PMU based algorithm for determination 50 Hz instrumentation channel error

WP 3.1 task 3.3.1

Participants: IMBIH, VSL

Vladimir Milojević
Srđan Čalija

Glasgow-EMRP Smart Grid II
January 2016.

Introduction

Formulaton of problem

The purpose of the instrumentation channel is to provide isolation from the high voltage power system and to reduce the voltages and currents to standard instrumentation level. Ideally, it is expected that the instrumentation channel will produce at the output a waveform that will be an exact replica of the high voltage or current and scaled by a constant factor. In reality, the instrumentation channel introduces an error. Specifically, each device in this chain, namely, Instrument Transformers, Control Cables, Burdens, Filters, and A/D converters, may contribute to some degree to signal degradation.

Main goal

- **Develop 3 phase algorithm which will be used for determination errors in instrumentation channel besed on PMU measurmets**
- **New method which will be used for the most general case: short/long lines that are fully transposed or untransposed and have balanced/unbalance loads.**

Formulation of the Calibration Factor

A CF is a vector (complex number) applied to the measured synchrophasor to correct its error by restoring it to the corresponding true value. Fig. 1 shows the concept of the calibration factor.

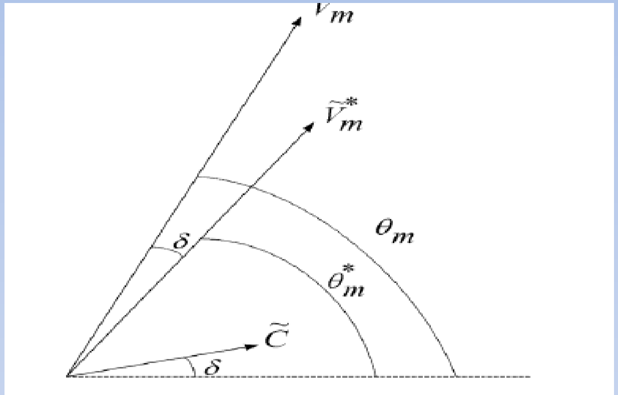


Figure 1. Presentation of calibration factor

$$\widetilde{V_m^*} = V_m^* e^{j\theta_m^*}$$

$$\widetilde{V_m} = V_m e^{j\theta_m}$$

$$\tilde{C} = C e^{j\delta}$$

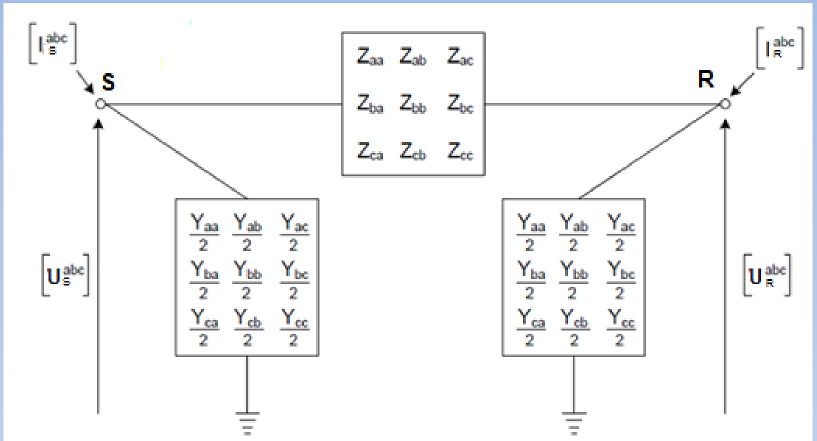
In this Figure 1. $\widetilde{\mathrm{V}_\mathrm{m}^*}$ and $\widetilde{\mathrm{V}_\mathrm{m}}$ presents measured (voltage/current) and corresponding true phasors respectively.

In order to corrects the error in $\widetilde{V_m^*}$ and restore it to $\widetilde{V_m}$, It is necessary to determine calibration factor (CF) which is formulated as:

$$\tilde{C} = \frac{1}{1+\varepsilon} e^{j\delta}$$

ε amplitude error and δ is the phase angle of the calibration factor.

Model of three phase transmission line in phasor frame



Matematical formulation of TL model with calibration factors taken into account:

$$\tilde{C}_{Vabc\,S} \cdot \tilde{V}^{S*}_{abc} - \tilde{C}_{VabcR} \cdot \tilde{V}^{R*}_{abc} = \tilde{Z}_{abc} \cdot \left[\tilde{C}_{Iabc\,S} \cdot \tilde{I}^{S*}_{abc} - \frac{1}{2}\tilde{Y}_{abc} \cdot \tilde{C}_{Vabc\,S} \cdot \tilde{V}^{S*}_{abc}\right]$$

$$\tilde{C}_{Iabc\,S} \cdot \tilde{I}^{S*}_{abc} - \tilde{C}_{IabcR} \cdot I^{R*}_{abc} = \frac{1}{2}\tilde{Y}_{abc} \cdot \left[\tilde{C}_{Vabc\,S} \cdot \tilde{V}^{S*}_{abc} + \tilde{C}_{VabcR} \cdot \tilde{V}^{R*}_{abc}\right]$$

6 complex equations

⇩

12 real equations

18 unknown param.

The proposed method requires THREE assumptions.

- ✓ First, PMUs are installed at both terminals (S and R) of the TL and all the 3-phase synchrophasor measurements are available.
- ✓ Second, the parameters of the TL are known a priori and
- ✓ Third, measurement of 3 phase voltage on one bus S or R is highly accurate.

Assuming N PMU samples taken at **N different time instants and states** are available, we can set up linear system of equations with following dimensions

$$([X]_{(12\cdot N)x18} + E) \cdot \beta_{(18\cdot N)x1} = Y_{(12\cdot N)x1} + e$$

X –is coeficient matrix containing PMU current and voltage measurements
Y- measurement vector, contains PMU current and voltage measurements
β- unknown parameter vector containing CFs
E **-**represents the correction matrix that compensates the measurement errors present in X.
e- represents the error vector due to noise in the current/voltage measurements in Y.

Proposed optimal estimator

Since there are parameters in system (data) matrix X as well as in the right-hand side (observation) matrix Y whose depend of the PMU measurements Total Least Squares can be used for estimation CFs

Unique solution of the TLS problem using SVD can be expressed as fallow:

$$\beta_{(TLS)} = (X^T X - \sigma_{N+1}^2 \cdot I)^{-1} X^T \cdot Y$$

Results obtained from simulation in case of transposed and untransposed TL

- Redundant PMU measurements are obtained by running the SimPowerSyst simulation multiple times with each simulation conducted with a different loading level between 20% and 80% of the TL’s capacity.

- Outputs from each PT/CT are processed by a DFT to generate the corresponding voltage/current phasors.

- The reference value of TL parameters obtained from tower geometries, have been used as reference value of TL parameters

- It is assumed that 3 phase voltages measurements on receiving side of transmission line is performed with highly accurate measurement device (highly accurate three phase VTs+PMU) with CFs:

$$\tilde{C}^{R}_{V_{a,b,c}} = 1e^{j0^{\circ}}$$

The first and the second columns of Table 1 and 2 shows the theoretical and calculated amplitude and phase error of CFs using proposed algorithm.

Table 1. Reference and calculated instrument transformers errors in case of transposed TL

Reference value	**Estimated value**
Ratio error and phase error on Sending VTs	Ratio error and phase error on Sending VTs
Amp Erorr VaS=0.0001 pu; Amp Erorr UbS=-0.0025 pu; Amp Erorr UcS =-0.0013 pu; Phase Erorr VaS=1/60 degree; Phase Erorr VbS=-5/60 degree; Phase Erorr VcS=6/60 degree;	Amp Erorr VaS=0.00009999 pu; Amp Erorr UbS=-0.0025063pu; Amp Erorr UcS=-0.0013017 pu; Phase Erorr VaS=0.016666666666413 degree; Phase Erorr VbS=-0.083333333333421 degree; Phase Erorr VcS=0.100000000000140 degree;
Ratio error and phase error on Sending CTs	Ratio error and phase error on Sending CTs
Amp Erorr IaS=0.0015 pu; Amp Erorr IbS=0.004 pu; Amp Erorr IcS=-0.00135 pu; Phase Erorr IaS=3/60 degree; Phase Erorr IbS=9/60 degree; Phase Erorr IcS=-4/60 degree;	Amp Erorr IaS=0.0014997pu; Amp Erorr IbS=0.0039893 pu; Amp Erorr IcS=-0.00135361 pu; Phase Erorr IaS=0.050000000000164 degree; Phase Erorr IbS=0.150000000010974 degree; Phase Erorr IcS=-0.066666666665418 degree;
Ratio error and phase error on Receiving CTs	Ratio error and phase error on Receiving CTs
Amp Erorr IaR=0.0005 pu; Amp Erorr IbR=0.006 pu; Amp Erorr IcR=-0.003 pu; Phase Erorr IaR=-5/60 degree; Phase Erorr IbR=-1.5/60 degree; Phase Erorr IcR=-6/60 degree;	Amp Erorr IaR=0.0005004 pu; Amp Erorr IbR=0.0059716 pu; Amp Erorr IcR=-0.003013 pu; Phase Erorr IaR=-0.083333333332549 degree; Phase Erorr IbR=-0.024999999988876 degree; Phase Erorr IcR=-0.099999999995771 degree;

Table 2. Reference and calculated instrument transformers errors in case of untransposed TL

Reference value	**Estimated value**
Ratio error and phase error on Sending VTs	Ratio error and phase error on Sending VTs
Amp Erorr VaS=-0.0032 pu; Amp Erorr UbS=-0.0001 pu; Amp Erorr UcS=-0.0027 pu; Phase Erorr VaS=3.8/60 degree; Phase Erorr VbS=-0.5/60 degree; Phase Erorr VcS=0.9/60 degree;	Amp Erorr VaS=-0.0032103; pu Amp Erorr UbS=-0.00010001pu; Amp Erorr UcS=-0.00270731 pu; Phase Erorr VaS=0.0633333333333346 degree; Phase Erorr VbS=-0.008333333333286 degree; Phase Erorr VcS=0.01500000000052 degree;
Ratio error and phase error on Sending CTs	Ratio error and phase error on Sending CTs
Amp Erorr IaS=0.0008 pu; Amp Erorr IbS=0.0016 pu; Amp Erorr IcS =-0.0005 pu; Phase Erorr IaS=3.7/60 degree; Phase Erorr IbS=0.9/60 degree; Phase Erorr IcS=-4.8/60 degree;	Amp Erorr IaS=0.0008004 pu; Amp Erorr IbS=0.0015995 pu; Amp Erorr IcS=-0.0005009 pu; Phase Erorr IaS=0.0616666666465 degree; Phase Erorr IbS=0.014999999995152 degree; Phase Erorr IcS=-0.080000000004888 degree;
Ratio error and phase error on Receiving CTs	Ratio error and phase error on Receiving CTs
Amp Erorr IaR=-0.0015 pu; Amp Erorr IbR=0.0026 pu; Amp Erorr IcR=-0.0016 pu; Phase Erorr IaR=-0.5/60 degree; Phase Erorr IbR=-11/60 degree; Phase Erorr IcR=-3.6/60 degree;	Amp Erorr IaR=-0.0015041 pu; Amp Erorr IbR=0.0025965 pu ; Amp Erorr IcR=-0.0016045 pu ; Phase Erorr IaR=-0.0083333333350730 degree; Phase Erorr IbR=-0.1833333333337816 degree Phase Erorr IcR=-0.0600000000003497 degree;

Impact of systematic errors and noise on calculation amplitude and phase errors of VTs/CTs.

❖Gauss noise exists in both PMUs measurements of three phase currents and voltages:

➢Amplitude noise with 0 mean and 0.001% standard deviation
➢Phase angle noise with 0 mean and 0.002 degree standard deviation

20 simulation with different noise has been performed. Mean value and standard deviation of 20 measurements were taken in calculation for estimation contribution of noise.

❖Systematic errors exist in reference 3 phase voltage measurements on bus R:

➢Systematic errors are inside of calibration uncertainty ±0.01% in amplitude and ±1 min phase error of reference voltage measurement (reference VTs)

30 different cases with amplitude and phase errors from specified uncertainty ranges are taken in calculation in order to overview max level of error.

❖ It is assumed that all CTs and VTs have Amp error=0.1% and Phase error=1 min

In case that there is noise in all PMUs measurements (voltage/current), uncertainty of determination amplitude and phase errors of VTs and CTs due to noise are:

VTs on sending side		CTs on sending side		CT on receiving side	
Amp (%) 2σ	Phase (min) 2σ	Amp (%) 2σ	Phase (min) 2σ	Amp (%) 2σ	Phase (min) 2σ
±0.002	±0.2	±0.1	±2	±0.1	±2

In case that there are systematic errors in reference VTs which are in range of calibration uncertainty of 0.01% amplitude and 1 min phase, uncertainty of determination amplitude and phase errors of VTs and CTs due to these systematic error are:

VTs on sending side		CTs on sending side		CT on receiving side	
Amp (%)	Phase (min)	Amp (%)	Phase (min)	Amp (%)	Phase (min)
±0.02	±2	±0.05	±2.5	±0.05	±2.5

Combined overall measurement uncertainty of determination VTs and CTs errors using proposed algorithm

Two above mentioned contributions are combined as square root value of the sum of their squares thus providing the input for the calculation of the combined overall measurement uncertainty.

$$U_{tot} = \sqrt{U_{noise}^2 + U_{sys}^2}$$

Combined overall measurement uncertainty of determination VTs and CTs

VTs on sending side		CTs on sending side		CT on receiving side	
Amp (%)	Phase (min)	Amp (%)	Phase (min)	Amp (%)	Phase (min)
±0.02	**±2**	**±0.11**	**±3.2**	**±0.11**	**±3.2**

Conclusion and further work

- **Developed new method for remote verification/calibartion CTs and VTs in power grids during their normal operating mode**
- **Proposed algorithm is applicable on transposed and untransposed lines**
- **This method requires well characterized voltage instrument transformers on one end of the transmission line that will be used as the reference for all other transducers**
- **Detailed models of instrument transformers are not required and the burdens attached to the secundars do not need to be analyzed.**
- **Presence noise in PMUs measurements are shown as important factor which degrade accuracy of method especially in case of determination CTs amplitude and phase errors.**
- **Accuarcy of proposed method can be better if lavel of noise in PMU measurments is decresed as well as decresed calibration uncertainty of reference VTs**
- **Since algorithm require accurate knowledge of line parameters, relationship between line parameter errors and accuracy calculated instrumentation channel errors is in this moment an open question?**
- **Further work will be focused on real measurment data analysis**

Thank you for atenttion!

vladimir.milojevic@met.gov.ba
srdjan.calija@met.gov.ba