Identification of Harmonic Injection and Distortion Power at Customer Location

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***Abstract*— This paper focuses on identifying harmonic injection by non-linear load at customer location. Presently, customer harmonic contribution cannot be accurately measured leading to penalizing customers not causing harmonic pollution. Hence this matter is of utmost importance since more non-linear loads penetrate into system. These harmonic currents causes voltage distortion at PCC affecting the linear loads. As a result distortion powers flows in the system creating additional power loss. A new index is defined for accurately identifying the harmonic injection of individual customer and distortion power is calculated as per IEEE standard 1459-2010. Simulation results validate the proposed method . Further development can lead to a tariff regime where only actual harmonic polluters be penalized.**

***Index Terms*-- Harmonic distortion, harmonics, power quality, distortion.**

I. Introduction

Harmonics is one of the growing power quality issue caused by the proliferation of non-linear loads into power system. Some of the problems include overheating and failure of equipment, false tripping of loads, maloperation of protective relays, and interference with communication circuit [6]. As a result, harmonic standards [1] have been developed to limit the amount of harmonic injection into power system. Both the utility and loads are responsible for harmonic distortion. As per IEEE standard 519, there exist a shared responsibility between the consumer and utility for maintaining harmonic distortion within limits. The customers should be made aware about individual contribution of harmonic current so that proper methods can be adopted to mitigate harmonic distortion. Thus, the challenge is to determine exactly the harmonic injection by individual customers.

The traditional parameters like active power, reactive power, and power factor used for electrical energy pricing cannot provide any information regarding the harmonic power flow. They are defined for sinusoidal conditions and become meaningless when applied to non-sinusoidal conditions. Under non-sinusoidal conditions, a new quantity known as nonactive apparent power assumes significance. They do not transfer net energy to load, at the same time causes additional losses in the system [3]. Measuring the distortion powers can quantify the harmonic injections at a particular customer location.

Harmonic source detection methods can be classified into distributed and single point measurement methods [8]. Distributed measurement methods give accurate information about the harmonic state of the power system, but are difficult to implement as they require complex and expensive measurement instrumentation. Single point measurement techniques are more suitable for estimating harmonic contribution at customer location due to easy implementation and low cost.

In this paper, using single point method, a new index is proposed to identify the harmonic contribution of non-linear loads. Also nonactive distortion power is computed as per IEEE standard 1459-2010. The effectiveness of the above method is carried out by analyzing simulation of a system under various distorted voltage conditions. The results shows that the above index can effectively measure the amount of distortion created by the non-linear load. The nonactive distortion power measured increases with the increase in distortion at supply side and utility.

II. Theoretical Background

Under non-sinusoidal conditions, apparent power can be decomposed as follows according to IEEE standard 1459-2010 [2].

$$S^2 = S_1^2 + D_I^2 + D_V^2 + S_H^2 \tag{1}$$

The fundamental apparent power is

$$S_1^2 = P_1^2 + Q_1^2 \tag{2}$$

Where P_1 is the fundamental active power and Q_1 is the fundamental reactive power.

$$P_1 = V_1 I_1 \cos\theta \tag{3}$$

$$Q_1 = V_1 I_1 \sin\theta \tag{4}$$

The Current Distortion Power is

$$D_I = V_1 I_H \tag{5}$$

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The Voltage Distortion power is

$$D_V = I_1 V_H \tag{6}$$

Harmonic apparent power is

$$S_H = V_H I_H = \sqrt{P_H^2 + D_H^2} \tag{7}$$

Where P_H is harmonic active power

$$P_H = \sum_{h \neq 1} V_h I_h \sin\theta_h \tag{8}$$

and D_H is harmonic distortion power

$$D_H = \sqrt{S_H^2 - P_H^2} \tag{9}$$

From [3], it is recognized that P_1 and P_H denotes active power and remaining terms constitute non-active power. The fundamental reactive power is essential for creating magnetic flux in transformers and machines. This reactive power needs to be supplied by utility or customer. The distortion powers D_V, D_I and D_H transfer no net energy to the loads, but all these powers contribute to losses in the system. They characterize the amount of harmonic pollution created by non-linear loads. Hence the utility has to take suitable measures to limit the flow of distortion powers in the system.

$$\text{Total Distortion power} = \sqrt{D_I^2 + D_V^2 + D_H^2} \tag{10}$$

The responsibility of harmonic injection can be placed either to utility or customer by comparing the waveshape of voltage and current at the customer location [4]. If the voltage and current waveforms are having identical waveshape, then the utility is responsible for harmonic injection and a difference in waveshape indicates the harmonic injection by either customer or both. To compare voltage and current waveforms, normalization is done first by dividing the waveform samples by the amplitudes of equivalent sine waves. Fast Fourier Transform analysis is done on the two waveforms to obtain harmonic quantities.

The normalized voltage and currents at the customer location for a particular harmonic component n can be represented as shown in Fig 1. Here V_n and I_n represents harmonic voltage and current of order n at the customer location, i_{cn} indicates the harmonic current of order n injected by the customer.

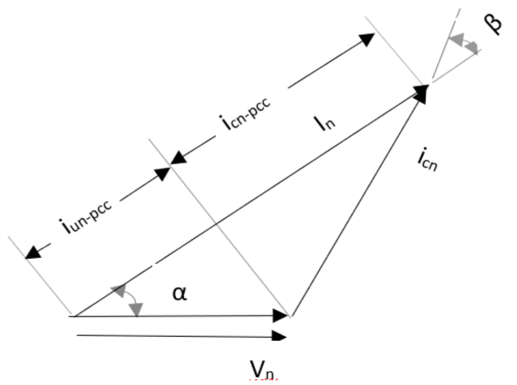

Fig 1. Phasor representation of voltage and currents for a particular harmonic order

The normalized magnitude of harmonic current of order n can be decomposed into $i_{un\text{-}pcc}$ and $i_{cn\text{-}pcc}$ which are the utility side and customer side contributions.

$$i_{un-pcc} = i_{un} \cos\alpha \tag{11}$$

$$i_{cn-pcc} = i_{cn} \cos\beta \tag{12}$$

where α is the angle between I_n and V_n and β is the angle between I_n and i_{cn}.

The total contribution of harmonic current at the customer location can be expressed as [5]

$$i_h = \sqrt{\sum_{n=2}^{h} (i_{cn} \cos\beta)^2} \tag{13}$$

The harmonic injection at the customer location can be quantified by a term known as Harmonic Distortion Index which can be obtained by dividing the total contribution of harmonic current at customer location by the fundamental current drawn by customer.

$$i_{HN} = i_h / I_1 \tag{14}$$

The above index indicates the actual total harmonic distortion of the customer and can be used for calculating distortion powers as in (5) – (10).

III. Simulation Studies

In this section, the validity of harmonic distortion index and distortion power is analyzed in a test system shown in Fig 2. The system was modelled using MATLAB Simulink and uses 240V, 50Hz single phase supply as the source. Two customers are considered in the analysis. Each customer is having a linear RL load and a rectifier load connected to them. Case studies are performed for different combinations of load at customer location.

Case1: Both customers are connected to RL loads with pure sinusoidal ac source.

Case2: Customer 1 has both RL load and rectifier load connected and customer 2 has only RL load while the source is purely sinusoidal.

Case3: Both customers have RL load and rectifier load connected with purely sinusoidal ac source.

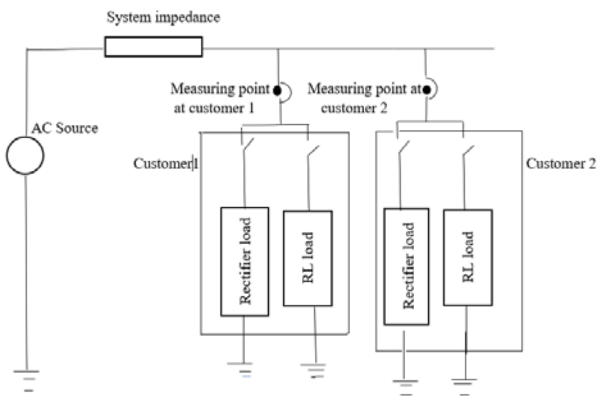

Fig 2. Model of simulation system

IV. Results And Discussions

Simulations are carried out considering a linear load of $P = 2000$W, $Q = 1500$VAR at customer 1 and customer 2 with a linear load of $P = 2000$W and $Q = 2700$ VAR respectively in addition to rectifier load and results are analyzed for three different combinations of loads.

A. Case 1

In this case, linear loads are applied to both customers with purely sinusoidal supply voltage and the parameters measured are shown in Table I. The values of THD_V, THD_I and harmonic distortion index (i_{HN}) is zero for both customers indicating that no harmonic pollution is created by them when the source is purely sinusoidal. The distortion power is also zero since there is no voltage or current distortion at customer location. The voltage and current waveforms at customer 1 and customer 2 are shown in Fig 3 and Fig 4. The system is also analyzed for distorted supply conditions and monitored the harmonic distortion index and distortion power. From table II, it is seen that the harmonic distortion index is almost negligible indicating that customer is not responsible for harmonic pollution. However there is a small distortion power due to the voltage distortion created by the utility. Hence the sole responsibility lies with the utility and remedial measures can be taken by utility to overcome distortion. The variation of distortion power with THD_V is shown in Fig 5.

TABLE I. Parameter Values With Sinusoidal AC Source

	Customer 1			Customer 2		
	Case 1	*Case 2*	*Case 3*	*Case 1*	*Case 2*	*Case 3*
THD_V	0	0.07	0.11	0	0.07	0.11
THD_I	0	0.13	0.11	0	0.02	0.10
i_{HN}	0	0.13	0.12	0	0.01	0.11
D_I	0	414	369	0	22	375
D_V	0	220	327	0	180	358
D_H	0	29	39	0	1.6	40
Total Distortion power	0	470	495	0	181	520

TABLE II. Parameter Values With Linear Load

THD_V	Customer 1		Customer 2	
	i_{HN}	*Total Distortion power*	i_{HN}	*Total Distortion power*
0	0	0	0	0
0.04	0	66	0	90
0.07	0.01	134	0.01	182
0.11	0.01	202	0.01	273
0.15	0.01	269	0.02	364
0.19	0.02	337	0.03	456
0.22	0.02	404	0.03	547
0.26	0.02	472	0.04	638

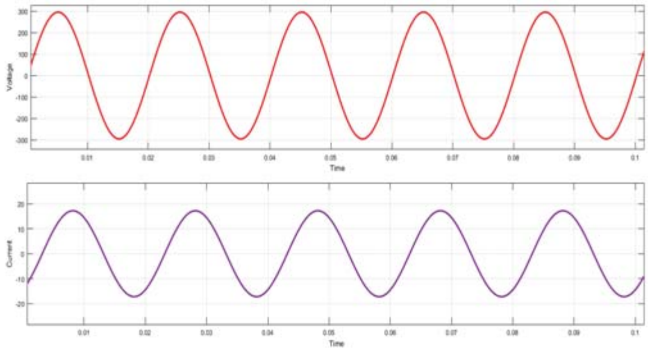

Fig 3. Voltage and current waveforms at customer 1 with linear load connected.

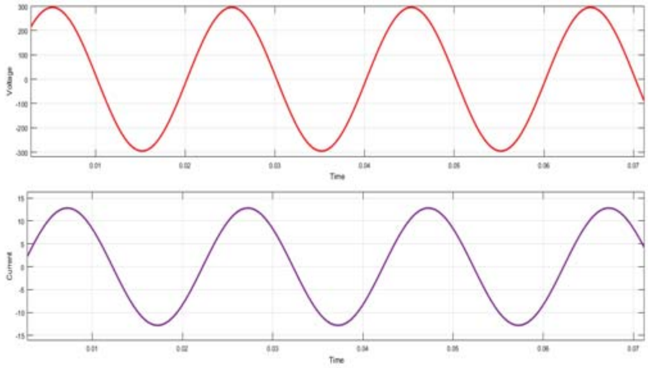

Fig 4. Voltage and current waveforms at customer 2 with linear load connected.

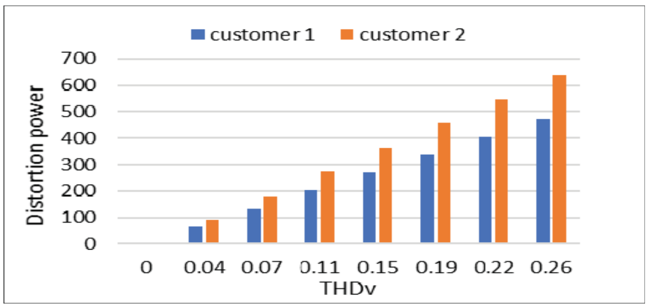

Fig 5. Variation of Distortion Power with THD_V at source

B. Case 2

In this case, customer 1 is having rectifier load connected to it along with linear load and customer 2 is having only linear load connected and the source is purely sinusoidal. With the introduction of nonlinear load at customer 1, voltage *THD* rises to 7%, current *THD* rises to 13% and harmonic distortion index rises to 0.13 indicating the contribution of customer 1 to harmonic pollution. The total distortion power is also increased due to distorted voltage and current at customer location. While for customer 2, where only linear load is connected has harmonic distortion index near to zero indicating that customer 2 is not contributing harmonic pollution. Even though customer 2 is linear, there is some distortion power of 181VA which may be due to the voltage distortion at PCC created by the rectifier load of customer 1.

The value of voltage distortion power is almost equal to total distortion power supporting the above fact. So the responsibility of harmonic injection can be placed on customer 1 and proper penalization can be done to overcome the losses associated with harmonic pollution. The voltage and current waveforms at customer locations are given in Fig 6-7. The system is also evaluated for various distorted conditions at source side and the values are mentioned in Table III. In actual case, the distortion at supply side can vary the harmonic distortion index depending on the order of harmonic injected by utility. Here, rectifier load consists of 3rd, 5th and 7th order harmonics and supply voltage variation is done by injecting harmonics of 3rd, 5th and 7th order proportionately. So the value of i_{HN} remains almost constant for customer 1 and almost zero for customer 2. Distortion power increases with THD_V at source due to the increase in voltage distortion power D_V created by distorted voltage. The variation of harmonic distortion index and distortion power with THD_V is shown in Fig 8-9.

TABLE III. PARAMETER VALUES WITH NONLINEAR LOAD AT CUSTOMER1

THD_V	Customer 1		Customer 2	
	i_{HN}	*Total Distortion power*	i_{HN}	*Total Distortion power*
0	0.13	470	0.01	181
0.04	0.14	465	0.01	160
0.07	0.14	490	0.01	200
0.11	0.14	547	0.01	275
0.15	0.14	638	0.02	364
0.19	0.16	750	0.02	457
0.22	0.17	875	0.03	552
0.26	0.18	1006	0.03	649

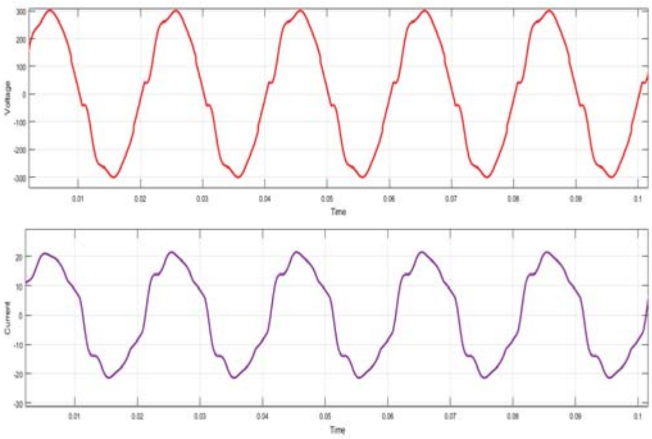

Fig 6. Voltage and current waveforms at customer 1 with nonlinear load connected.

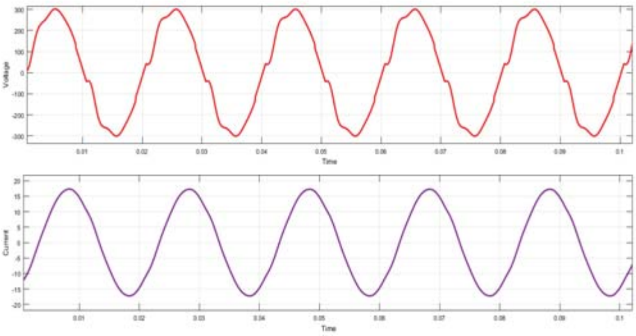

Fig 7. Voltage and current waveforms at customer 2 with nonlinear load connected at customer 1.

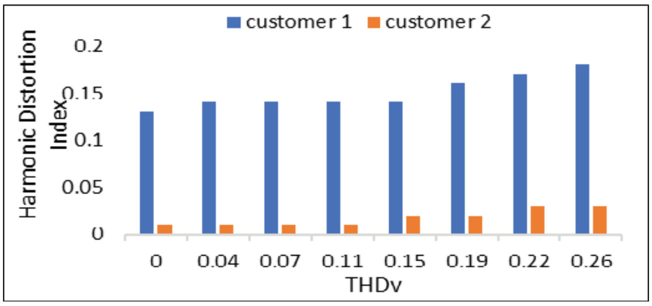

Fig 8. Variation of Harmonic Distortion Index with THD_V at source

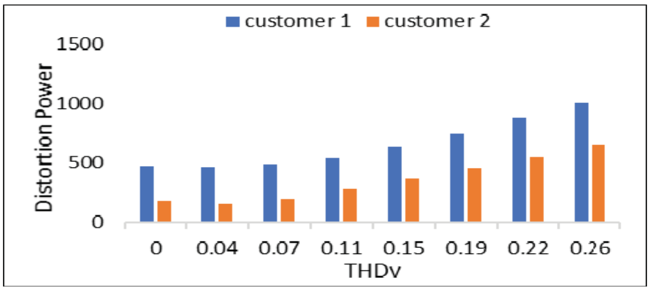

Fig 9. Variation of Distortion Power with THD_V at source

C. Case 3

In this case, both customers have identical rectifier load and RL load connected to them respectively. From table I, the value of THD_V, THD_I and harmonic distortion index is increased for both customers indicating their harmonic contribution. Since both customers draws harmonic current from source, the THD_V at the PCC is increased more than in case 2. The slight variation in the distortion power is due to the fundamental apparent power of the loads connected to each customer. Here both the customers are having equal responsibility of harmonic pollution and can be penalized. The voltage and current waveforms at customer locations are shown in Fig 10-11. The system is also evaluated for various THD_V at source side and the values are mentioned in Table IV. The distortion power is increasing with THD_V for both customers. The variation of harmonic distortion index and distortion power with THD_V is shown in Fig 12-13.

TABLE IV PARAMETER VALUES WITH NONLINEAR LOAD AT BOTH CUSTOMERS

THD_V	Customer 1		Customer 2	
	i_{HN}	*Total Distortion power*	i_{HN}	*Total Distortion power*
0	0.12	495	0.11	520
0.04	0.13	494	0.13	520
0.07	0.14	511	0.13	541
0.11	0.14	540	0.13	576
0.15	0.13	578	0.13	623
0.19	0.12	632	0.12	687
0.22	0.12	707	0.11	776
0.26	0.11	798	0.11	884

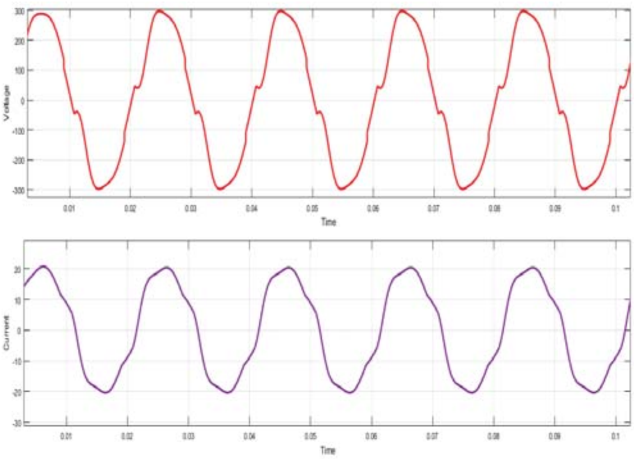

Fig 10. Voltage and current waveforms at customer 1 with nonlinear load connected.

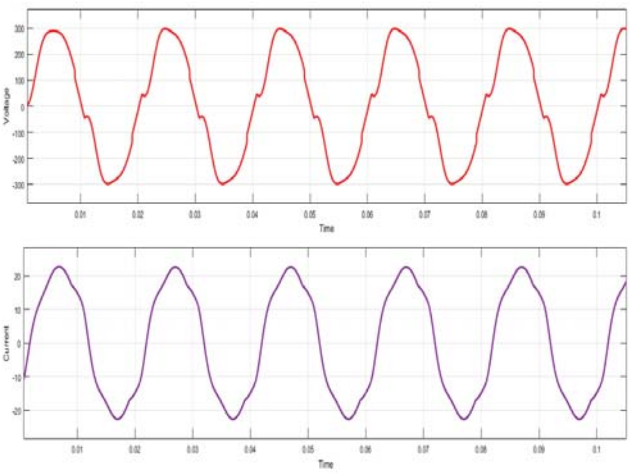

Fig 11. Voltage and current waveforms at customer 2 with nonlinear load connected.

Fig 12. Variation of Harmonic Distortion Index with THD_V at source

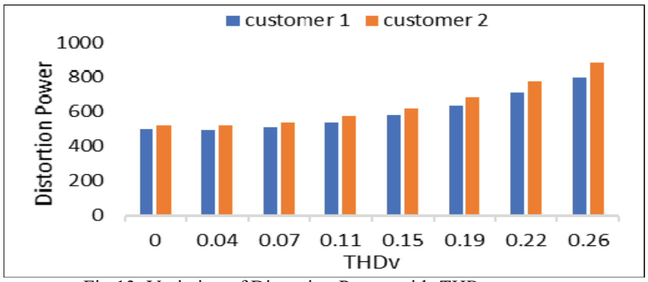

Fig 13. Variation of Distortion Power with THD_V at source

V CONCLUSIONS

In this paper, harmonic distortion index to measure harmonic injection by non-linear load is suggested. This index can be considered as a factor for placing responsibility of harmonic pollution to the right customers. The concept can be included in the tariff regime and proper penalization from harmonic polluters can be obtained. Also enables customers to use proper mitigation techniques to reduce their harmonic contribution thereby enhancing the power quality of system.

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