# Estimating the Harmonic Contributions of Utility and Costumer in a distorted power system

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**ABSTRACT**

This paper presents an improved method for determining the contribution of harmonic distortion generated by utility and customer at the Point of Common Coupling (PCC) in a distorted power system. For this purpose, first the magnitude and phase of voltage and current at the PCC in each frequency are estimated by adaptive Kalman filter. Then the parameters of Thevenin equivalent circuits of load and utility sides are estimated using the recursive least squares technique based on singular value decomposition (SVD). Finally, the contribution of utility and customer in harmonic distortion of the 3-phase voltage waveforms has been calculated by three approaches. A case study has been made to verify the accuracy of the proposed method. Also, the presented method has been used in a 13-bus IEEE standard distribution system. Presented simulation results show that the proposed method can accurately determine the harmonic contributions of utility and customer for measurements made at the PCC.

**Keywords**: Contribution of Harmonic Distortion, Adaptive Kalman Kilter; Recursive Least-Squares, Singular Value Decomposition, Distorted Power System

## 1. INTRODUCTION

Use of nonlinear loads, such as thyristor controlled inductors for FACTs devices, converters for HVDC transmission and large adjustable speed motor drives, is expected to grow rapidly. All of these loads inject harmonic currents and reactive power into the power system. These harmonics distort fundamental voltage and current waveforms and have many negative effects on power systems. It may cause resonance problems, overheating in capacitor banks and transformers, wrong operation of protection devices and reduction of power quality which eventually increases the maintenance costs of the system. Power distribution companies are now considering the application of penalties in the energy tariff in order to decrease the waveform distortion. This has led to the need for estimating the respective contributions to voltage waveform distortion at the PCC by the consumer and utility. Before taking the necessary harmonic control measures, it is important to know who is responsible for the cause of harmonic distortion. Several methods have been proposed to identify the location of harmonic sources so as to determine whether the source is from the utility or customer side.

In [1]a method for harmonic source localization is based on the real power flow direction. However, the accuracy of the real power flow direction method is less than 50% and therefore the reliability of this method is questionable [2-3]. This method is impractical because it requires knowledge of actual impedances of the system for its calculation [2-3]. Other methods for harmonic source localization are such as the critical impedance method [4] and voltage magnitude comparison method [5] which requires implementation of switching tests for obtaining the harmonic impedance. Hence, the switching tests do not allow its application in practical power systems. A recent method for harmonic source localization which is called as the harmonic vector method (HVM) [6] uses resistance as the reference impedance for modeling the customer side and uses the equations in [2-3] for determining the harmonic contribution of utility and customer. However, modeling the customer side by an equivalent resistance may introduce inaccuracy in calculating the harmonic contribution factors especially in cases where loads contain inductive elements such as motors. In [7], the total harmonic distortion (THD) is used for finding the share of harmonic distortion from utility and customer sides. The disadvantage of this method is that the THD value cannot show the variation of contributions caused by changes in phase angle of harmonic sources. In [8-11], several multiple harmonic sources localization methods were developed based on harmonic state estimation (HSE) and independent component analysis (ICA). In HSE based method, a complete knowledge about system parameters at different harmonic frequencies is necessary but these parameters are usually unknown. In addition, the method requires various types of harmonic measurements such as voltage, active and reactive power measurements, which are costly for large systems. The ICA based method, however, requires historical load data and harmonic impedance matrix of the system to eliminate indeterminacies caused by

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the ICA algorithm [12-13].

In this paper, a technique is proposed for estimating the utility's and consumer's contribution to voltage waveform distortion at the PCC. The input data required are the voltage and current waveforms at the PCC. By applying parameter estimation techniques, the equivalent circuit of the consumer's load and utility has been determined. (In contrast, the techniques presented in the literature require this impedance as input data). Subsequently, an analysis of the utility's equivalent circuit is carried out and the relative contributions of the utility and consumer to waveform distortion are calculated.

This paper also addresses the problem of tuning Kalman filters so that they can properly track harmonic fluctuations. A method for self-tuning of the model error covariance is used, showing fast adaptive capability under sudden changes of the input signal [14].

There are different techniques to identify the parameters of the circuit. Although least square method is a fast tracker of the time-varying individual harmonic components, it has some limitations such as high computation cost of performing the calculations due to the matrix inversions.

To eliminate the problem of the least square algorithm particularly reducing the computational requirement and using in the on-line monitoring a least square algorithm based on singular value decomposition (SVD) is used. The SVD is a powerful and computationally stable mathematical tool for solving rectangular matrices which eliminates the matrix inversion [15-16].

Finally, waveform measurements have been made in a 13-bus standard IEEE distribution system and contribution of harmonic distortion generated by utility and customer at the Point of Common Coupling (PCC) have been estimated.

## 2. ON-LINE IDENTIFICATION PROCEDURE

The proposed technique is based on measurement of the waveforms of the 3-phase voltages and currents at the PCC, as shown in Fig. 1. The process of estimating the utility's and consumer's contribution to voltage waveform distortion at the PCC will be done in three steps. In the first step, the sampled measurements of voltage and current at the PCC are used to estimate the phasors of bus voltage and current at fundamental and harmonic frequencies by Adaptive Kalman filter [17-19]. The Kalman filter is an optimal estimator that takes into account the presence of white noise in the measurements. At the end of this step, samples of the voltage phasor at the PCC ($V_{ix,\omega}+jV_{iy,\omega}$) and the load current phasor ($I_{ix,\omega}+jI_{iy,\omega}$) are both available at each angular frequency $\omega$. In the second step of the procedure the identification of the Thevenin equivalent circuit parameters at fundamental and harmonic frequencies is performed by recursive least squares based on singular value decomposition method using the estimates of the voltage and current phasors given by the adaptive Kalman filters in the first step of the procedure. The singular value decomposition (SVD) is a powerful and computationally stable mathematical tool for solving rectangular matrices which has found many applications in numerical computing. The singular value decomposition is fully described in [16, 20]. In the third step the utility's and consumer's contribution to harmonic distortion will be estimated by the approaches which will be explained.

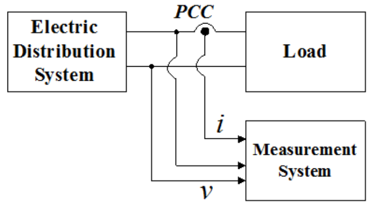


***Fig.1:*** *Measurement of waveforms at the PCC.*

### 2.1 Recursive least squares based on singular value decomposition

The least squares (LS) approach has wide-spread applications in many fields, such as statistics, numerical analysis and engineering. Its greatest progress in the 20$^{th}$ century was the development of the recursive least squares (RLS) algorithm, which has made the LS method one of the few most important and widely used approaches for real-time applications in such areas as signal and data processing, communications and control systems. Considerable efforts and significant achievements have been made in developing even more efficient RLS algorithms. Application of The SVD approach in the RLS algorithms eliminates the matrix inversion problem of the recursive least square algorithm and also provides better noise immunity for estimation. We assume the waveform of the voltage or current as the sum of harmonics with unknown magnitude and phases:

$$x(t) = \sum_{k=1}^{N} X_k \cos(\omega_k t + \varphi)k) + K_S e(t) \qquad (1)$$

Where, $X_k$, $\omega_k$ and $\varphi_k$ are the unknown amplitude, angular frequency and phase of the k$^{th}$ harmonic and N is the number of these harmonics. The variable e(t) represents the additive Gaussian noise with unity variance and $K_S$ is the gain factor. Further let us consider the set of n measured samples $x_1, x_2, \ldots, x_n$ of the waveform.

Now we have an over determined system of algebraic equation:

$$Ah = b \tag{2}$$

Where the matrix A and vectors h and b are given as follows:

$$A=\begin{bmatrix} x_l & x_{l-1} & \cdots & x_1 \\ x_{l+1} & x_l & \cdots & x_2 \\ \cdots & \cdots & \cdots & \cdots \\ x_{n-1} & x_{n-2} & \cdots & x_{n-1} \\ x_2 & x_3 & \cdots & x_{l+1} \\ x_3 & x_4 & \cdots & x_{l+2} \\ \cdots & \cdots & \cdots & \cdots \\ x_{n-l+1} & x_{n-l+2} & \cdots & x_n \end{bmatrix}, h=\begin{bmatrix} h_1 \\ h_2 \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ h_l \end{bmatrix}, b=\begin{bmatrix} x_{l+1} \\ x_{l+2} \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ x_{n-l} \end{bmatrix} \tag{3}$$

The solution for vector h is possible in least square (LS), which is by minimising the summed squared error between the left and right hand sides of the equation. The objective function to be minimised may be expressed in the norm-2 vector notation form as [20]:

$$E = \frac{1}{2}\|Ah - b\|_2^2 \tag{4}$$

To solve (4), the SVD approach has been used. In this approach, the rectangular matrix A was defined as the product of three matrices.

$$A = USV^T \tag{5}$$

Where, U and V are orthogonal matrices with dimension $n \times n$ and $l \times l$ respectively, while S is the quasidiagonal $n \times l$ matrix of singular values $s_1, s_2, \ldots, s_p$ ordered in a descending way. So we will have:

$$(A)^{-1} = (USV^T)^{-1} = VS^{-1}U^T \tag{6}$$

To initialize the RLS based SVD approach, we assumed: $P_o = (A_m^T A_m)^{-1}$ and $h_o = P_m A_m^T b_m$, Where $P_o$ is the initial estimation error covariance, $h_o$ is the initial estimation, the pair $(A_m; b_m)$ represents the first m data pairs and the pair $(A_k; b_k)$ represents the k$^{\text{th}}$ data pairs. Finally we have used following formulas to solve the problem.

$$[U, S, V] = SVD(1 + A_{k+1} P_K A_{k+1}^T) \tag{7}$$

$$P_{k+1} = P_k - (P_k A_{k+1} A_{k+1}^T P_k)(VS^{-1}U^T) \tag{8}$$

$$h_{k+1} = h_k + (b_{k+1} - A_{k+1} h_k) A_{k+1} P_{k+1} \tag{9}$$

## 2.2 Parameter Estimation in Single Phase Circuits

The proposed technique represents the load & the utility by its equivalent at each frequency, as shown in Fig. 2. The current phasor ($I_{ix,\omega}$+j$I_{iy,\omega}$) and the voltage phasor ($V_{ix,\omega}$+j$V_i y, \omega$) are both available from the Adaptive Kalman filter. Superscript i denote the sample number and subscript $\omega$ indicates the angular frequency under consideration.

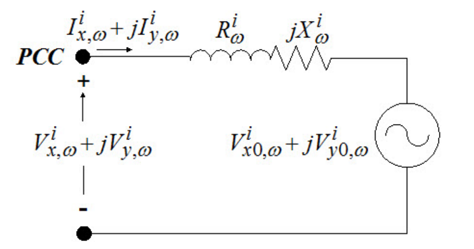


***Fig.2:*** *Load & utility model at angular frequency.*

Applying Kirchhoff's voltage law to the equivalent circuit of the load,

$$V^i_{x,\omega} + jV^i_{y,\omega} = V^i_{x0,\omega} + jV^i_{y0,\omega} + (R^i_\omega + jX^i_\omega) \cdot (I^j_{x,\omega} + jI^i_{y,\omega}) \tag{10}$$

Equations (1) may be put in the form of a matrix equation:

$$\begin{bmatrix} I^i_{x,\omega} & I^i_{y,\omega} & 1 \end{bmatrix} \cdot \begin{bmatrix} R_1 & X_2 \\ X_1 & R_2 \\ V^i_{x0,\omega} & V^i_{y0,\omega} \end{bmatrix} = \begin{bmatrix} V^i_{x,\omega} & V^i_{y,\omega} \end{bmatrix} \tag{11}$$

Where R1 = R2 = Ri and X2= -X1= $X^i_\omega$. Considering several successive samples, the recursive least-squares based on singular value decomposition estimate of the parameters R1, X1, R2, X2, $V^i_{x0,\omega}$, $V^i_{y0,\omega}$ are obtained subject to the constraints R1 = R2 and X1 = -X2. The recursive least-squares procedure for estimating the parameters values is fully described in [21]. The procedure explained before will be repeated for the utility side. Fig. 3 shows the equivalent circuit of the load and the utility system at the PCC.

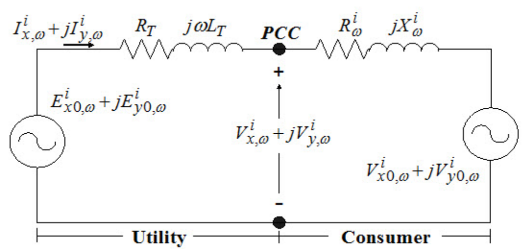


***Fig.3:*** *Equivalent circuit of the load & utility at the PCC.*

## 2.3 Parameter Estimation in Three Phase Circuits

At the point of common coupling between a 3-phase distribution system and an industrial load, the variables to be measured are the 3-phase voltages $(Va^i, Vb^i, Vc^i)$ and the currents $(Ia^i, Ib^i, Ic^i)$. The frequencies in each of the waveforms are estimated and the Kalman filter provides estimates of the voltage and current phasors for each phase, at each frequency. Let the voltage phasors be $(Va^i_{x,\omega}+jVa^i_{y,\omega})$, $(Vb^i_{x,\omega}+jVb^i_{y,\omega})$, $(Vc^i_{x,\omega}+jVc^i_{y,\omega})$ and the current phasors be $(Ia^i_{x,\omega}+jIa^i_{y,\omega})$, $(Ib^i_{x,\omega}+jIb^i_{y,\omega})$, $(Ic^i_{x,\omega}+jIc^i_{y,\omega})$.

The voltage and current phasors are then resolved into the positive, negative and zero sequence components, at each frequency, using the symmetrical components transformation:

$$\begin{bmatrix} Vp^i_{x,\omega}+jVp^i_{y,\omega} \\ Vn^i_{x,\omega}+jVn^i_{y,\omega} \\ Vz^i_{x,\omega}+jVz^i_{y,\omega} \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} Va^i_{x,\omega}+jVa^i_{y,\omega} \\ Vb^i_{x,\omega}+jVb^i_{y,\omega} \\ Vc^i_{x,\omega}+jVc^i_{y,\omega} \end{bmatrix} \quad (12)$$

$$\begin{bmatrix} Ip^i_{x,\omega}+jIp^i_{y,\omega} \\ In^i_{x,\omega}+jIn^i_{y,\omega} \\ Iz^i_{x,\omega}+jIz^i_{y,\omega} \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} Ia^i_{x,\omega}+jIa^i_{y,\omega} \\ Ib^i_{x,\omega}+jIb^i_{y,\omega} \\ Ic^i_{x,\omega}+jIc^i_{y,\omega} \end{bmatrix} \quad (13)$$

Where $a = e^{j120}$.

After that the parameters of the equivalent circuit in positive, negative and zero sequences will be estimated by using recursive least square based on SVD method.

### 2.4 Estimating the Contribution to Voltage Distortion

The procedure for estimating the contribution to voltage distortion will be applied to each sequence, at each frequency. For example the pair $(Vp^i_{x,\omega}+jVp^i_{y,\omega})$, $(Ip^i_{x,\omega}+jIp^i_{y,\omega})$ are used to estimate the positive-sequence voltages at the PCC due the utility and the consumer. In a similar manner, the zero-sequence and negative-sequence contributions at the PCC are calculated. In order to estimate these contributions three approaches will be used which are 1) using the superposition principle 2) critical impedance 3) voltage rate.

By applying the superposition principle in Fig. 3, the contribution to the voltage at the PCC in frequency, $\omega$, is given by:

$$V_{Utility,\omega} = \frac{R^i_\omega+jX^i_\omega}{(R^i_\omega+jX^i_\omega)+(R_T+j\omega L_T)} \cdot (E^i_{x0,\omega}+jE^i_{y0,\omega}) \quad (14)$$

$$V_{Consumer,\omega} = \frac{R_T+j\omega L_T}{(R^i_\omega+jX^i_\omega)+(R_T+j\omega L_T)} \cdot (V^i_{x0,\omega}+jV^i_{y0,\omega}) \quad (15)$$

where

$E_{x0}$ = real part of source voltage phasor;
$E_{y0}$ = imaginary part of source voltage phasor;
$V_{x0}$ = real part of load voltage phasor;
$V_{y0}$ = imaginary part of load voltage phasor;
R= real part of load impedance;
X = imaginary part of load impedance;
$R_T$ = real part of source impedance;
$\omega L_T$ = - imaginary part of source impedance;
Superscript i = the $i^{th}$ sampling interval;
Subscript $\omega$ = the angular frequency $\omega$.

In critical impedance approach [5] a quantitative index will be defined by the name of critical impedance:

$$CI = 2\frac{Q}{I^2} \quad (16)$$

The Q is reactive power which is generated by the load and "I" is the current in the Fig. 3. If CI>0 then the load is dominant in producing distortions. If CI>0 then there will be three conditions: if $|CI| > X_{max}$ then the utility side is the main harmonic contributorthe ($X_{max}$ is the maximum of all possible values), if $|CI| < X_{min}$ then load side is the main harmonic contributorthe ($X_{min}$ is the minimum of all possible X values) and if $X_{min} < |CI| < X_{max}$ then no definite conclusion can be drawn. In voltage rate approach [5] the following rate has been proposed:

$$\theta_v = |Z + Z_c| / |Z - Z_u| \quad (17)$$

With applying the voltage rate in Fig. 3, the contribution to the voltage at the PCC in frequency $\omega$ is given by:

$$V_u = (E_c)/\theta_v(1 + Z_u/Z_c) \quad (18)$$

$$V_c = \theta_v(E_u)/(1 + Z_u/Z_c) \quad (19)$$

Where, $E_c$ is the harmonic source of customer side, $E_u$ is the harmonic source of utility side; $Z_c$ and $Z_u$ are the harmonic impedances of the customer and utility side respectively.

The voltage rate method uses the following decision criteria for localizing dominant harmonic sources:

$$D = \begin{cases} D_c & if \ \ \theta_v < 1 \\ D_n & if \ \ \theta_v = 1 \\ D_u & if \ \ \theta_v > 1 \end{cases} \quad (20)$$

Where $D_c$, $D_n$, $D_u$, are the decisions: 'load is dominant', neutral decision and 'utility is dominant'.

## 3. SIMULATION RESULTS

The procedure described above for estimating the parameters of the load & supply circuit was verified for two circuits which will be explained.

***Table 1:*** *parameter estimation for the hypothetical system for the utility side.*

| $f$ (Hz) | $Z_{Utility}$ (Exact) | $Z_{Utility}$ (Estimated) | Positive-sequence Utility Source \|V\|∠θ (Exact) | Positive-sequence Utility Source \|V\|∠θ (Estimated) | Negative-sequence Utility Source \|V\|∠θ (Exact) | Negative-sequence Utility Source \|V\|∠θ (Estimated) | Zero-sequence Utility Source \|V\|∠θ (Exact) | Zero-sequence Utility Source \|V\|∠θ (Estimated) |
|---|---|---|---|---|---|---|---|---|
| **60** | 2.5+j15 | 2.5+j15 | 100∠0.00° | 99.8277∠-1.1 | 0∠0.00° | 0∠0.00° | 0∠0.00° | 0∠0.00° |
| **300** | 2.5+j73 | 2.5+j73 | 0∠0.00° | 0∠0.00° | 0.94∠32.09° | 0.9417∠30 | 0∠0.00° | 0∠0.00° |
| **420** | 2.5+j105 | 2.5+j105 | 0.12∠34.95° | 0.12∠27.52 | 0∠0.00° | 0∠0.00° | 0∠0.00° | 0∠0.00° |
| **660** | 2.5+j165 | 2.5+j165 | 0∠0.00° | 0∠0.00° | 0.09∠12.61° | 0.09∠11 | 0∠0.00° | 0∠0.00° |

***Table 2:*** *parameter estimation for the hypothetical system for the consumer side.*

| $f$ (Hz) | $Z_{Consumer}$ (Exact) | $Z_{Consumer}$ (Estimated) | Consumer Source \|V\|∠θ (Exact) | Consumer Source \|V\|∠θ (Estimated) | Consumer Source \|V\|∠θ (Exact) | Consumer Source \|V\|∠θ (Estimated) | Consumer Source \|V\|∠θ (Exact) | Consumer Source \|V\|∠θ (Estimated) |
|---|---|---|---|---|---|---|---|---|
| **60** | 130+j25 | 129.97+j25 | 0.36∠85.94° | 0.37∠86.3372 | 0∠0.00° | 0∠0.00° | 0∠0.00° | 0∠0.00° |
| **300** | 130+j125 | 130+j125 | 0∠0.00° | 0∠0.00° | 11.409∠37.82° | 10.6951∠34.11 | 0∠0.00° | 0∠0.00° |
| **420** | 130+j175 | 130+j175 | 6.95∠30.37° | 6.5667∠24.8817 | 0∠0.00° | 0∠0.00° | 0∠0.00° | 0∠0.00° |
| **660** | 130+j275 | 130+j275 | 0∠0.00° | 0∠0.00° | 3.08∠35.52° | 2.9054∠25.17 | 0∠0.00° | 0∠0.00° |

***Table 3:*** *The contribution of load & utility for the hypothetical system with superposition principle.*

| $f$ (Hz) | \|V\|∠θ $_{Utility\ Contribution}$ (Exact) | \|V\|∠θ $_{Utility\ Contribution}$ (Estimated) | \|V\|∠θ $_{Consumer\ Contribution}$ (Exact) | \|V\|∠θ $_{Consumer\ Contribution}$ (Estimated) | *Dominant source* |
|---|---|---|---|---|---|
| **60** | 95.65∠-5.73° | 95.4852∠-7° | 0.04∠119.75° | 0.0407∠146 | utility |
| **300** | 0.71∠19.48° | 0.7096∠14° | 3.57∠69.33° | 3.5685∠64° | consumer |
| **420** | 0.09∠23.49° | 0.0892∠17.2° | 2.36∠54.43° | 2.3528∠46.7° | consumer |
| **660** | 0.06∠4.01° | 0.0618∠7.51° | 1.12∠51.57° | 1.1039∠39° | consumer |

***Table 4:*** *The contribution of load & utility with critical impedance.*

| $f$ (Hz) | Q(var) | CI | Dominant source |
|---|---|---|---|
| **60** | -20.6258 | -87 | Utility |
| **300** | 0.0414 | 40 | Consumer |
| **420** | 0.0024 | 9.7796 | Consumer |

***Table 5:*** *The contribution of load & utility for the hypothetical system with voltage rate.*

| $f$ (Hz) | θv | \|V\|∠θ $_{Utility\ Contribution}$ (Estimated) | \|V\|∠θ $_{Consumer\ Contribution}$ (Estimated) | Dominant source |
|---|---|---|---|---|
| **60** | 0.0036 | 95.64∠80° | 0.34∠-5 | utility |
| **300** | 12.14 | 0.71∠25.4° | 8.63∠19.7° | consumer |
| **420** | 57.92 | 0.08∠19° | 4.89∠23° | consumer |
| **660** | 34.22 | 0.06∠26° | 2.03∠4° | consumer |

## 3.1 Simulation in a Hypothetical System

As mentioned before, at first the procedure is verified for the three-phase circuit of Fig. 4. In this circuit, the impedances and voltage sources behind the utility's impedances have been set to the values shown in Table 1 & 2.

The voltage source behind the consumer's impedance and utility system impedance comprises the positive-sequence fundamental frequency component, as well as the Negative-sequence 5th, positive-sequence 7th and Negative-sequence 11th harmonic components. The impedance of the load comprises the series combination of 130 Ω resistor and 66.3mH inductor. The utility system impedance is 2.5 Ω resistor and 39.8mH inductor. The circuit was analyzed and the voltage and current waveforms at the PCC were extracted. Then, these waveforms were used

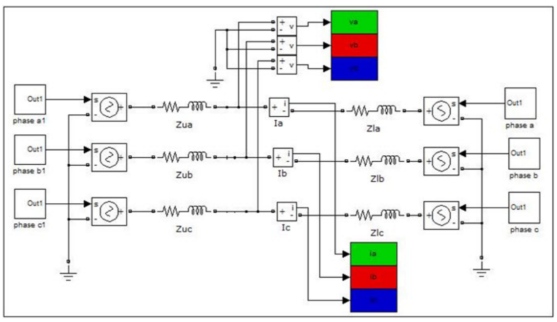


***Fig.4:*** *Three-phase test circuit.*

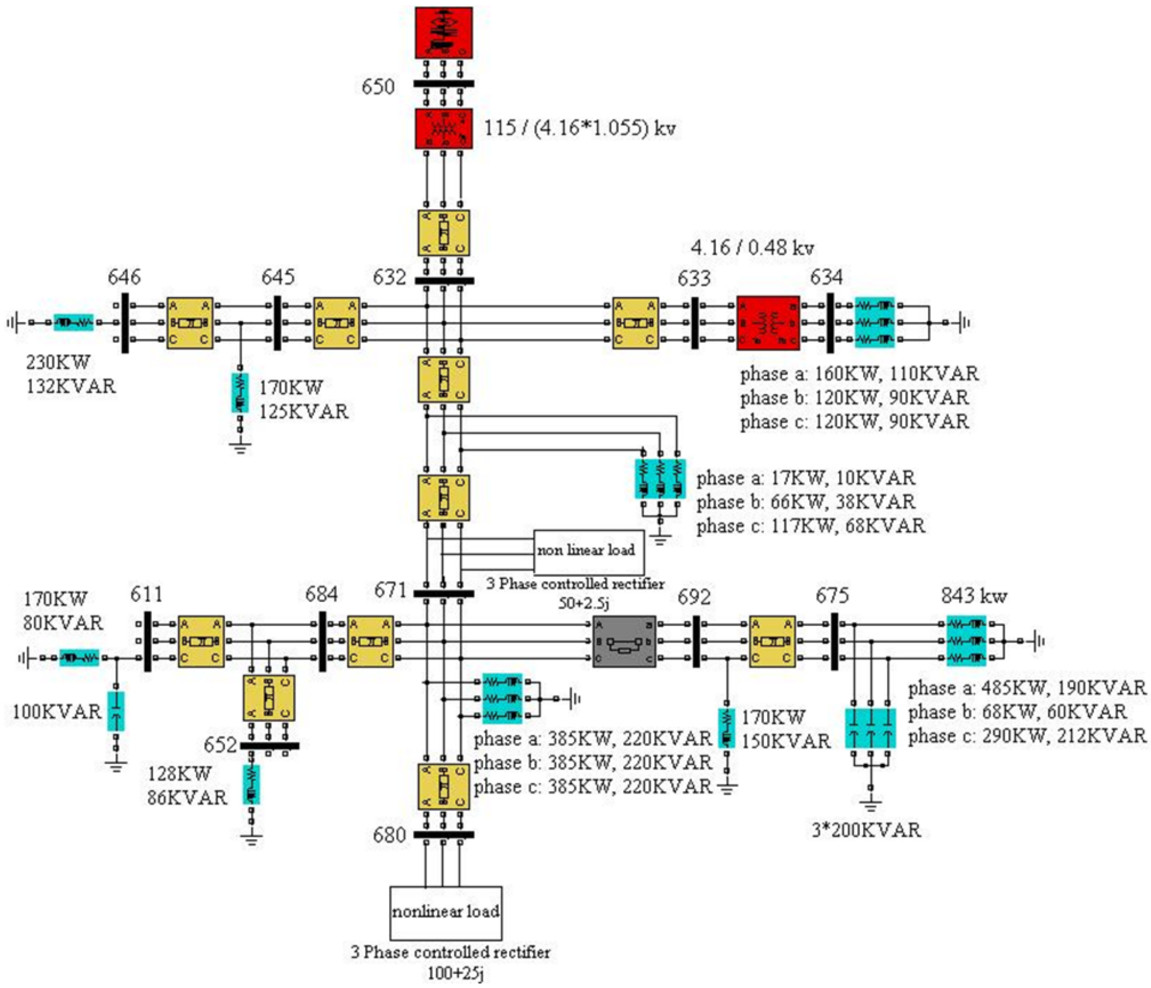


***Fig.5:*** *IEEE standard 13-bus power system.*

as the input data for the parameter estimation algorithm and the electrical circuit of the load and supply were estimated. The estimated parameters and their exact values are shown in Table 1. The agreement between them is satisfactory.

#### 3.1.1 Determination of Utility and Consumer Contribution

After estimating the parameters of load and utility, the three methods that had been introduced in section 2.3 are used to estimate the contribution of load and utility to harmonic distortion. The results are shown in Tables 3, 4 and 5.

### 3.2 Simulation Results of IEEE 13-Bus Standard Test System

The IEEE-13 bus test distribution power system shown in Fig. 5 is used as a test case for above described approach. In this case study it was assumed that the sources of the harmonic are Thyristor based 6-pulse drives which are connected to the node 680 and 671 and the point PCC is considered node 680.The firing angle of the Thyristor based rectifier which is connected to the consumer side is considered 45 degree from 0 to 1 seconds, 75 degree from 1 to 2 seconds and the firing angle of the rectifier which is connected to the utility side is considered 45 degree from 0 to 2 seconds.

Three-phase bus voltage and current waveforms at PCC were observed during two seconds. All of signals were sampled with 20000 Hz (128samples/cycle). 3-Phase voltage and current waveforms of bus 680 at PCC are shown in Fig. 6. It is obvious that the voltage and current waveforms are severely distorted because of the harmonics.

Figs. 7, 8, 9, 10,11,12,13 and 14 show the Thevenin equivalent circuit parameters at fundamental and harmonic frequencies which are performed by adaptive Kalman filter and recursive least squares based on singular value decomposition.

Figs. 7, 8, 9 and 10 show the amplitude of positive, negative and zero sequence of fundamental, $5^{th}$, $7^{th}$ and $11^{th}$ harmonic components. It can be seen from these figures that the adaptive Kalman filter is tracking the changes of harmonic components of voltage and current in distorted power system.

Figs. 11, 12, 13 and 14 show the estimation of

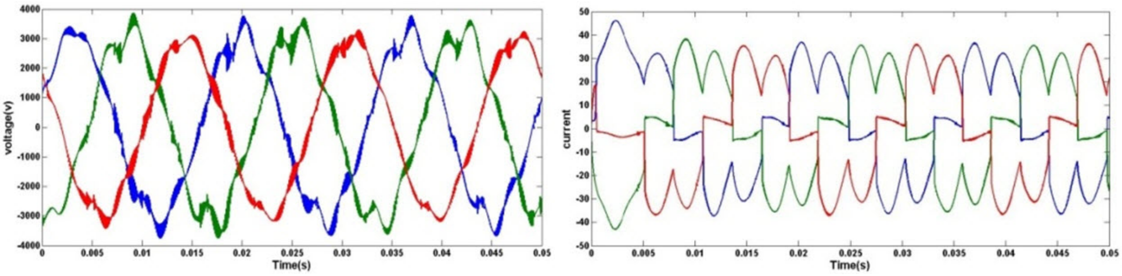


***Fig.6:*** *Three phase voltage & current at PCC.*

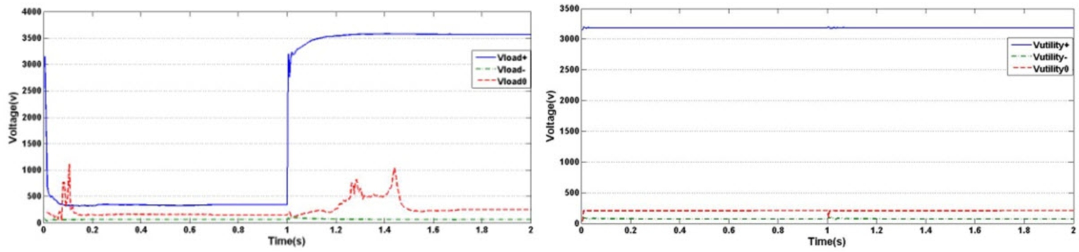


***Fig.7:*** *Amplitudes of positive, negative and zero sequence of fundamental component of utility & load voltage.*

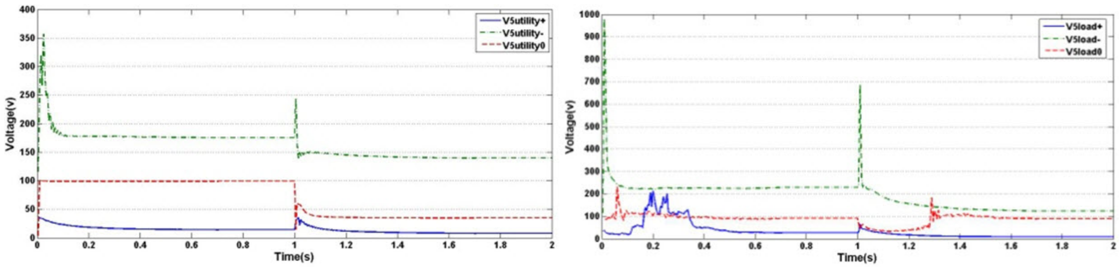


***Fig.8:*** *Amplitudes of positive, negative and zero sequence of 5th harmonic of utility & load voltage.*

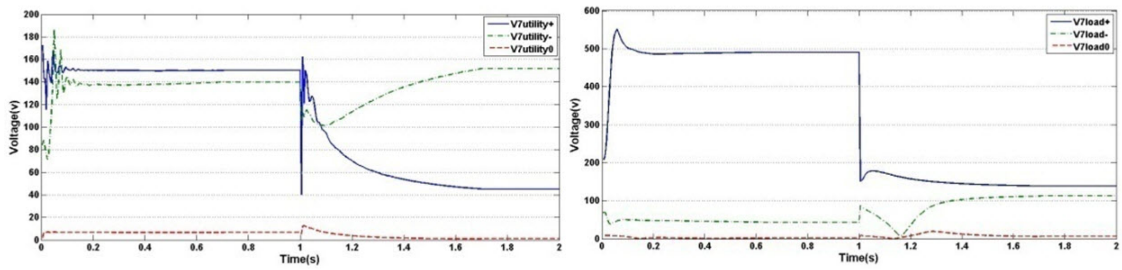


***Fig.9:*** *Amplitudes of positive, negative and zero sequence of the 7th harmonic of utility & load voltage.*

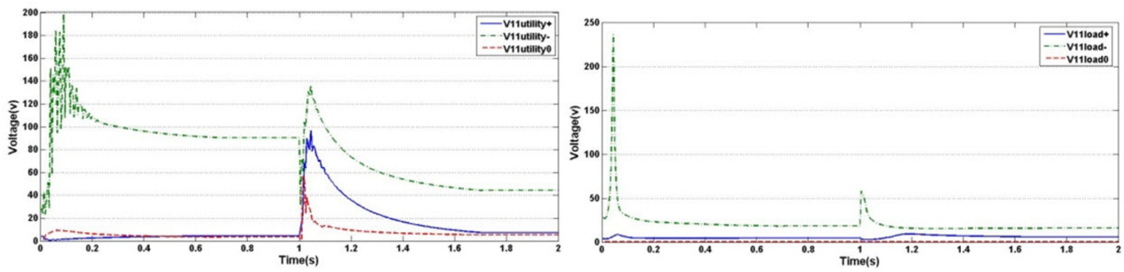


***Fig.10:*** *Amplitudes of positive, negative and zero sequence of the 11th harmonic of utility & load voltage.*

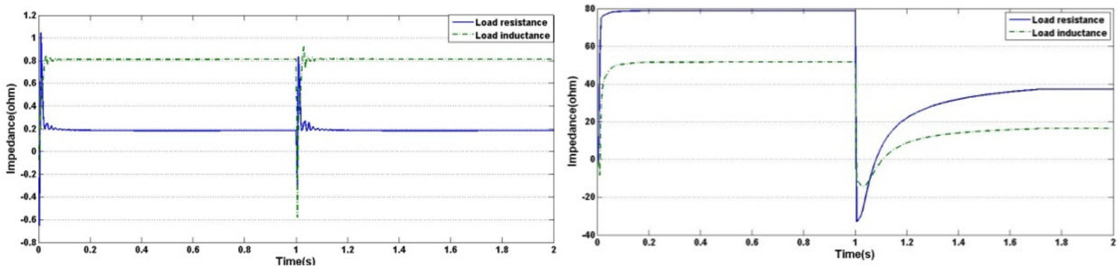


***Fig.11:*** *Positive sequence impedance of the load & utility side at the fundamental harmonic.*

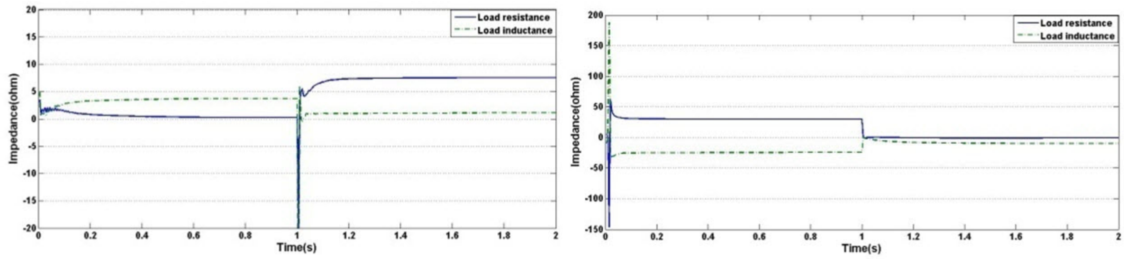


***Fig.12:*** *Negative-sequence impedance of the load & utility side at 5th harmonic.*

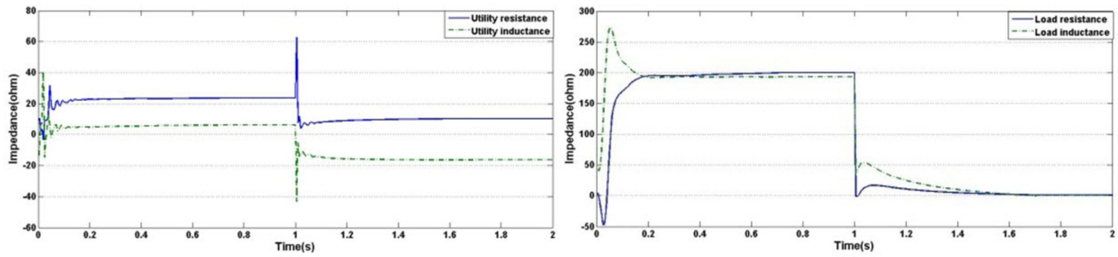


***Fig.13:*** *positive-sequence impedance of the load & utility side at 7th harmonic.*

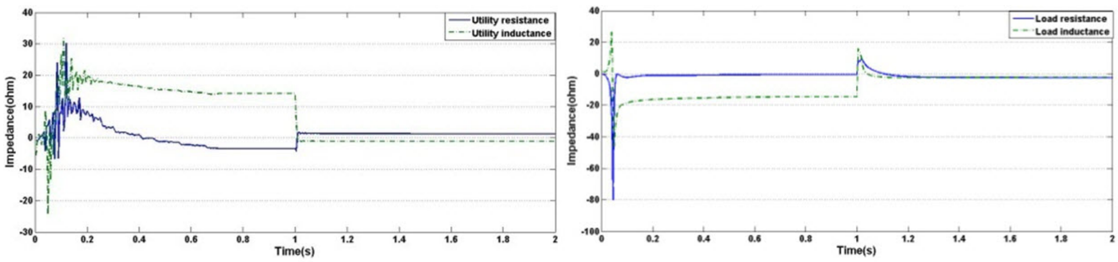


***Fig.14:*** *Negative-sequence impedance of the load & utility side at 11th harmonic.*

***Table 6:*** *The contribution of load & utility based superposition method.*

| f (Hz) | $\lvert V\rvert\angle\theta_{\text{Utility Contribution}}$ (Estimated) | $\lvert V\rvert\angle\theta_{\text{Consumer Contribution}}$ (Estimated) | Dominant source |
|---|---|---|---|
| **60** | $3135\angle 10°$ | $303.3\angle 100$ | Utility |
| **300** | $60.98\angle 0°$ | $190\angle 20.5°$ | Consumer |
| **420** | $134\angle -175°$ | $32\angle -120°$ | Utility |
| **660** | $15\angle -150°$ | $38.24\angle -162°$ | Consumer |

***Table 7:*** *TThe contribution of load & utility based critical impedance method.*

| *f (Hz)* | *Q(var)* | *CI* | *Dominant source* |
|---|---|---|---|
| *60* | *-1000* | *-2.2* | *Utility* |
| *300* | *400* | *3.3* | *consumer* |
| *420* | *-90* | *-40* | *Utility* |
| *660* | *12* | *0.48* | *consumer* |

***Table 8:*** *The contribution of load & utility based voltage rate method.*

| *f (Hz)* | $\theta_V$ | *Dominant source* | *\|V\|∠θ Utility Contribution* | *\|V\|∠θ Consumer Contribution* |
|---|---|---|---|---|
| 60 | 0.11 | Utility | 3135∠10° | 303.3∠100 |
| 300 | 1.17 | Consumer | 60.98∠0° | 190∠20.5° |
| 420 | 0.26 | Utility | 134∠-175° | 32∠-120° |
| 660 | 3.6 | Consumer | 15∠-150° | 38.24∠-162° |

the positive, negative and zero sequence component of load and utility side impedance at the fundamental, $5^{th}$, $7^{th}$ and $11^{th}$ harmonics. It can be seen from these figures that the recursive least squares based on singular value decomposition as well as estimates the changes of load and utility side impedances in different harmonic components at distorted power system.

### 3.2.1 Determination of contribution of utility and consumer in IEEE 13- bus standard power system

Tables 6, 7 and 8 show the utility and consumer's contributions to the fundamental, $5^{th}$, $7^{th}$ and $11^{th}$ components of the voltage at the PCC.

The fundamental and $7^{th}$ component mainly appears from the utility side whereas the estimated contributions to the $5^{th}$ and $11^{th}$ harmonic components come chiefly from the consumer side.

Results show that the distortions in the voltage waveforms at the PCC are due to the 5th and 11th harmonic negative-sequence components and the 1th and 7th harmonic positive-sequence components

## 4. CONCLUSIONS

A technique for estimating the utility's and consumer's contribution to harmonic distortion of the voltages at the PCC has been presented. The recursive least-squares technique has been used to estimate the parameters of the load and utility. The contributions to harmonic distortion are estimated by three approaches. The validity of the technique has been checked by means of a simulation. The technique has been applied to an IEEE 13-bus standard system and the contributions of utility and consumer in generating harmonic is determined. Presented simulation results show the validity and effectiveness of adaptive Kalman filter and recursive least squares based singular value decomposition methods in estimating the load and utility side parameters and contributions in harmonic distortions at a distorted power system.

## References


[1] W. Xu, et al., "An Investigation on the Validity of Power direction Method for Harmonic Source Determination," *Power Engineering review, IEEE*, vol. 22, pp. 62–65, 2002.

[2] X. Wilsun and L. Yilu, "A method to determine customer harmonic contributions for incentive-based harmonic control applications," *Power Engineering Society Summer Meeting, IEEE*, pp. 361–366, 1999.

[3] X. Wilsun and L. Yilu, "A method for determining customer and utility harmonic contributions at the point of common coupling," *IEEE Transactions on Power Delivery*,vol. 15, pp. 804–811, 2000.

[4] C. Chaoying, et al., "Critical impedance method - a new detecting harmonic sources method in distribution systems," *IEEE Transactions on Power Delivery*, vol. 19, pp. 288–297, 2004.

[5] N. Hamzah, et al., "Harmonic source location at the point of common coupling based on voltage magnitude," *TENCON 2004. 2004 IEEE Region 10 Conference*, pp. 220–223, 2004.

[6] T. Pfajfar, et al., "Harmonic Contributions Evaluation with the Harmonic Current VectorMethod," *IEEE Transactions on Power Delivery*, vol. 23, pp. 425–433, 2008.

[7] S. F. de Paula Silva and J. C. de Oliveira, "The sharing of responsibility between the supplier and the consumer for harmonic voltage distortion: A case study," *Electric Power Systems Research*, vol. 78, pp. 1959–1964, 2008.

[8] Z. P. Du, et al., "Identification of harmonic sources of power systems using state estimation," *Generation, Transmission and Distribution, IEE Proceedings*, vol.146, pp.7-12, 1999.

[9] G. D'Antona, et al., "State Estimation for the Localization of Harmonic Sources in Electric Distribution Systems," *IEEE Transactions on Instrumentation and Measurement*, vol. 58, pp. 1462-1470, 2009.

[10] A. Kumar, et al., "Determination of location of multiple harmonic sources in a power system," *International Journal of Electrical Power & Energy Systems*, vol. 26, pp. 73–78, 2004.

[11] E. Gursoy, "Independent component analysis for harmonic source identification in electric power systems," *Phd Thesis in Drexel University*, 2007.

[12] E. Oja and A. Hyvarinen, "Independent component analysis: algorithms and applications," *Neural Networks*, vol. 13, pp. 411–430, 2000.

[13] D. Niebur, et al., "Independent Component Analysis Techniques for Power System Load Estimation," *Applied Mathematics for Restructured Electric Power Systems*, pp. 287–317, 2005.

[14] J.A. Rosendo Macías, A. G. Expósito, "self-

tuning of Kalman Filters for Harmonic Computation," *IEEE Trans. on Power Delivery*, vol.21, no. 1, 2006.

[15] T.Lobos, T.Kozina and H.j.Koglin, "Power System Harmonic Estimation using linear least square method and SVD," *IEE Proc. Generation, Transmission and Distribution*, vol. 148, pp. 567–572, 2001.

[16] S.Osowski, "SVD technique for estimation of harmonic components in a power system, a statistical approach," *IEE Proc. Generation, Transmission and Distribution*, vol. 141, pp. 471–479, 1994.

[17] H. Ma and A. A. Girgis, "Identification and tracking of harmonic sources in a power system using a Kalman filter," *IEEE Trans. on Power Delivery*, vol.11, no. 3, July 1996.

[18] F. F. Costa, "Estimation of harmonics and interharmonics in electric systems," *Phd Thesis in Federal University of Campina Grande*, Brazil, 2005.

[19] G. Fusco, A. Losi, and M. Russo, "Constrained least squares methods for parameter tracking of power system steady-state equivalent circuits," *IEEE Trans. on Power Delivery*, vol.15, no. 3, pp. 1073–1080, 2000.

[20] T.Lobos, T.Kozina and H.j.Koglin, "Power System Harmonic Estimation using linear least square method and SVD," *IEE Proc. Generation, Transmission and Distribution*, vol. 148, pp.567–572, 2001.

[21] G. V. de Andrade Jr., S. R. Naidu, M. G. G. Neri, and E. G. da Costa, "Estimation of the utility's and consumer's contribution to harmonic distortion," *IMTC 2007, Warsaw, Poland*, May 1-3, 2007.

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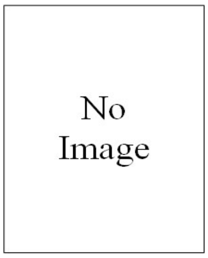


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