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Determination of harmonic current contributions based on robust state estimation

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Abstract: In this paper, a state estimation based method is proposed to determine harmonic current contributions of plants supplied from a point of common coupling (PCC). This work mainly aims to reduce gross error of capacitive voltage transformer (CVT) measurements at harmonic frequencies using robust weighted least absolute value (WLAV) state estimation method, which provides the optimum state estimates for harmonic voltages in the presence of a redundant enough measurement set. Estimated harmonic voltages are then used to solve the harmonic current contribution problem based on superposition theorem. It has been shown that the proposed method can provide optimum harmonic estimates when CVTs are used. The use of the proposed method with proper measurement placement makes resistive-capacitive voltage transformers (RCVTs) redundant. Results of the proposed method are comparable with measurements of RCVTs, which have the disadvantages of having high costs and being cumbersome to install.

Key words: Harmonic current contribution, power quality, state estimation, weighted least absolute value estimation

1. Introduction

In transmission systems, harmonic currents are generally produced by nonlinear loads, such as electric arc furnaces and ladle furnaces, which in turn cause harmonic distortion at point of common coupling (PCC) voltage. As discussed in previous studies, the total harmonic distortion depends on both the amplitudes and phase angles of the harmonic currents of each load [1–3]. Considering the regulations and legal sanctions for harmonic disturbances, it is important to identify the harmonic contribution of each plant connected to the PCC separately, which enables authorities find the load or loads responsible for the harmonic distortion. Measurement-based determination of harmonic current contributions is an expensive solution, since either voltage harmonic measurements should be taken via resistive capacitive voltage transformers (RCVTs) or current harmonics flowing through a static VAr compensator (SVC) of one of the plants should be measured [1–3]. Those necessities arise from the fact that harmonic responses of capacitive voltage transformers (CVTs) are unreliable although the current transformers have a much better harmonic response [4]. This work utilizes a robust state estimation-based method to determine the harmonic current contributions of the connected loads and it does not use measurements acquired from expensive RCVTs; rather it employs measurements of harmonic currents flowing through an SVC or a capacitor bank at the PCC, which is much cheaper compared to the RCVT solution. The estimated harmonic current contributions are to be applied with the obligations stated by standards, and hence even low measurement errors must be taken into account. Use of state estimation [5–7]

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reduces measurement errors of CVTs significantly and as a consequence better harmonic current contributions can be obtained.

In the literature, there are state estimation-based techniques applied to the harmonic contribution determination problem [8–12]. In [8], a circuit theory-based harmonic state estimation method is implemented and compared with the singular value decomposition (SVD) technique. In [9] remote harmonic sources and load impedances are identified by using synchronous, partial, and asymmetric measurements. In [10], optimal measurement placement and observability analysis in state estimation are discussed for harmonic state estimation. The methods proposed in [11,12] are based on the weighted least squares (WLS) state estimator, which is not robust against bad data, such that even in the presence of a single bad data harmonic state estimates may be biased. In order to filter out the bad measurements, a postestimation bad data identification process should be employed, which increases the solution time significantly. This work employs a robust weighted least absolute value (WLAV) estimator, which can provide unbiased estimates in the presence of gross error, provided that enough measurement redundancy is satisfied [13]. Comparative studies between WLS- and WLAV-based methods are presented via simulations. Once the proposed method is employed, the necessity for bad data analysis is disregarded, and the harmonic contribution computation can be performed much faster, which may enable online application possible in the future. As time passes the accuracy of each device varies. This variation is not always deterministic. Moreover, calibration is another problem associated with measurement transformers as well as transducers. By employing a state estimator, the effect of those inaccuracies is minimized. In addition, WLAV provides rejection of bad measurements, e.g., incorrect current measurement polarities, which may cause significantly biased results. A CVT actually provides redundancy required by a robust state estimator. If its accuracy is low, it is automatically rejected by WLAV.

The rest of the paper is organized as follows. In Section 2, the proposed harmonic contribution determination method is explained in detail. In Sections 3 and 4 the proposed method is verified in a simulation environment and applied to a set of field data, respectively. In Section 5 contributions of this work are summarized and the method is discussed profoundly. In Section 6 the conclusions are given.

2. Proposed method

Due to legal sanctions, it is extremely important to identify the harmonic contribution of each plant connected to the same PCC in the most accurate manner. Therefore this paper proposes a state estimation-based method, which is robust against the gross error associated with measurements.

The proposed method employs a WLAV-based state estimation in order to filter the gross error due to CVTs. Once the unbiased estimates are obtained, the harmonic contribution detection method proposed in [1–3] is applied to determine the individual harmonic current contribution of each plant connected to the PCC.

The block diagram of the proposed method [14] is presented in Figure 1. Firstly, the WLAV estimator is applied to estimate harmonic voltages ($\hat{V}_i^n$) using the measured harmonic currents (I_i^n) and harmonic voltages (V_i^n) together with the power system topology given in Figure 2. Note that superscript n represents the order of the harmonics being analyzed throughout this work. The harmonic current contribution algorithm is run after the estimation process.

2.1. Harmonic voltage estimation with WLAV at the PCC

Harmonic voltage measurements at the PCC are unreliable when CVTs are used. Those measurements include both Gaussian and gross errors; thus they cannot be used in calculations directly. Gross error can be reduced

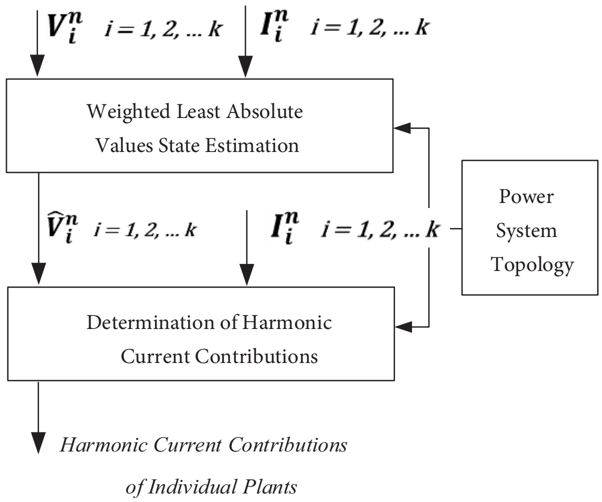

Figure 1. Flowchart of the proposed method.

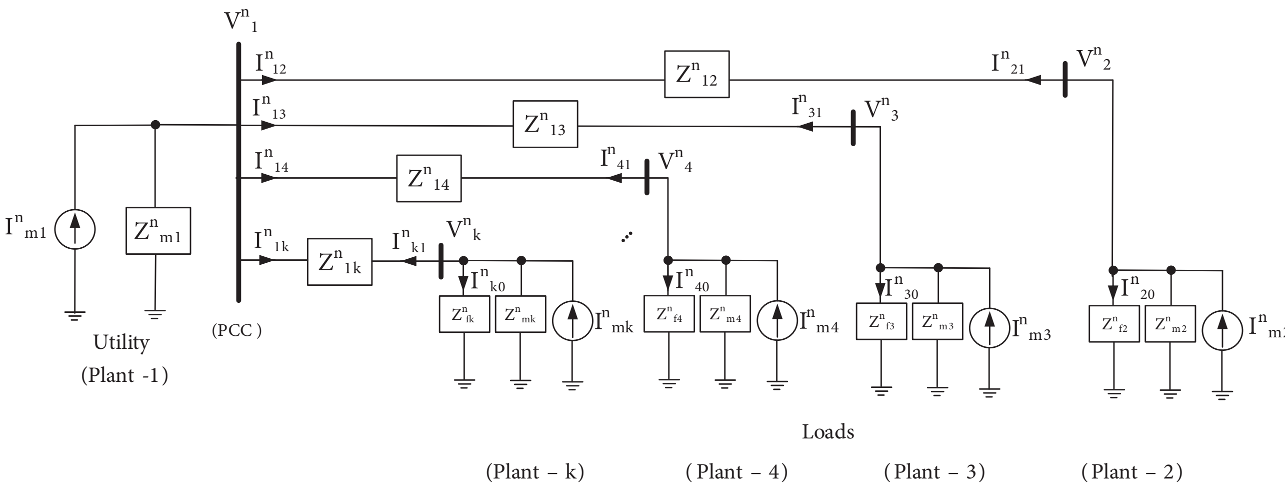

Figure 2. General representation of the utility and plants carrying harmonic filters supplied from the PCC.

through calibration based on the correction factors provided by the manufacturer for the frequency spectrum of the CVTs. In critical cases, i.e. when highly reliable measurements are needed, however, calibration may not be enough. Both the gross error and the Gaussian error should be eliminated as much as possible in such cases. To achieve this goal, a WLAV estimator is proposed, which is known to be robust against gross error in the presence of redundant measurements [15,16].

In order to perform harmonic voltage estimation, synchronized measurements must be taken from the PCC and the plants connected to the PCC. This work employs synthetic data for validation purposes and the synchronized harmonic measurements received via the power quality analyzers (PQ^+) developed through the National Power Quality Project of Turkey by TÜBİTAK [17] for the application of the proposed method to field data. In contrast to the traditional power system state estimation problem, which involves iterative solutions [5], in this work, thanks to the linearity between the synchronized harmonic measurements (both voltage and current) and the system states, which are the harmonic voltages, the state estimation problem can be solved without any iteration [15].

Considering the pi-equivalent model of a transmission line, state estimation variables and equations can be defined as follows [11]:

$$Y_{12}^n = G_{12}^n + jB_{12}^n \tag{1}$$

$$\begin{aligned} I_1^{n,r} &= G_{12}^n V_1^{n,r} - \left(B_1^n + B_{12}^n\right) V_1^{n,i} - G_{12}^n V_2^{n,r} + B_{12}^n V_2^{n,i} \\ I_1^{n,i} &= \left(B_1^n + B_{12}^n\right) V_1^{n,r} + G_{12}^n V_1^{n,i} - B_{12}^n V_2^{n,r} - G_{12}^n V_2^{n,i} \end{aligned} \tag{2}$$

$$\begin{aligned} I_2^{n,r} &= -G_{12}^n V_1^{n,r} + B_{12}^n V_1^{n,i} + G_{12}^n V_2^{n,r} - (B_{12}^n + B_2^n) V_2^{n,i} \\ I_2^{n,i} &= -B_{12}^n V_1^{n,r} - G_{12}^n V_1^{n,i} + (B_{12}^n + B_2^n) V_2^{n,r} + G_{12}^n V_2^{n,i} \end{aligned} \tag{3}$$

In (1), Y_{12}^n is series admittance between the two terminal buses, while B_1^n and B_2^n are line charging susceptances of the buses corresponding to the nth harmonic. V_1^n and V_2^n are the nth harmonic voltages of the buses. The relation between the nth harmonic current measurements I_1^n and I_2^n (line currents flowing from bus 1 to bus 2 and from bus 2 to bus 1, respectively) is expressed as in (2) and (3). All measurements are decoupled to real and imaginary parts. Superscripts r and i represent the real and imaginary parts of the corresponding vector, respectively. States are also defined as real and imaginary parts of voltage measurements, in order to obtain a linear measurement model.

Formulation of WLAV-based state estimation for a system with m measurements and n states with measurement vector z and Jacobian matrix H is given in (4a), which is solved using a linear programming solver. The details of WLAV can be found in [15].

$$\begin{aligned} &\min \;\; c^T y \\ &s.t. \quad My = b \\ &\qquad\quad \mathrm{y} \geq 0 \end{aligned} \tag{4a}$$

$$\begin{aligned} c^T &= \begin{bmatrix} Z_n & W_m \end{bmatrix} \qquad y = \begin{bmatrix} X_a^T & X_b^T & U^T & V^T \end{bmatrix} \\ M &= \begin{bmatrix} H & -H & I & -I \end{bmatrix} \qquad b = z \end{aligned} \tag{4b}$$

In (4b), Z_n is the 1x*2n* vector consisting of zeros and W_m is the 1x*2m* vector consisting of reciprocals of the variances of measurements. X_a and X_b are 1xn, and U and V are 1xm vectors, where

$$\begin{aligned} x &= X_a^T - X_b^T \\ r &= U^T - V^T \end{aligned} \tag{5}$$

Considering (1)–(3) with the knowledge of the defined states, the components of the estimator can be built as given in (6)–(8). Standard deviations of the measurements are represented as σ.

$$x = \begin{bmatrix} V_1^{n,r} & V_1^{n,i} & V_2^{n,r} & V_2^{n,i} \end{bmatrix}^T \tag{6}$$

$$z = \begin{bmatrix} V_1^{n,r} & V_1^{n,i} & V_2^{n,r} & V_2^{n,i} & I_1^{n,r} & I_1^{n,i} & I_2^{n,r} & I_2^{n,i} \end{bmatrix}^T \tag{7}$$

$$W = \begin{bmatrix} \sigma^2_{V_1^{n,r}} & \sigma^2_{V_1^{n,i}} & \sigma^2_{V_2^{n,r}} & \sigma^2_{V_2^{n,i}} & \sigma^2_{I_1^{n,r}} & \sigma^2_{I_1^{n,i}} & \sigma^2_{I_2^{n,r}} & \sigma^2_{I_2^{n,i}} \end{bmatrix}^T \tag{8}$$

$$H = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ G_{12}^n & -(B_1^n + B_{12}^n) & -G_{12}^n & B_{12}^n \\ (B_1^n + B_{12}^n) & G_{12}^n & -B_{12}^n & -G_{12}^n \\ -G_{12}^n & B_{12}^n & G_{12}^n & -(B_2^n + B_{12}^n) \\ -B_{12}^n & -G_{12}^n & (B_2^n + B_{12}^n) & G_{12}^n \end{bmatrix} \tag{9}$$

In the presence of one reliable voltage measurement and current harmonic measurements, the use of WLAV state estimation annihilates the need for calibration of the CVTs, which is not reliable, and hence gross error can be reduced considerably.

The reliable voltage measurement can be obtained using the current measurements on a passive load with a known model. Harmonic filters or capacitor banks can be considered for this purpose. Hence the reliable voltage measurement required in the state estimation equations is obtained through the current measurement on any known-impedance load. Therefore, the need for using RCVTs, which is an expensive and difficult solution, is avoided.

WLAV requires a redundant enough measurement set for state estimation robustness [16]. The measurement design given in Figure 2 is used in this work to perform the WLAV estimation. The harmonic currents are measured at both the sending end and the receiving end of the lines. The voltage at the PCC is represented by V_1^n. The receiving end voltages, which are represented with V_2^n to V_k^n in Figure 2, are measured at the end of the transmission lines. The utility side is also labelled as a plant for convenience. All the operations conducted in this work require synchronously obtained measurements.

Once the optimum estimated voltages are obtained using measured harmonic voltages and currents (V_i^n and I_i^n, where n represents the harmonic order) by state estimation, estimated voltages ($\hat{V}_i^n$) and currents are used to compute the harmonic current contributions of the individual plants [1–3].

2.2. Determination of harmonic current contributions

Using the related voltage estimations and currents, superposition theorem is applied to determine current injections (I_{m1}^n, I_{m2}^n, … I_{mk}^n) in the model given in Figure 2. In the proposed method, an alternative model including line impedances in addition to utility and load impedances, which have solely been used in earlier studies [1–3], is utilized to get more accurate results [11].

Accordingly, measurements and injection currents are related as given in (10).

$$\begin{gathered} Y = \begin{bmatrix} \hat{V}_1^n & I_{12}^n & I_{13}^n & \dots & I_{1n}^n \end{bmatrix}^T \\ X = \begin{bmatrix} I_{m1}^n & I_{m2}^n & I_{m3}^n & \dots & I_{mk}^n \end{bmatrix}^T \\ Y = A.X \\ X = A.^{-1}Y \end{gathered} \tag{10}$$

In (10), X consists of harmonic current injections of the plants and Y consists of PCC voltage and sending end currents. This paper especially proposes using estimated PCC voltage to obtain best harmonic injections;

otherwise injection estimations will carry significant errors. Thanks to the superposition theorem applied to the topology in Figure 2, the A matrix is obtained as given in (11).

$$A = \begin{bmatrix} \frac{J_2^n}{J_2^n+Z_2^n} Z_2^n & \frac{-Z_{p2}^n}{J_2^n+Z_2^n} Z_2^n + Z_{p2}^n & \frac{J_2^n}{J_2^n+Z_2^n} \frac{Z_{p3}^n}{Z_3^n} Z_2^n & \cdots & \frac{J_2^n}{J_2^n+Z_2^n} \frac{Z_{pk}^n}{Z_k^n} Z_2^n \\ \frac{J_2^n}{J_2^n+Z_2^n} & \frac{-Z_{p2}^n}{J_2^n+Z_2^n} & \frac{J_2^n}{J_2^n+Z_2^n} \frac{Z_{p3}^n}{Z_3^n} & \cdots & \frac{J_2^n}{J_2^n+Z_2^n} \frac{Z_{pk}^n}{Z_k^n} \\ \frac{J_3^n}{J_3^n+Z_3^n} & \frac{J_3^n}{J_3^n+Z_3^n} \frac{Z_{p2}^n}{Z_2^n} & \frac{-Z_{p3}^n}{J_3^n+Z_3^n} & \cdots & \frac{J_3^n}{J_3^n+Z_3^n} \frac{Z_{pk}^n}{Z_k^n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \frac{J_k^n}{J_k^n+Z_k^n} & \frac{J_k^n}{J_k^n+Z_k^n} \frac{Z_{p2}^n}{Z_2^n} & \frac{J_k^n}{J_k^n+Z_k^n} \frac{Z_{p3}^n}{Z_3^n} & \cdots & \frac{-Z_{pk}^n}{J_k^n+Z_k^n} \end{bmatrix} \tag{11}$$

A is composed of total feeder impedances Z_i^n s ($Z_i^n = Z_{pi}^n + Z_{1i}^n$), total plant impedances Z_{pi}^n s ($Z_{pi}^n = Z_{fi}^n + Z_{mi}^n$), and Thevenin impedances seen by each feeder at the sending end (J_i^n s). Note that total plant impedances (Z_{pi}^n in (11)) at the receiving ends in Figure 2 are equal to the parallel equivalent impedances of the constant loads (Z_{fi}^n s) and corresponding model impedances (Z_{mi}^n s). Line charging capacitances are not shown in Figure 2 in order to not complicate the figure. However, these capacitances are taken into account in the computations as shown in (9).

Derivation of the A matrix and a detailed explanation of the proposed harmonic contribution determination method are given in [11]. The A matrix in [11], however, does not contain the constant loads (Z_{fi}^n in Z_{pi}^n representation) in Figure 2. These computations involve superposition theorem and phasor analysis; they are applied to only steady-state conditions [2].

3. Verification of the proposed method

In this section the accuracy and the computational performance of the proposed method are validated using synthetic data. The system topology presented in Figure 3 is used. It is assumed that all voltage measurements are acquired from CVTs. This condition coincides with the most extreme condition for such a state estimation problem. A short transmission line model is employed, such that the charging susceptances are ignored, which only simplifies the mathematical formulations but does not affect the solution procedure. In real applications the complete line model should be employed for more accurate results. During the tests of WLAV, harmonic order (n) is supposed to be 7. Line and load impedances at fundamental frequency are specified in Figure 3.

In this study, the accuracy and the computational performance of the proposed method are compared to those of the WLS state estimator-based method [11]. WLS is one of the most commonly employed and fastest estimators, and hence it is taken as the reference for validation. The WLS-based methods scale the measurements with the constants provided by the CVT manufacturers to reduce the gross error associated with them. A sample graph that presents the calibration constant of CVTs is presented in the Appendix section, in Figure 4. However, if the real field measurements are considered, the calibration may not filter out the gross error. Note that WLS is not a robust estimator, and hence WLS estimates will be biased even in the presence of a single bad item of data. Therefore, once the estimation is completed, a bad data detection method should be employed. In this study, the normalized residuals test (NRT) [5] will be employed for bad data detection and identification purposes. Since the proposed method is based on a WLAV estimator, it does not require a bad data analysis, which significantly reduces the computational load for large systems.

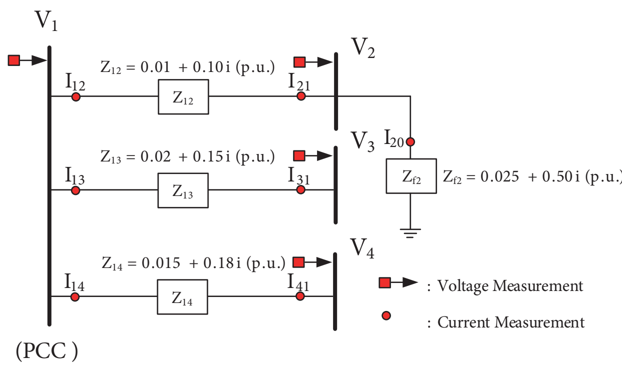

Figure 3. State estimation test system.

In order to test the proposed method, a known harmonic voltage set without any error is generated for the given system in Figure 3. Those values are stated in Table 1. The true harmonic currents are calculated based on those values and impedances stated in Figure 3. The harmonic voltage measurements are multiplied with constants based on the phase and angle coefficients corresponding to 350 Hz given in Figure 4. The amplitude coefficient is determined as 1.6 p.u. and the phase angle coefficient is determined as –40 degrees. As is well known, according to the age of the CVT and the environmental conditions those constant may vary. Therefore, the coefficients given in Figure 4 are distorted by adding Gaussian error with standard deviation 0.1, in order to obtain more realistic constants, which are not directly equal to the values stated by the manufacturer.

Table 1. Voltage values of Figure 3, without any error.

Voltage	True value
V_1^n	1 p.u.
V_2^n	0.9862 + j0.0863 p.u.
V_3^n	0.9551 + j0.1702 p.u.
V_4^n	0.8927 + j0.3249 p.u.

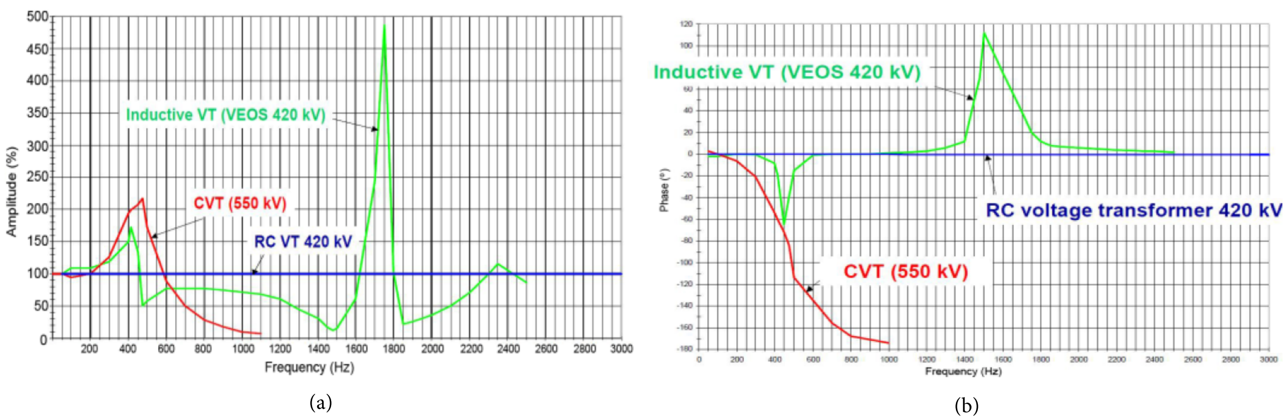

Figure 4. Comparison of a) amplitude and b) phase shift errors of RCVTs and CVTs [2].

Once the effect of CVT is reflected in the voltage measurements, to obtain a realistic study, Gaussian error is added to both the corrupted voltage measurements and the true current measurements. The Gaussian errors of current and voltage measurements have standard deviation of 0.005 and 0.05, respectively. In order to evaluate the proposed method, Monte Carlo simulations are carried out. Mean squared error (MSE) of the estimation is calculated by evaluating 1000 estimations as shown in (12).

$$\mathrm{MS}E = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\hat{x}_i - x_i)^2} \tag{12}$$

In (12), n being the number of simulations is equal to 1000, $(\hat{x}_i)$ represents estimated states, and x_i represents the true states. The MSE of the real and imaginary parts of V_{PCC} (V_1) estimation are presented in Table 2. Note that total computational time includes the execution time of the NRT, since it is required to perform the NRT to obtain unbiased estimates. Considering the results presented in Table 2, it is clear that the accuracy of the proposed method is better once an error associated with the calibration constants exists. Even though the error due to the saturation of CVTs is reduced using the calibration constants, it cannot be cleared completely. In this case WLAV provides more accurate estimates compared to WLS. The computational times of the two methods are close to each other. If the number of plants increases and there is a significant error in the calibration constants, then the time difference between those two methods will become significant in favor of the proposed method. A detailed comparison between WLAV and WLS can be found in [15].

Table 2. Results obtained from designed test system.

Estimator	$MSE\,of\,V^r_{PCC}$	$MSE\,of\,V^i_{PCC}$	Mean computation time (s)
WLAV	0.0026	0.0025	0.003053
WLS&NRT	0.0612	0.0454	0.002243

4. Application of the method to field data

The method, which is detailed and verified above, is applied to real-time field measurements obtained from a substation supplying an industrial plant. The data are collected at a sampling rate of 25.6 kHz per channel by the PQ^+ analyzers [17]. The plant supplied at 13.8 kV. The measurements, which had been collected at the receiving end in Figure 5 previously, are used in this work and are the same as those in the previous works reported in [1–3]. Note that this paper proposes to collect sending end voltages in such applications, as well. Absence of sending end voltages and currents is handled by calculating them based on line impedances and receiving end measurements. Gaussian error is added to both calculated voltage and current measurements to simulate the realistic case. Voltage measurements are acquired from RCVTs; thus all voltage measurements are corrupted with coefficients to simulate CVT measurements. To evaluate harmonic current contributions, Norton's equivalent circuit models given in Figure 5 are taken into account. Both utility and load are represented by impedances and current sources since they are all sources of harmonics. Thus it is not possible to exactly measure the amount of current flowing over model impedances, Z_{mi}. Note that for the topology in Figure 5 only Z_{12} and Z_{f2} can be used in the state estimation process. In this work, both state estimation and contribution analysis are applied on only phase-A measurements and impedances. Both model impedance (Z_{m2}) and the filter impedance (Z_{f2}) in Figure 5 are calculated at fundamental frequency as the ratio of voltages to currents. Impedances are also updated for an interval being 10-cycle of the fundamental. Moreover, all calculations are carried out in the phasor domain; therefore, the steady-state assumption is made and transient periods are ignored [2]. Harmonic phasor measurements are obtained from raw measurement data applying DFT and harmonic impedances are obtained by linearly amplifying the imaginary parts of the fundamental impedances.

After the required harmonic impedances and measurements are obtained, the WLAV state estimation process is run. PCC voltage is corrected and then a new measurement set is acquired.

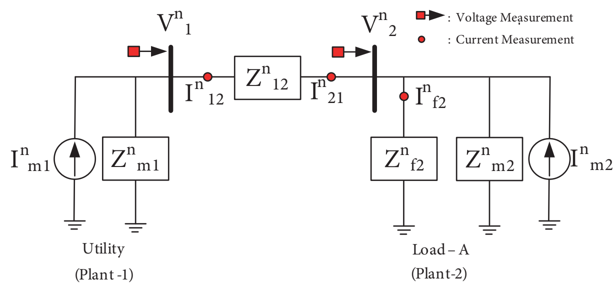

Figure 5. General representation of the circuit with measurement points.

All injection currents are determined by employing the harmonic current determination model referred to in Section 2.2 for every nonoverlapping 200-ms period. Using those harmonic injection currents, current contributions of load and utility are calculated. Harmonic current contributions are obtained for the 2nd, 3rd, 5th, and 7th harmonics for a measurement period of 20 s and the results are illustrated in Figure 6.

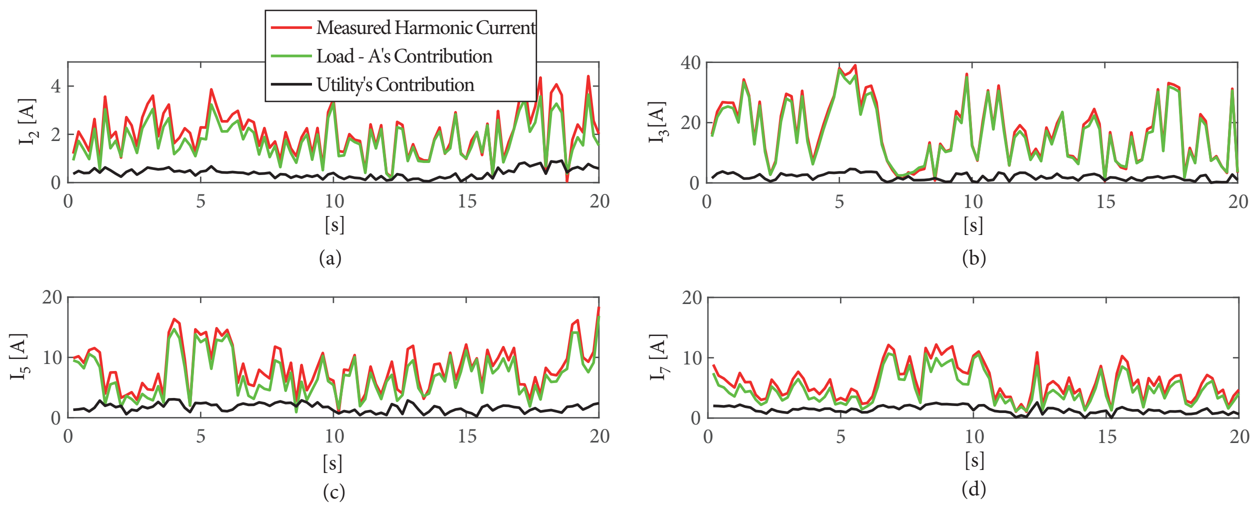

Figure 6. Computed Load-A and utility contributions to PCC current: a) 2nd (I^2), b) 3rd (I^3), c) 5th (I^5), and d) 7th (I^7) harmonic currents.

The results obtained may be summarized as follows:

- Load-A is responsible for the 2nd, 3rd, 5th, and 7th harmonic currents.
- Contribution of the utility is highly insignificant; especially for the 3rd harmonic, it is observed to be negligible.
- It is observed that at all harmonic levels the harmonic current contribution of both Load A and the utility is smaller than the measured harmonic current at the PCC.
- Finally, at the 2nd, 3rd, 5th, and 7th harmonic levels, the angle between load and utility harmonic current phasors is lower than 90°, and therefore harmonic current measured at the PCC is larger than the individual contributions of the utility and Load-A.

5. Contributions

Outstanding features of the proposed approach are stated below.

- A robust state estimation-based method to detect harmonic current contribution of the loads connected to a PCC is developed, which can filter out measurement and calibration errors.
- Compared to the installation of RCVTs, the proposed method is much easier and cheaper to perform.
- Thanks to the robustness of the WLAV estimator, the proposed method does not require execution of bad data analysis, such as NRT.
- The state estimation based method is competitive with classical methods in terms of computational performance. For the sake of simplicity only the effect of CVTs on the magnitude of the harmonics is considered. The proposed method employs Cartesian coordinates, which means that even if there is gross error associated with harmonic current angle measurements, it will not affect the results of the proposed method, since the error associated with angle will change the values of the real and imaginary parts, which are already incorrect.

6. Conclusions

In this paper, to determine harmonic current contributions, a robust state estimation-based method is introduced. Compared to the previous studies, the proposed method provides more accurate results yet with a good computational performance.

The robustness of the proposed method is guaranteed in the presence of enough measurement redundancy. To satisfy this condition, this work proposed use of the measurement design provided in Figure 3. The measurement design requires synchronized harmonic current and voltage measurements taken at both the sending and receiving ends of the transmission lines between the PCC and the loads.

Note that a reliable measurement is also required to obtain unbiased estimates. This work proposes use of a current measurement taken by a passive load, such as a capacitor bank or a passive harmonic filter. Because of the poor harmonic performance of CVTs, the current of that passive load is used to calculate the real value of the voltage at that point.

The harmonic voltage measurements are added to the state estimation problem to obtain a general formulation, although it is known that they are unreliable. With the proposed method, even in the presence of a single RCVT, the harmonic contributions of the plants can be computed successfully.

The tests with field data show that the accuracy of the proposed method despite using CVTs is comparable with the harmonic voltage measurements taken via RCVTs.

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Appendix

Comparison of the performance of the RCVTs with the CVTs in terms of amplitude and phase shift errors with respect to frequency. The sample tests given by Trench Group AG [4] are presented in Figures 4a and 4b [2].