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Harmonic Current Pollution in a Low Voltage Network

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Abstract—Modern household customers use many power electronic based devices for their daily usage. Those devices emit harmonic current pollutions and eventually increase harmonic voltage distortion level in the network. In the future network, the background harmonic pollution in the MV and upstream networks could increase with the integration of more distributed generations. Thus, the harmonic related problem will increase in the network and therefore should be considered seriously. With the distorted supply voltage, most of the devices produce even more harmonic current pollutions. In this paper, three typical households are modeled with their various connected devices. Each device is tested in the laboratory to find out its harmonic current emission spectrum for different grid voltage conditions. Also, harmonic current spectrums are measured in the laboratory at each of the three house model's terminal. Further, harmonic simulation is done on a typical low voltage network in which several household customers are connected and the above measured harmonic spectrums of households are used in the analysis. Harmonic current emission levels at different points of the network are calculated. Those values are compared with the laboratory measurements and also with the available standard limits. This analysis gives an overview of harmonic current emission level at different installations of a low voltage network.

Index Terms— Harmonic current emission, THD(i), voltage distortion, harmonic fingerprint.

I. INTRODUCTION

The increasing usage of power electronic devices in the low voltage network has a large influence on the harmonic pollution level in the network. The low voltage customers (such as households) use a significant amount of modern power electronic based devices for their daily life. Thus, it can become a threat to the network operators in the near future when the harmonic current level in the network would increase beyond a certain level, decreasing the electricity voltage quality of the network. In extreme cases, poor power

quality because of high harmonic distortion may damage or decrease the service lifetime of the network components. Moreover, when a device manufacturer introduces a specific device in the market, he guarantees that it should perform satisfactorily at clean supply voltage condition. However, its optimum performance is not guaranteed when the supply voltage is distorted. Laboratory experiments show that a specific device can produce significantly large amount of harmonic current pollution when the supply voltage is distorted. At present, the available standards give restrictions on harmonic current emission for a device only under clean sinusoidal voltage condition. Hence, the present standards have to be modified to make them compatible to this changing situation. Also, the device manufacturer has to develop a high quality device to restrict its harmonic current emissions even under polluted grid conditions. In this paper, three typical households are modeled with their various connected devices to represent three loading conditions in the network: high load (current demand of approximately 7.5A), average load (current demand of 5.6A) and low load condition (current demand of 2.3A). In the Power Quality laboratory (PQ lab) of TU/Eindhoven, various household devices are tested to find out their individual harmonic current spectrums under clean and polluted grid conditions. Thus, a harmonic fingerprint database is developed for each device and is fed to the simulation model for analysis. Similarly, in the PQ lab, combined measurements are also done for each of the above described three household models and the harmonic spectrum of each of them is measured. Further, simulations are done in the network analysis tool 'Power Factory' on a typical low voltage network in which several household customers connected. Harmonic current emission levels at different points of the network are noted. The study results are compared with the field measurement data that have been gathered under this research project. The analysis of this paper can be used as a guiding tool to predict harmonic current emission level at different points of an average LV network.

II. MODELS USED FOR ANALYSIS

A. Development of Harmonic Fingerprints

A harmonic fingerprint is a database that contains a large set of harmonic current measurements for a single device at different conditions of the supply voltage. In the PQ lab of TU/Eindhoven, various household appliances and lighting devices are chosen for measurement (refer Table I). First, each

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device is tested separately for a clean sinusoidal voltage condition and its harmonic spectrum, total harmonic current distortion, true power factor, displacement power factor, fundamental current component and total rms current value are recorded. Fig. 1 shows the harmonic spectrum of a PC under clean grid condition. Subsequently, the supply voltage is polluted with various odd harmonics (from 3rd harmonic up to 25th harmonic), having an amplitude variation of 1% to 10% (with a step of 1%) and also a phase shift of 0° to 360° (with a step of 30°) and respective harmonic currents are measured. So, for each device two matrices (each of 12x10 dimensions) are formed with new harmonic current amplitude and new phase angle data respectively, for different voltage harmonic pollution conditions. Fig. 2 shows the harmonic current fingerprint of a PC when the supply voltage is polluted with 25th order harmonic voltage, varying in the range of 1% to 10% of fundamental voltage. References [1] and [2] give more information on harmonic fingerprint development method.

Fig. 1. Harmonic spectrum of a PC under clean grid condition

Fig. 2. Harmonic fingerprint plot for a PC (for n=25)

In the measurements, it is found that even harmonics are quite lower than odd harmonics and therefore, they are neglected in the present analysis. Also, it is noticed that the effects of harmonics for household devices are significant up to the order of 25th harmonics. So, the harmonic fingerprints for various devices are restricted up to 25th harmonic only.

B. Network Used for Analysis

A typical model of the LV network is developed in the simulation tool 'Power Factory'. In the model network various low voltage loads (such as households) are connected and is simulated to analyze harmonic propagation in the power system. The detail description of this model network can be found in reference [3]. In this design it is assumed that three household customers are coupled together, and each of them has a single phase 25A connection. A 400 kVA transformer can supply the demand of approximately 300 households. Therefore, each phase of a LV feeder can feed to a maximum of 20 household customers. Further, it is assumed that the household customer's average demand is 1.2 kW and the load type is a mixture of linear (for example: cooking element, electric iron etc.) and nonlinear loads (e.g. TV, PC, CFL, fridge etc.). Fig. 3 shows a typical point of connection (POC) of a household terminal.

Fig. 3. An average household terminal with its connected loads

The point of common coupling (PCC), shown in Fig. 3, is a point in a bus where different customers are connected. A connection cable is used to connect the nodes between PCC and POC. In the simulation, it is assumed that three household customers are connected at a three phase terminal of a POC (thus, every single house is connected to each phase of the connection cable). For simulations, first it is assumed that no background harmonic pollution is present in the MV and upstream networks that pollute the LV network. Later, simulation is also done with polluted grid voltage condition. Total harmonic voltage distortion (THD(v)) is measured at the POC; whereas total harmonic current distortion (THD(i)) values can be measured for each individual device and also at the POC. The formulas for calculating THD(i) and THD(v) are shown in (1) and (2).

$$THD(i) = \sqrt{\sum_{n=2}^{40} \left(\frac{I_n}{I_{rms}} \right)^2} \quad (1); \quad THD(v) = \sqrt{\sum_{n=2}^{40} \left(\frac{V_n}{V_{rms}} \right)^2} \quad (2)$$

Where, I_n = current of each order harmonic 'n'

I_{rms} = total rms current

V_n = voltage of each order harmonic 'n'

V_{rms} = total rms voltage

n = harmonic order, n=1 for fundamental component

C. Cases Used in Simulation

In the simulation, three types of household load models are considered and are described in Table I. Before doing the simulation with LV network, each household model type is simulated separately to check its accuracy with the PQ lab measured data.

TABLE I
DEFINITIONS FOR HOUSEHOLD MODELS

Model name	Devices used	Total I_{rms} (A)
High load case	TV- 1 no ($I_{rms}=0.77A$, $pf=0.76$, $THD(i)=64\%$) PC- 2 nos. (PC1: $I_{rms}=0.88A$, $pf=0.49$, $THD(i)=82\%$; PC2: $I_{rms}=0.64A$, $pf=0.75$, $THD(i)=62\%$) Fridge – 1 no. ($I_{rms}=0.75A$, $pf=0.60$, $THD(i)=10\%$) CFL – 10 nos. ($I_{rms}=0.06A$, $pf=0.63$, $THD(i)=72\%$) Vacuum cleaner – 1 no. ($I_{rms}=4.5A$, $pf=0.98$, $THD(i)=17\%$) (at full load condition) Linear load – 125W	7.5
Average load case*	TV- 1 no PC- 2 nos. Fridge – 1 no. CFL – 6 nos. Vacuum cleaner – 1 no. ($I_{rms}=2.8A$, $pf=0.56$, $THD(i)=60\%$) (at half-load condition) Linear load – 125W	5.6
Low load case	TV- 1 no PC- 1 no Fridge – 1 no. CFL – 2 nos. Linear load – 125W	2.3

Note: *For average load case, another case study is done by including an inverter load ($I_{rms}=3.7A$, $pf=0.99$, $THD(i)=3\%$). Then the average current demand is 3.5A approximately. 'pf' indicates true power factor of the device.

First, a case study is done to check the accuracy of the model. In the PQ lab, measurement is done for individual device to find out its harmonic spectrum for clean and polluted grid voltage condition as described before (from 3rd up to 25th harmonic order). All the harmonic fingerprints are fed to the network simulation tool's database. A household terminal is made with the loads as described for low load case in Table I. Harmonic simulation is done on the house model to find out its harmonic current spectrum at the POC. Next, in the PQ lab, a combined harmonic measurement is done at the common connection terminal with the same set of devices. Fig. 4 compares the findings of the PQ lab measurements and the simulation results and a close match is found between them. Therefore, the simulation model can be considered to be quite accurate and is used for further analysis. From the field measurements done by the Dutch network operators, it is found that the average daily peak loading of a LV feeder is approximately 70A. The described load models of Table I are fed in to the LV network model in such a way so that the current loading of each LV feeder is restricted to 70A.

Fig. 4. Comparison of simulation result with laboratory measurement

III. ANALYSIS OF FINDINGS FOR A HOUSEHOLD

A. Harmonic Spectrum for an Individual Device

In the laboratory, devices used for household model are separately measured to identify their individual harmonic emission pattern under various grid conditions. It is observed that during a polluted grid condition, the harmonic current emission of a device can change significantly. Also, some of the devices show random behavior of harmonic current emissions with the linear increase of supply harmonic voltage. From the harmonic fingerprint plot (an example is shown in Fig. 2), it is often possible to identify the internal characteristic of a device. In Fig. 5, a harmonic current emissions are plotted for a CFL when the 25th harmonic voltage pollution is increased from 1% to 10% of the fundamental voltage for phase shifts of 0°, -30°, +30°, -180°, and +180° respectively. It shows that the harmonic current emission of a CFL increases almost 10 times when the 25th harmonic voltage pollution at the supply terminal changes from 1% to 10% of its magnitude (with constant phase shift of 0°). With a pollution of 1% magnitude of 25th harmonic voltage, current harmonic emissions from a CFL changes 2-3 times for different phase angles (with respect to reference phase shift of 0°).

Fig. 5. Harmonic currents of a CFL for 25th harmonic voltage pollutions

B. Harmonic Spectrum of Devices Used in Low Load Case

A simulation with low load condition at a household terminal is done for clean and polluted grid conditions to compare harmonic current emissions of different connected

devices. THD(i) values of various devices, as found from simulation, are compared in Table II. Fig. 6 shows the harmonic currents of various devices under the sinusoidal supply voltage condition. From field measurement of the Dutch grids [4], the background harmonic pollution of a MV network is estimated and is shown in Table III. These values represent a ‘worst case’ pollution level at this moment in the MV-grid. It is further used in the simulation to analyze the performance of model network in a polluted grid condition.

TABLE II
THD(i) VALUES OF DIFFERENT DEVICES USED IN LOW LOAD CASE

Device	THD(i) under clean voltage condition	THD(i) under polluted grid condition*
TV	48%	55%
PC-1	87%	89%
Fridge	10%	18%
CFL	72%	79%
Combined load	42%	45%

Note: * Pollution grid condition is taken as mentioned in Table III.

Fig. 6. Harmonic currents spectrum of devices used in ‘low load’ case

TABLE III
TYPICAL HARMONIC POLLUTION LEVEL IN A MV DUTCH GRID

Harmonic number	Magnitude (p.u)	Phase angle (deg)
3 rd	0.017	15
5 th	0.047	200
7 th	0.030	180
9 th	0.008	180
11 th	0.009	150
13 th	0.010	180
15 th	0.002	180
17 th	0.005	135
19 th , 21 st , 23 rd , 25 th	0.003	180

Note: THD(v) of the pollution voltage is approximately 5%.

C. Simulation Results for Average Load Case

Simulation is done with the average load model at a household terminal with the devices mentioned in Table I. Also, in the laboratory, the same combination of devices is measured to find out the harmonic fingerprints at the common connection point. Total harmonic current distortion (THD(i)) with respect to the total rms current at the same household terminal is found around 30% and the power factor of 0.87. In the field measurement with similar type of household loads, the THD(i) value varies between 25-30% and the THD(v) is

around 1.5-2% [5]. Fig. 7 shows the harmonic currents measured in the PQ lab for a house with average load demand for clean grid voltage condition.

Fig. 7. Harmonic currents at POC of a house with average load (clean grid)

It was found from the PQ lab measurement that a vacuum cleaner (VC) at low power stand generates high harmonic currents for low order harmonics (mainly 3rd, 5th and 7th harmonics). Also, the two PCs emit large harmonic currents of all order harmonics compared to other devices connected at the POC. CFL lamps generate harmonic currents too, but their contributions are small compared to the total harmonic currents measured at the POC.

D. Case study with Average Load and Inverter Load

A field measurement [5] is done at a household terminal that has a 3-phase 25A connection. At this installation, normal household loads are connected in the first phase (‘Ch-1’), and a solar inverter (3.75kW peak power) is connected in the second phase (‘Ch-2’). A 3-phase heat pump is also connected at the installation, but is not operating during the measurement period. The highest values of harmonic currents, during the 95% of measured time, at the two phases of the installation are shown in Fig. 8. It is also noticed that the highest THD(i) recorded in ‘Ch-1’ is 60% and that for ‘Ch-2’ is 20% for 95% of the measured time; and the THD(v) is around 2-3%. Fig. 9 shows harmonic currents distribution (at ‘Ch-1’) for a specific day that are recorded during the same measurement period at the beginning of a LV feeder in which 17 houses similar to the above mentioned type are connected.

Fig. 8. Harmonic current distribution at an installation with normal household load and inverter load in two different phases (field data)

Fig. 9. Harmonic currents recorded at the beginning of a LV feeder that feeds to 17 installations with normal household loads and inverter loads (field data)

The field measurements at the beginning of the LV feeder show that THD(i) is below 52% during the 95% of the measured time. THD(i) varies depending on the loading of the installation. THD(v) found at the LV busbar is around 1.9%. Simulation is also done with a solar inverter of 2.5kW along with an average load house model. The net load demand of the household is around 3.5A and a power factor of 0.40 at the POC. THD(i) is found 60% as compared to 30% for the case with average load demand without inverter, described before. However, THD(i) is not only the deciding factor to estimate harmonic pollution at a point in the network. Each order of harmonic current is required to be checked and compared with the available standards (discussed in section V of this paper) to reach a conclusion on harmonic pollution in the network.

E. Simulation Results for High Load Case

In the laboratory, harmonic distortion is measured at a household terminal with the same combination of devices as mentioned in Table I for the high load case. THD(i) at the simulated household terminal is found around 20% and power factor of 0.97. In this case, more CFL lamps were used as compared to the average load case and the VC was kept at high power stand. It is noticed that VC generates low harmonic currents at high power stand condition in comparison to the 'average load' case when it was operating at low power stand. Other devices produce approximately same harmonic currents as that of the average load case.

IV. SIMULATION WITH MODELED LV NETWORK

The modeled LV network is simulated in 'Power Factory' by combining various household load models. Three cases are analyzed with the following combinations:

- **Case 1:** A mix of high load and low load models for various households of the LV network model.
- **Case 2:** Only with average load model in the Network
- **Case 3:** This case simulates a situation when some customers (60%) have high load demand; and others have average load demand and have a solar inverter installed at their homes (40%). This case is a futuristic

representation of the network situation when a number of houses in the neighborhood will contain solar panels and export power in to the network.

A. Simulation results for 'Case 1'

A mix of high load and low load household terminals are selected for the simulation with LV network model, considering that the fundamental current of 70A is maintained at the beginning of a LV feeder. Fig. 10 shows the harmonic currents at the beginning of a LV feeder. THD(i) value is around 16% at the beginning of the LV feeder, whereas THD(i) at a high load house terminal varies between 26-28% and at a low load house terminal between 48-49%. THD(v) is found in the range of 0.5-1.5% at different household's POC. The harmonic spectrum at two house terminals with high load and low load respectively are compared in Fig. 11.

Fig. 10. Harmonic currents of LV feeder for 'Case 1' (clean grid)

Fig. 11. Harmonic currents at different house terminals- 'Case 1' (clean grid)

The 3rd harmonic current of the house with high load demand is quite high as compared to the house with low load demand. This extra 3rd harmonic current is mainly contributed by two additional devices: second PC (PC-2) and vacuum cleaner (VC) that are connected at the high load house's terminal. It is noticed that when a specific order harmonic current from different devices has opposite phase angles, the net harmonic current of that order is reduced due to the attenuation effect. However, they can increase considerably when the phase angles of similar order harmonic currents are in the identical direction. Fig. 11 shows an example of such a house (with high load demand), where 3rd harmonics currents are increased significantly.

B. Simulation results for 'Case 2'

This case study considers that all houses of the LV network have average load model. Fig. 12 shows harmonic currents of

different orders at the beginning of a LV feeder of the model network. All values are found higher than that of Case 1. THD(i) values at different house terminals and the beginning of LV feeder vary between 32-34% and THD(v) is in the range of 1.5-3.5% at different household's terminals. Fig. 13 shows the harmonic current values of two houses: one located at the beginning of the LV feeder and the other at the end of the same feeder. It can be seen that the harmonic current spectrums of the two example houses are quite similar.

Fig. 12. Harmonic currents of LV feeder for 'Case 2' (clean grid)

Fig. 13. Harmonic currents at different house terminals- 'Case 2' (clean grid)

C. Simulation results for 'Case 3'

This case considers that 60% houses in the LV network have high load and 40% of the houses have average load with solar inverter (2.5kW) installed at their house terminals. The harmonic current at the beginning of LV feeder is shown in Fig. 14. Some harmonic currents (such as 7th and 17th order) are found relatively lower than other two cases. THD(i) value at the beginning of LV feeder is found 24%.

Fig. 14. Harmonic currents of LV feeder for 'Case 3' (clean grid)

THD(i) values at the houses with high load demand vary between 26-28%, whereas those of houses with solar inverters are in the range of 50-52%. THD(v) is found in the range of 1.0-2.5% at different household's terminals. Harmonic currents at different house terminals are shown in Fig. 15. The house with high load demand has a high 3rd harmonic current demand, same as the previously described Case 1.

Fig. 15. Harmonic currents at different house terminals- 'Case 3' (clean grid)

This case study is repeated considering MV background pollution (as shown in Table III) in the LV network. THD(i) at the beginning of LV feeder is found 36%, whereas it is around 35% for the houses with high load; and 70% for the houses with inverter connected. Fig. 16 shows harmonic currents at different house terminals. Comparing Fig.15 and Fig. 16, it can be noticed that harmonic currents for different harmonic orders have increased significantly when MV background pollution is included in the simulation. THD(v) is found in the range of 5.0-7.5% at different household's terminals. This large value of THD(v) is mainly contributed by the background harmonic pollution voltage.

Fig. 16. Harmonic currents at different house terminals (polluted grid)

V. PRESENT STANDARDS ON HARMONICS

A. Standards for the utilities

The European Standard EN50160 [6] is commonly used by the utilities to evaluate the quality of supply voltage in the MV and LV public grids. This standard gives restriction on harmonic voltage values for each harmonic order in the network. Under normal operating conditions, during each period of one week, 95% of the 10 min mean rms values of each individual harmonic voltage shall be less than or equal to

the values as mentioned in Table IV. Moreover, the standard gives restriction on THD(v) of the supply voltage (including all harmonics up to the order 40) that should be less than or equal to 8% for 95% of the measurement time. The Dutch grid code [7] follows mainly the standard EN50160. In addition to the above, it gives restriction on THD(v) value of 12% for all harmonics up to 40th for 99.9% of the measurement time.

TABLE IV
HARMONIC VOLTAGE POLLUTION LIMITS AS PER EN50160

Odd harmonics				Even harmonics	
Not multiples of 3		Multiples of 3			
Harmonic order (n)	Relative voltage Un %	Harmonic order (n)	Relative voltage Un %	Harmonic order (n)	Relative voltage Un %
5	6	3	5	2	2
7	5	9	1.5	4	1
11	3.5	15	0.5	6...24	0.5
13	3	12	0.5		
17	2				
19, 23, 25	1.5				

Note: Various relative values of harmonic voltages are calculated with respect to the fundamental component of voltage.

B. Standards regarding point of connection / network

The technical report IEC/TR 61000-3-6 [8] gives restriction on harmonic current value in the MV installations, and the document IEC/TR 61000-3-14 [9] recommends harmonic current emission limits for different LV installations. Fig. 17 shows harmonic current emission limits at the LV household installations (current capacities of 25A and 40A). The standard IEEE 519 [10] also gives maximum harmonic current limits at an installation in percent of maximum load current demand at fundamental frequency (I_L). For various ratios of short circuit current (I_{sc}) to I_L , it recommends harmonic current limits for various harmonic orders. The limits given by IEEE 519 are relatively higher than that of IEC/TR 61000-3-14 and are mentioned here only for reference. Table V compares harmonic current emission limits at an installation for different harmonic orders that are given in various documents.

TABLE V
HARMONIC CURRENT POLLUTION LIMITS IN VARIOUS DOCUMENTS

Applicable standard	Harmonic current emission limit (%) relative to the size of customer's installation for different harmonic order (n)						
	3	5	7	9	11	13	>13
IEC/TR 61000-3-6 ¹ (MV installations)	-	5	5	-	3	3	$\frac{500}{n^2}$
IEC/TR 61000-3-14 ² (LV installations)	4	5	5	1	3	3	$\frac{500}{n^2}$
IEEE 519 ³ (all installations)	Maximum harmonic current distortion limit (%) with respect to maximum demand load current (I_L) at fundamental frequency in the installation for various harmonic order						
	<11	11≤n<17	17≤n<23	23≤n<35			
	7	3.5	2.5	1.0			

Note: ¹ It applies to customers with an agreed power $S_L \leq 1$ MVA and with $S_L/S_{sc} < 1\%$

² The condition $S_L/S_{sc} < 1\%$ should be satisfied

³ Harmonic current emission limits are shown for the condition with $50 > I_{sc}/I_L > 20$

Fig. 17. Harmonic currents emission limits as per IEC/TR 61000-3-14

C. Comparison of simulation results with standard values

Various simulation results found in section IV of this paper are analyzed to estimate the maximum harmonic current emission levels at different installations. In Fig. 18, harmonic currents of different households obtained from the simulations of this paper are compared with the limits recommended in the document IEC/TR 61000-3-14.

Fig. 18. Comparison of harmonic currents obtained from simulations and the values of IEC/TR 61000-3-14

Fig. 18 shows that the harmonic currents obtained from different simulations exceed the limits (both for 25A and 40A installations) in some cases, mainly when the simulation is done with polluted grid voltage. The simulation results on total THD(v) at various points in the LV network for different cases are within the limit of 8%, as given in the standard EN 50160. The present standards give limits that are valid for clean voltage condition only. However, the grid voltage is not sinusoidal as many polluting devices are present in the network. Therefore, the standards have to be improved and should recommend values that are also applicable during polluted grid voltage condition.

VI. CONCLUSION

In this paper, harmonic fingerprint concept is applied to measure harmonic current emission of a device / or an installation under different grid voltage conditions. In the PQ lab, some household devices are measured individually and also by combining them together to model various fictitious household installations. Simulation results show that average THD(i) of a house terminal can vary 20-70% depending on the combination of the household loads. Along with THD(i) value, individual order harmonic current emission is also compared with the available standard values. The harmonic fingerprint measurement of an individual device shows that the harmonic current emission of a device can vary largely depending on the supply voltage pollution conditions. In the simulations of a typical LV network with various combinations of household loads, it was found (refer Fig. 18) that harmonic currents of 3rd order and other higher orders exceed the limit of IEC/TR 61000-3-14 (both for the installation capacities of 25A and 40A). The installations emit more harmonic current pollutions when the grid voltage is polluted with background harmonic pollutions. In the future network, the background harmonic pollution in the MV and upstream networks could increase when more distributed generations are integrated in to the power system.

A field measurement result is also included in the paper that shows harmonic current pollutions at a household terminal and at the beginning of a LV feeder. In the presented case, the measurement is done in a neighborhood where 17 houses, each having a 3-phase 25A installation, are connected. The results showed that the LV feeder has a current loading of 40A or less for 95% of the measured time, as compared to the average capacity of 70A for a typical Dutch LV feeder (which is used in the simulation). Therefore, harmonic currents obtained from the field measurements are relatively lower than the simulation results. However, harmonic current spectrum obtained for a household terminal with normal household load is comparable to the simulation result for low load case. From the discussion of this paper, it can be concluded that the harmonic pollutions originating from different installations demand attention. The present standard also needs to be adjusted to restrict the harmonic current emissions at a customer's installation. Alternatively, various devices can be manufactured with stricter specification so that they produce less harmonic pollution in the network. More studies and field measurements from different countries of the world are required to verify the above observations and recommendations.

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VIII. BIOGRAPHIES

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