A New Concept for Calibration of Capacitive Voltage Transformers using PMU Measurements

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***Abstract*—In this paper, two problems from synchronised phasor measurements are considered: first, identification of capacitive voltage transformers (CVTs) which require calibration and second, estimation of systematic errors in CVTs. These two problems are actually correlated but analysed independently in this work. First, a test to identify CVTs that require calibration is proposed. This test is validated using actual field measurements. The conventional method for calibration of CVTs requires one accurately calibrated CVT as a reference in order to calibrate all other CVTs in the system. However, as we move away from the reference CVT, the errors in the estimation of calibration factors increase. In this paper, a method for CVT calibration with multiple accurate voltage transformers (VTs) is proposed. Generally, at a generator bus, a voltage transformer (VT) is installed. The VTs are accurate and maintain accuracy over years while CVT accuracy drifts due to ageing, temperature and moisture. Hence, the VT at generator bus is considered to be accurate. Case studies for 10 bus system and high voltage network of 118 bus system using ATP/EMTP simulations are discussed. These simulation results show the accuracy of proposed approach and substantiate the claims.**

***Index Terms*—ATP/EMTP, Capacitive voltage transformers (CVTs), magnitude correction factors (MCFs), phase angle correction factors (PACFs), phasor measurement units (PMUs),**

I. Introduction

With the emergence of Phasor Measurement Unit (PMU) technology, PMU based Wide Area Measurement System (WAMS) is being deployed for monitoring, control, and protection of the power system. A PMU gives a phasor representation of the measured sinusoidal quantities with precise timestamps, usually through a global positioning system (GPS) receiver. The PMUs estimate the phasor representation of the sinusoidal signals. These estimated phasors are timestamped and transmitted to Phasor Data Concentrator (PDC), where such measurement data from several other substations are collected according to their timestamps. Thus, samples in all PMUs and the estimated phasors collected at PDC are time-synchronized with GPS timestamps.

The PMUs are connected to a substation through instrument transformers (ITs) viz., voltage transformers (VTs) or capacitive voltage transformers (CVTs), and current transformers (CTs). The VTs and CTs provide signal level voltages and currents, respectively, to the PMUs from the high voltage transmission line. The PMUs associated with biased ITs would deliver inaccurate measurements to different grid applications. A detailed list of grid applications and their data accuracy requirements are presented in [1]. The PMU data fed to various grid applications plays an important role in decision-making towards grid stability. Thus, if CVTs and CTs have systematic errors, then they should be calibrated to ascertain the accuracy of data fed to various analytics. Further, ITs provide reduced-level voltage and current signals for measurement, protective relaying, and control applications. Metering instrument transformers with systematic error will make economic losses to the utility. There are chances of malfunction of the protection system due to biased ITs. Hence, it is necessary to calibrate ITs periodically to prevent all these issues.

Even the problem of calibration of ITs was studied significantly in Supervisory Control and Data Acquisition (SCADA) system [2]–[8]. The authors in [5]–[8] developed a comparator type calibrator for calibration of both high-and low-precision current transformers and voltage transformers. Reference [9] proposed a new high-accuracy measurement system to calibrate electronic instrument transformers with digital output under various measurement conditions. Reference [10] presented use of lock-in amplifier for voltage instrument transformers calibration. In [11], authors proposed high precision dual-slope measurement technique based digitizer which directly gives ratio and phase angle errors of instrument transformers in a digital form. In recent papers [12], [13], authors developed calibration system to evaluate harmonic measurement accuracy of instrument transformers. References [14]–[17] developed methods for soft calibration of voltage magnitude, current magnitude, active power, and reactive power SCADA measurements at substation-level.

References [18]–[20] proposed a tracking state estimation approach to detect gross errors in both PMU and SCADA measurements. The authors in [21] discussed tracking state estimation approach for IT calibration problem. In [21], it is shown through both theory and simulations that tracking state estimator could not detect a systematic error in IT. The authors in [22] presented a non-linear constrained optimization method which minimizes the sum of squares of residuals for correction of ratio correction factor (RCF). In this approach, they have imposed constraints on the range of RCFs, which is not realistic. Reference [23] investigated measurement error of PMU data by employing probability distribution stability property and redundant measurement approach. Reference [24] characterized measurement error in PMU data using clustering technique based on Gaussian mixture model. The authors in [23], [24] found that the measurement error in PMU data follows non-Gaussian distribution. Therefore, quantification of IT systematic errors which is the major source of error in PMU measurements is required. The authors of [25] developed calibration method to test PMUs and instrument transformers under non-sinusoidal and distorted condition.

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With the recent development of intelligent electronic devices (IEDs), inverter based resources (IBRs), and PMUs, the monitoring and measurement systems need to be improved. In 2012, authors in [26] were the first to propose a method for instrument transformer (IT) calibration using PMU measurements. However, in this paper, authors have assumed that transmission line parameters are known accurately. On the other hand, reference [27] developed three-phase IT calibration method which does not require accurate value of line parameters. References [28]–[31] addressed the problem of simultaneous estimation of transmission line parameters and ratio correction factors for ITs using least squares technique. The methods proposed in above references considered IT at one bus as reference and then calculated voltages and currents at other buses in the entire network by a "V-IZ" type of calculations. However, the authors in [32] found these methods inaccurate and formulated binary integer programming (BIP) algorithm for optimal placement of accurate CVT measurements.

To the best of author's knowledge, nobody has addressed multiple reference CVTs approach in prior literature. All the research papers have considered only one reference CVT (conventional approach) to calibrate all the remaining CVTs in the system. Therefore, there is a need to discuss the drawback of conventional approach and propose new efficient algorithm for the CVT calibration. In this paper, the limitation of conventional approach is first discussed. Thereafter, a new method which considers multiple accurate VTs for calibration of capacitive voltage transformers (CVTs) using PMU data is proposed. An optimization algorithm for estimation of ratio correction factors (RCFs) of CVTs in the positive sequence domain is proposed. In this algorithm, it is assumed that transmission line parameters are accurately known. Further, in this paper, the problem of detection of CVTs which require calibration is discussed independently from this optimization algorithm. The Coefficient of Variation (CV) test is proposed to identify biased CVTs. The CV test will detect the bias in each phase of CVT magnitude. The CV test is validated on real field PMU data.

The rest of the paper is organized as follows. Section II presents Coefficient of Variation (CV) test to detect phase wise biased CVTs. Section III discusses limitation of conventional calibration approach and formulates new algorithm for correction of systematic errors in CVTs in positive sequence domain. Section IV concludes the paper.

II. Identification of Systematic Errors in CVTs

The power grid contains large number of CVTs. It is very time consuming and impractical task to calibrate each CVT. Fig. 1 shows the voltage magnitude measured by bus and line CVTs at one of the 400 kV substations in the Western Region (WR) of India. Practically, it is the same voltage measured by different bus and line CVTs. It can be seen that the voltages are varying from 0.99 pu to 1.04 pu. The voltage angular difference for the same substation is shown in Fig. 2. It can be observed that the angle difference varies approximately from -0.4 degrees to 1.4 degrees. Therefore, from Figs. 1 and 2, we infer that there is a need to calibrate CVTs of this substation.

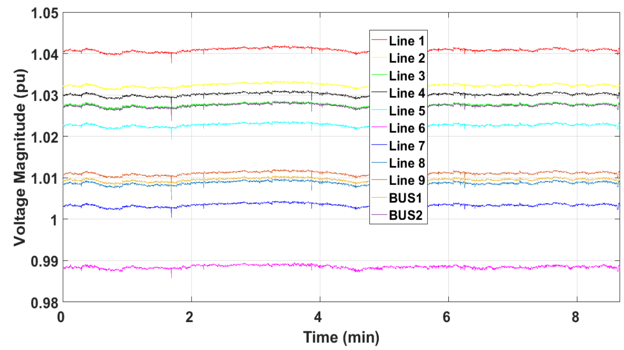

Fig. 1. Line CVTs voltage magnitude reported in a 400 kV substation.

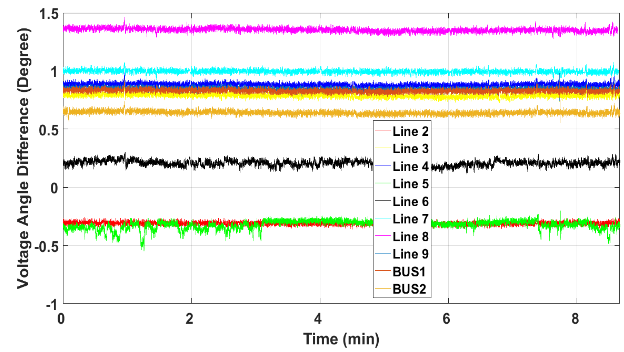

Fig. 2. Line CVTs voltage angle difference reported in a 400 kV substation.

However, in most of the other cases, it is not so obvious and we need to device a sensitive method to detect bias errors in ITs.

Hence, a coefficient of variation (CV) test for identifying CVTs which require calibration is proposed. CV is defined as the ratio of the standard deviation (σ) to the mean (μ) [33]. CV is a statistical measure of the scatter of data points around the mean. The lower the CV, the lesser the dispersion in the samples. As per IEC standard 61869-5 [34], the allowable MCF errors for the metering 1 class CVTs are $\pm 1\%$. Therefore, in our case, a threshold (ϵ) of 1% for CV is set in order to detect bias in CVT magnitude. CV is calculated using voltage magnitude measured by group of line CVTs of each phase corresponding to same time instant for every substation. The only important aspect in this test is that it considers that multiple CVTs are measuring the same line voltages in the same substation.

A. Field Results

The CV test was implemented on real field PMU data of four substations in the Northern Region (NR) of India. The single-line diagram for all four substations is shown in Fig. 3. All substations have one and half breaker arrangements. There are four 400 kV transmission lines connected to both substation-1 and substation-2. There are two 400 kV transmission lines connected to substation-3 and four 400 kV transmission lines connected to substation-4. Fig. 4, Fig. 5, Fig. 6, and Fig. 7 show voltage magnitude measured by CVTs at 400 kV substations 1,2,3, and 4, respectively. Table I shows the coefficient of variation of each phase voltage for all four

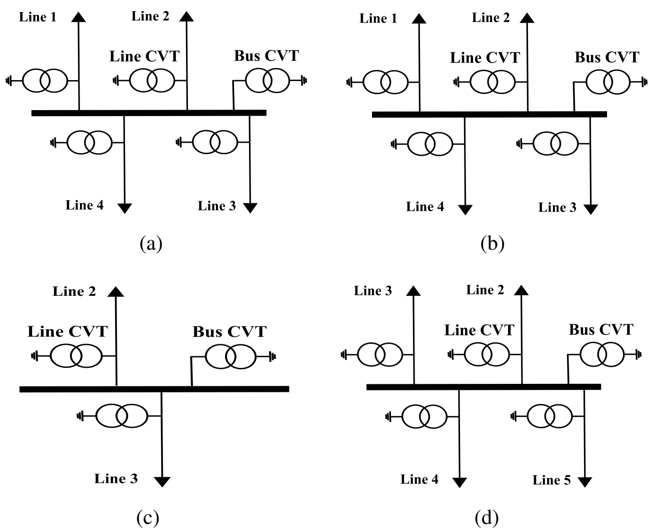

Fig. 3. Single line diagrams for field test. (a) Substation 1. (b) Substation 2. (c) Substation 3. (d) Substation 4.

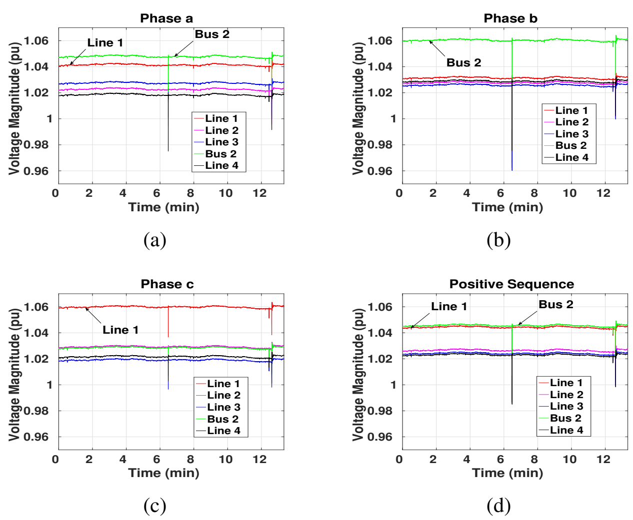

Fig. 4. Voltage magnitude measured by CVTs at 400 kV substation 1. (a) Phase *a*. (b) Phase *b*. (c) Phase *c*. (d) Positive sequence.

substations. The field PMU data over period of 15 minutes have been used to test the proposed approach. It is observed from Table I that the CV is more than 1% for all three phases in case of substation 1. Therefore, there may be a bias in at least one of line CVTs of each phase. While in case of other three substations, the CV is less than 0.5%.

TABLE I
COEFFICIENT OF VARIATION FOR ALL FOUR SUBSTATIONS.

	$\frac{\sigma}{\mu}$ (%)			
	Substation 1	Substation 2	Substation 3	Substation 4
Phase *a*	1.22 ✗	0.11 ✓	0.35 ✓	0.17 ✓
Phase *b*	1.39 ✗	0.12 ✓	0.22 ✓	0.34 ✓
Phase *c*	1.58 ✗	0.10 ✓	0.15 ✓	0.23 ✓
Positive Sequence	1.09 ✗	0.11 ✓	0.23 ✓	0.21 ✓

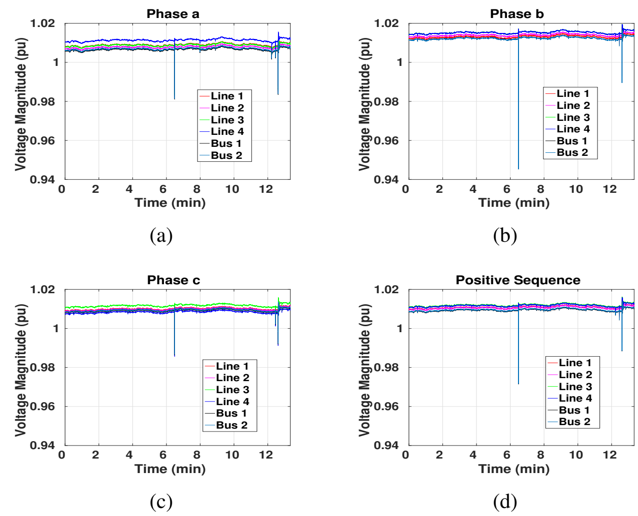

Fig. 5. Voltage magnitude measured by CVTs at 400 kV substation 2. (a) Phase *a*. (b) Phase *b*. (c) Phase *c*. (d) Positive sequence.

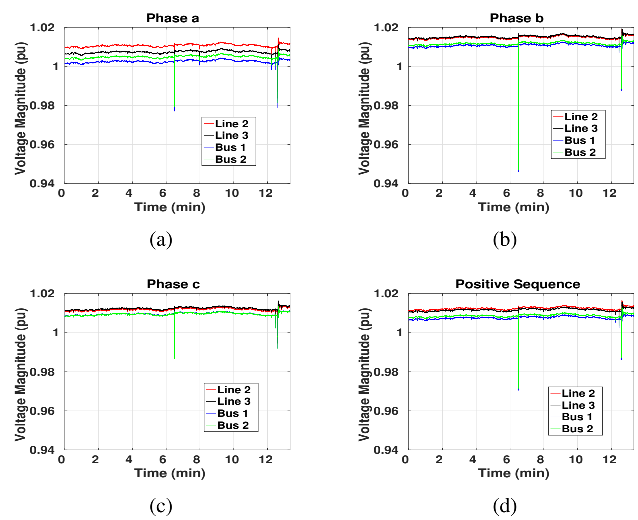

Fig. 6. Voltage magnitude measured by CVTs at 400 kV substation 3. (a) Phase *a*. (b) Phase *b*. (c) Phase *c*. (d) Positive sequence.

III. CORRECTION OF SYSTEMATIC ERRORS IN CVTS

Now consider the problem of estimating systematic errors in CVTs in the positive sequence domain. First, the conventional method reported in literature for CVT calibration using PMU measurements is discussed. Later on, the nonlinear optimization algorithm to overcome the deficiency of the conventional method is presented.

A. Conventional Calibration Method

In this subsection, the conventional CVT and CT calibration method proposed in [28]–[31] using PMU data is demonstrated. The method proposed in above references considered one CT and CVT as reference in the entire network to calibrate remaining CTs and CVTs using a linear least squares approach. Consider a two-bus transmission line π - model as shown in Fig. 8. By applying Kirchhoffs voltage law (KVL),

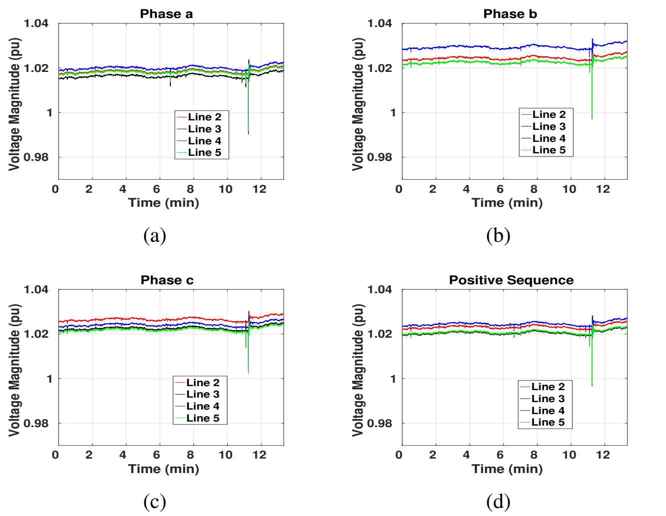

Fig. 7. Voltage magnitude measured by CVTs at 400 kV substation 4. (a) Phase a. (b) Phase b. (c) Phase c. (d) Positive sequence.

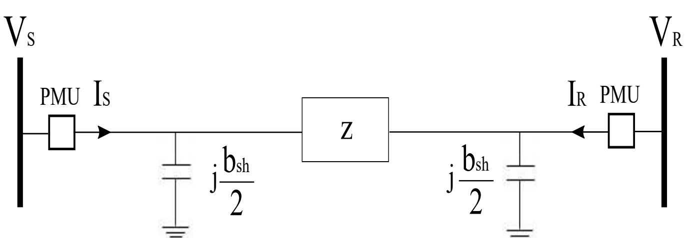

Fig. 8. Two bus transmission line π-model.

the voltage and current phasors at both the ends of line can be related as,

$$\vec{I}_S = \left(y + j\frac{b_{sh}}{2}\right)\,\vec{V}_S - y\,\vec{V}_R \tag{1}$$

$$\vec{I}_R = \left(y + j\frac{b_{sh}}{2}\right)\,\vec{V}_R - y\,\vec{V}_S \tag{2}$$

where, $y = \frac{1}{z}$ The above equations describe the relationship between true values of currents and voltages. However, practically we know the measured phasors instead of true phasors. Therefore, by replacing these true values with measured values using RCFs,

$$\vec{K}_{is}\,\vec{I}_{Sm} = \left(y + j\frac{b_{sh}}{2}\right)\,\vec{K}_{vs}\,\vec{V}_{Sm} - y\,\vec{K}_{vr}\,\vec{V}_{Rm} \tag{3}$$

$$\vec{K}_{ir}\,\vec{I}_{Rm} = \left(y + j\frac{b_{sh}}{2}\right)\,\vec{K}_{vr}\,\vec{V}_{Rm} - y\,\vec{K}_{vs}\,\vec{V}_{Sm} \tag{4}$$

where, $\vec{K}_{is} = \alpha_{is}\angle\delta_{is}$, $\vec{K}_{ir} = \alpha_{ir}\angle\delta_{ir}$, $\vec{K}_{vs} = \alpha_{vs}\angle\delta_{vs}$, and $\vec{K}_{vr} = \alpha_{vr}\angle\delta_{vr}$ are RCFs for CTs and CVTs, respectively.

Considering the sending-end CVT and CT as reference (accurate), from (3) and (4),

$$\vec{I}_S = \left(y + j\frac{b_{sh}}{2}\right)\,\vec{V}_S - y\,\vec{K}_{vr}\,\vec{V}_{Rm} \tag{5}$$

$$\vec{K}_{ir}\,\vec{I}_{Rm} = \left(y + j\frac{b_{sh}}{2}\right)\,\vec{K}_{vr}\,\vec{V}_{Rm} - y\,\vec{V}_S \tag{6}$$

By considering multiple time segments related to different loading levels, (5) and (6) in matrix form,

$$\begin{bmatrix} (\vec{I}_S)_1 \\ \vdots \\ \vdots \\ (\vec{I}_S)_n \end{bmatrix} = \begin{bmatrix} (\vec{V}_S)_1 & -(\vec{V}_{Rm})_1 \\ \vdots & \vdots \\ \vdots & \vdots \\ (\vec{V}_S)_n & -(\vec{V}_{Rm})_n \end{bmatrix} \begin{bmatrix} y + j\frac{b_{sh}}{2} \\ \\ y\,\vec{K}_{vr} \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} -(\vec{I}_{Rm})_1 \\ \vdots \\ \vdots \\ -(\vec{I}_{Rm})_n \end{bmatrix} = \begin{bmatrix} (\vec{V}_S)_1 & -(\vec{V}_{Rm})_1 \\ \vdots & \vdots \\ \vdots & \vdots \\ (\vec{V}_S)_n & -(\vec{V}_{Rm})_n \end{bmatrix} \begin{bmatrix} (K_{ir})^{-1}\,Y \\ \\ (K_{ir})^{-1}\left(y + j\frac{b_{sh}}{2}\right)K_{vr} \end{bmatrix} \tag{8}$$

The equations (7) and (8) are of **Ax = b** form. Therefore, unknown **x** (consists of line parameters and RCFs) can be computed by least squares technique. After correcting voltage and current using estimated $\vec{K}_{vr}$ and $\vec{K}_{ir}$, respectively, calibration factors for the next pi-section can be calculated with these corrected voltage and current as reference using the above least squares approach. With random noise errors in the voltage and current measurements, unknown RCFs for CVT and CT cannot be estimated accurately. If there is error in the estimation of ratio correction factors for current pi-section, then it will estimate erroneous calibration factors for the next pi-section. Hence, as one keeps moving away from the reference CVT, the errors in the estimation of calibration factors increase. Therefore, multiple accurate CVTs are required to calibrate all the ITs in the network. A methodology for CVT calibration with multiple reference CVTs is proposed in the next subsection.

B. Proposed Non-linear Optimization Method

In this section, the non-linear optimization method (weighted least squares) for estimating systematic errors in CVTs using synchrophasor data is proposed. It is difficult to have multiple accurate CVTs in the entire grid. Therefore, in the proposed method, VTs installed at generator buses are considered as reference meters because VTs are accurate and maintain accuracy over years compared to CVT accuracy which drifts due to ageing, temperature and moisture.

For CVT calibration, the following non-linear optimization problem is formulated.

$$\min_{\alpha_j,\delta_j} \Bigg[\sum_{j=1}^{nbus} \omega_{\alpha j}\Big(\alpha_j - \alpha_{ref}\Big)^2 + \sum_{j=1}^{nbus} \omega_{\delta j}\Big(\delta_j - \delta_{ref}\Big)^2 + \sum_{k=1}^{N} \sum_{\substack{i=1 \\ j=i+1}}^{nbus-1} \Big(V_i^k - V_{i\,calc}^k\Big)^2 + \Big(V_j^k - V_{j\,calc}^k\Big)^2 \Bigg]$$

$$V_i = (\alpha_i\angle\delta_i)V_{im}, \qquad V_j = (\alpha_j\angle\delta_j)V_{j\,m}$$

$$V_{icalc} = \left(1 + z_{ij}\frac{b_{ij}}{2}\right)V_j - z_{ij}I_{ji},$$

$$V_{j_{calc}} = \left(1 + z_{ij}\frac{b_{ij}}{2}\right)V_i - z_{ij}I_{ij}$$

where,
N : Number of samples;
$nbus$: Number of buses;
α : Magnitude correction factor (MCF);
δ : Phase angle correction factor (PACF);
V_m : Measured voltage;
z_{ij}, b_{ij} : Branch series impedance and shunt susceptance, respectively;
$\omega_\alpha, \omega_\delta$: Weights corresponding to MCFs and PACFs, respectively;
i, j : Subscripts to denote sending end (i) and receiving end (j) of a branch.
Here, actual values of α_j and δ_j are unknown. Hence, the references values are set to be ideal conditions i.e., $\alpha_{ref} = 1$ and $\delta_{ref} = 0°$. Further, the values for weights ω_α and ω_δ are set to 10^6 for MCFs and PACFs of accurate CVTs (at generator bus) and unity for MCFs and PACFs of remaining CVTs.

C. Simulation Results

The proposed method is tested on 4-generator 10-bus system as specified in [35]. The ATP/EMTP software is used to model the 10 bus system. The instantaneous voltage and current samples generated through ATP simulations were converted into synchrophasors by applying Discrete Fourier Transform (DFT) method. To simulate real field measurements, Gaussian random noise with zero mean and 3σ of 3% standard deviation was introduced to the phasor measurements. Tables II and III show estimated MCFs and PACFs, respectively. As discussed earlier, due to random noise errors in the voltage measurements, CVT RCFs cannot be estimated accurately. If there is error in the estimation of ratio correction factors for Bus 5 of the current pi-section (pi-section consists of buses 1 and 5), then it will estimate erroneous calibration factors for Bus 6 of next pi-section (pi-section consists of buses 5 and 6). Hence, as one keeps moving away from the reference CVT (Bus 1 in this case), the errors in the estimation of calibration factors keep increasing. It can be seen from Tables II and III that as we move away from reference CVT (at Bus 1), the estimated MCFs and PACFs are far from the actual MCFs and PACFs. However, in case of multiple accurate CVTs (at buses 1, 2, 3 and 4), the estimated MCFs and PACFs are close to the actual MCFs and PACFs.

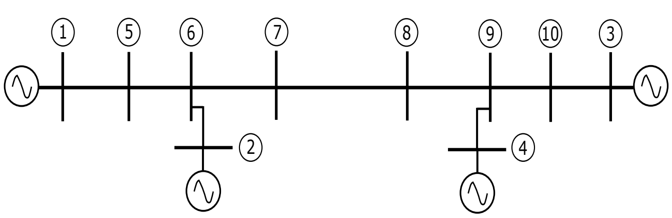

Fig. 9. 4-generator 10-bus system.

The proposed method is also tested on the high voltage network of IEEE 118-bus system which is modelled in the ATP/EMTP software. It has 11 high voltages buses as shown in Fig. 10. Tables IV and V show estimated MCFs and PACFs, respectively. It is seen that as we move away from accurate CVT, the estimated MCFs and PACFs are far from the actual MCFs and PACFs with one accurate CVT (at Bus 10). However, in case of multiple accurate CVTs (at buses 10, 8, 26 and 65), the estimated MCFs and PACFs are close to the actual MCFs and PACFs.

TABLE II
MAGNITUDE CORRECTION FACTORS FOR 10 BUS SYSTEM (A) WITH ONE ACCURATE CVT. (B) WITH MULTIPLE ACCURATE CVTS

(a)

Bus Number	Actual	Estimated	Error (%)
1	1	0.999	-0.1
5	0.955	0.954	-0.11
6	0.98	0.977	-0.31
2	0.96	0.953	-0.73
7	0.972	0.964	-0.82
8	0.95	0.935	-1.57
9	0.985	0.957	-2.84
4	0.967	0.915	-5.38
10	0.99	0.939	-5.15
3	0.982	0.911	-7.23

(b)

Bus Number	Actual	Estimated	Error (%)
1	1	0.999	-0.1
5	0.955	0.954	-0.11
6	0.98	0.978	-0.2
2	1	0.999	-0.1
7	0.972	0.971	-0.11
8	0.95	0.947	-0.32
9	0.985	0.984	-0.1
4	1	0.999	-0.1
10	0.99	0.988	-0.2
3	1	0.999	-0.1

TABLE III
PHASE ANGLE CORRECTION FACTORS FOR 10 BUS SYSTEM (A) WITH ONE ACCURATE CVT. (B) WITH MULTIPLE ACCURATE CVTS

(a)

Bus Number	Actual (deg.)	Estimated (deg.)	Difference (deg.)
1	0	0.002	0.002
5	2.5	2.492	-0.008
6	1	1.015	0.015
2	3.8	3.818	0.018
7	5	4.939	-0.061
8	1.5	1.385	-0.115
9	4.3	4.108	-0.192
4	2.8	3.085	0.285
10	3.7	3.972	0.272
3	1.4	1.763	0.363

(b)

Bus Number	Actual (deg.)	Estimated (deg.)	Difference (deg.)
1	0	0.002	0.002
5	2.5	2.493	-0.007
6	1	1.008	0.008
2	0	0.003	0.003
7	5	4.994	-0.006
8	1.5	1.489	-0.011
9	4.3	4.305	0.005
4	0	0.002	0.002
10	3.7	3.706	0.006
3	0	0.002	0.002

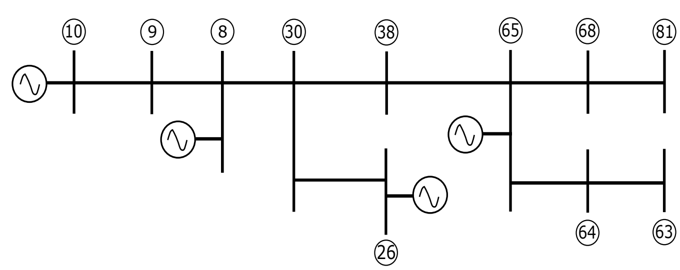

Fig. 10. High voltage network of 118 bus system.

TABLE IV
MAGNITUDE CORRECTION FACTORS FOR 118 BUS SYSTEM (A) WITH ONE ACCURATE CVT. (B) WITH MULTIPLE ACCURATE CVTS

(a)

Bus Number	Actual	Esti-mated	Error (%)
10	1	0.998	-0.2
9	0.974	0.972	-0.21
8	0.98	0.976	-0.41
30	0.967	0.959	-0.83
26	0.95	0.935	-1.58
38	0.955	0.939	-1.68
65	0.975	0.944	-3.18
68	0.97	0.911	-6.08
81	0.95	0.837	-11.89
64	0.985	0.923	-6.29
63	0.96	0.842	-12.29

(b)

Bus Number	Actual	Esti-mated	Error (%)
10	1	0.999	-0.1
9	0.974	0.974	0
8	1	0.999	-0.1
30	0.967	0.966	-0.11
26	1	0.999	-0.1
38	0.955	0.954	-0.11
65	1	0.999	-0.1
68	0.97	0.968	-0.21
81	0.95	0.946	-0.42
64	0.985	0.982	-0.3
63	0.96	0.955	-0.52

TABLE V
PHASE ANGLE CORRECTION FACTORS FOR 118 BUS SYSTEM (A) WITH ONE ACCURATE CVT. (B) WITH MULTIPLE ACCURATE CVTS

(a)

Bus Number	Actual (deg.)	Esti-mated (deg.)	Differ-ence (deg.)
10	0	0.026	0.026
9	2.3	2.309	0.009
8	1	0.983	-0.017
30	5	4.959	-0.041
26	3.8	3.896	0.096
38	1.5	1.379	-0.121
65	2.2	2.314	0.114
68	2	2.207	0.207
81	3	3.489	0.489
64	1.8	1.809	0.009
63	2.5	2.275	-0.225

(b)

Bus Number	Actual (deg.)	Esti-mated (deg.)	Differ-ence (deg.)
10	0	0.004	0.004
9	2.3	2.301	0.001
8	0	-0.005	-0.005
30	5	5.001	0.001
26	0	0.006	0.006
38	1.5	1.497	-0.003
65	0	0.003	0.003
68	2	2.006	0.006
81	3	3.015	0.015
64	1.8	1.797	-0.003
63	2.5	2.489	-0.011

IV. CONCLUSION

In this paper, two problems have been studied independently. First, a test for detection of CVTs that require calibration is presented. The proposed test is verified using real field PMU data. Then, the problem of correction of systematic errors in CVT is discussed. It is shown that conventional calibration method (which requires one accurate CVT to calibrate remaining CVTs in the network) gives erroneous calibration factors as we move away from the accurate CVT. Therefore, a very accurate calibration approach for CVTs from PMU data is proposed. The proposed non-linear least squares formulation can handle multiple VTs which act as reference. The proposed method is also compared with the conventional calibration method reported in prior literature. The quality of results obtained with proposed formulation is far more better than existing methods which only use one reference device. The proposed method assumes that transmission line parameters are accurately known. Future work should consider to verify proposed non-linear approach using actual PMU data.

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