Appendix to the paper “A Benchmark Test System to Evaluate Methods of Harmonic Contribution Determination”

Harmonic voltages and currents in the network

Table 1: Results of harmonic voltages and currents for Case A

Harmonic order	PCC 1				PCC 3			
	U_{RMS} [V]	φ [°]	I_{RMS} [A]	φ [°]	U_{RMS} [V]	φ [°]	I_{RMS} [A]	φ [°]
1st (50 Hz)	11955.56	-92.55	6.04	-104.28	11954.64	-92.55	5.77	-106.77
5th (250 Hz)	24.97	-16.91	1.92	86.76	23.57	-14.92	0.04	-102.10
7th (350 Hz)	18.91	-93.79	1.05	13.86	17.87	-92.78	0.02	-178.99
11th (550 Hz)	23.15	-71.31	0.84	44.30	21.96	-71.46	0.00	-10.11
13th (650 Hz)	5.77	-127.13	0.18	-7.05	5.50	-127.75	0.00	-49.42

Table 2: Results of harmonic voltages and currents for Case B

Harmonic order	PCC 1				PCC 3			
	U_{RMS} [V]	φ [°]	I_{RMS} [A]	φ [°]	U_{RMS} [V]	φ [°]	I_{RMS} [A]	φ [°]
1st (50 Hz)	11943.30	-92.68	6.04	-104.37	11933.00	-92.68	17.83	-111.33
5th (250 Hz)	25.19	-17.45	1.92	86.31	23.81	-15.52	0.02	-94.52
7th (350 Hz)	19.37	-94.67	1.05	13.55	18.37	-93.81	0.02	-13.66
11th (550 Hz)	27.62	-91.26	0.80	52.84	27.61	-94.31	0.52	-26.91
13th (650 Hz)	4.62	-125.94	0.19	-11.34	4.17	-126.17	0.05	154.04

Table 3: Results of harmonic voltages and currents for Case C (PCC 1 and PCC 2)

Harmonic order	PCC 1				PCC 2			
	U_{RMS} [V]	φ [°]	I_{RMS} [A]	φ [°]	U_{RMS} [V]	φ [°]	I_{RMS} [A]	φ [°]
1st (50 Hz)	12033.74	-92.71	6.10	-104.31	12025.26	-92.72	11.83	-99.61
5th (250 Hz)	39.53	-3.80	1.96	86.78	39.91	-1.66	0.90	137.58
7th (350 Hz)	36.13	-88.20	1.10	14.39	35.92	-86.69	0.43	63.12
11th (550 Hz)	38.99	-116.97	0.83	73.45	39.51	-119.77	0.31	-53.38
13th (650 Hz)	16.90	112.44	0.28	-3.86	17.72	113.31	0.20	-95.51

Table 4: Results of harmonic voltages and currents for case C (PCC 3 and PCC 4)

Harmonic order	PCC 3				PCC 4			
	U_{RMS} [V]	φ [°]	I_{RMS} [A]	φ [°]	U_{RMS} [V]	φ [°]	I_{RMS} [A]	φ [°]
1st (50 Hz)	12032.88	-92.71	5.73	-106.70	239.86	-64.21	591.20	-69.61
5th (250 Hz)	38.30	-2.09	0.06	-88.95	2.96	3.79	45.01	107.59
7th (350 Hz)	35.05	-87.50	0.03	-173.47	2.09	-15.91	21.42	93.16
11th (550 Hz)	38.77	-118.71	0.01	-59.00	2.57	-168.94	15.54	-83.36
13th (650 Hz)	17.28	111.24	0.01	-166.25	1.74	-164.90	9.45	-62.72

Upstream (utility) and downstream (customer) impedances

Table 5: Harmonic impedances for Case A

Harmonic order	PCC 1		PCC 3	
	Utility	Customer	Utility	Customer
	$\underline{Z}$ [Ω]	$\underline{Z}$ [Ω]	$\underline{Z}$ [Ω]	$\underline{Z}$ [Ω]
1st (50 Hz)	0.69 + 2.59i	1685.89 - 579.68i	0.87 + 2.74i	15.43 + 100.83i
2nd (100 Hz)	1.00 + 5.15i	1579.85 - 1010.49i	1.20 + 5.46i	16.89 + 206.48i
3rd (150 Hz)	1.50 + 7.68i	1027.16 - 1139.75i	1.75 + 8.15i	19.18 + 321.56i
4th (200 Hz)	2.20 + 10.15i	567.98 - 992.32i	2.51 + 10.79i	23.05 + 453.44i
5th (250 Hz)	3.09 + 12.55i	372.30 - 822.84i	3.50 + 13.35i	30.65 + 614.51i
6th (300 Hz)	4.17 + 14.86i	186.96 - 628.33i	4.73 + 15.90i	42.79 + 826.53i
7th (350 Hz)	5.47 + 17.09i	97.02 - 447.92i	6.28 + 18.42i	63.95 + 1139.78i
8th (400 Hz)	6.85 + 19.19i	58.29 - 275.09i	8.31 + 21.01i	145.04 + 1665.81i
9th (450 Hz)	8.32 + 21.12i	53.43 - 148.13i	11.69 + 23.34i	547.99 + 2820.42i
10th (500 Hz)	10.12 + 22.99i	34.53 - 43.22i	21.01 + 19.48i	5209.94 + 7227.01i
11th (550 Hz)	12.00 + 24.79i	29.56 + 53.84i	9.03 + 18.81i	2465.07 - 5263.91i
12th (600 Hz)	13.98 + 26.25i	24.26 + 138.86i	10.72 + 23.89i	522.21 - 2185.72i
13th (650 Hz)	16.18 + 27.64i	22.25 + 217.74i	12.93 + 26.41i	240.33 - 1299.87i
14th (700 Hz)	18.57 + 28.84i	23.31 + 291.04i	15.04 + 28.19i	149.15 - 867.11i
15th (750 Hz)	21.26 + 29.82i	20.85 + 357.43i	17.04 + 29.63i	107.93 - 603.90i

Table 6: Harmonic impedances for Case B

Harmonic order	PCC 1		PCC 3	
	Utility	Customer	Utility	Customer
	$\underline{Z}$ [Ω]	$\underline{Z}$ [Ω]	$\underline{Z}$ [Ω]	$\underline{Z}$ [Ω]
1st (50 Hz)	0.69 + 2.59i	1710.24 - 579.170i	0.87 + 2.74i	15.96 + 102.26i
2nd (100 Hz)	1.00 + 5.16i	1579.42 - 1005.50i	1.20 + 5.46i	19.87 + 219.28i
3rd (150 Hz)	1.51 + 7.70i	1016.55 - 1134.77i	1.75 + 8.15i	29.11 + 374.70i
4th (200 Hz)	2.23 + 10.21i	570.10 - 995.56i	2.51 + 10.79i	58.42 + 637.03i
5th (250 Hz)	3.15 + 12.67i	356.72 - 837.94i	3.49 + 13.36i	215.11 + 1319.66i
6th (300 Hz)	4.30 + 15.09i	184.28 - 628.98i	4.71 + 15.90i	7685.41 - 208.81i
7th (350 Hz)	5.71 + 17.47i	95.22 - 422.12i	6.24 + 18.44i	239.66 - 1192.28i
8th (400 Hz)	7.46 + 19.87i	64.79 - 269.75i	8.30 + 20.98i	71.40 - 540.71i
9th (450 Hz)	9.83 + 22.34i	48.38 - 151.15i	11.70 + 23.47i	38.98 - 290.33i
10th (500 Hz)	14.02 + 25.03i	34.98 - 43.20i	20.77 + 19.46i	26.09 - 148.88i
11th (550 Hz)	27.68 + 20.73i	27.56 + 52.25i	8.83 + 18.63i	20.57 - 50.94i
12th (600 Hz)	8.26 + 14.31i	23.94 + 138.98i	10.68 + 23.90i	17.41 + 24.14i
13th (650 Hz)	10.23 + 22.10i	21.99 + 217.81i	12.92 + 26.42i	15.53 + 86.30i
14th (700 Hz)	12.74 + 25.10i	22.94 + 290.83i	15.03 + 28.20i	14.330 + 140.28i
15th (750 Hz)	14.99 + 26.98i	20.52 + 357.59i	17.04 + 29.64i	13.51 + 188.71i

Table 7: Harmonic impedances for Case C (PCC 1 and PCC 2)

Harmonic order	PCC 1		PCC 2	
	Utility	Customer	Utility	Customer
	$\underline{Z}$ [Ω]	$\underline{Z}$ [Ω]	$\underline{Z}$ [Ω]	$\underline{Z}$ [Ω]
1^{st} (50 Hz)	0.70 + 2.60i	1780.53 - 709.80i	1.13 + 2.77i	1093.97 - 190.56i
2^{nd} (100 Hz)	1.05 + 5.29i	1534.25 - 966.52i	1.49 + 5.60i	668.63 - 521.24i
3^{rd} (150 Hz)	1.73 + 8.21i	1022.23 - 1125.34i	2.10 + 8.65i	326.83 - 437.15i
4^{th} (200 Hz)	4.27 + 12.18i	607.26 - 981.44i	3.14 + 12.02i	37.11 - 64.09i
5^{th} (250 Hz)	3.96 + 14.11i	350.30 - 845.30i	4.86 + 15.73i	31.04 + 287.83i
6^{th} (300 Hz)	6.48 + 18.09i	189.65 - 624.70i	7.70 + 20.07i	94.85 + 517.05i
7^{th} (350 Hz)	10.43 + 22.46i	98.00 - 427.37i	12.64 + 24.89i	176.86 + 665.50i
8^{th} (400 Hz)	16.92 + 26.78i	67.83 - 273.27i	22.11 + 29.26i	215.07 + 781.27i
9^{th} (450 Hz)	27.35 + 29.56i	49.33 - 150.79i	39.11 + 25.52i	263.17 + 890.18i
10^{th} (500 Hz)	42.14 + 26.47i	36.54 - 42.87i	34.72 - 1.39i	286.94 + 1002.05i
11^{th} (550 Hz)	55.16 + 11.91i	29.61 + 52.80i	28.57 + 21.31i	325.85 + 1076.72i
12^{th} (600 Hz)	54.99 - 8.67i	26.03 + 139.03i	53.09 + 11.07i	326.31 + 1160.83i
13^{th} (650 Hz)	43.75 - 21.85i	24.35 + 217.76i	50.78 - 12.60i	354.54 + 1254.45i
14^{th} (700 Hz)	31.68 - 25.76i	24.42 + 290.19i	37.06 - 22.29i	351.55 + 1350.12i
15^{th} (750 Hz)	22.76 - 25.00i	23.02 + 357.88i	25.96 - 23.01i	374.42 + 1447.45i

Table 8: Harmonic impedances for Case C (PCC 3 and PCC 4)

Harmonic order	PCC 3		PCC 4	
	Utility	Customer	Utility	Customer
	$\underline{Z}$ [Ω]	$\underline{Z}$ [Ω]	$\underline{Z}$ [Ω]	$\underline{Z}$ [Ω]
1^{st} (50 Hz)	0.88 + 2.76i	15.44 + 100.84i	0.0005 + 0.012i	0.44 - 0.07i
2^{nd} (100 Hz)	1.26 + 5.61i	17.00 + 206.54i	-0.0004 + 0.023i	0.33 - 0.18i
3^{rd} (150 Hz)	1.99 + 8.70i	19.20 + 321.55i	0.00001 + 0.036i	0.14 - 0.21i
4^{th} (200 Hz)	4.75 + 12.92i	22.90 + 453.72i	0.001 + 0.047i	0.02 - 0.07i
5^{th} (250 Hz)	4.46 + 15.01i	30.46 + 613.94i	0.0008 + 0.059i	0.01 + 0.06i
6^{th} (300 Hz)	7.36 + 19.37i	44.47 + 825.37i	0.002 + 0.072i	0.04 + 0.14i
7^{th} (350 Hz)	12.23 + 24.03i	75.89 + 1133.4i	0.006 + 0.084i	0.07 + 0.19i
8^{th} (400 Hz)	21.27 + 28.20i	160.19 + 1660.33i	0.008 + 0.010i	0.09 + 0.23i
9^{th} (450 Hz)	37.42 + 25.06i	520.94 + 2844.87i	0.017 + 0.10i	0.11 + 0.26i
10^{th} (500 Hz)	34.43 - 1.10i	5193.21 + 6793.53i	0.013 + 0.11i	0.11 + 0.29i
11^{th} (550 Hz)	27.21 + 20.75i	2600.95 - 4892.50i	0.013 + 0.13i	0.13 + 0.31i
12^{th} (600 Hz)	51.32 + 13.23i	545.02 - 2176.8i	0.021 + 0.13i	0.13 + 0.34i
13^{th} (650 Hz)	52.50 - 9.89i	252.31 - 1297.74i	0.022 + 0.13i	0.14 + 0.37i
14^{th} (700 Hz)	40.27 - 21.89i	157.06 - 866.32i	0.015 + 0.14i	0.14 + 0.39i
15^{th} (750 Hz)	28.95 - 24.33i	113.87 - 603.43i	0.01 + 0.15i	0.15 0.42i

Emission results

Table 9: Results of emission for Case A

Harmonic order	PCC 1			PCC 3		
	VHV	IEC	SIM	VHV	IEC	SIM
	U_{RMS} [V]	U_{RMS} [V]	U_{RMS} [V]	U_{RMS} [V]	U_{RMS} [V]	U_{RMS} [V]
5th (250 Hz)	24.88	24.88	24.97	0.00	0.00	23.57
7th (350 Hz)	18.93	18.93	18.91	0.00	0.00	17.87
11th (550 Hz)	23.19	23.21	23.15	0.00	0.08	21.96
13th (650 Hz)	5.72	5.71	5.77	0.01	0.14	5.50

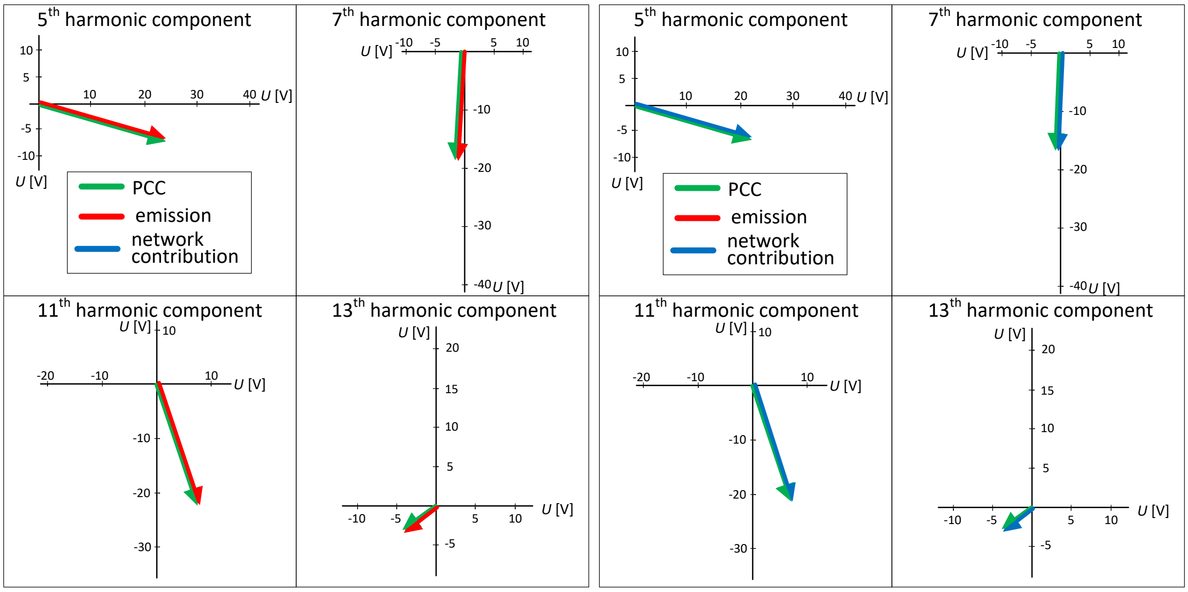

Figure 1: Phasors diagrams of VHV method (PCC 1 – left and PCC 3 – right)

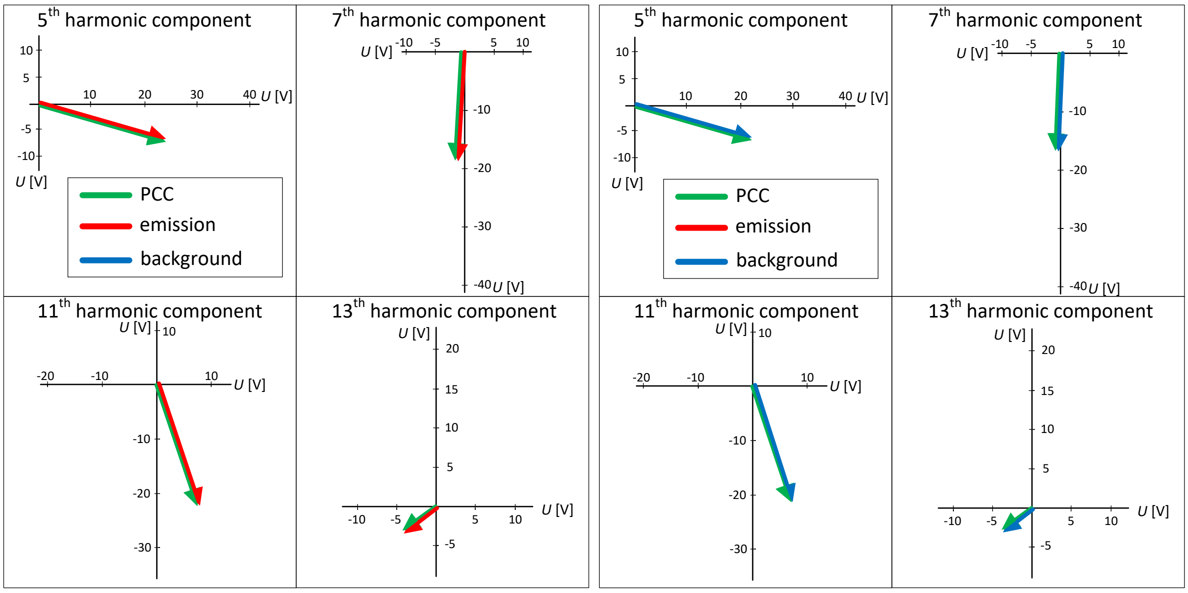

Figure 2: Phasors diagrams of IEC method (PCC 1 –left and PCC 3 – right)

Table 10: Results of emission for Case B

Harmonic order	PCC 1			PCC 3		
	VHV	IEC	SIM	VHV	IEC	SIM
	U_{RMS} [V]	U_{RMS} [V]	U_{RMS} [V]	U_{RMS} [V]	U_{RMS} [V]	U_{RMS} [V]
5th (250 Hz)	25.08	25.08	25.19	0.00	0.00	23.81
7th (350 Hz)	19.34	19.34	19.37	0.03	0.33	18.37
11th (550 Hz)	27.58	27.64	27.62	0.44	10.69	27.61
13th (650 Hz)	4.59	4.59	4.62	0.00	0.00	4.17

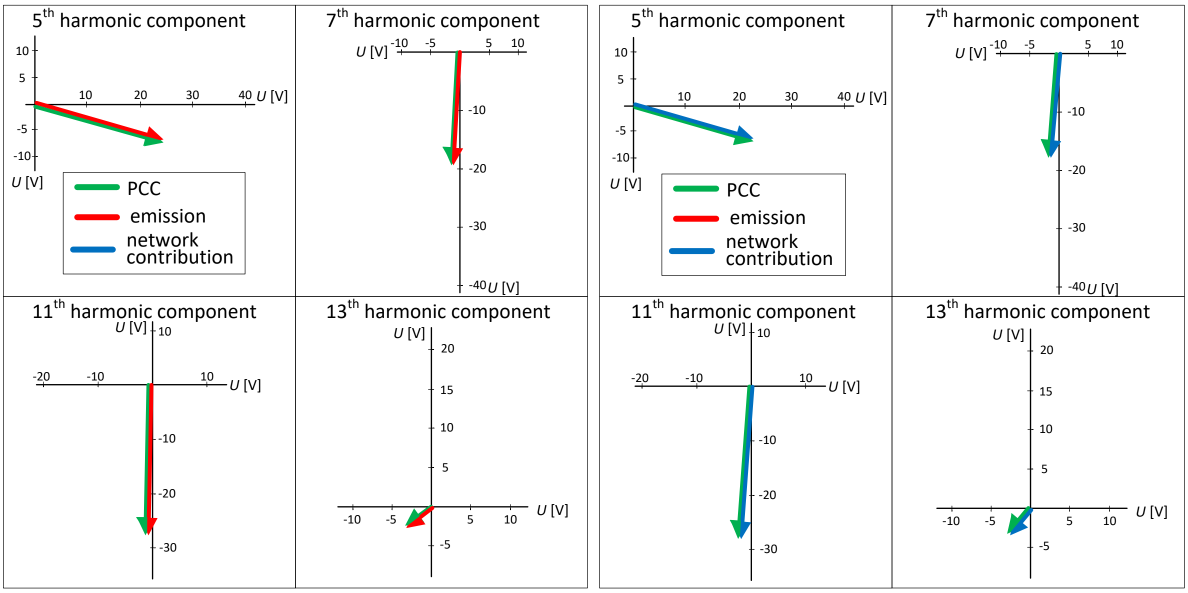

Figure 3: Phasors diagrams of VHV method (PCC 1 – left and PCC 3 – right)

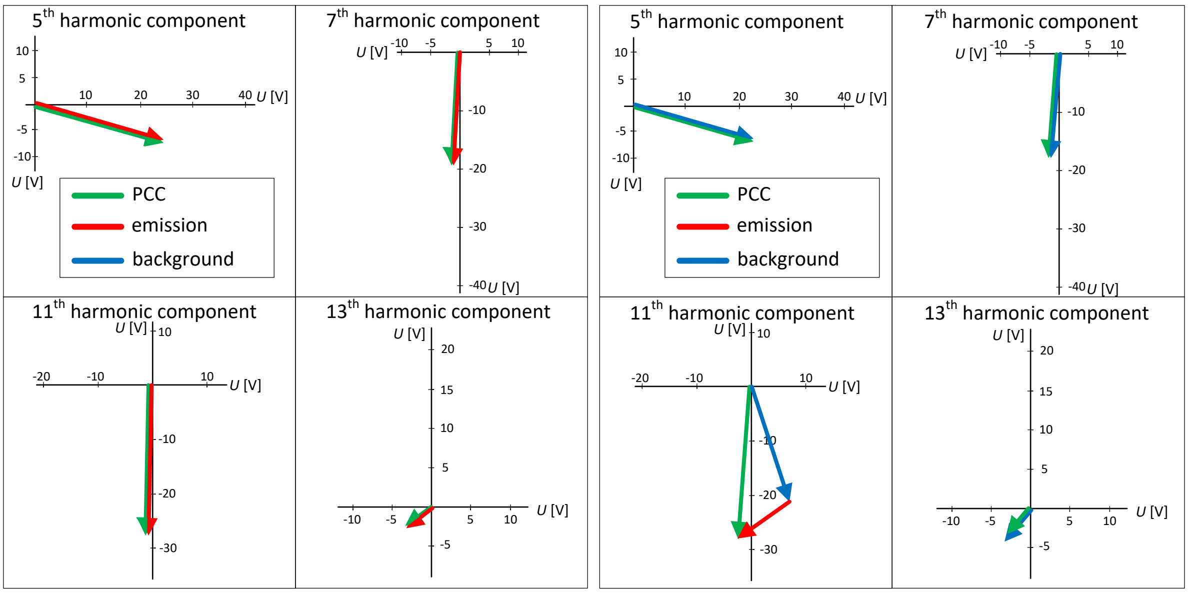

Figure 4: Phasors diagrams of IEC method (PCC 1 – left and PCC 3 – right)

Table 11: Results of emission for Case C

Harmonic order	PCC 1			PCC 2			PCC 3			PCC 4		
	VHV	IEC	SIM	VHV	IEC	SIM	VHV	IEC	SIM	VHV	IEC	SIM
	U_{RMS} [V]	U_{RMS} [V]	U_{RMS} [V]	U_{RMS} [V]	U_{RMS} [V]	U_{RMS} [V]	U_{RMS} [V]	U_{RMS} [V]	U_{RMS} [V]	U_{RMS} [V]	U_{RMS} [V]	U_{RMS} [V]
5th (250 Hz)	28.44	28.67	39.53	15.66	14.80	39.91	0.00	0.00	38.30	2.81	2.66	2.96
7th (350 Hz)	26.64	27.29	36.13	12.53	11.95	35.92	0.01	0.00	35.05	1.90	1.79	2.09
11th (550 Hz)	38.48	46.67	38.99	11.74	11.06	39.51	0.00	0.24	38.77	2.09	1.96	2.57
13th (650 Hz)	11.34	13.71	16.90	10.88	10.39	17.72	0.15	0.00	17.28	1.40	1.28	1.74

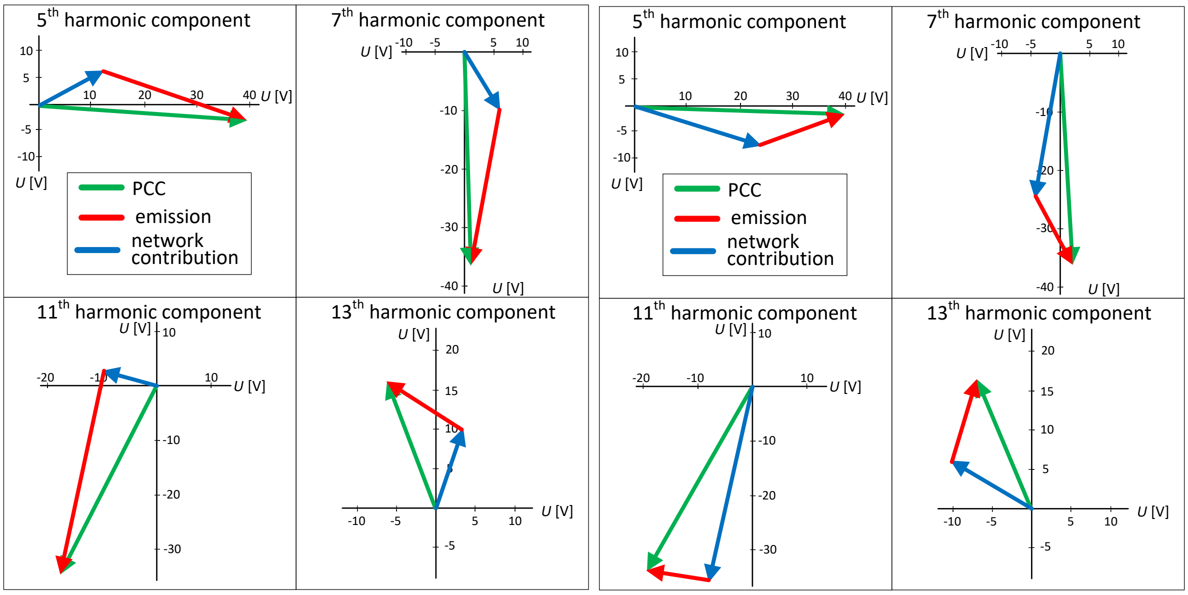

Figure 5: Phasor diagrams of VHV method (PCC 1 – left and PCC 2 - right)

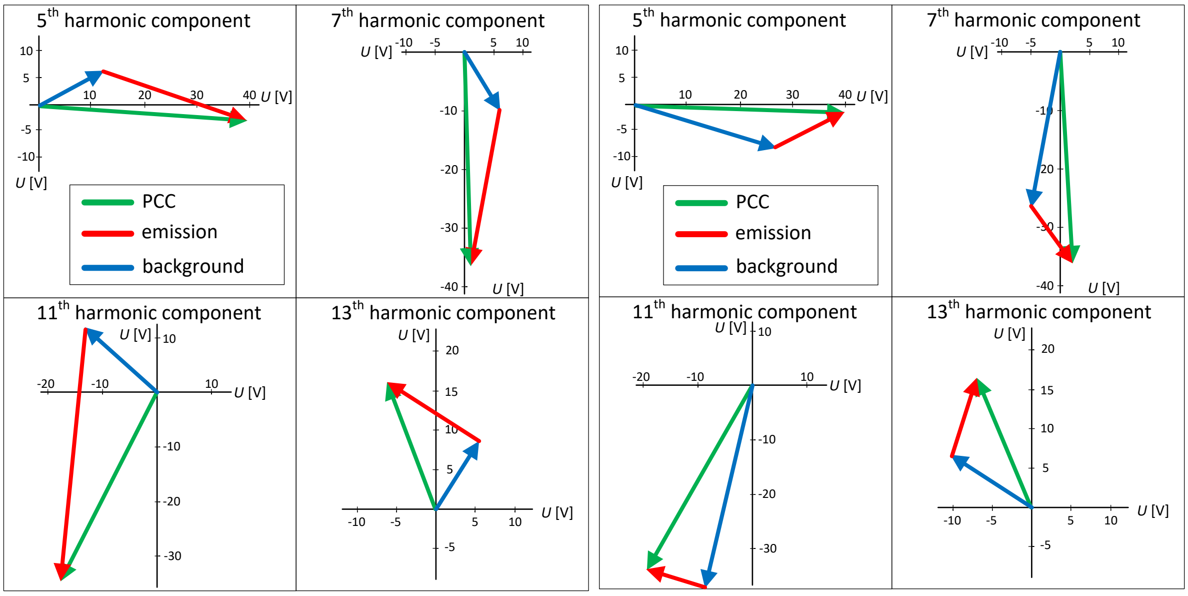

Figure 6: Phasors diagrams of IEC method (PCC 1 – left and PCC 2 - right)

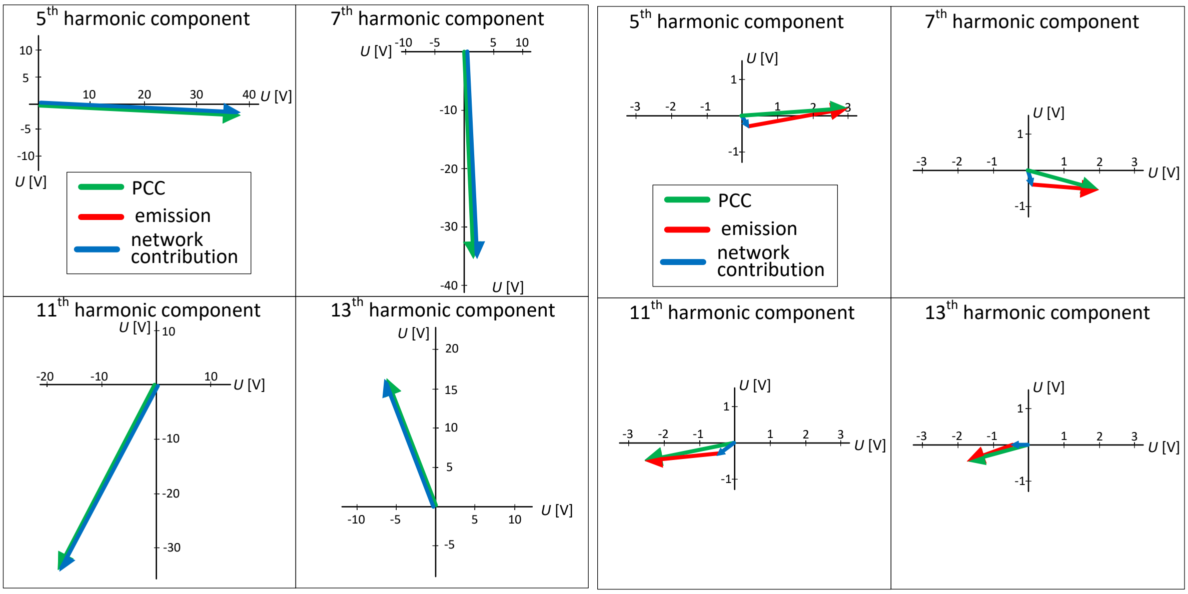

Figure 7: Phasors diagrams of VHV method (PCC 3 – left and PCC 4 - right)

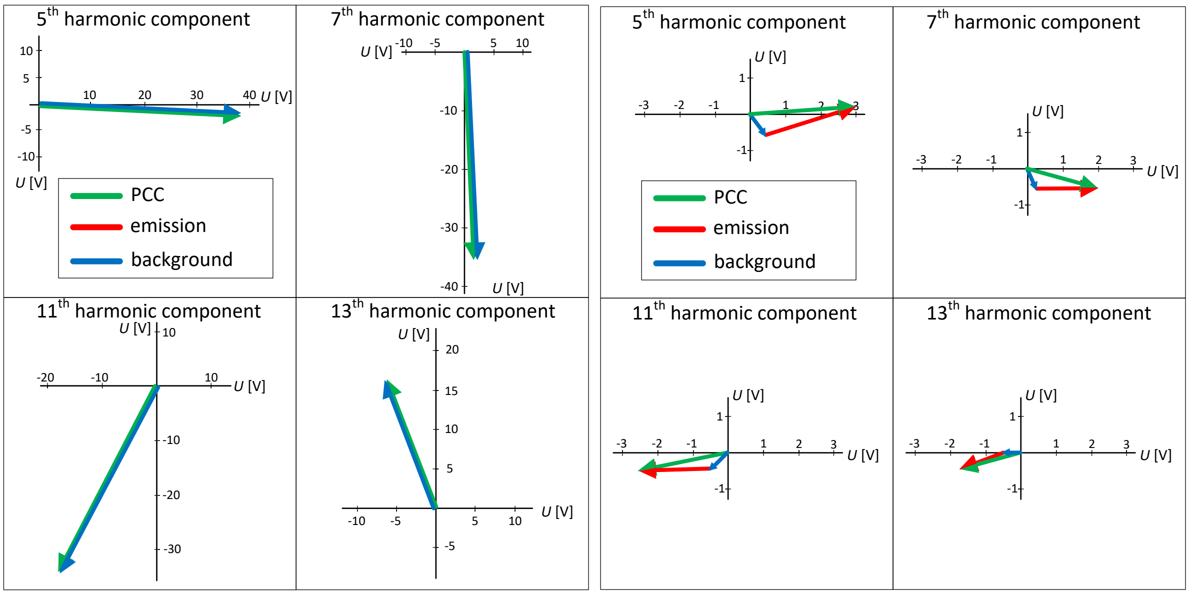

Figure 8: Phasors diagrams of IEC method (PCC 3 – left and PCC 4 – right)

Some remarks on background harmonic distortion

Background harmonic distortion can be defined as the aggregated level of harmonic distortion present in the supply voltage at a PCC excluding the connection of a new linear or non-linear load or generator to the PCC.

The test system takes into account endogenous background harmonics (e.g. Case A - those created by LOAD 1 connected to PCC 1 into PCC 3).

Adding exogenous background harmonics is possible and quite easy from the modelling point of view. In fact, the HV grid equivalent is constituted by the series of an ideal voltage source at 50 Hz with a resistance and an inductance; so it is easy to insert in series more ideal voltage generators at specific harmonic frequencies.

Of course superimposing both exogenous and endogenous background distortion require the management of an increased number of sources making more difficult the analyses. Moreover, this could not reflect on the comparison among different methods.

Proposed unsymmetrical network model

The proposed three phase unsymmetrical benchmark model for harmonic analysis (Fig. 9) is under development.

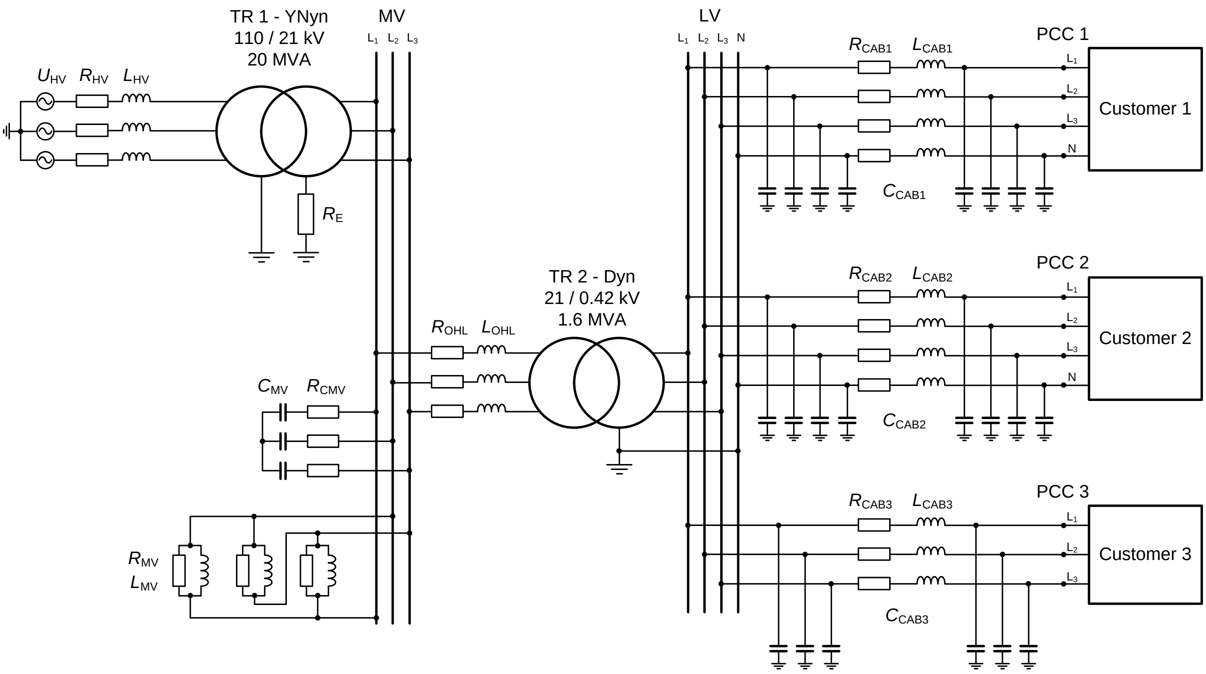

Figure 9: Network model

Customer 1

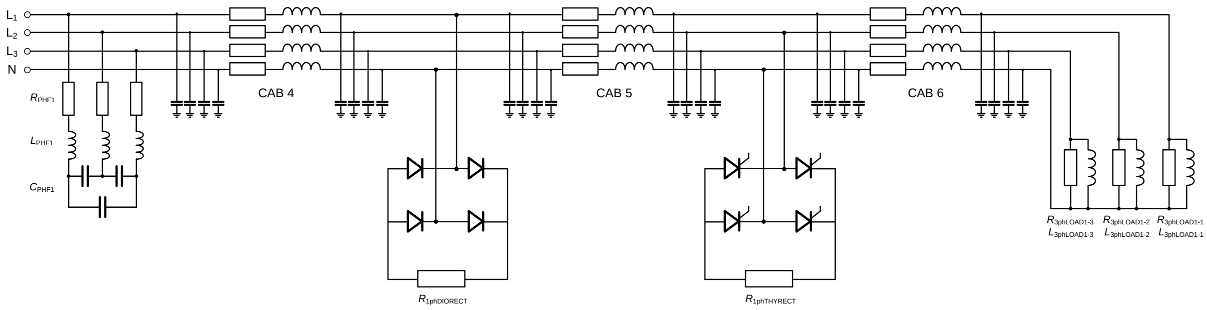

Figure 10: Model of Customer 1

Customer 2

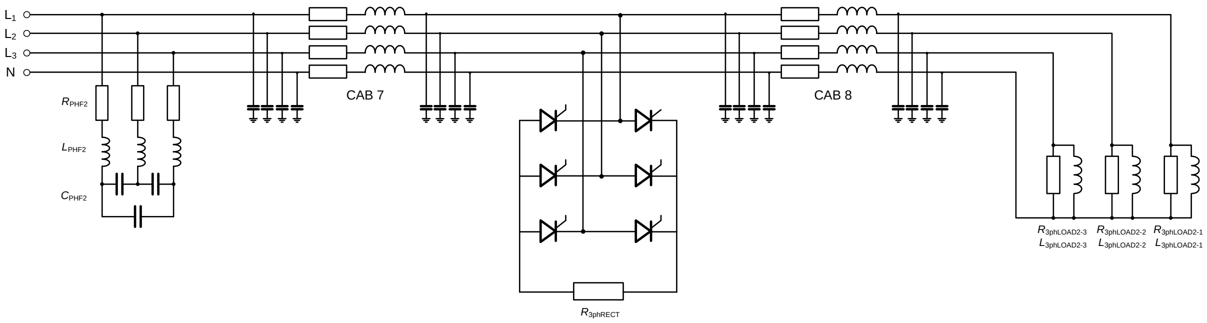

Figure 11: Model of Customer 2

Customer 3

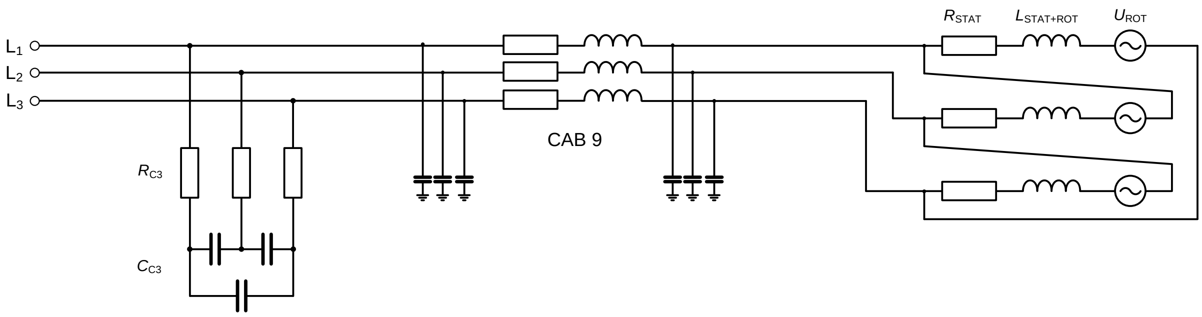

Figure 12: Model of Customer 3