

# An Approach for Assessing Harmonic Emission Level Based on Robust Partial Least Squares Regression

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## Abstract

*An approach to evaluate harmonic contributions at the point of common coupling is presented in this paper. The proposed approach is based on robust partial least squares regression, which estimates system harmonic impedance by utilizing the signals of harmonic voltage and current measured synchronously at the point of common coupling. Consequently according to the IEC Technical Report 61000-3-6 the harmonic emission level of user is calculated. The presented method overcomes the disadvantage of variable dependence in establishing of the system model and reduces or removes the effect of outlying data points. The method is verified through a simulation study and with extensive field measurements.*

**Keywords:** *point of common coupling, harmonic emission level, system harmonic impedance, robust partial least squares regression*

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## 1. Introduction

In the past few years there has been considerable increase in the harmonic distortion level in the distribution system due to extensive use of power electronic devices. These harmonics often has many negative effects such as resonance problems, overheating of conductors, stress in capacitor banks and false operation of protection device, which eventually increases the maintenance costs of the system [1]. Efforts are being made to reduce the level of harmonics through the introduction of guidelines, recommended practices and standards [2, 3]. Based on the philosophy of power factor penalties, incentive-based schemes were proposed [4] to encourage the utility and the customer side to retain harmonic distortion between the limits.

The main idea behind the incentive-based schemes is to identify harmonic-producing facilities for their contributions to the harmonic distortion. Therefore, a method for quantifying customer and utility share of harmonics at the point of common coupling (PCC) is needed. Various techniques have already been presented. The power-direction method [5] has been widely used but according to [6] may lead to wrong results. Now the existing approaches to estimate the harmonic emission level are mostly based on estimation of the utility harmonic impedance including invasive methods and non-invasive methods. Considering the background harmonic, the two methods are calculating harmonic impedance with harmonic disturbance at PCC, not harmonic itself [7]. The invasive methods [8] accurately estimate utilities and customers parameters by injecting the harmonic (or interharmonic) current to utilities or switching on (or off) any loads. These methods may be harmful to power system. As utilizing natural disturbance of the customer or utility, the non-invasive methods have the advantage of simple and safe operation. The non-invasive methods compute the utility harmonic impedance by measuring harmonic voltage and current at PCC, which mainly include the reference impedance method [9], the utility harmonic impedance linear regression method [10-13] and the fluctuation method [14, 15]. The reference impedance method calculates the user harmonic emission level by means of given parameters of utilities and customer side. The method is effective, but it needs to reduce errors caused by the changes of utilities and customers parameters. The fluctuation method estimates the utility harmonic impedance by the harmonic

fluctuation ration of voltage to current. However, it may induce big errors for evaluation results because of the harmonic parameters variation of the utility side and measurement noise. The linear regression method assesses the harmonic emission level based on voltage and current equations at PCC. Robust regression is a method for the analysis of data containing outliers. However, this method is lack of analysis of the correlation variables. Partial least squares (PLS) regression method can estimate parametric relationships between these variables, but the presence of outliers can have a significant and undesired influence upon the bilinear model obtained.

In practical project, the modeling data may contain outlying observations made by the power system fluctuation or measurement error. To solve this problem, this paper proposes an advanced approach to assess the harmonic emission level based on robust PLS regression. This method focuses on incorporating robust regression method into PLS, overcomes the deficiencies of existing work. Section 2 gives a brief introduction of robust PLS algorithm and its procedure. Section 3 presents harmonic source model, describes its basic principle and makes simulation studies. Section 4 presents the field measurement results, and Section 5 concludes this paper.

## 2. Robust PLS Algorithm

The classical PLS procedures are known to be severely affected by the presence of outliers in the data or deviations from normality [16]. It's because both stages of the algorithm are not resistant towards outlying observations. The main strategies for robust PLS regression is robust estimation of the covariance matrix. The PLS method are robustified by replacing the sample cross-covariance matrix  $S_{xy}$  by a robust estimate of  $\sum_{xy}$  and the empirical covariance matrix  $S_x$  by a robust estimate of  $\sum_x$  and by performing a robust regression method instead of multiple linear regression (MLR) [17].

Throughout this section column vectors are printed in bold. A matrix  $V'$  stands for the transpose of  $V$  and  $X_{n,p}$  is an  $(n \times p)$ -dimensional matrix.  $(\mathbf{x}_1, \dots, \mathbf{x}_n)' = X_{n,p}$  and  $(\mathbf{y}_1, \dots, \mathbf{y}_n)' = Y_{n,p}$  are the regressors and the response variables, respectively.

The linear regression model we consider is:

$$\mathbf{y}_i = \boldsymbol{\beta}_0 + \mathbf{B}'_{q,p} \mathbf{x}_i + \mathbf{e}_i \quad (1)$$

Where the error terms  $\mathbf{e}_i$  satisfy  $E(\mathbf{e}_i) = 0$  and  $\text{cov}(\mathbf{e}_i) = \sum_e$  of size  $q$ . The unknown  $\boldsymbol{\beta}_0 = (\beta_{01}, \dots, \beta_{0q})'$  and  $\mathbf{B}_{p,q}$  are the  $q$ -dimensional intercept and the unknown slope matrix, respectively.

Assuming that the  $x$  and  $y$  variables are related through a bilinear model.

$$\mathbf{x}_i = \bar{\mathbf{x}} + \mathbf{P}_{p,k} \mathbf{t}_i + \mathbf{g}_i \quad (2)$$

$$\mathbf{y}_i = \bar{\mathbf{y}} + \mathbf{A}'_{q,k} \mathbf{t}_i + \mathbf{f}_i \quad (3)$$

In this model,  $\bar{\mathbf{x}}$  and  $\bar{\mathbf{y}}$  are the means of the  $x$ - and  $y$ - variables. The  $\mathbf{t}_i$  are  $k$ -dimensional, which are the scores of mean-centered data.  $\mathbf{P}_{p,k}$  and  $\mathbf{A}_{k,q}$  are the matrix of  $x$ -loadings and the slope matrix in the regression of  $\mathbf{y}_i$  on  $\mathbf{t}_i$ , respectively.  $\mathbf{g}_i$  and  $\mathbf{f}_i$  are the residuals of each equation.

The bilinear structure (2) and (3) implies a two-step algorithm. In the first stage, we should obtain the robust scores  $\mathbf{t}_i$ . First, we apply robust principal component analysis

(ROBPCA) on  $Z_{n,m} = (X_{n,p}, Y_{n,q})$ . Then a robust estimate of the center of  $Z$ ,  $\mu_Z = (\mu'_x, \mu'_y)'$ , and an estimate of its shape  $\Sigma_Z$  are yielded.  $\Sigma_Z$  can be split into:

$$\Sigma_Z = \begin{pmatrix} \Sigma_x & \Sigma_{xy} \\ \Sigma_{yx} & \Sigma_y \end{pmatrix} \quad (4)$$

We estimate the cross-covariance matrix  $\Sigma_{xy}$  instead of  $S_{xy}$  and compute the weight vectors  $r_a$  in robust PLS algorithm. In each step the robust scores are calculated as:

$$t_{ia} = (x_i - \mu'_x) r_a \quad (5)$$

In the second stage, the response are regressed onto these  $k$  components. The regression model is thus:

$$y_i = \alpha_0 + A'_{q,k} t_i + f_i \quad (6)$$

Where  $E(f_i) = 0$  and  $\text{cov}(f_i) = \Sigma_f$ . Multiple linear regression provides estimates:

$$A_{k,q} = (\Sigma_t)^{-1} \Sigma_{ty} = (R'_{k,p} \Sigma_x R_{p,k})^{-1} R'_{k,p} \Sigma_{xy} \quad (7)$$

$$\alpha_0 = \bar{y} - A'_{q,k} \bar{t} \quad (8)$$

Where  $\Sigma_y$  and  $\Sigma_t$  are the robust covariance matrices of the  $y$ - and  $t$ - variables. By inserting  $t_i = R'_{k,p} (x_i - \bar{x})$  in (3), we obtain estimates for the parameters in the original model (1), i.e.:

$$B_{p,q} = R_{p,k} A_{k,q} \quad (9)$$

$$\beta_0 = \bar{y} - B'_{q,p} \bar{x} \quad (10)$$

### 3. Verification by Simulation Study

A simulation study of the method of assessing harmonic emission based on robust PLS regression was performed with the MATLAB software. The simulation study includes three cases. In case 1, the simulation results are obtained based on PLS without outliers. In case 2, the results are based on PLS with outliers, and in case 3, based on robust PLS with outliers. All the results are compared with each other. The basic equivalent circuit for harmonic analysis and the principle of assessing emission level are introduced before the simulation study.

#### 3.1. The Basic Principle

The equivalent circuit is presented in Figure 1. In Figure 1, the disturbance sources are the customer harmonic source  $I_{ch}$  and the utility harmonic source  $U_{sh}$ ;  $Z_{ch}$  and  $Z_{sh}$  are the harmonic impedances of the respective systems. The current phasor  $I_{ph}$  and voltage phasor  $U_{ph}$  are measured at the PCC.  $h$  is a particular harmonic order.

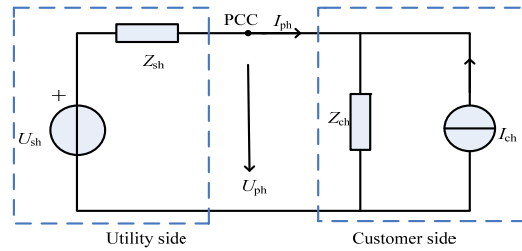


Figure 1. Basic Equivalent Circuit for Harmonic Analysis

Assuming that the circuit impedances are known, the harmonic source on the utility side can be calculated directly from the measured quantities:

$$\dot{U}_{sh} = \dot{U}_{ph} + \dot{I}_{ph} Z_{sh} \tag{11}$$

Split phasor Equation (5) into the real part and imaginary part:

$$U_{shx} = U_{phx} + I_{phx} Z_{shx} - I_{phy} Z_{shy} \tag{12}$$

$$U_{shy} = U_{phy} + I_{phx} Z_{shy} + I_{phy} Z_{shx} \tag{13}$$

Regression coefficients  $U_{shx}$ ,  $U_{shy}$ ,  $Z_{shx}$ ,  $Z_{shy}$  are worked out through linear regression.

Due to the equivalent model, the custom harmonic source is equal to a constant current source with a very small internal resistance while the system harmonic source is equal to a constant voltage source with a large internal resistance. Therefore owing to  $|Z_{ch}| \ll |Z_{sh}|$ , the customer harmonic emission level can be calculated approximately as Equation (14).

$$U_{ch} = \left[ \left( \frac{U_{ph}}{Z_{ch}} \right) - I_{ph} \right] \frac{Z_{ch} Z_{sh}}{Z_{ch} + Z_{sh}} \approx |Z_{sh}| |I_{ph}| \tag{14}$$

### 3.2. Simulation Results and Discussion

The computer simulation based on the harmonic source detection model evaluates the  $h$ th harmonic voltage emission level using the software Matlab/Simulink, where  $U_{ph} = 50 \angle 51^\circ$  V,  $I_{ph} = 6.36 \angle 45^\circ$  A, the mean value of  $Z_{sh}$  and  $Z_{ch}$  are  $15 + j30 \Omega$  and  $25 + j300 \Omega$  respectively. The simulation create sufficient waveform changes for utility impedance determination.

The harmonic voltage and current data measured at PCC are shown in Figure 2, which has 500 sample points.

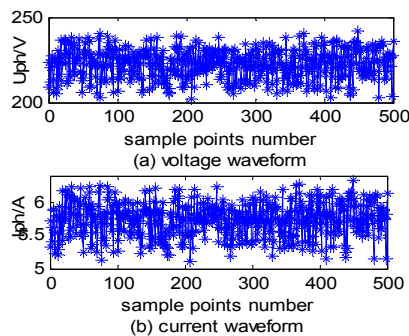


Figure 2. Magnitude Waveforms of  $h$ -th Voltage and Current at PCC

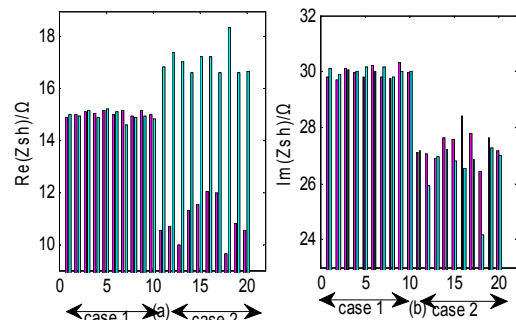


Figure 3.  $h$ -th Harmonic Impedance of Harmonic Power System

The results of the  $Z_{sh}$  are estimated in three different cases (50 sample points as a subinterval). In case 1, the estimation results are computed based on PLS regression. In case 2, five outliers are added in every 50 sample voltage and current points artificially. As shown in Figure 4, it's difficult to remove the outliers directly. The results of the  $Z_{sh}$  are estimated with these data based on PLS again. In case 3, the results are estimated based on robust PLS with outliers. The results in three cases are shown in Figure 3 and Figure 5.

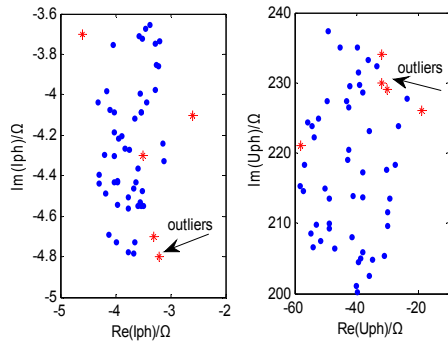


Figure 4. 50 Sample Points of Voltage and Current at PCC and Five Outliers

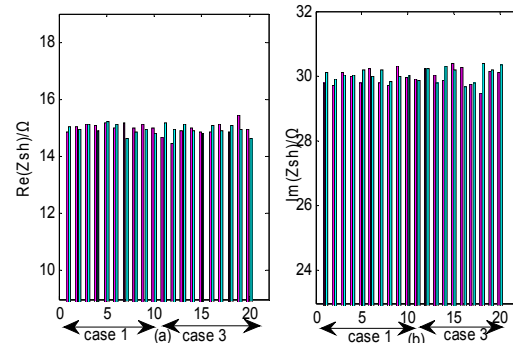


Figure 5.  $h$ -th Harmonic Impedance of Power System

The relative errors of  $Z_{shx}$  and  $Z_{shy}$  estimated in case1, case2 and case 3 are shown in Table 1. The error of every estimation is mean valve of results by Equation (12) and Equation (13).

Table 1. Comparison of Errors of  $Z_{sh}$  of Case 1, Case 2 and Case 3

	Error%										
	$Z_{shx}$										
	1	2	3	4	5	6	7	8	9	10	Mean Value
Case 1	0.49	0.27	0.89	0.56	1.32	0.39	1.91	0.51	0.68	0.62	0.764
Case 2	20.98	22.39	23.61	17.76	19.10	17.30	15.59	29.01	19.37	20.65	20.576
Case 3	1.60	2.02	0.75	0.36	0.98	0.73	0.81	0.76	1.57	1.37	1.095
	$Z_{shy}$										
Case1	0.51	0.64	0.24	0.10	0.66	0.37	0.64	0.75	0.55	0.12	0.458
Case2	9.55	11.77	10.23	8.54	9.39	8.46	8.87	15.65	8.48	9.76	10.07
Case3	0.42	0.80	0.40	0.71	0.98	1.03	0.80	1.51	0.56	0.82	0.803

As is shown in Figure 3 and Figure 5, the estimation results of  $Z_{sh}$  are nearly the same by Equation (13) and Equation (14) in case 1 and case 3. However, the results are very different in case 2. And from Table 1, we can see the estimation errors in case 2 are about ten times in case 1 and case 3. Estimation errors in case 1 and case 3 are both small. The simulation results show the sensibility to outliers of PLS and effectiveness and robustness of robust PLS.

According to Equation (14), the customer harmonic emission level is 193.04V, about 86.91% of the harmonic voltage at PCC. The assessment result agreed in the theoretical calculation result indicates that the proposed method is valid.

#### 4. Result from Field Study

In this section, we use robust PLS regression mentioned above to calculate the utility harmonic impedances and the harmonic voltage emission levels of the customer in real-world.

Measurements have been taken at a 35KV bus of Qinggang Substation connected to a disturbing load: a steel mill. The minimum short-circuit capacity is 120.8MVA and the maximum short-circuit capacity is 250MVA.

The sample frequency of the instrument is 128 samples per 50Hz-cycle; FFT (Fast Fourier Transform) is implemented to get the harmonic voltage and current parameters. The 500 transformation data are obtained. The waveform of the 5th harmonic voltage and current at the PCC are shown in Figure 6

The estimated results of the utility harmonic impedance based on robust PLS regression are shown in Figure 7.

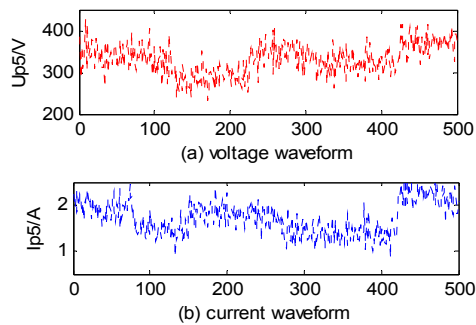


Figure 6. 5th Harmonic Voltage and Current at PCC

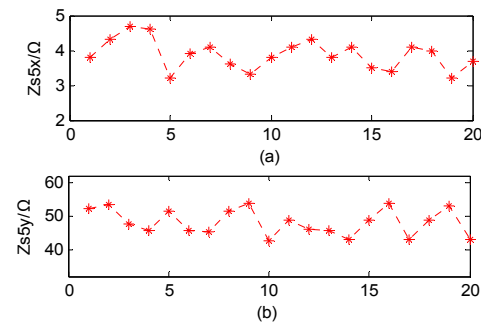


Figure 7. 5th Harmonic Impedance of Power System

The mean value of  $Z_{s5}$  calculated based on the estimated results is  $48.276\Omega$ . Then the customer harmonic emission level is calculated by the Equation (15). It's about 82.827V, 24.92% of the harmonic voltage at PCC. Due to the low ratio of nonlinear load, the custom harmonic emission level is low. However, this steel has little impact on the utility grid.

According to the short-circuit capacity mentioned above, the fundamental wave impedance of the real system ranges from  $5.476\Omega$  and  $11.333\Omega$ . The estimated fifth harmonic reactance is  $48.12\Omega$ , then the fundamental wave reactance is  $9.624\Omega$ , which is consistent with the actual impedance variation range. The estimated results of the real system further verify the accuracy and effectiveness of robust PLS regression.

## 5. Conclusion

This paper presents a new approach to the evaluation of customer and utility harmonic contributions at PCC. The proposed approach is based on robust PLS regression. Essential advantage of PLS approach are its ability to deal with collinear variables and optimize the complexity of the model. However, it's severely affected by outliers. In practical project, the observations at PCC may contain some outliers due to the power system fluctuation or measurement error. The robust PLS overcomes the defect of PLS and retains its advantage. The proposed method has been tested using simulation studies and field measurements. Its performance and accuracy have been found very good. The method is adequate for determining the system harmonic impedance and system or customer emission level.

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