A NETWORK-WIDE EVALUATION OF SINGLE-POINT HARMONIC CONTRIBUTIONS FROM CUSTOMER INSTALLATIONS: COMPARISON OF DIFFERENT METHODS

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ABSTRACT

This paper compares three different methods for a single-point assessment of harmonic contribution from customer installation in terms of their suitability and accuracy for a network-wide evaluation of harmonic distortion levels. The analysis is performed on a benchmark network model (BNM) recently introduced by IEEE PES Task Force on Harmonic Modelling, Simulation and Assessment, which has three customers connected to three PCCs and also features background distortion. The paper shows how the total harmonic distortion at three PCCs can be disaggregated into network (or "true background") contribution, considered customer contribution, and contribution of all other connected customers. The presented results allow to compare how different methods evaluate effects of harmonic interactions between the network and customers, as well as between different customers in terms of harmonic cancellation, attenuation, summation and resonances.

INTRODUCTION

Practically all existing approaches for assessing harmonic contribution from a customer installation are "single-point" evaluation methods, in which harmonic emission of an individual customer in the considered network is assessed at the point of common coupling (PCC), where distinction is made between the "background distortion" and "customer contribution". While this distinction is crucial for a correct allocation of responsibilities in mitigating possible harmonic emission problems, e.g. when a new customer with disturbing load should be connected at specific PCC, a more general problem is assessment of network-wide harmonic distortion levels, where contributions of all connected customers (with or without disturbing loads, e.g. with capacitor banks, CBs) and network contribution (e.g. due to presence of network-controlled CBs, or active/passive filters, or HVDC links) should be assessed at *all PCCs*.

Essentially, a network-wide evaluation could be done by simply repeating single-point assessment of individual customer contributions at their respective PCCs and then following propagation of their individually assessed harmonic emissions to all PCCs, where other customers are connected. Accordingly, this paper compares two common methods for assessing harmonic contribution from customer installation: IEC method, [1], and voltage harmonic vector, VHV, method, [2], with a recently introduced voltage-only method (VoM), [3], for evaluation of network-wide harmonic distortion levels.

The analysis is performed on a benchmark network model (BNM) recently introduced by IEEE PES Task Force on Harmonic Modelling, Simulation and Assessment in [4]. The BNM has three customers connected to three PCCs and also contains background distortion. The paper shows how the total harmonic distortion at three PCCs can be disaggregated into network (or "true background") contribution, considered customer contribution, and contribution of all other connected customers.

The presented results allow to compare how different methods evaluate network-wide effects of harmonic interactions between the network and customers, as well as between different customers, in terms of harmonic cancellation, attenuation, summation and resonances (the BNM features harmonic resonance around the 11th harmonic).

OVERVIEW OF EXISTING METHODS

At a specific PCC, where harmonic emission from the considered customer (CC) is evaluated, both IEC and VHV methods consider distortions from the network (NET) and all other customers (OC) as the *resulting background distortion*. Consequently, information on the separate NET and OC contributions to the total PCC distortion, i.e. information on NET-OC harmonic interactions, is lost in both IEC and VHV methods. Conversely, VoM considers only *network distortion as a true background distortion*, while distortions coming from the other connected customers are evaluated as a separate contribution. In that way, VoM allows to separately evaluate NET, OC and CC contributions to a total PCC distortion.

VHV and IEC Methods

Both VHV and IEC methods for calculation use Thevenin equivalent circuit, Fig. 1, which should be applied for each harmonic order, *k*. The circuit is separated into utility and customer sides, where both sides have an impedance and a voltage harmonic source. Utility voltage harmonic source ($\underline{V}_{\mathrm{U}-k}$) represents resulting background voltage distortion (from the network, NET, and other connected customers, OC) that will be present at the PCC if considered customer is not connected, or if its disturbing load is switched off. A more detailed description of both methods is given in [1], [2] and [6].

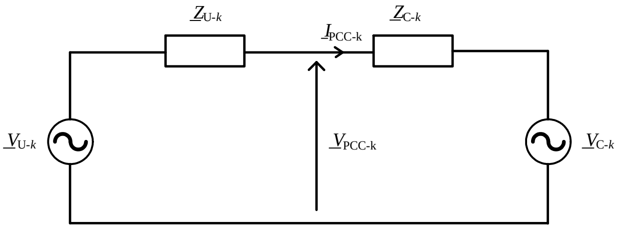

Figure 1: Thevenin equivalent circuit

Two steps are required to apply IEC and VHV methods for a network-wide evaluation of harmonic distortions. Let us assume that there are j=1, 2, …, N disturbing customers in the network, connected to k=1, 2, …, N PCCs, i.e. that each disturbing customer has its own separate PCC. The first step is related to a single-point evaluation of the customers contributions (CC) to the total distortions (TOT) at their PCCs. The following notation is introduced: total distortions at all PCCs are denoted as $\underline{V}_{TOT_k}$, k=1, 2, …, N; the harmonic emissions of disturbing customers at their own PCCs are denoted as $\underline{V}_{e,CC_j,\text{PCC}_k}$, for $j=k$. The calculation is repeated for all customers at their corresponding PCCs, for $j=k$=1, 2, …, N, resulting in a set of individual CC harmonic emissions obtained at PCCs where each CC. In the second step, all calculated CC contributions are propagated to all other PCCs, for $k \neq j$, where they are summed up to represent other customer (OC) contributions to the total distortions at all PCCs. For example, OC contribution at the k^{th} PCC is obtained as $\underline{V}_{e,OC_k,\text{PCC}_k} = \sum_{j=1}^{N} \underline{V}_{e,CC_j,\text{PCC}_j}$, for all $j \neq k$, and this is again repeated for all k=1, 2, …, N PCCs. The second step allows to evaluate total distortion at each PCC in terms of the contributions of the customer connected at that PCC (CC), all other disturbing customers (OC) connected elsewhere in the network, and network-only background distortion (NET), which is at k^{th} PCC denoted as $\underline{V}_{NET_k}$. The calculation is illustrated below, where (1) shows network contribution without customers' emissions.

$$\underline{V}_{NET_k} = \underline{V}_{TOT_k} - \underline{V}_{e,\text{CC}_k,\text{PCC}_k} - \underline{V}_{e,OC_k,\text{PCC}_k} = \\ = \underline{V}_{TOT_k} - \underline{V}_{e,\text{CC}_k,\text{PCC}_k} - \sum_{j=1}^{N} \underline{V}_{e,CC_j,\text{PCC}_j} \quad (1)$$
$$\text{for } k=1, 2, ..., \text{N and } j \neq k$$

Two above steps allows to calculate joint contribution to the total distortion at the k^{th} PCC, $\underline{V}_{TOT_k}$, from the network and considered customer (NET+CC) as $\underline{V}_{TOT(NET+CC)_k}$, as well as the joint contribution from the network and other customers (NET+CC) as $\underline{V}_{TOT(NET+OC)_k}$:

$$\underline{V}_{TOT(NET+CC)_k} = \underline{V}_{NET_\text{k}} + \underline{V}_{e,CC_k,\text{PCC}_k} \quad (2)$$
$$\underline{V}_{TOT(NET+OC)_k} = \underline{V}_{NET_\text{k}} + \underline{V}_{e,OC_k,\text{PCC}_k} \quad (3)$$
$$\text{for } k=1, 2, ..., \text{N}$$

Finally, sum and difference of CC and OC contributions at k^{th} PCC show harmonic interactions between customer connected at this PCC and all other customers connected elsewhere in the network:

$$\underline{V}_{e(CC\pm OC)_k} = \underline{V}_{e,CC_k,\text{PCC}_k} \pm \underline{V}_{e,OC_k,\text{PCC}_k} \quad (4)$$
$$\text{for } k=1, 2, ..., \text{N}$$

Voltage-Only Method

The Voltage-Only Method (VoM) is based on a simple evaluation of changes in total harmonic distortion at the PCC after connecting and disconnecting considered customer and all other customers, both individually and in groups. Based on the steps described in Table 1, VoM allows to disaggregate the total PCC distortion into the three general estimated parts, similar to those discussed in the previous section: network-only contribution (NET), contribution of considered customer (CC) and contribution of all other customers (OC). At each PCC, the first two steps use original models of customer loads, while in the third step customer loads is replaced with harmonic current sources corresponding to supply with ideally sinusoidal voltage waveform. A short description of steps and cases for analysed BNM (see next section) is given in Table 1, while a more detailed description of VoM can be found in [3] (Note: The analysis of BNM in this paper differs from [3] in the connection status of MV load in Figure 2, which is always connected to network).

Table 1: Description of VoM Steps and Considered Cases

Case	***Customer Connection Status***	***Customer C1 Represented by***	***Evaluated Quantity***
	STEP 1		
1A	C1: Connected OC=C2&C3: Connected	Original Model	PCC1 Distortion $\underline{V}_{TOT}$(NET+OC+C1)
2A	C1: Connected OC=C2&C3: Disconnected	Original Model	PCC1 Distortion $\underline{V}_{TOT}$(NET+C1)
3A	C1: Disconnected OC=C1&C3: Connected	Original Model	PCC1 Distortion $\underline{V}_{TOT}$(NET+OC)
4A	C1: Disconnected OC=C2&C3: Disconnected	Original Model	PCC1 (True Background) Distortion $\underline{V}_{BG}$(NET)
	STEP 2		
5A	C1: Connected to an ideally sinusoidal voltage source	Original Model	Inherent Harm. Current Emission of C1 (IHCE1)
	STEP 3		
1B	C1: Connected OC=C2&C3: Connected	IHCE1 const. current source	PCC1 Distortion $\underline{V}_{TOT}$(NET+OC+C1) for C1 represented by IHCE1
2B	C1: Connected OC=C2&C3: Disconnected	IHCE1 const. current source	PCC1 Distortion $\underline{V}_{TOT}$(NET+C1) for C1 represented by IHCE1

A network-wide assessment of harmonic distortions by VoM is simply done by calculating all three NET, CC and OC contributions at all PCCs in the considered network. However, while IEC and VHV methods can be used for a continuous assessment in operational studies, VoM is primarily intended for network planning studies, as it relies on the use of simulation models for both network and customer installations and as it requires sequential connection and disconnection of considered customer and other customers, as described in [3] and Table 1. However, VoM does not require information on network and customer harmonic impedances and is therefore used as a reference for evaluating IEC and VHV methods.

TEST NETWORK

Test network, Fig. 2, is BNM developed by IEEE-PES Task Force on Harmonic Modelling and Simulation specifically for analysis of harmonic distortion, [4]. It has three voltage levels: high voltage (HV), medium voltage (MV) and low voltage (LV) and three different customers, which are connected at MV PCCs. Customers have compensators and loads on LV level.

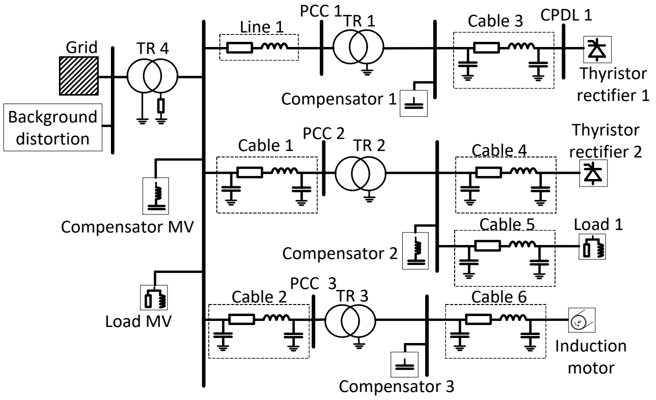

Figure 2: Benchmark network model (BNM) from [4].

The grid supply is on HV level, which is represented by an ideally sinusoidal voltage source. Background distortion is represented by voltage harmonics injected at the HV side of transformer TR4, as presented in Table 2.

Table 2: Background distortion

Harmonic order	Magnitude		Phase Angle	
	HV Side	*MV Side*	*HV Side*	*MV Side*
1st	89.8 kV	17.1 kV	0°	0°
5th	224.5 V	42.9 V	80°	80°
7th	188.6 V	36.0 V	-5°	-5°
11th	224.5 V	42.9 V	-30°	-30°
13th	53.9 V	10.2 V	-140°	-140°

RESULTS AND DISCISSION

Results for all three methods are shown in Tables 3-6 for only four main low-frequency harmonics (5th, 7th, 11th and 13th), as other harmonics have very low magnitudes and are therefore omitted. Each contribution (NET, CC, OC and their combinations) are obtained as harmonic vectors, which are then calculated as the projections on the vector of the total voltage harmonic distortion (TOT).

Influence of Individual Customers to other PCCs

Table 3 shows results for harmonic emissions of all three customers at their own PCCs, i.e. CC contributions, which are propagated to two other PCCs as OC contributions (differences are due to CC projections on different total distortion vectors). Individual CC contributions can be calculated in two ways: a) as vector difference of the results for the Cases 1A and 3A in Table 1, i.e. as $\underline{V}_E(CC)=\underline{V}_{TOT}(NET+OC+CC)-\underline{V}_{TOT}(NET+OC)$, and b) as vector difference of the results for the Cases 2A and 4A in Table 1, i.e. as $\underline{V}'_E(CC)=\underline{V}_{TOT}(NET+CC)-\underline{V}_{BG}(NET)$. The same applies for the calculation of OC contributions: a) as a difference of results for Cases 1A and 2A, i.e. $\underline{V}_E(OC)=\underline{V}_{TOT}(NET+OC+CC)-\underline{V}_{TOT}(NET+CC)$, and b) as a difference of results for Cases 3A and 4A, i.e. as $\underline{V}'_E(OC)=\underline{V}_{TOT}(NET+OC)-\underline{V}_{BG}(NET)$. With this analysis, the diagonal elements in Table 3 correspond to the values $\underline{V}_{e,CC_k,\mathrm{PCC}_k}$, k=1, 2, 3, while sum of off-diagonal elements in each row corresponds to $\underline{V}_{e,OC_k,\mathrm{PCC}_k}=\sum_{j=1}^{3}\underline{V}_{e,CC_j,\mathrm{PCC}_j}$ for $j\neq k$ and j=1, 2, 3. The calculation is illustrated in Fig. 3 with 11th harmonic vectors for PCC1.

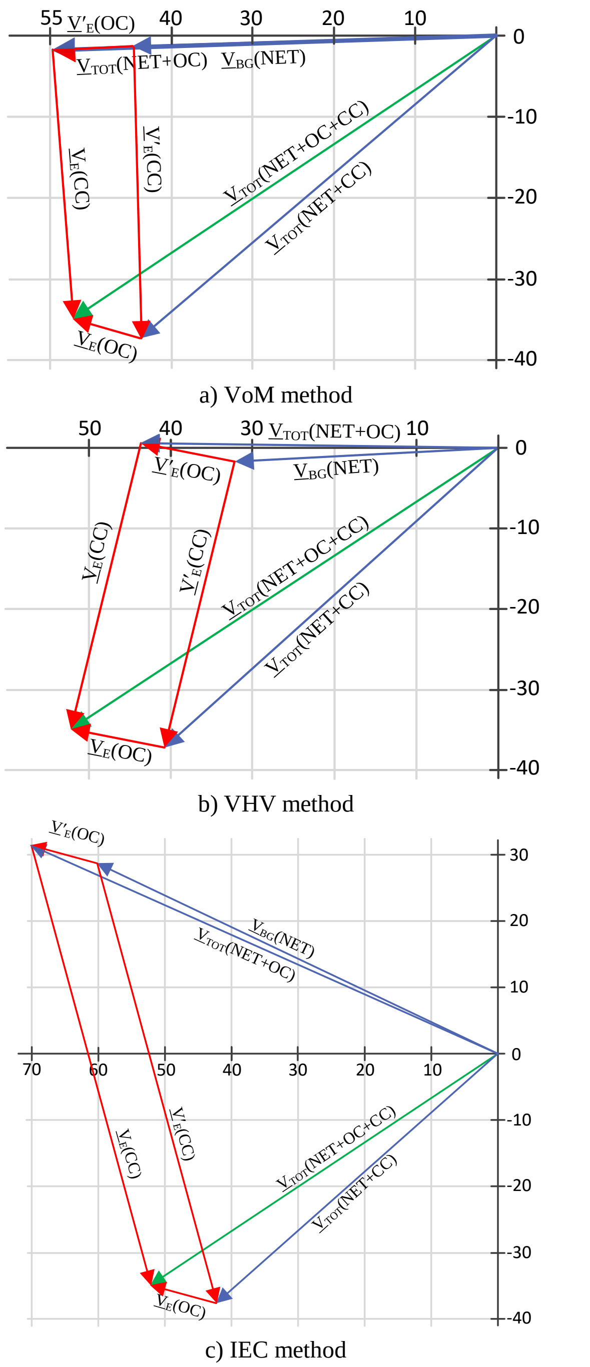

Figure 3: Calculation of CC and OC contributions by VHV and VoM (Step 1, PCC1, 11th harmonic).

Table 3: Results for CC and OC contributions at all PCCs

Considered customer	Harm. comp.	Considered customer's emission at					
		PCC1		PCC2		PCC3	
		V_e	V'_e	V_e	V'_e	V_e	V'_e
Customer 1 (PCC 1)	*5th*	**28.55**	**29.38**	27.11	27.91	27.17	28.05
	7th	**26.43**	**27.67**	25.31	26.54	25.33	26.65
	11th	**16.29**	**19.23**	16.61	19.65	16.68	19.85
	13th	**4.43**	**5.02**	4.83	5.42	4.84	5.52
Customer 2 (PCC 2)	*5th*	**10.75**	**10.33**	12.32	11.87	10.70	10.33
	7th	**8.13**	**7.59**	8.78	8.19	8.08	7.57
	11th	**7.69**	**11.28**	8.86	12.58	7.83	11.48
	13th	**11.10**	**10.92**	11.25	10.92	11.20	11.10
Customer 3 (PCC 3)	*5th*	**-2.36**	**-1.05**	-2.34	-1.05	-2.53	-1.13
	7th	**-3.04**	**-1.33**	-3.01	-1.32	-3.23	-1.41
	11th	**-2.04**	**-0.11**	-2.11	-0.10	-2.44	-0.25
	13th	**1.35**	**1.63**	1.37	1.64	1.23	1.64

Results of Step 1

Table 4 lists results of all three methods for Cases 1A-4A from Step 1 in Table 1, related to the assessment of CC and OC contributions to the 5th, 7th, 11th and 13th harmonic distortion at PCC1. All three methods provide similar results, except for the 11th harmonic, due to presence of resonant frequency around that harmonic in the network. All three methods calculate different network-only ("true background") distortion, $V_{BG}(NET)$, where VoM provides correct value (based on case 4A, when all customers are disconnected). The most relevant results are for CC emissions, as they show contribution of each customer to the total harmonic distortion at its PCC. The biggest differences between the three methods are for the 11th harmonic (around the network resonance), with VoM and VHV values more similar than IEC values, because magnitude values of IEC vectors are two times higher than the magnitude values of VHV and VoM method (Fig. 3), which is due to the differences in the phase angles of calculated network-only (true background) distortions.

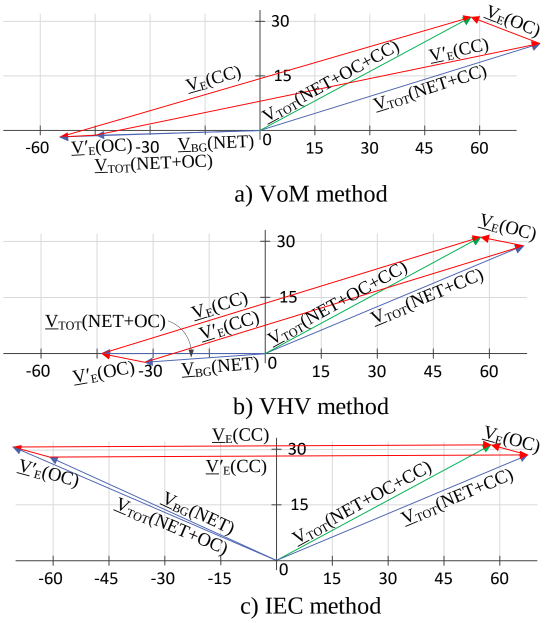

Figure 4: Calculation for Step 3 (PCC1, 11th harmonic).

Table 4: Step-1, Cases 1A-4A for PCC1

Harm. comp.	Calculated Contribution	Method		
		VoM	IEC	VHV
5th	$V_{BG}(NET)$	34.21	35.64	31.22
	$V_{TOT}(NET+CC)$	63.59	64.74	59.74
	$V_{TOT}(NET+OC)$	43.48	42.93	43.51
	$V_E(CC+OC)$	37.81	36.38	40.80
	$V_E(CC-OC)$	20.11	21.80	16.24
	$V_E(OC)$	8.43	7.29	12.28
	$V'_E(OC)$	9.27	/	/
	$V_E(OC)_{FINAL}$	**8.85**	**7.29**	**12.28**
	$V_E(CC)$	28.55	/	/
	$V'_E(CC)$	29.38	/	/
	$V_E(CC)_{FINAL}$	**28.96**	**29.09**	**28.52**
7th	$V_{BG}(NET)$	36.18	35.05	33.05
	$V_{TOT}(NET+CC)$	63.85	64.01	60.23
	$V_{TOT}(NET+OC)$	42.56	40.03	41.81
	$V_E(CC+OC)$	32.80	33.93	35.93
	$V_E(CC-OC)$	21.30	23.98	18.42
	$V_E(OC)$	5.13	4.98	8.75
	$V'_E(OC)$	6.37	/	/
	$V_E(OC)_{FINAL}$	**5.75**	**4.98**	**8.75**
	$V_E(CC)$	26.43	/	/
	$V'_E(CC)$	27.67	/	/
	$V_E(CC)_{FINAL}$	**27.05**	**28.95**	**27.18**
11th	$V_{BG}(NET)$	38.00	34.09	27.69
	$V_{TOT}(NET+CC)$	57.22	56.07	54.56
	$V_{TOT}(NET+OC)$	46.51	40.84	35.95
	$V_E(CC+OC)$	24.81	28.72	35.12
	$V_E(CC-OC)$	10.71	15.23	18.61
	$V_E(OC)$	5.59	6.74	8.25
	$V'_E(OC)$	8.52	/	/
	$V_E(OC)_{FINAL}$	**7.05**	**6.74**	**8.25**
	$V_E(CC)$	16.29	21.97	26.86
	$V'_E(CC)$	19.23	/	/
	$V_E(CC)_{FINAL}$	**17.76**	**21.97**	**26.86**
13th	$V_{BG}(NET)$	4.64	3.02	6.09
	$V_{TOT}(NET+CC)$	9.66	11.20	10.75
	$V_{TOT}(NET+OC)$	17.19	13.43	16.96
	$V_E(CC+OC)$	16.98	18.60	15.52
	$V_E(CC-OC)$	-7.52	-2.24	-6.22
	$V_E(OC)$	11.95	10.42	10.87
	$V'_E(OC)$	12.55	/	/
	$V_E(OC)_{FINAL}$	**12.25**	**10.42**	**10.87**
	$V_E(CC)$	4.43	8.18	4.65
	$V'_E(CC)$	5.02	/	/
	$V_E(CC)_{FINAL}$	**4.73**	**8.18**	**4.65**

Results of Step 2

The results of Step-2 in Table 5 show that harmonic currents of Customer 1 are higher when its disturbing load is connected to a strong grid with ideally sinusoidal 50 Hz voltage. This emission is denoted as "inherent harmonic current emission" (IHCE) of Customer 1, which is in Step 3 modelled with IHCE constant current harmonic sources.

Results of Step 3

Difference between results in Steps 1 and 3 helps to assess change in Customer 1 contribution to the total distortion at its PCC due to presence of background voltage distortion. If customer contribution in Step 3 reduces, this suggests that partial responsibility for increased emission in Step 1 is due to a general inability of the network (which is not "strong enough") to provide sinusoidal voltage supply at PCC1. Accordingly, Customer 1 should not be responsible for this increase of emission from Step 3 to Step 1.

Table 5: Step-2 for Customer 1 at PCC1

Harmonic Order	Harm. Curr. Emis. for Case 5A (IHCE)		Harm. Curr. Emis for Case 1A (Original)	
	Mag. (A)	*Phase Angle (°)*	*Mag. (A)*	*Phase Angle (°)*
1st (fund.)	389.64	-87.99	354.54	-96.16
5th	91.74	105.37	71.20	57.61
7th	37.76	82.06	25.32	50.37
11th	31.19	-75.78	8.90	-166.77
13th	16.58	-90.26	7.89	-175.46

Table 6: Step-3, Case 1B (IEfor PCC1

Harm. comp.	Calculated Contribution	Method		
		VoM	IEC	VHV
5th	$V_{BG}(NET)$	28.57	28.93	25.32
	$V_{TOT}(NET+CC)$	62.81	63.17	59.20
	$V_{TOT}(NET+OC)$	41.00	40.12	40.48
	$V_E(CC+OC)$	45.79	45.43	49.04
	$V_E(CC-OC)$	21.81	23.06	18.71
	$V_E(OC)$	11.55	11.19	15.16
	$V'_E(OC)$	12.44	/	/
	$V_E(OC)_{FINAL}$	**11.99**	**11.19**	**15.16**
	$V_E(CC)$	33.36	34.24	33.87
	$V'_E(CC)$	34.24	/	/
	$V_E(CC)_{FINAL}$	**33.80**	**34.24**	**33.87**
7th	$V_{BG}(NET)$	30.01	29.53	27.64
	$V_{TOT}(NET+CC)$	68.06	67.20	64.12
	$V_{TOT}(NET+OC)$	39.37	37.69	38.89
	$V_E(CC+OC)$	45.36	45.83	47.72
	$V_E(CC-OC)$	28.69	29.51	25.23
	$V_E(OC)$	7.30	8.16	11.25
	$V'_E(OC)$	9.37	/	/
	$V_E(OC)_{FINAL}$	**8.34**	**8.16**	**11.25**
	$V_E(CC)$	35.99	37.67	36.48
	$V'_E(CC)$	38.06	/	/
	$V_E(CC)_{FINAL}$	**37.02**	**37.67**	**36.48**
11th	$V_{BG}(NET)$	-40.06	-40.41	-29.61
	$V_{TOT}(NET+CC)$	78.74	73.04	74.59
	$V_{TOT}(NET+OC)$	-49.02	-47.85	-38.60
	$V_E(CC+OC)$	105.67	106.01	95.21
	$V_E(CC-OC)$	127.76	120.89	113.20
	$V_E(OC)$	-13.13	-7.44	-8.99
	$V'_E(OC)$	-8.96	/	/
	$V_E(OC)_{FINAL}$	**-11.05**	**-7.44**	**-8.99**
	$V_E(CC)$	114.62	113.45	104.20
	$V'_E(CC)$	118.80	/	/
	$V_E(CC)_{FINAL}$	**116.71**	**113.45**	**104.20**
13th	$V_{BG}(NET)$	2.25	5.59	1.66
	$V_{TOT}(NET+CC)$	14.80	17.75	18.34
	$V_{TOT}(NET+OC)$	-6.67	-1.37	-5.90
	$V_E(CC+OC)$	8.53	5.19	9.12
	$V_E(CC-OC)$	21.46	19.12	24.23
	$V_E(OC)$	-4.01	-6.96	-7.55
	$V'_E(OC)$	-8.92	/	/
	$V_E(OC)_{FINAL}$	**-6.47**	**-6.96**	**-7.55**
	$V_E(CC)$	17.45	12.16	16.68
	$V'_E(CC)$	12.54	/	/
	$V_E(CC)_{FINAL}$	**15.00**	**12.16**	**16.68**

All three methods show that customer emission increases from Step 1 to Step 3, with biggest increase for the 11th harmonic (network resonance). The harmonic vectors calculated by IEC and VHV methods that include only OC and NET contributions are the same as in Step 1, although there is a new emission of Customer 1, also resulting in change of the total PCC distortion, which influences change in projected values.

Comparison of harmonic vectors for Step 1 (Fig. 3) and Step 3 (Fig. 4) shows that CC emission in Step 1 adds to vector $\underline{V}_{TOT}(NET+OC)$, while in Step 3 it fully cancels $\underline{V}_{TOT}(NET+OC)$ and then contributes to total distortion. This is the reason why projection of CC emission is higher than total distortion, but CC emission has a positive sign, due to difference of phase angles being smaller than 90°.

CONCLUSIONS

This paper compares three methods for assessment of harmonic contribution from customer installation in terms of their suitability for a network-wide evaluation of harmonic distortion. By repeating single-point assessment of individual customer contributions at their respective PCCs and following propagation of their emissions to all other PCCs, the paper shows how total PCC distortion can be separated in network-only contribution, contribution of considered customer, and contribution of other customers connected elsewhere in the network. The presented results allow to compare how different methods evaluate effects of harmonic interactions (cancellation, attenuation, resonances, etc.) between the network and customers, as well as between different customers, including evaluation of the impact of the network strength. Presented results suggest that all three methods could indicate how network and specific customers contribute to total PCC distortion, which can be helpful in evaluating responsibilities when allowed limits are violated, or for evaluating contributions of different customers connected to the same PCC.

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