A Novel Approach for Calibration of Instrument Transformers using Synchrophasors

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***Abstract*—This paper presents a novel approach for calibration of Instrument Transformers (ITs) using synchrophasor data. The proposed algorithm detects the presence of bad data using Largest Normalized Residual (LNR) test in a step and discards the corresponding measurements. This method is intended to work as a filtering scheme that can significantly improve the accuracy of Current Transformers (CT) and Capacitive Voltage Transformers (CVT) measurements. Once calibrated, accurate measurements are available to execute State Estimation (SE), to enhance dynamic security of system, and analytics for Wide Area Monitoring Systems (WAMS). Case studies based on simulated data are presented to prove the effectiveness of the proposed method.**

***Index Terms*—Bad data estimation and computation, calibration of CT and CVT, Largest Normalized Residual test, Least Square method, synchronised measurements, transmission lines.**

I. Introduction

The performance of the Wide Area Measurements (WAMs) based State Estimation (SE), Dynamic Security Assessment (DSA) and other analytics depends upon the accuracy of measurements from CT and CVT. However, in real life CT and CVT measurements are prone to noise and errors due to prevailing burden, age, environmental conditions, modeling restrictions etc., [1], [2]. Further, the measurements are also prone to errors due to data conversion abnormalities, communication delays and sensor de-synchronization. If the measurements involves large errors, the accuracy of devised SE algorithm deteriorates substantially. Earlier, in SCADA system, weights were assigned to Instruments Transformers (ITs) considering that the measurements from meters of known greater accuracy are treated more favorably than less accurate measurements [3]. Hence, it is well known that the measurement chain is not ideal. Also, practical Instrument Transformers (IT) always have Ratio error (Ratio Correction Factors - RCF) and Phase Angle error (Phase Angle Correction Factor - PACF). Ideally, as required by IEEE standard [4], the Total Error Vector (TVE) between the measured phasor and its estimated value should be well within 1% under steady state operating conditions. Therefore, it is important to calibrate ITs using appropriate algorithms to correct erroneous measurements.

Current Transformers (CT) and Capacitive Voltage Transformers (CVT) are the eyes and ears of the power system which are installed at the substations. The CT and CVT measurements are used to execute control and protection algorithms. Also, with the availability of communication, GPS synchronization and Phasor Measurements Unit (PMU), time synchronised measurements are easily available at substations. However, CT and CVT errors can not be ignored and are increasing with operating conditions, age, and other factors. If these errors are not compensated a priori then the algorithm which uses these as an input may malfunction. CT and CVT outages for calibration are also not permitted by system operator because of labor-intensive and costly process. The frequent replacement of erroneous CT and CVT is not encouraged for economic considerations. Hence, uncalibrated ITs degrade the performance of the system for SE and DSA. Many attempts have been made to detect and calibrate the errors in ITs [5], [6], [7], [8], [9].

Reference [5] analyze and compute multiple bad data originated in voltage or current transformer using Largest Normalized Residual test. Reference [6] describes a measurement calibration method which identifies calibration models for the uncalibrated measurements and estimate the calibration model parameters along with the system states using multiple scans of measurements.

In recent past, synchrophasors (Phasor Measurement Unit-PMU) are deployed on many power systems to acquire time synchronized data of current and voltage. The data generated from PMU is used for CT and CVT calibration [7]. In this paper, the time synchronized phasor data of PMU, placed in the system optimally or otherwise is used to estimate error in ITs, non-iteratively.

II. Motivation

Let us consider the two bus system wherein transmission line is represented by equivalent-π model of as shown in Fig. 1. Consider CT and CVT at node `'i'` are accurate however CT and CVT at node `'j'` are erroneous. Measurements of voltage at node `'i'` and node `'j'` are derived from PMU. In a large system, although PMUs are not placed on every bus, however data of respective bus i.e. currents and voltages can be computed from state estimators which may be working on synchrophasor data. The time synchronized data may be available from PMU or WAMS based state estimator. Therefore, positive sequence equations for transmission line after

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compensating line charging current is written as

$$V_i - V_j = I_i^{ser} Z \tag{1}$$

where

$$I_i^{ser} = I_i^{line} - j\frac{B}{2}V_i \tag{2}$$

is the series branch current at node `'i'`, that can be computed after removing line-charging currents from line currents.

I_i^{line}, I_j^{line}	Line currents at bus `'i'` and `'j'` respectively.
V_i, V_j	Voltage at bus `'i'` and `'j'` respectively.
Z	Impedance of transmission line
B	Susceptance of transmission line

Similarly, at node *'j'*

$$V_j - V_i = I_j^{ser} Z \tag{3}$$

where

$$I_j^{ser} = I_j^{line} - j\frac{B}{2}V_j \tag{4}$$

is the series branch current at node `'j'`, that can be computed after removing line-charging currents from line currents. Adding (1) and (3), we get

$$V_i - V_j = \frac{(I_i^{ser} - I_j^{ser})Z}{2} \tag{5}$$

Let us consider, the measurements error in CVT and CT

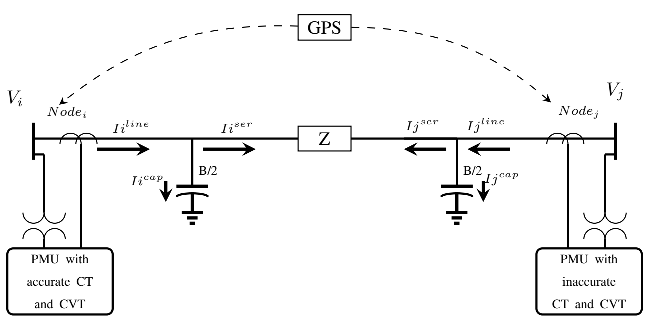

Fig. 1. Single line representation of equivalent-π model of three phase transposed transmission line

at node `'j'` as Me^{jN} and Ae^{jB} respectively. Node `'i'` currents and voltages are estimated from the positive sequence measurements available from PMU at node `'j'`. Using the erroneous measurements of node `'j'`, voltage estimated V_i^{est} at node `'i'` as,

$$V_i^{est} = \frac{(I_i^{ser} - I_j^{line} * Pe^{jQ})Z}{2} + V_j * Te^{jF}(1 + j\frac{ZB}{4}) \tag{6}$$

Arranging (6)

$$\begin{aligned} V_i^{est} = \frac{(I_i^{ser} - I_j^{line} * Pe^{jQ})Z}{2} + V_j * Te^{jF}(1 + j\frac{ZB}{4}) \\ + V_j - V_j + \frac{I_j^{ser}Z}{2} - \frac{I_j^{ser}Z}{2} \end{aligned}$$

Segregating error terms,

$$\begin{aligned} V_i^{est} = V_j + \frac{I_i^{ser}Z}{2} - \frac{I_j^{ser}Z}{2} + V_j(Te^{jF} - 1 + Te^{jF} * j\frac{ZB}{4}) \\ + \frac{Z}{2}(I_j^{ser} - I_j^{line}Pe^{jQ}) \end{aligned}$$

Therefore,

$$V_i^{est} = V_i + e_t \tag{7}$$

where,
V_i is measurement of voltage at node `'i'` with accurate PMU,

$$e_t = V_j(Te^{jF} - 1 + Te^{jF} * j\tfrac{ZB}{4}) + \tfrac{Z}{2}(I_j^{ser} - I_j^{line}Pe^{jQ})$$

The numerical term e_t in (7) indicates an error in the estimation of V_i. And, if these measurements are used for further computation then subsequent computations will be populated with multiple errors. Hence, for the compensation of CT and CVT errors, computation and compensation of errors are required. Once the errors are estimated, CT and CVT are calibrated remotely using proposed algorithm. This process is known as "*Soft Calibration*". Hence, the following section discuss the proposed method for the "*Soft Calibration*" of Instrument Transformers.

III. Proposed Method

A. Detection of Bad Data

With reference to Fig. 1, Let Z_t be a vector of positive sequence synchronised measurements derived from line current and bus voltage measurements for a particular time instant *'t'*.

$$V_i = V_i + e_1; \tag{8}$$

$$I_i^{(ser)} = (V_i - V_j)Y + e_2 \tag{9}$$

Therefore,

$$\begin{bmatrix} V_i \\ I_i^{(ser)} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ Y & -Y \end{bmatrix} \begin{bmatrix} V_i \\ V_j \end{bmatrix} \tag{10}$$

Hence, State Estimator model can be represented as follows:

$$Z_t = M_t V_t + e_t \tag{11}$$

The modal Matrix M_t is assembled from positive sequence data of transmission line. V_t is the positive sequence bus voltage vector. e_t is the error vector for measurement Z_t. The least square estimate of V_t is given by

$$V_t^{est} = M_t{}^{+} Z_t \tag{12}$$

where M^+ is the pseudoinverse of M. Here, it can be seen that, estimation problem is solved in one step [10]. Thus, from (11), the residual vector is given by

$$r_t = (I_m - M_t M_t{}^{+})Z_t \tag{13}$$

where, r_t is the positive sequence or three phase residual vector of measurement vector Z_t and I_m is the m x m identity matrix and m is the number of measurement. The normalized residual vector is given as follows:

$$r^n = (diag(R_r))^{-1/2} r_t \tag{14}$$

where, $R_r =$ is the covariance matrix of the residual estimate vector and is given by $\vec{R_r} = (\vec{r_t}\vec{r_t}^T - \vec{M_t}\vec{M_t}^+)$
If normalized residues are above standard deviation '**3**', then presence of bad data is detected [11] and corresponding samples should be discarded. But if normalized residue is below standard deviation '**3**' then we compute calibration factors required for CT and CVT measurements.

B. Computation of Calibration Factors for CT and CVT

Measurements in power system are available from secondary circuits of Instrument Transformers i.e. CT and CVT. An ideal instrument transformer always reflect primary signal faithfully in secondary circuits. However, practical instrument transformers are always associated with phase angle error and magnitude error due to ageing of instruments. Measurements from CT and CVT are utilized to execute State Estimation and Dynamic Security Assessment at control center; so erroneous measurements may envisage inadvertent results in processes. Therefore, here we attempt to compute calibration factors required to correct measurements received from CT and CVT.

Consider in Fig. 1, equation for series currents in case of no fault situation is given by,

$$I_i^{ser} = -I_j^{ser} \tag{15}$$

Assuming error in CVT (complex) as (R + jS), and that of CT (complex) as (A + jB), substituting (2) in (15)

$$I_i^{ser} = -[I_j^{line}(A + jB) - j\frac{B}{2}V_j(R + jS)] \tag{16}$$

Segregating real (RE) and imaginary (IM) components from above

$$[I_i^{ser}]_{RE} = -[I_j^{ser}]_{RE}A + [I_j^{ser}]_{IM}B + [\frac{B}{2}V_j]_{RE}R - [\frac{B}{2}V_j]_{IM}S \tag{17}$$

$$[I_i^{ser}]_{IM} = -[I_j^{ser}]_{IM}A - [I_j^{ser}]_{RE}B + [\frac{B}{2}V_j]_{IM}R + [\frac{B}{2}V_j]_{RE}S \tag{18}$$

Similarly, voltage at node '*j*' in equation (3) is rewritten as,

$$V_j(R+jS) - V_i = Z[I_j^{line}(A+jB) - j\frac{B}{2}V_j(R+jS)] \tag{19}$$

Segregating real (RE) and imaginary (IM) components from above

$$[V_i]_{RE} = [V_j]_{RE}R - [V_j]_{IM}S - [I_j^{line}]_{RE}ZA + [I_j^{line}]_{IM}ZB + [\frac{B}{2}V_j]_{RE}ZR + [\frac{B}{2}V_j]_{IM}ZS \tag{20}$$

$$[V_i]_{IM} = [V_j]_{IM}R + [V_j]_{RE}S - [I_j^{line}]_{IM}ZA + [I_j^{line}]_{RE}ZB + [\frac{B}{2}V_j]_{IM}ZR + [\frac{B}{2}V_j]_{RE}ZS \tag{21}$$

equations (17), (18), (20) and (21) represents four complex equations with four unknown as A, B, R and S. Arranging the same in matrix form i.e.

$$Z_{tt} = M_{tt}U_t$$

The solution for unknown errors is obtained using Least Square estimate as

$$U_t = (M_{tt}^+ M_{tt})^{-1} M_{tt}^+ Z_{tt} \tag{22}$$

where M_{tt}^+ is the conjugate transpose of M_{tt}.
The calibration factors for CT and CVT are expressed as reciprocals of Pe^{jQ}, Te^{jF} respectively and are computed in a step, non-iteratively from,

$$\begin{aligned} P &= \sqrt{A^2 + B^2} \\ Q &= \arctan(\frac{A}{B}) \\ T &= \sqrt{R^2 + S^2} \\ F &= \arctan(\frac{R}{S}) \end{aligned} \tag{23}$$

IV. Proposed Algorithm

The flowchart for bad data detection and calibration of CT and CVT is shown in Fig. 2 and described as follows:

1) Input transmission line parameters, set bad data threshold=3.
2) Acquire latest GPS-synchronised time-tagged samples of 3 phase voltages and currents i.e. $V_i^{(abc)}(t)$, $I_i^{line(abc)}(t)$ and $V_j^{(abc)}(t)$, $I_j^{line(abc)}(t)$ from node '*i*' and node '*j*' of line resp. Time "*t*" indicates an instant corresponding to latest sample and *a*, *b* and *c* designate the three phases.
3) Obtain phasors using Full Cycle Recursive Discrete Fourier Transform (FCRDFT)[12] of voltages and currents.
4) Compute I_i^{ser} and I_j^{ser} using (2) and (4)
5) Estimate presence of bad data using (14).
6) Check if :
   standard deviation of normalized residues > *threshold*
   If TRUE, then discard the samples (as bad data) and goto to step 2
   else, goto to next step.
7) Compute calibration factors using (22)
8) Compensate error due to CT and CVT using calibration factor and this accurate measurements can be used for State Estimation, DSA and for other analytics of WAMs.

V. Case Study

Fig. 3 depicts the network topology of IEEE 14 bus system. System is modeled with 100 MVA, 220 kV base, 50 Hz frequency. The system is simulated in ATP-EMTP environment [13] with sampling frequency as 1 kHz. Transmission lines

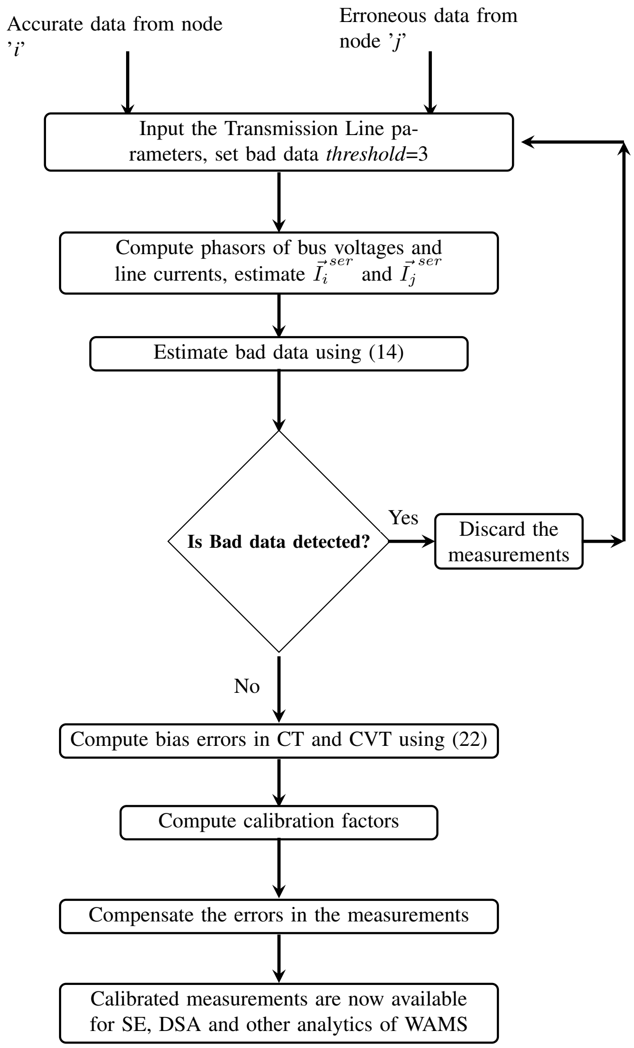

Fig. 2. Flowchart for bad data detection and instrument transformer calibration

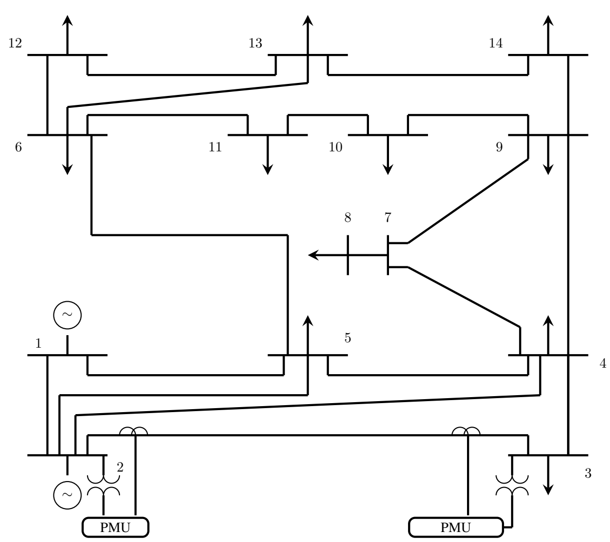

Fig. 3. IEEE 14 Bus Test System

are represented by equivalent-π model with 100 kM length. Measurements available at Bus 3 are considered as erroneous measurement in CT and CVT while Phasor Measurement Unit with accurate CT and CVT is located at Bus 2. ANSI 500:5, class C400 CT model and 250 kV:100 V CVT model have been used for obtaining realistic CT and CVT response during ATP simulations [2].

Voltages and currents at Bus 2 is computed from the measurements obtained from Bus 3, and bad data is detected and corresponding measurements are discarded. Samples are obtained from ATP-EMTP simulations are considered as GPS synchronised time-tagged and processed in MATLAB; phasors are estimated using Full Cycle Recursive Discrete Fourier Transform (FCDFT). The speed of computation is less than 32sec on 1kHz sampling frequency with MATLAB R2013a and Intel(R) Core(TM) i7-3770 CPU@ 3.40GHZ with 32-bit operating system, 4 GB RAM. Performance of proposed methods is evaluated for various bias errors. In simulations, implementation is carried out in three-phase domain while for convenience, the proposed method is discussed in positive sequence representation.

TABLE I
ESTIMATION OF CALIBRATION FACTORS FOR CVT AND CT

Error in CVT i.e. Te^{jF}	Estimated Calibration factor for CVT i.e. $\frac{1}{Te^{jF}}$	Error in CT i.e. Pe^{jQ}	Estimated Calibration factor for CT $\frac{1}{Pe^{jQ}}$
$1\ \angle 0^\circ$	$1.01\ \angle -0.318^\circ$	$1\ \angle 0^\circ$	$1\ \angle 0.00^\circ$
$1\ \angle 10^\circ$	$1.01\ \angle -10.16^\circ$	$1\ \angle 10^\circ$	$1.00\ \angle -10.06^\circ$
$1\ \angle 10^\circ$	$1.01\ \angle -10.5^\circ$	$1\ \angle 5^\circ$	$1.0\ \angle -5.15^\circ$
$1\ \angle 5^\circ$	$1.03\ \angle -5.467^\circ$	$1\ \angle 10^\circ$	$1.0\ \angle -10.07^\circ$
$1\ \angle 10^\circ$	$1.02\ \angle -10.35^\circ$	$1\ \angle 9^\circ$	$1.0\ \angle -9.07^\circ$

Table I presents the estimation of calibration factors for errors associated with CVT and CT. First and third columns indicate the error in the measurement of CVT and CT respectively, whereas second and fourth columns show that if for measurement errors varied from 0° to 10°, then proposed algorithm computes calibration factors accurately for CVT and CT.

VI. CONCLUSION

The algorithm proposed novel approach to detect and discard bad data and calibrate the ITs using synchronized measurement. The computation efforts are less as the algorithm do not need sequence components computation and do not use iterative method. No extra efforts or specialized equipments are needed to calibrate CT and CVT. Extensive simulations studies demonstrate the merits of proposed scheme.

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