A Novel Method for Assessing the Contribution of Harmonic Sources to Voltage Distortion in Power Systems

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ABSTRACT This paper presents a method for evaluating the harmonic contributions of multiple harmonic sources to voltage distortion at the point of common coupling (PCC). The proposed method quantitatively represents harmonic contributions based on the equivalent voltage models of harmonic sources. The equivalent voltage models can be estimated using the recursive least square (RLS) algorithm and measured voltage and current at the PCC. The assessment of harmonic contribution heavily depends on the accuracy of equivalent model estimation. Many existing studies have assumed that the equivalent model parameters of harmonic sources are not changed. However, because harmonic source parameters and system operating conditions are not constant in real power systems, this assumption can lead large errors in harmonic contribution assessment. In this paper, we propose a new assessment method based on variable forgetting factor RLS and parameter change detection to solve the problem. The proposed method is also effective for evaluating comprehensive harmonic contributions as well as individual harmonic contributions. The case studies show that the proposed method is superior to the previous one even under parameter changing conditions.

INDEX TERMS Distribution network, forgetting factor, harmonic contribution, power quality, recursive least square, voltage distortion.

I. INTRODUCTION

As the use of nonlinear loads increases, various problems such as additional losses, equipment malfunctions and degradation arise due to harmonic distortion [1]–[3]. These harmonic problems will be intensified due to the continuous increase of various power conversion devices. Traditionally, to manage system harmonic level and restrict harmonic emission, indices such as total harmonic distortion (THD) and total demand distortion (TDD) introduced in IEEE Std-519 and IEC 61000-3 are evaluated. However, these indices are only a quantitative measure of the level of harmonic distortion at a measurement point and do not represent the individual contribution of harmonic sources to voltage distortion at the measurement point. In addition, to effectively reduce harmonic distortion, a penalty program for harmonic sources has been proposed internationally [4]. However, to implement this program, harmonic contribution of individual source must be assessed accurately [4], [5]. The assessment of harmonic distortion contribution is a technique for quantitatively evaluating the individual contribution of multiple harmonic sources to voltage distortion at the point of common coupling (PCC) [5]. Some assessment methods have been presented [6]–[9]. To assess harmonic contribution, basically, we need to know the harmonic impedances of network and harmonic sources. In [10] and [11], the harmonic current injection and switching capacitor methods were introduced. These methods are experimental approaches based on changes in transient harmonic voltages and currents during intentional short-term disturbances. However, these methods can adversely impact power systems and lead to high cost to apply. Therefore, non-experimental methods have
A typical distribution network with several feeders connected to a PCC is as shown in Fig. 1. Large loads are normally supplied by a dedicated feeder. If harmonic sources exist on customer or power utility side, the voltage at PCC is distorted by harmonic injection from the sources. To assess the harmonic contribution of each harmonic sources, voltage and current measurements at some points are required as shown in Fig. 1. Basically, voltages at PCC and currents flowing into customers should be measured, and to calculate accurate harmonic impendence of utility system, voltages at utility side should also be measured. If the voltage cannot be measured on the utility side, the impedance of utility network can be approximately calculated using a short-circuit condition and current measurements at the required points are possible.

II. BASIC OF HARMONIC CONTRIBUTION ASSESSMENT

A. EQUIVALENT CIRCUIT FOR DISTRIBUTION NETWORK WITH HARMONIC SOURCES

A typical distribution network with several feeders connected to a PCC is as shown in Fig. 1. Large loads are normally supplied by a dedicated feeder. If harmonic sources exist on customer or power utility side, the voltage at PCC is distorted by harmonic injection from the sources. To assess the harmonic contribution of each harmonic sources, voltage and current measurements at some points are required as shown in Fig. 1. Basically, voltages at PCC and currents flowing into customers should be measured, and to calculate accurate harmonic impendence of utility system, voltages at utility side should also be measured. If the voltage cannot be measured on the utility side, the impedance of utility network can be approximately calculated using a short-circuit condition and current measurements at the required points are possible.

B. RLS ALGORITHM WITH FORGETTING FACTOR FOR PARAMETER ESTIMATION

The RLS method is the preferred technique for finding accurate solutions for underdetermined systems because the method is relatively simple and has a good convergence characteristic. The RLS is an adaptive filter algorithm that is widely used for time-varying parameter estimation as an application of the basic least square (LS) method. The LS method is to determine unknown parameters for which the sum of squared errors between measured and estimated values are minimized. The estimated solution \( \hat{\Theta}(t) \) that we want to find is calculated as equation (1).

\[
\hat{\Theta}(t) = \left( A^T(t)A(t) \right)^{-1} A^T(t)Y(t)
\]  

where

\[
A(t) = \begin{bmatrix} a^T(t_1) \\ a^T(t_2) \\ \vdots \\ a^T(t_N) \end{bmatrix}, \quad Y(t) = \begin{bmatrix} y(t_1) \\ y(t_2) \\ \vdots \\ y(t_N) \end{bmatrix}
\]

A(t) and Y(t) represent the input and output in the linear equation of \( Y = A\Theta \).

Parameter estimation based on the LS method has been used in various fields including linear regression, but the RLS method with forgetting factor is more effective for time-varying parameter estimation such as the equivalent harmonic assessment.
model parameters of harmonic sources. A typical RLS algorithm with forgetting factors is as follows [27], [28].

\[
G_{n+1} = P_n A_n^T \left( I + A_n P_n A_n^T \right)^{-1} \\
Θ_{n+1} = Θ_n + G_{n+1} (Y_{n+1} - A_{n+1} Θ_n) \\
P_{n+1} = (I - A_n A_n^T) P_n / λ.
\]

where \( Θ \) is the unknown parameter matrix, \( G \) is the gain matrix, \( P \) is the covariance matrix, \( λ \) is the forgetting factor, and \( I \) is the unit matrix.

In the iterative calculation, the weights of past and present measurements vary depending on the forgetting factor \( λ \) value, which is reflected in the covariance matrix \( P \). As the value of forgetting factor \( λ \) becomes smaller, the weight for new measurement data increase. On the other hand, the large value of forgetting factor \( λ \) makes less sensitive to the changes in measurement data.

C. CONSTRAINTS FOR ESTIMATING EQUIVALENT MODELS

The basic algorithm for parameter estimation of the harmonic voltage model can be described using the system consisting of utility and one customer as shown in Fig. 3. Both the utility and customer are represented by equivalent harmonic voltage source and impedance corresponding to \( h \) harmonic frequency. In this model, the circuit equation for the PCC voltage can be expressed by equation (5). If there are \( n \) customers connected to the PCC, we need to formulate \( n \) voltage equations for the PCC voltage, and estimate equivalent parameters for each customer individually using the RLS algorithm.

\[
V_{h,pcc,r} + jV_{h,pcc,i} = \left( R_{h,c} + jX_{h,c} \right) \left( I_{h,c,r} + jI_{h,c,i} \right) + V_{h,c,r} + jV_{h,c,i}
\]

where the subscript \( h \) means harmonic order, \( r \) and \( i \) represent the real and imaginary parts, respectively.

The linear equation (5) can be expressed in the form of a matrix as follows [24], [29].

\[
Y(t) = A(t)Θ
\]

where \( R_1 = R_2 = R_{h,c} \) and \( X_2 = -X_1 = X_{h,c} \) for the equivalent harmonic impedance \( Z_{h,c} = R_{h,c} + jX_{h,c} \) and \( V_{h,c,i} \) are real and imaginary parts of harmonic source voltage \( V_{h,c} = V_{h,c,r} + jV_{h,c,i} \).

The unknown parameter matrix \( Θ \) is firstly calculated using the RLS algorithm of (3)–(4) and measured voltage and current of \( V_{h,pcc}(t) \) and \( I_{h,c}(t) \). Then the final estimate \( \hat{Θ} \) that satisfies the constraints of equation (11) is obtained using the Lagrange Multiplier for the objective function (10) [29].

\[
\min J(\hat{Θ})
\]

subject to

\[
R_1 - R_2 = 0 \\
X_1 + X_2 = 0
\]

\[
J(\hat{Θ}) \equiv ε_1^T ε_1 + ε_2^T ε_2
\]

where

\[
[ε_1; ε_2] = Y - A\hat{Θ} = \left[ Y_1 - A\hat{Θ}_1 Y_2 - A\hat{Θ}_2 \right]
\]

\[
Y = [Y_1 Y_2] = \left[ y^T(t_1) \ldots y^T(t_N) \right]^T
\]

\[
A = \left[ a^T(t_1) \ldots a^T(t_N) \right]^T
\]

\( ε_1 \) and \( ε_2 \) are the errors between measured and estimated values, \( Θ = [\hat{Θ}_1; \hat{Θ}_2] \), with \( \hat{Θ}_1 \) and \( \hat{Θ}_2 \) column vectors in \( R^3 \) and \( Y = [Y_1 Y_2] \), with \( Y_1 \) and \( Y_2 \) column vectors in \( R^1 \).

\[
\hat{Θ} = Θ - \frac{P}{p_{11} + p_{22}} \begin{bmatrix} R_2 - R_1 & X_2 + X_1 \\ X_1 + X_2 & R_1 - R_2 \end{bmatrix}
\]

where \( p_{11} \) and \( p_{22} \) are the elements of the covariance matrix \( P \).

III. PROPOSED METHOD TO ASSESS HARMONIC CONTRIBUTION

A. RLS WITH VARIABLE FORGETTING FACTOR

In the RLS method, forgetting factor is an important factor in determining the weights for measured voltages and currents. The classical RLS method without forgetting factors can lose the ability of parameter estimation because the covariance matrix becomes zero over time [27]. Therefore, RLS with forgetting factor is common and the forgetting factor value ranges \( 0 < λ ≤ 1 \). If the forgetting factor value is close to 1, parameter estimation is relatively stable because the weight for past data become large. However, the convergence is very slow when system operating condition changes. On the other hand, small forgetting factor makes fast convergence, but parameter estimation is very sensitive to noise. Typical values of \( λ \) that are used in many studies range from 0.9 to 1 [30], [31]. Some methods for harmonic contribution assessment are based on RLS with constant forgetting factor.
Measurement noise and fluctuation of PCC voltage within when the change of PCC voltage is within the reference range. Voltage is outside the specific reference range. Harmonic, therefore, it is effective to start a new estimation when the PCC voltage changes. There-quent restarting RLS can lead to unstable estimation. There-fore, existing methods have this potential problem. The ‘wind-up’ problem refers to an exponential increase in the covariance matrix, which makes the parameter estimation extremely sensitive and causes large errors. Therefore, existing methods have this potential problem. The ‘wind-up’ problem can be solved by applying variable forgetting factor. The variable forgetting factor with tracing the covariance matrix can limit the increase of the covariance matrix. A RLS algorithm using the variable forgetting factor can be expressed as in equations (17)-(19). \( \alpha \) represents the weighting factor of the variable forgetting factor.

\[
\begin{align*}
\lambda_{n+1} &= \lambda_n \alpha + (1 - \alpha) \\
G_{n+1} &= P_n A_{n+1}^T \left( I_{\lambda_{n+1}} + A_{n+1} P_n A_{n+1}^T \right)^{-1} \\
\Theta_{n+1} &= \Theta_n + G_{n+1} (Y_{n+1} - A_{n+1} \Theta_n) \\
P_{n+1} &= (I - G_{n+1} A_{n+1}) P_n / \lambda_{n+1}
\end{align*}
\]  

B. PARAMETER CHANGE DETECTION FOR ESTIMATING EQUIVALENT MODEL

Equivalent impedances and voltages of harmonic sources can be changed due to the variation of operating condition. Therefore, for fast parameter estimation, RLS estimation only needs to include new measurement data ignoring past data when the equivalent parameter is changed. If past measured data are continuously reflected in the RLS parameter estimation despite changes in equivalent harmonic parameters, estimation errors increase and it takes a long time to converge. To improve estimation performance, it is needed to fast detect harmonic parameters changes and to restart RLS estimation with new measured data. However, existing methods have not considered the changes of harmonic parameters. Naturally, even if past data before changing harmonic parameters is involved, if new data after changing the parameters is enough, RLS estimation can converge to new equivalent parameters but it takes a very long time for estimation.

In this paper, in order to effectively estimate harmonic parameters, we propose a scheme of parameter change detection based on the changes of voltages at PCC. Basically, harmonic parameter changes lead to the changes of PCC voltage. Therefore, when PCC voltage changes, we can start a new estimation by ignoring past data to improve the estimation performance. However, even with small voltage changes, frequent restarting RLS can lead to unstable estimation. Therefore, it is effective to start a new estimation when the PCC voltage is outside the specific reference range. Harmonic sources are regarded as the steady-state operating condition when the change of PCC voltage is within the reference range. Measurement noise and fluctuation of PCC voltage within the reference range do not significantly affect parameter estimation and long term contribution assessment. As an example, when the equivalent model parameters are changed, the PCC voltage can be changed as shown in Fig. 4(a). If RLS estimation is applied over entire time interval without considering parameter changes, it is difficult to expect an accurate parameter estimation. In this case, estimation performance can be improved by separately applying RLS to each A to G time section as shown in Fig. 4(b). To apply this concept, it is necessary to calculate the change rates of the PCC voltage as equations (21) and (22). If the change rate of (21) or (22) for each measured data exceeds a given threshold, all past measured data is ignored and new RLS estimation is started. In practical applications, if there is a sudden change in a short time period like a transient condition, or if there is not enough data in the estimation section such as B, D and F as shown in Fig. 4(b), the results of RLS estimation for the sections can be ignored to improve the reliability of contribution assessment.

\[
\begin{align*}
\Delta V_{\text{pcc},r} &= \left( \frac{V_{\text{start} \text{pcc},r}^{(N)} - V_{\text{start} \text{pcc},r}^{(N)}}{V_{\text{start} \text{pcc},r}^{(N)}} \right) \times 100(\%) \quad (21) \\
\Delta V_{\text{pcc},i} &= \left( \frac{V_{\text{start} \text{pcc},i}^{(N)} - V_{\text{start} \text{pcc},i}^{(N)}}{V_{\text{start} \text{pcc},i}^{(N)}} \right) \times 100(\%)
\end{align*}
\]

where \( \Delta V_{\text{pcc}} \) is the change rate of PCC voltage. \( V_{\text{start} \text{pcc}}^{(N)} \) is the starting value of PCC voltage which is the reference value for parameter change detection. \( V_{\text{pcc}}^{(N)} \) is the sequential data after the starting value.
where $V_{\text{utility}}$ and $I_{\text{utility}}$ are the voltage and current on utility side.

Then, the PCC voltage in the equivalent circuit can be explained by the principle of superposition with the vector sum of each $V_{h,\text{utility}}$ and $V_{h,\text{customer}}$ as shown in Fig. 6. Therefore, the relationship between voltages and impedances of utility and customers ($k = 1, 2, \ldots, N$) follows equations (24)–(28) [21].

**C. CONTRIBUTION ASSESSMENT BASED ON THE PRINCIPLE OF SUPERPOSITION**

While the equivalent voltage and impedance of customers are estimated by the proposed RLS algorithm, the impedance of utility can be calculated by the following equation (23) using measured voltage and current.

$$Z_{h,\text{utility}} = \frac{V_{h,\text{utility}} - V_{h,\text{pcc}}}{I_{h,\text{utility}}} \quad (23)$$

where $V_{h,\text{utility}}$ and $I_{h,\text{utility}}$ are the voltage and current on utility side.

The proposed procedure of parameter estimation is summarized as shown in Fig. 5. The RLS algorithm with variable forgetting factor is performed for sequential measurement data. Then, the change rate of PCC voltage is calculated. If the change rate is less than a given threshold, the forgetting factor is updated by equation (26) and RLS estimation continues for next measurement data. If not, all RLS parameters including forgetting factor are initialized for new estimation.

![FIGURE 5. Procedure of the proposed RLS estimation.](image)

![FIGURE 6. PCC voltage according to the principle of superposition.](image)
contribution ratio (HCR) intuitively indicate the relative contribution of each harmonic source to voltage distortion.

\[
HCR_h = \frac{HVC_h}{|V_{h, \text{pcc}}|} \times 100\% \tag{31}
\]

where \(HCR_h\) is the harmonic contribution ratio at \(h^{th}\) harmonic, and \(HVC_h\) is the \(h^{th}\) harmonic voltage contribution of a harmonic source.

The harmonic contribution for individual harmonic frequency can be assessed using the principle of superposition and scalar projection. However, there is a need for a comprehensive evaluation method taking into account all harmonic orders. In [21], the total harmonic contribution (THC) was introduced based on the similar concept of THD as equations (32) and (33). The THC is defined as the ratio of all harmonic contribution voltages to the fundamental voltage contribution. THC is a quantitative measure of how much each harmonic source is involved in PCC voltage distortion for all harmonic orders.

\[
THC_{\text{utility}} = \frac{\sqrt{\sum_{h=2}^{h_{\text{end}}}(HVC_{h, \text{utility}})^2}}{|HVC_{1, \text{total}}|} \times 100\% \tag{32}
\]

\[
THC_{\text{customer}_{-k}} = \frac{\sqrt{\sum_{h=2}^{h_{\text{end}}}(HVC_{h, \text{customer}_{-k}})^2}}{|HVC_{1, \text{total}}|} \times 100\% \tag{33}
\]

\[
HVC_{1, \text{total}} = HVC_{1, \text{utility}} + \sum_{k=1}^{k_{\text{end}}} HVC_{1, \text{customer}_{-k}} \tag{34}
\]

where \(h_{\text{end}}\) is the highest harmonic order and \(k_{\text{end}}\) is the last customer.

### D. SEQUENCE CONTRIBUTIONS IN THREE PHASE SYSTEM

The proposed method can be easily applied to three-phase unbalanced conditions using the symmetrical component transformation. Three phase voltage and current can be decomposed into three symmetrical components of positive, negative and zero. Reversely, sequence components can be also transformed into phase voltage and current using equations (35) and (36) [21], [22]. Therefore, after transforming harmonic voltage and current for each harmonic frequency into balanced three sequence components, the harmonic contributions in the three sequence circuits can be assessed.
according to the procedure described above. The concept of THC can also be applied to each sequence circuit for unbalanced condition. THCs for three sequences are calculated using positive, negative, and zero contributions of individual harmonic frequency.

\[
\begin{bmatrix}
V^p_{h, \text{pcc}} \\
V^n_{h, \text{pcc}} \\
V^z_{h, \text{pcc}}
\end{bmatrix} = \frac{1}{3} \begin{bmatrix}
1 & \alpha & \alpha^2 \\
1 & \alpha^2 & \alpha \\
1 & \alpha & 1
\end{bmatrix}
\begin{bmatrix}
V^a_{h, \text{pcc}} \\
V^b_{h, \text{pcc}} \\
V^c_{h, \text{pcc}}
\end{bmatrix}
\]

(35)

\[
\begin{bmatrix}
I^p_k \\
I^n_k \\
I^z_k
\end{bmatrix} = \frac{1}{3} \begin{bmatrix}
1 & \alpha & \alpha^2 \\
1 & \alpha^2 & \alpha \\
1 & \alpha & 1
\end{bmatrix}
\begin{bmatrix}
I^a_k \\
I^b_k \\
I^c_k
\end{bmatrix}
\]

(36)

where \(\alpha = e^{j120^\circ}\) and \(p, n, z\) are positive, negative, and zero sequences respectively.

E. ENTIRE PROCEDURE OF HARMONIC CONTRIBUTION ASSESSMENT

The entire procedure of harmonic contribution assessment is shown in Fig. 8.

First, voltage and current are measured at PCC and required points as shown in Fig. 1. Then, FFT analysis and symmetrical component transformation are performed. For each harmonic order and sequence circuit, equivalent parameters of harmonic voltage model as shown in Fig. 2 are estimated based on the proposed RLS algorithm and data change detection. The RLS estimation continues to iterate until all equivalent harmonic voltages and impedances of customers are calculated in parallel. Then, HVC and HCR of utility and all customers are assessed by the superposition principle and scalar projection for each harmonic frequency. After assessing harmonic contributions for all harmonic orders, THC is calculated using equations (32) and (33).

IV. CASE STUDY

The case study was carried out using a test system which consists of a power utility and two customers 1 and 2 as shown in Fig. 9. With the PSCAD / EMTDC, the test system was modeled as a three-phase 13.2kV with fundamental frequency of 60Hz. Also, the models of the utility and customers can reflect arbitrary harmonic voltage and impedance variations. The voltages \(V_{\text{pcc}}, V_s\) and currents \(I_{c1}, I_{c2}\) are measured with 10,000 samples of each waveform over a 1-s window, and the total simulation time for each case is 6sec. And it is assumed that the voltage source on the utility side contains 1.5% random white noise. Two customers were assumed main harmonic sources in the system, and to reflect the real condition, a small harmonic source was considered...
to exist at the utility side. The initial equivalent values of each harmonic voltages and impedances are summarized in Table 1. The test system contains 3rd, 5th, and 7th order harmonics and the harmonic voltages and impedances vary arbitrary. To intuitively understand the proposed method, all harmonic components were assumed to be balanced. To show the performance of the proposed method, the harmonic contribution assessment was performed for the following three cases.

1. Case 1: HVC and HCR in case of the 5th harmonic parameter changes on utility side
2. Case 2: HVC and HCR in case of the 7th harmonic parameters changes on the both sides of utility and customers
3. Case 3: THC in case of all harmonic parameter changes on customers

A. UTILITY’S VOLTAGE AND IMPEDANCE CHANGE

We assessed the harmonic contribution under the condition that only changed in the 5th harmonic voltage and impedance of the utility. In this case, the 5th harmonic voltage on the utility side was changed from 0.001+j0.000kV to 0.049+j0.009kV at 1.4sec, and the harmonic impedance was changed from 1.000+j1.885Ω to 3.000+j5.655Ω at 3.2sec. First, to build equivalent voltage model corresponding to 5th harmonic circuit, all parameters of the utility and two customers were estimated using the proposed RLS algorithm and the measured data at the PCC. The voltage threshold was set at 3% to detect parameter changes. As an example, the estimated harmonic voltage and impedance of customer 1 are shown in Fig. 10. The solid lines with different colors in the figure are the estimation results using the RLS with two different constant forgetting factors, and the dotted line is the result using the proposed RLS algorithm. The initial forgetting factor and weighting factor of the proposed RLS were 0.5 and 0.9922, respectively. The estimation result shows that the proposed RLS has a better estimation performance than the previous RLS even when the utility’s parameters change at 1.4 and 3.2sec. The estimated harmonic impedance and voltage of customer 1 by the proposed method were approximately 4.996+j18.838Ω and 1.159+j0.641kV respectively while the actual values were 5.000+j18.850Ω and 1.161+j0.640kV. In addition, the harmonic voltage of customer 1 was estimated at 0.453+j0.251kV, and the harmonic impedance of customer 1 was changed from 5.000+j26.389Ω to 4.000+j21.112Ω at 1.4sec. Also, the equivalent harmonic circuit, all parameters of the utility and two customers were estimated using the proposed RLS algorithm. The estimated impedance and voltage of customer 1 by the proposed method were approximately changed from 4.985+j26.342Ω to 3.992+j21.111Ω at 1.4sec. To assess harmonic contribution, equivalent voltage model for utility and two customers both in the 7th harmonic condition, only positive sequence component appears. The 7th order harmonic voltages of utility and customer 2 were changed from 0.0001+j0.000kV to 0.0295+j0.005kV at 3sec and from 0.761+j0.292kV to 0.238+j0.091kV at 4.5sec, respectively. Also, the harmonic impedance of customer 1 was changed from 5.000+j26.389Ω to 4.000+j21.112Ω at 1.4sec. To assess harmonic contribution, equivalent voltage model for utility and two customers was estimated. Fig. 12 shows the parameter estimation results for customers 1 and 2. The estimated impedance of customer 1 was approximately changed from 4.985+j26.342Ω to 3.992+j21.111Ω at 1.4sec. Also, the equivalent harmonic voltage of customer 1 was estimated at 0.453+j0.251kV while the actual value was 0.448+j0.253kV. In addition, the impedance of customer 2 was a 3.003+j13.193Ω, and the voltage was estimated to change from 0.759+j0.291kV to 0.236+j0.091kV at 4.5sec. The proposed RLS algorithm
showed good estimation performance even when various parameter were changing.

The HVC and HCR to the PCC voltage were assessed as shown in Fig. 13. Until the initial 1.4sec, the average HVCs of utility and two customers were calculated at 0.00kV, 0.04kV, and 0.13kV, and the average HCRs were 0.4%, 24.2%, and 75.4%, respectively. After 4.5sec, the HVC of customer 2 decreased from 0.13kV to 0.04kV, and the HCRs of utility and customers were changed to 20.2%, 46.1%, and 33.7% due to the parameter changes.

**C. TOTAL HARMONIC CONTRIBUTION FOR THE TWO CUSTOMER’S PARAMETER CHANGES**

In this case, THCs of harmonic sources were assessed for the parameter change conditions as shown in Table 2. The 3rd, 5th, 7th harmonic voltages of customer 1 changes at 3.2 sec., and the harmonic impedances of customer 2 changes at 1.5sec. Fig. 14 shows that the changes in 3rd, 5th, and 7th harmonic voltages through FFT analysis of PCC voltage. All parameters of harmonic voltage model were estimated by the proposed RLS algorithm and harmonic contribution for each harmonic order was also calculated.

Then, THC considering all harmonic components were calculated by equations (32) and (33) as shown in Fig. 15.

The utility has very small THC value because the utility is the main source of fundamental voltage, while the harmonic content is very small. The THCs of the customers 1 and 2 were relatively higher than the utility’s one because they basically contained a lot of harmonic components. Fig. 16 shows that the THCs with HVCs of all harmonic orders for each time section. The values in the figure are the average of each time section. The THC of customer 1 was the highest between 1.5 and 3.2sec, and the customer 2 significantly contributed to PCC voltage distortion between 0 and 1.5sec. Comprehensive harmonic contribution as well as individual contribution of
V. CONCLUSION

This paper presented the method to assess the harmonic contribution of harmonic sources to voltage distortion at PCC. The assessment of harmonic contribution is an essential technology for managing system harmonic level and identifying harmonic sources that have serious impacts on the system. Basically, it is necessary to know the equivalent circuit of harmonic order of interest can be effectively assessed by the proposed method.
harmonic voltage models for the contribution evaluation. In this paper, to estimate equivalent voltage models of harmonic sources, the RLS with variable forgetting factor was proposed. Also, the parameter change detection scheme was applied to improve the estimation performance. This allows fast and accurate estimation even if equivalent parameter changes. And through case studies the validity of the proposed method was investigated for various operating conditions. The results of not only the case studies presented but also additional tests have shown that the proposed method outperforms the previous methods in terms of estimation accuracy and speed. Along with the advance in data measurement and system monitoring technology, the proposed method can be effectively used to assess harmonic contribution in power systems.

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