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Application of Superposition and Fuzzy Logic Methods to Determine the Contribution of the Utility and Customer in Creation of Harmonic Distortions in PCC Bus

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Abstract This paper presents a new method for determination of the relative contribution of utility and customer in creation of voltage and current harmonic distortions in PCC (Point of Common Coupling) bus. In proposed method, accurate information of harmonic impedance of customers is not needed. At first, using superposition method and definition of harmonic contribution, new indices are defined and an algorithm is proposed. Then, an appropriate fuzzy inference system is designed and combined with the proposed algorithm in order to determine the approximate contribution of utility and customer in creation of harmonic distortions. In contrast to the other methods, in proposed method the precise amount of harmonic impedances of customer is not needed in any case and a pretty estimation of contribution of two sides is obtained even in cases where their contribution is close to each other. The analysis is verified by simulating IEEE 13-bus industrial distribution system in DIGISILENT software.

Keywords Power Quality, Harmonic Contribution, Fuzzy Logic, Digsilent Software

1. Introduction

Harmonic distortions are among the most important issues related to power quality which have been increased in past years. The main reason for harmonic pollution is the use of non-linear loads[1-3]. Therefore from one aspect "customers" are the main source of these distortions. However, due to complexity and topology of networks along with existence of power factor correcting capacitors in them, these distortions spread over the whole network. Thus in today's modern networks, by measuring the harmonics in one point, it cannot be determined whether the upstream or downstream network is the main source of distortions. So, the important question is which side is the dominant cause of harmonic pollution in one point. In order to answer this question, an accurate definition for the term "harmonic contribution" should be obtained which is the focus of the second part of this paper.

The most common method for identification of main harmonic source is based on harmonic power direction at PCC bus. However, it has been shown and proved that this method does not always provide correct results[4-5]. Thunberg and Soder[6] have adopted the Norton model of harmonic source consisting of harmonic current source in parallel with harmonic impedance. Upstream and downstream networks seen from PCC bus in the form of Thevenin or Norton equivalent circuits have been modeled in[5] and[7]. Then, the current and voltage harmonic contributions of each side at the PCC bus have been defined using superposition method. This definition requires the accurate value of harmonic impedances of upstream and downstream networks that are usually unknown or difficult to obtain. Different methods have been proposed for the measurement and calculation of harmonic impedance at a specific point in a network; however they are usually expensive and difficult to implement[8-15].

Using the proposed definition for harmonic contribution, it is shown that in order to identify the dominant source in the creation of current (voltage) distortion in PCC bus, it is sufficient to compare the corresponding voltage (current) sources in equivalent Norton (Thevenin) models. Accordingly, different methods have been introduced [16-19]. The most important of which is the "Critical Impedance" method[18-19]. Some studies[20] have been shown that in cases where the harmonic contribution of customers and utility is close to each other or there is not enough information about the harmonic impedance of customer, the critical impedance method may provide incorrect results. This problem has been solved in[20] by defining new indices and employing appropriate method. However, this method is not able to estimate the relative

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contribution of network and customers in the creation of the harmonics and it may give uncertain results in some cases.

To address mentioned shortcomings, using the definition of harmonic contribution in[5],[7] and the proposed algorithm in[20], and by designing an appropriate fuzzy inference system, a new method is proposed. Some advantages of this work are listed in the following:

● An intelligent method is proposed to determine the approximate relative contribution of utility and customer in creation of harmonic distortions at PCC bus. For this purpose, fuzzy logic is used, which is very popular smart method.

● In proposed method, the precise amount of harmonic impedances of customer is not needed.

● This method not provide incorrect results in contrast to[19].

● The proposed method does not give uncertain results in some cases in contrast to[20].

In this regard, definitions of harmonic contribution are presented and then the proposed method and fuzzy system are presented. The validity of the proposed method is verified by simulating IEEE 13-bus industrial distribution system[21] using Digsilent software.

2. Definition of Harmonic Contribution Based on Superposition

The definitions of harmonic contribution of voltage and current in a specific point are presented here. Then their results are used to identify the dominant source of harmonics.

2.1. Harmonic Contribution in Creating Current Distortions

As shown in Fig. 1, the upstream and downstream networks seen from PCC are modeled by their equivalent Thevenin circuit which consists of a voltage source in series with harmonic impedance for each specific harmonic. The subscripts "u" and "c" denote upstream (utility) and downstream (customer) networks seen from PCC bus respectively. $\bar{I}_{PCC}$, $\bar{V}_{PCC}$, P and Q are equal the phasors of harmonic current phasor, harmonic voltage phasor, harmonic active power and harmonic reactive power respectively as measured in PCC.

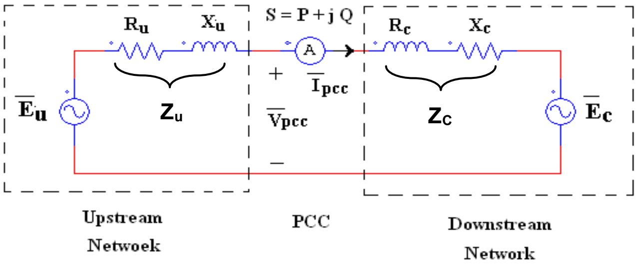

Figure 1. Harmonic Thevenin equivalent circuit for utility and costumer seen from PCC bus

If $\bar{I}_{u\text{-}PCC}$ is the harmonic current due to $\bar{E}_u$ alone and $\bar{I}_{c\text{-}PCC}$ is the harmonic current due to $\bar{E}_c$ alone in PCC bus, according to Fig. 1 and using superposition method, following equations can be written:

$$\bar{I}_{u-PCC} = \frac{\bar{E}_u}{Z_u + Z_c} \tag{1}$$

$$\bar{I}_{c-PCC} = \frac{\bar{E}_c}{Z_u + Z_c} \tag{2}$$

$$\bar{I}_{pcc} = \bar{I}_{u\text{-}pcc} - \bar{I}_{c\text{-}pcc} \tag{3}$$

By depicting $\bar{I}_{u\text{-}PCC}$ and $\bar{I}_{c\text{-}PCC}$ on $\bar{I}_{PCC}$, $\bar{I}_{uf}$ and $\bar{I}_{cf}$ scalar quantities are obtained. These quantities are defined[5] as utility and customer contribution in producing of $\bar{I}_{PCC}$ respectively, where $|\bar{I}_{PCC}|$ is the algebraic sum of these two quantities. It should be noted that $\bar{I}_{uf}$ and $\bar{I}_{cf}$ can be both positive or one positive and the other negative. These quantities are positive if they are in the same direction as $\bar{I}_{PCC}$.

Using phasor equations, $\bar{I}_{uf}$ and $\bar{I}_{cf}$ can be obtained by the following equations:

$$I_{cf} = \frac{|\bar{I}_{pcc}|^2 + |\bar{I}_{c\text{-}pcc}|^2 - |\bar{I}_{u\text{-}pcc}|^2}{2|\bar{I}_{pcc}|} \tag{4}$$

$$I_{uf} = \frac{|\bar{I}_{pcc}|^2 + |\bar{I}_{u\text{-}pcc}|^2 - |\bar{I}_{c\text{-}pcc}|^2}{2|\bar{I}_{pcc}|} \tag{5}$$

2.2. Harmonic Contribution in Creating Voltage Distortions

As shown in Fig. 2, the upstream and downstream networks seen from PCC, are modeled by their equivalent Norton circuit for each specific harmonic. Actually, the circuit in Fig. 2 is dual for the circuit shown in Fig. 1 and the relationships $\bar{E}_c = Z_c \bar{I}_c$ and $\bar{E}_u = Z_u \bar{I}_u$ held in it. According to Fig. 2 and using superposition, the equations (6) to (10) can be written for determination of voltage harmonic contribution.

$$\bar{V}_{u\text{-}pcc} = \frac{Z_u Z_c}{Z_u + Z_c} \bar{I}_u \tag{6}$$

$$\bar{V}_{c\text{-}pcc} = \frac{Z_u Z_c}{Z_u + Z_c} \bar{I}_c \tag{7}$$

$$\bar{V}_{pcc} = \bar{V}_{u\text{-}pcc} + \bar{V}_{c\text{-}pcc} \tag{8}$$

$$V_{cf} = \frac{|\bar{V}_{pcc}|^2 + |\bar{V}_{c\text{-}pcc}|^2 - |\bar{V}_{u\text{-}pcc}|^2}{2|\bar{V}_{pcc}|} \tag{9}$$

$$V_{uf} = \frac{|\bar{V}_{pcc}|^2 + |\bar{V}_{u\text{-}pcc}|^2 - |\bar{V}_{c\text{-}pcc}|^2}{2|\bar{V}_{pcc}|} \tag{10}$$

Where V_{uf} and V_{cf} are defined as utility and customer contribution in producing harmonic $\bar{V}_{PCC}$, respectively[5].

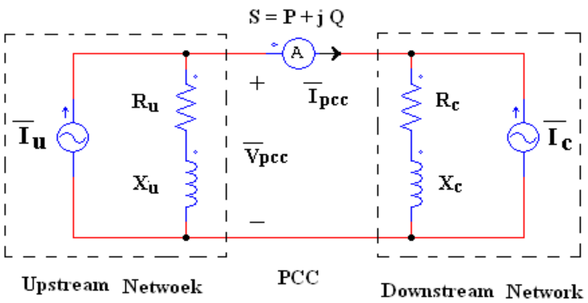

Figure 2. Harmonic Norton equivalent circuit for utility and costumer seen from PCC bus

2.3. Identifying the Dominant Source in the Creation of Harmonic Based on Definitions of Harmonic Contribution

According to the equations (1) to (10), it is seen that in order to accurately determine the harmonic contribution, along with the measured values in PCC bus, precise values of harmonic impedances Z_u and Z_c are needed. This is difficult to obtain due to numerous uncertainties in harmonic impedances of the loads. Thus, if the precise amounts of harmonic impedances are not accessible, another criterion for identification of dominant harmonic sources must be presented.

By differentiating equations (4) and (5) and using (1) and (2), equation (11) can be derived as follows:

$$I_{uf} - I_{cf} = \frac{|\bar{I}_{u\text{-}pcc}|^2 - |\bar{I}_{c\text{-}pcc}|^2}{|\bar{I}_{pcc}|} = \frac{|\bar{E}_u|^2 - |\bar{E}_c|^2}{|\bar{I}_{pcc}|\,|Z_u + Z_c|^2} \quad (11)$$

In the same way by differentiating equations (9) and (10) and using (6) and (7), equation (12) is obtained as follows:

$$V_{uf} - V_{cf} = \frac{|\bar{V}_{u\text{-}pcc}|^2 - |\bar{V}_{c\text{-}pcc}|^2}{|\bar{V}_{pcc}|} = \frac{|\bar{I}_u|^2 - |\bar{I}_c|^2}{|\bar{V}_{pcc}|}\left(\frac{Z_u Z_c}{Z_u + Z_c}\right)^2 \quad (12)$$

It is shown by (11) and (12) that in order to determine the dominant source in the creation of harmonic current $\bar{I}_{PCC}$, a comparison between $|\bar{E}_u|$ and $|\bar{E}_c|$ will suffice. And in order to determine the dominant source in the creation of harmonic voltage $\bar{V}_{PCC}$, a comparison between $|\bar{I}_u|$ and $|\bar{I}_c|$ will be sufficient. Based on this, different methods have been presented[16-20].

3. Fuzzy Set Theory and Fuzzy Inference Systems

a) Fuzzy set theory

Fuzzy set introduced by "Zadeh"[22], has no accurate boundaries as compared to the classic sets. Elements of a fuzzy set belong to it by a certain "degree of membership" which is a real value in interval[0 1]. In a classic set, On the contrary, an element either belongs or does not belong to the set i.e. the degree of membership can be 0 or 1. The membership of elements in a fuzzy set is described with the aid of a "membership function" valued in the real unit interval[0 1]. For example the classic set A can be defined as:

$$A = \{x | x \rangle 5\} \quad (13)$$

The fuzzy set B is written below in which $\mu_B(x)$ is the membership function (MF) of the variable x in B:

$$B = \{x, \mu_B(x) | x \in X\} \quad (14)$$

Examples of fuzzy and classic membership functions related to "being tall" are shown in Fig 3.

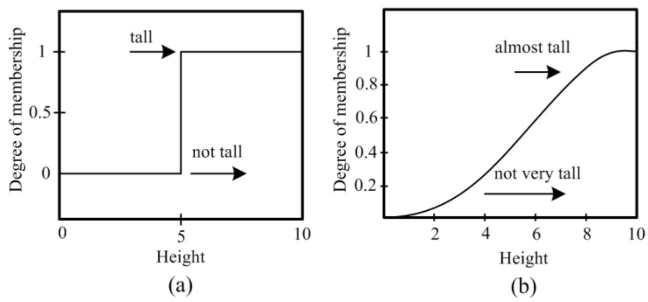

Figure 3. Membership function rated to "being tall" a) Classic b) Fuzzy

Fuzzy logic is a generalization of the standard Boolean logic in which, as opposed to the latter, the fuzzy quantities not only can be correct or incorrect but can have any value between 0 and 1. The Boolean logic operators such as And, Or, Not etc. also exist in fuzzy logic. So, using fuzzy sets the bivalent logic can be generalized which can have many applications.

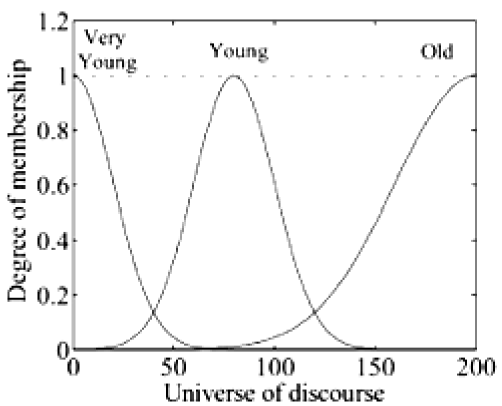

Figure 4. Description of linguistic variable "age"

Using fuzzy logic conditional sentences known as "if-then rules"[23] can be easily implemented. These rules consist of two parts: 1) the premise or "if" and 2) the conclusion or "then". For example these rules can be written as "if x is A then y is B" in which A and B are linguistic variables and their values are in sentential form in natural language. Fig. 4 shows examples of membership functions for the linguistic variable "age" titled as "very young", "young" and "old".

b) Fuzzy inference system

Fuzzy inference is the process of mapping an input value to a desired output using fuzzy logic. According to Fig. 5 each fuzzy inference system can be described as following:

1) Fuzzification: in this stage every crisp (not fuzzy) value is transformed to its corresponding linguistic variable (fuzzy value). This is done using appropriate membership functions.

2) Knowledge base: this part includes definitions of membership functions and the necessary "if-then" rules.

3) Inference- engine: This part simulates human decision making process.

4) Defuzzification: in this step the fuzzy output is converted to a crisp value.

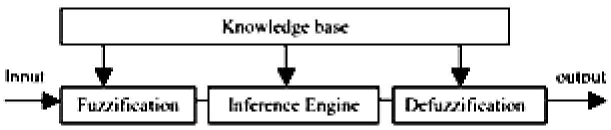

Figure 5. Block Diagram of a Fuzzy Inference System (FIS)

4. Proposed Method

In the proposed method it is assumed that the upstream network harmonic impedance Z_u is known (similar to methods presented in[19-20]). This is because uncertainty in equivalent harmonic impedance is mostly due to uncertainties in harmonic impedances of the loads. If there is no power factor correction capacitor in the upstream network in the vicinity of PCC, it can be assumed that Z_u is dominated by the impedance of step down transformer[1-3]. Furthermore; it is assumed that the range of variation of downstream network harmonic impedance Z_c is known[19-20].

To explain the proposed method, it is assumed that the goal is to identify the dominant source in the creation of harmonic current $\bar{I}_{PCC}$. According to (11), to compare I_{uf} and I_{cf}, a comparison between $|\bar{E}_u|$ and $|\bar{E}_c|$ can be made. According to Fig. 1 and circuit laws, following per-unit relationships can be expressed:

$$\begin{aligned}\bar{E}_u &= \bar{V}_{pcc} + (R_u + jX_u)\bar{I}_{pcc} \\ &= \bar{V}_{pcc} + (R_u + jX_u)\left(\frac{P - jQ}{\bar{V}_{pcc}^{\ *}}\right)\end{aligned} \tag{15}$$

$$\begin{aligned}\bar{E}_c &= \bar{V}_{pcc} - (R_c + jX_c)\bar{I}_{pcc} \\ &= \bar{V}_{pcc} - (R_c + jX_c)\left(\frac{P - jQ}{\bar{V}_{pcc}^{\ *}}\right)\end{aligned} \tag{16}$$

By separating above relations into real and imaginary parts, one can have:

$$\left|\bar{E}_u\right|^2 = \left|Z_u\right|^2 \left|\bar{I}_{pcc}\right|^2 + \left|\bar{V}_{pcc}\right|^2 + 2(R_u P + X_u Q) \tag{17}$$

$$\left|\bar{E}_c\right|^2 = \left|Z_c\right|^2 \left|\bar{I}_{pcc}\right|^2 + \left|\bar{V}_{pcc}\right|^2 - 2(R_c P + X_c Q) \tag{18}$$

$$\left|\bar{E}_u\right|^2 - \left|\bar{E}_c\right|^2 = IU - IC \tag{19}$$

Where according to the definition, IC and IU are:

$$IU = \left|Z_u\right| \left[\left|Z_u\right|\left|\bar{I}_{pcc}\right|^2 + 2\,(P\cos\phi_u + Q\sin\phi_u)\right] \tag{20}$$

$$IC = \left|Z_c\right| \left[\left|Z_c\right|\left|\bar{I}_{pcc}\right|^2 - 2\,(P\cos\phi_c + Q\sin\phi_c)\right] \tag{21}$$

Where ϕ_u and ϕ_c are defined as follows:

$$\begin{aligned}&\phi_u = tg^{-1}\left(\frac{X_u}{R_u}\right),\ \phi_c = tg^{-1}\left(\frac{X_c}{R_c}\right) \\ &,\ -90 < \phi_u,\ \phi_c < 90\end{aligned} \tag{22}$$

Given the equation (19) and since the denominator in (11) is positive in every case, it is seen that if IU is greater than IC, then the upstream network is the dominant source in the creation of $\bar{I}_{PCC}$ and vice versa. Also based on (20) and (21), IU is only a function of quantities measured in PCC bus and the phase and amplitude of Z_u and IC is only a function of quantities measured in PCC bus and the phase and amplitude of Z_c. Thus according to the assumptions made for harmonic impedances at the beginning of this section, IU is approximately known while IC is unknown. Meanwhile, having the range of variation of Z_c and its possible states, a maximum and minimum can be found for IC. These points are the basis for the proposed approach in this paper.

Using the concept of "duality" similar expressions can be derived for the identification of the dominant source in the creation of harmonic voltage $\bar{V}_{PCC}$. Duals of (19) to (22) are as follows:

$$\left|\bar{I}_u\right|^2 - \left|\bar{I}_c\right|^2 = VU - VC \tag{23}$$

$$VU = \left|Y_u\right| \left[\left|Y_u\right|\left|\bar{V}_{pcc}\right|^2 + 2\,(P\cos\gamma_u - Q\sin\gamma_u)\right] \tag{24}$$

$$VC = \left|Y_c\right| \left[\left|Y_c\right|\left|\bar{V}_{pcc}\right|^2 - 2\,(P\cos\gamma_c - Q\sin\gamma_c)\right] \tag{25}$$

$$\begin{aligned}&\gamma_u = tg^{-1}\left(\frac{b_u}{g_u}\right),\ \gamma_c = tg^{-1}\left(\frac{b_c}{g_c}\right) \\ &,\ -90 < \gamma_u,\ \gamma_c < 90\end{aligned} \tag{26}$$

Where

$$Y_u = \frac{1}{Z_u} = g_u + j\,b_u\ ,\ Y_c = \frac{1}{Z_c} = g_c + j\,b_c \tag{27}$$

As in IU and IC, the value of VU is known while the value of VC is unknown but its maximum and minimum can be found.

In the following section, the proposed algorithm will be explained and afterwards the designed fuzzy system will be introduced.

4.1. Designed Algorithm

The proposed algorithm for the estimation of relative contribution of the utility and customer in the creation of

$\overline{I}_{PCC}$ (in case that the amplitude and harmonic phase of Z_c is unknown) is as follows:

- Measurement of $\overline{I}_{PCC}$, $\overline{V}_{PCC}$, P and Q.
- Calculation of IU using (20) and with the assumption that Z_u is known.
- Calculation of IC_{min} and IC_{max} using (21) based on the range of variations and possible states for Z_c.
- Entering IU, IC_{min} and IC_{max} to designed fuzzy system.
- Deriving the results from the designed fuzzy system and calculation of relative contribution of network and customer.

As it is seen in the proposed algorithm, in contrast to past well-known method[19], there is no need for the precise value of Z_c.

For calculating the relative contribution of the utility and customer in the creation of $\overline{V}_{PCC}$ the same algorithm can be employed. However, instead of IU and IC, VU and VC should be replaced, respectively.

4.2. Designed Fuzzy System

Before describing the fuzzy system, it should be noted that the definition of indices, membership functions and "if-then" rules has been done according to experimental results in different conditions, practical values of elements used in power systems and harmonic models.

In this section the fuzzy system which is used for calculating the relative contribution of the utility and customer in the creation of $\overline{I}_{PCC}$ is described. As it was mentioned earlier, the inputs to these systems are the values of IU, ICmin and ICmax. Calculation of relative contribution of the utility and customer in the creation of $\overline{V}_{PCC}$ is carried out in a similar way but in this case the inputs are values of VU, VCmin and VCmax.

a) Definition of indices

The two indices K_1 and K_2 as inputs to the fuzzy system are defined as follows:

$$K_1 = \frac{IC_{max} - IU}{|IC_{max}|} \quad , \quad K_2 = \frac{IC_{min} - IU}{|IC_{min}|} \tag{28}$$

If K_1 is negative then IU is surely greater than IC and the contribution of the upstream network is greater. Also if K_2 is positive then IU is surely smaller than IC and the contribution of upstream network is less. However it is not known how much greater or less this contribution exactly is.

b) Fuzzification of inputs and outputs

Triangular membership functions are used for fuzzification of K_1 and K_2 crisp values and 8 linguistic variables are used for their expression:

- "Very Very Large" (VVL): for values greater than 0.8.
- "Very Large" (VL): for values between 0.5 and 0.8.
- "Moderately Large" (ML): for values between 0.25 and 0.5.
- "Little Large" (LL): for values between 0 and 0.25.
- "Little Small" (LS): for values between -0.25 and 0.
- "Moderately Small" (MS): for values between -0.25 and -0.5.
- "Very Small" (VS): for values between -0.5 and -0.8.
- "Very Very Small" (VVS): for values smaller than -0.8.

Therefore the membership functions for each of the inputs K_1 and K_2 is as shown in Fig. 6.

After applying the "if-then" rules to K_1 and K_2, the output K_3 is obtained. K_3 is also described using triangular membership functions and ranges from 0 to 1. It is used for comparing IU and IC and thus for comparing the contribution of utility and customer. Definition of K_3 and its results are shown in Table 1 and its membership functions are shown in Fig. 7.

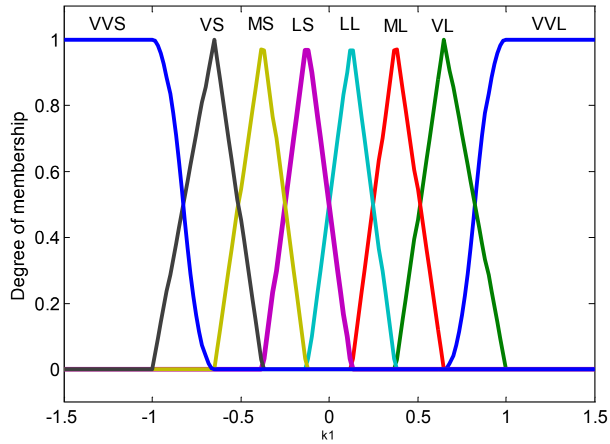

Figure 6. Membership functions of inputs K1 and K2

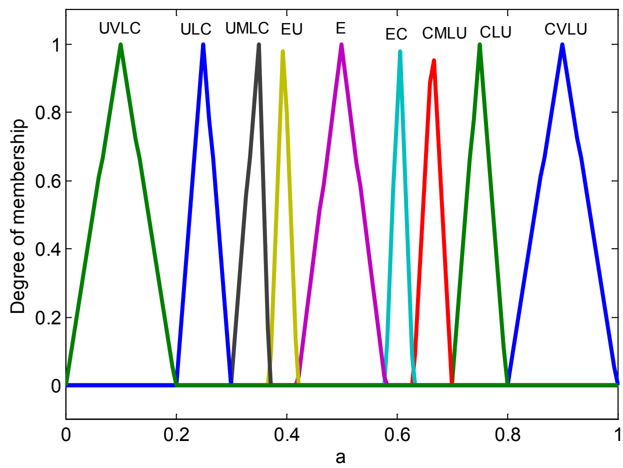

Figure 7. Membership functions of output K3

c) Fuzzy "if-then" rules

36 rules are used for obtaining K_3 some of which are shown in Table 2. These rules are based on different combinations of K_1 and K_2 using AND operator.

d) Fuzzy inference mechanism

"Mamdani fuzzy inference" is used in implementation of this fuzzy system.

e) Defuzzification

For difuzzification of K_3 the "centroid of area" method is employed and the resulting crisp value is linguistically described using intervals in Table 1.

Table 1. Definition of K_3 and Its Results

Value of K_3	Linguistic Description	Result
Between 0.8 and 1	CVLU	Contribution of customer is much greater than utility
Between 0.7 and 0.8	CLU	Contribution of customer is relatively greater than utility
Between 0.63 and 0.7	CMLU	Contribution of customer is approximately greater than utility
Between 0.58 and 0.63	EC	Contribution of two sides is close with a little dominancy at customer side
Between 0.42 and 0.58	E	Contribution of two sides is approximately equal
Between 0.37 and 0.42	EU	Contribution of two sides is close with a little dominancy at utility side
Between 0.3 and 0.37	UMLC	Contribution of utility is approximately greater than customer
Between 0.2 and 0.3	ULC	Contribution of utility is relatively greater than customer
Between 0 and 0.2	UVLC	Contribution of utility is much greater than customer

Table 2. Some of defined if-then rules

Rule No.	K_1	K_2	K_3
1	VVL	VVL	CVLU
2	VVL	VL	CLU
3	VVL	ML	CMLU
4	VVL	LL	EC
7	VVL	VS	E
9	VL	VL	CLU
10	VL	ML	CMLU
11	VL	LL	EC
12	VL	LS	EC
14	VL	VS	E
16	ML	ML	CMLU
17	ML	LL	EC
18	ML	LS	E
21	ML	VVS	EU
22	LL	LL	EC
23	LL	LS	E
26	LL	VVS	EU
27	LS	LS	EU
33	MS	VVS	UMLC
35	VS	VVS	ULC
36	VVS	VVS	UVLC

5. Implementation of Proposed Method on a Sample Network

To evaluate the proposed method, the IEEE 13-bus industrial distribution system[21] is used. The simulated network in Digsilent software is shown in Fig. 8.

In order to perform better evaluation the following modifications have been made on the network:

Half of the RECT load is modeled as current source with ASD harmonic spectrum mentioned in[21] and the other half is modeled as RL load with a power factor equal to that of the RECT load.

The 39:T3 SEC load is also considered as harmonic load and is modeled like RECT load.

The 29:T11 SEC load is also considered as harmonic load. 25% of it is modeled as a current source with ASD harmonic spectrum and the rest is modeled as RL load with the same RECT load power factor.

The 5th, 7th and 11th voltage harmonics with the amplitudes of 0.015, 0.009 and 0.005 per-unit respectively and a phase of zero degree are injected in 100: UTIL-69 bus as background voltage harmonics so that the voltage THD reaches 3% in the bus.

The simulation is done in two different cases for upstream and downstream networks of PCC bus.

a) First case

In this case, 03 MILL-1 is selected as PCC bus and the customer side includes the F1 feeder along with its transformers and its downstream loads. The rest of the system is considered as upstream network. So the current of F1 is the same as $\bar{I}_{PCC}$. The results of current measurement in PCC bus for 5th, 7th and 11th harmonics are presented in Table 3. Using real data and with the aid of software, the percentage of ratio of voltage and current harmonics with respect to their fundamental component and the real values of Z_u and Z_c are also mentioned in Table 3. THD of voltage and current in PCC is 7.6 and 6.64 percent, respectively.

Using superposition method and real data, the real values for customer and network contribution in the creation of harmonic distortions in PCC bus are given in Table 4. The negative signs in this table are due to harmonic cancellation in two sides.

Now let's assume that the values for harmonic impedances of the loads have an error of $\pm 50\%$ and $\pm 45\%$ in their amplitude and phase, provided that their phases will stay in the interval between +90 and -90 degrees. The error in data related to the "05 FRD F" loads will result in an error in phase and amplitude of Z_u. In a similar way error in information of "29 T11 SEC" loads will lead to an error in Z_u This error, however, can be neglected and Z_u can be assumed as fixed and known.

To determine the relative harmonic contribution of the utility and customer in the creation of I_{PCC}, quantities IU, IC_{min} and IC_{max} are calculated for the 5th, 7th and 11th harmonics and presented in Table 5 (the values related to above quantities in this table have to be multiplied with 104). In the same way, in order to estimate the relative contribution of either sides in the creation of V_{PCC}, quantities VU, VC_{min} and VC_{max} are calculated for the 5th, 7th and 11th harmonics and presented in Table 6. Using the values of K_1 and K_2 in Table 5 and Table 6 and the proposed fuzzy inference system, the relative contribution of customer and the network in the creation of desired harmonics is estimated and given in Table 7.

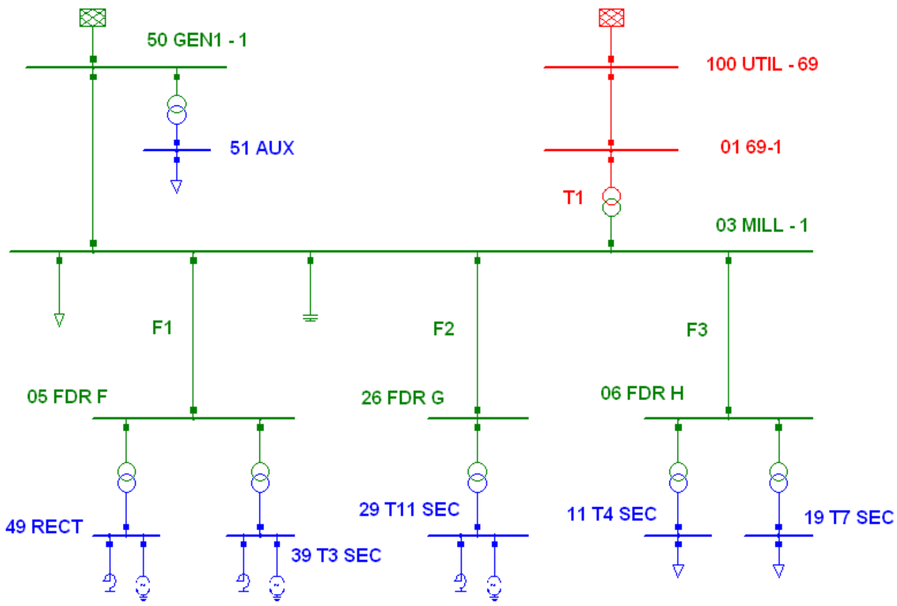

Figure 8. IEEE 13 bus industrial distribution network simulated in Power Factory Digsilent software

Comparing the real contributions in Table 4 and the estimated relative contributions using fuzzy system in Table 7, it is observed that:

In cases of 5th and 11th current harmonics and 5th and 7th voltage harmonics the results are exactly the same. In other words, in these cases one side is the dominant source with much greater contribution than the other. Similar results have been produced by the fuzzy system, too.

Table 3. The results of current measurement in PCC bus in the first case

Harmonic order	5	7	11
$\lvert \bar{I}_{pcc} \rvert$ %	3.42	2.11	2.36
$\lvert \bar{V}_{pcc} \rvert$ %	1.95	7.06	0.38
Amplitude of Z_c (ohm)	311.5	406.9	606.9
Phase of Z_c (degree)	63.3	69.5	76.2
Amplitude of Z_u (ohm)	6.14	112.7	4.98
Phase of Z_u (degree)	87.9	70.3	-89.6

Table 4. The real harmonic contribution in PCC bus in the first case

Harmonic order (percent)	5	7	11
I_{uf}	-10.4	62.3	0.76
I_{cf}	110.4	37.7	99.24
V_{uf}	84.5	113.9	57
V_{cf}	15.5	-13.9	43

For 7th current harmonic the real values of relative contribution of the network and customer are 62 and 38 percent respectively. For 11th voltage harmonic these values are 57 and 43 percent. In these cases, fuzzy system resulted in "approximately equal" which is not far from the reality. In other words, in these cases the fuzzy system produced responses that were close to the real ones (not exactly the same as them).

Table 5. Calculated quantities to determine the relative harmonic contribution of the utility and customer in the creation of I_{PCC} in the first case

Harmonic order	IU	IC_{min}	IC_{max}	K_1	K_2
5	-1.8	158	1200	1.001	1.011
7	108	-94	300	0.64	-2.15
11	-0.18	193	1860	1.00	1.00

Table 6. Calculated quantities to determine the relative harmonic contribution of the utility and customer in the creation of V_{PCC} in the first case

Harmonic order	VU	VC_{min}	VC_{max}	K_1	K_2
5	455	2.1	8.84	-50.47	-215.7
7	47	-6	-2.4	-20.58	-8.83
11	4.77	0.04	4.51	-0.058	-118.25

Table 7. Estimation of the relative contribution of customer and utility in creation of desired harmonics in the first case by means of fuzzy inference system

	The results of fuzzy inference system
Current (h=5)	Contribution of costumer is much greater than utility
Current (h=7)	Contribution of customer and utility are approximately equal
Current (h=11)	Contribution of customer is much greater than utility
Voltage (h=5)	Contribution of of utility is much more greater than customer.
Voltage (h=7)	Contribution of of utility is much more greater than customer.
Voltage (h=11)	Contribution of customer and utility are approximately equal.

b) Second case

The “03 MILL-1” bus is selected as PCC bus in this case too. However; the T1 transformer and its upstream network are considered as upstream network of PCC and the rest of the network are considered as the downstream network of this bus. Thus the current in second side of the T1 transformer is the I_{PCC}. The real values resulting from the measurements in PCC bus for 5th, 7th and 11th harmonics are given in Table 8 and the real values of contribution of two sides in the creation of current and voltage harmonics are shown in Table 9 THD of PCC current is 21%.

In this case the error range for available values of harmonic impedances is the same as the first case. Furthermore Z_u is assumed fixed and known and its value is equal to harmonic impedance of the T1 step-down transformer. Similar to the first case the, results of proposed method are presented in Table 10 to Table 12.

Table 8. The results of current measurement in PCC bus in the second case

Harmonic order	5	7	11
$\left\|\overline{I}_{pcc}\right\|$ %	2	20.6	1.81
$\left\|\overline{V}_{pcc}\right\|$ %	1.95	7.06	0.38
Amplitude of Z_c (ohm)	186.6	9.28	3.64
Phase of Z_c (degree)	-2.8	-88.5	-89.7
Amplitude of Z_u (ohm)	6	8.44	13.27
Phase of Z_u (degree)	89.3	89.5	89.7

Table 9. The real harmonic contribution in PCC bus in the second case

Harmonic order (%)	5	7	11
I_{uf}	-0.78	144.3	80.8
I_{cf}	100.78	-44.3	19.2
V_{uf}	77.4	138.4	46.7
V_{cf}	22.6	-38.4	53.3

Table 10. Calculated quantities to determine the relative harmonic contribution of the utility and customer in the creation of I_{PCC} in the second case

Harmonic order	IU	IC_{min}	IC_{max}	K_1	K_2
5	-2.85	66.9	910	1.003	1.043
7	-92.3	-93.8	-93.3	-0.0107	-0.016
11	0.2	-0.23	-0.22	-1.91	-1.87

Table 11. Calculated quantities to determine the relative harmonic contribution of the utility and customer in the creation of V_{PCC} in the second case

Harmoni c order	VU	VC_{min}	VC_{max}	K_1	K_2
5	309	-4.96	185.8	-0.663	-63.3
7	-3429	-3500	-3480	-0.0146	-0.0202
11	-17.9	-18.2	-12.3	0.455	-0.0165

Table 12. Estimation of the relative contribution of customer and utility in creation of desired harmonics in the second case by means of fuzzy inference system

	The results of fuzzy inference systems
Current (h=5)	Contribution of customer is much greater than utility
Current (h=7)	Contribution of customer and utility are approximately equal
Current (h=11)	Contribution of utility is much more greater than customer
Voltage (h=5)	Contribution of utility is much greater than customer
Voltage (h=7)	Contribution of two sides is close with a little dominancy at utility side
Voltage (h=11)	Contribution of customer and utility are approximately equal

Comparing the real values for contributions in Table 9 and the estimated relative contributions using fuzzy system in Table 12 it is observed that:

In cases of 5th and 11th current harmonics and 5th voltage harmonics, the results are exactly the same. In other words in these cases one side has much greater contribution than the other and the fuzzy system has also shown this.

For 11th voltage harmonic, the real values of relative contribution of the utility and customer are 57 and 43 percent. In these cases fuzzy system resulted in “approximately equal” which is not far from the reality.

In case of 7th current harmonic, it is seen that a harmonic cancellation has taken place and the real contributions of two sides are in opposite direction. Considering the fact that the real value of customer contribution is -44% it can be concluded that the customer can have a contribution of 44%. So the contributions of two sides can be assumed to be close to each other. The output of the fuzzy system also confirms this result.

In case of 7th voltage harmonic, the real contributions of two sides are in opposite direction and the contribution of customer is -38% so it can be concluded that the customer can have a contribution of 38%. So the contributions can be assumed as equal with a little dominance in the utility side. The fuzzy system shows the same result.

According to the simulation results it is seen that using the proposed method, the approximate relative contribution of the utility and customer in the creation of harmonic distortions in PCC bus can be determined. It is also seen that in proposed method there is no need for precise data related to the harmonic impedances of customers.

6. Conclusions

Due to importance of determination of the relative harmonic contribution of the utility and customer in the creation of harmonic distortions in PCC bus and lack of reliable method in this field, a new method is proposed by application of superposition method and fuzzy logic technique. The required data for this purpose are the measurement results in PCC bus and approximate information about harmonic impedances of customers. The proposed method in comparison with other well-known methods, never results in an incorrect answer and offers approximately correct estimation of relative contributions of two sides in the creation of the distortions. The specifications and validation of this method have been verified by simulating the IEEE 13 bus industrial distribution system in DIGISILENT software.

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