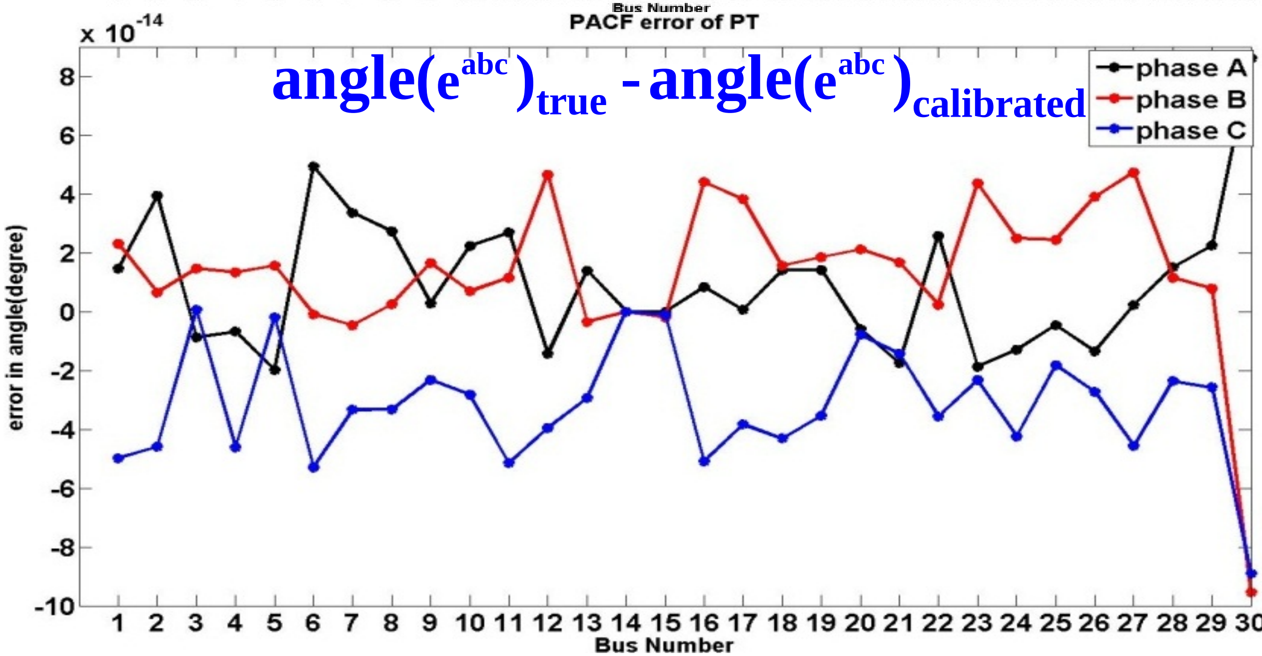
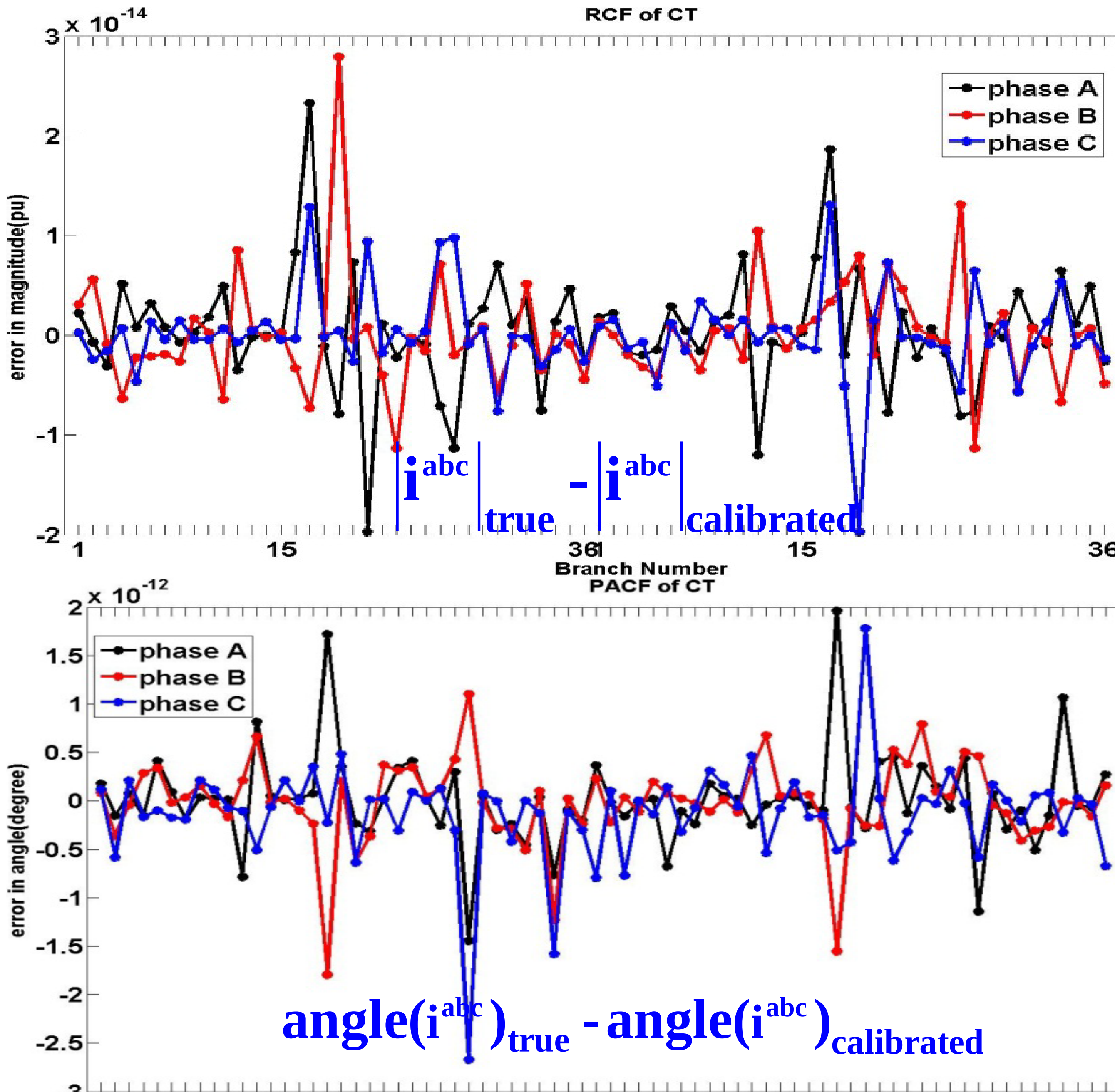

RCF error of PT
x 10^-15
|e^abc|true - |e^abc|calibrated
phase A
phase B
phase C
error in magnitude(pu)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Bus Number


PACF error of PT
x 10^-14
angle(e^abc)true - angle(e^abc)calibrated
phase A
phase B
phase C
error in angle(degree)
8
6
4
2
0
-2
-4
-6
-8
-10
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Bus Number


RCF of CT
x 10^-14
phase A
phase B
phase C
error in magnitude(pu)
|i^abc|true - |i^abc|calibrated
Branch Number
PACF of CT
x 10^-12
phase A
phase B
phase C
error in angle(degree)
angle(i^abc)true - angle(i^abc)calibrated
Bus Number

Conclusion

- In two-bus system, with perfect voltages at one bus and enough redundancy provided by measurements, the other bus voltage and branch currents can be calibrated.
- Key point: with one bus voltage calibrated, the other voltage and current can be calibrated. Power system is fully connected, then the calibration process can pass from one two-bus to the connected two-bus to the next, throughout the whole system.

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