Proceedings of the Seventh IASTED International Conference
POWER AND ENERGY SYSTEMS
August 29–31, 2007, Palma de Mallorca, Spain
ISBN Hardcopy: 978-0-88986-689-8 / CD: 978-0-88986-690-4

ESTIMATION OF HARMONIC EMISSION LEVELS WITH HARMONIC CURRENT VECTOR METHOD WITH REFERENCE IMPEDANCES

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ABSTRACT
This paper proposes a method for estimation of customer harmonic emission levels at the point of common coupling. The proposed method is based on the harmonic current vector method where reference impedances are introduced. The results of the proposed method are compared with the results of the method where customer harmonic emission levels are determined with switching manoeuvres of the customer distorting load. The proposed method can also evaluate the responsibility for harmonic distortion at the point of common coupling. The presented method allows calculation of harmonic emission levels without any switching manoeuvres or without knowing the actual customer impedances. It also enables the evaluation of customer and utility harmonic contributions in resonance conditions.

KEY WORDS
Power quality, harmonic emission level, resonance conditions, reference impedances

1. Introduction

To ensure high power quality, customers influence on the power system at the connection point need to be assessed. Due to the widespread use of power electronic loads the harmonics present an important factor in power quality. The harmonic problems arise especially in case when capacitance in the system results in resonance at a critical harmonic frequency [1]. Therefore an estimation of harmonic emission levels and determination of responsibility for harmonic distortion are necessary. Harmonic emission level from a distorting load is defined as the harmonic current or voltage which would be caused by the load into the power system if no other distorting load was present [2]. Many techniques to estimate harmonic emission levels have been proposed although many of them are complex or based on switching manoeuvres of the considered load or auxiliary elements [3, 4].

This paper proposes a method for estimation of harmonic emission levels. Harmonic current vector method (HCVM) where reference impedances are used [5, 6] is proposed to estimate the customer harmonic emission levels at the point of common coupling (PCC). The method is based on Norton/Thevenin equivalent circuit where actual customer and utility impedances are replaced with the reference impedances. The utility reference impedance is determined with the sum of the short circuit network impedance and the last transformer before the connection point. As the widespread power factor management policy claims that a customer load should be purely resistive, the resistance is introduced as customer reference impedance. The customer reference impedance can be calculated directly from measurement data at PCC.

The determination of the harmonic emission levels and the responsibility for harmonic distortion with the HCVM with reference impedances is verified through the simulation study in PSCAD simulation software.

2. Harmonic Current Vector Method with Reference Impedances

Harmonic current vector method represents the utility and customer side with the Norton/Thevenin equivalent circuit. The method separates harmonic currents and voltages at PCC into two components, the utility and the customer component, from which individual harmonic contributions to harmonic distortion can be determined. With the basic HCVM [7], the equivalent circuit is composed of a current or voltage harmonic source (for the customer and utility side) and the actual impedance for a particular harmonic order. Although the utility side impedance can usually be obtained, the customer impedances and especially their frequency characteristics are rarely available. The customer impedances also vary accordingly to the customer loading conditions, which makes the customer impedances determination even more demanding. Therefore, reference impedances were introduced as equivalent impedances. The main idea is to transform any deviation of customer or utility impedance from the reference one into an additional harmonic source. The determination of the customer reference impedance depends on whether the current or voltage harmonic contributions are calculated.

2.1 Harmonic Current Contributions

The Norton equivalent circuit with reference impedances is shown in Fig. 1. The circuit is composed of the customer and the utility current harmonic sources ($\underline{I}_{Ch}$ and $\underline{I}_{Uh}$) and reference impedances, where $\underline{Z}_{Ch\text{-}ref}$ stands for customer reference impedance and $\underline{Z}_{Uh\text{-}ref}$ for utility reference impedance at a particular harmonic order h. Measurements are taken at the PCC and are represented with current phasor $\underline{I}_{Ph}$ and voltage phasor $\underline{U}_{Ph}$. Letter h in variable indexes is an integer representing the harmonic order.

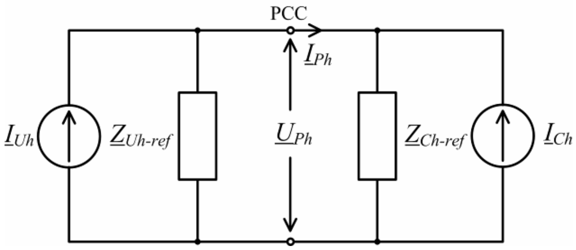

Figure 1. Norton equivalent circuit with reference impedances.

The customer load resistive component was proposed as the customer reference impedance ($\underline{Z}_{Ch\text{-}ref}$) [5]. The customer reference impedance is defined with the customer load resistive component (R_{C1p}) which can be calculated directly from the measurement data at fundamental frequency at PCC. On the utility side the sum of the short circuit network impedance and the last transformer impedance before the connection point was proposed as the utility side reference impedance ($\underline{Z}_{Uh\text{-}ref}$).
When dealing with harmonic current contributions, the customer impedance is represented as a parallel connection of the resistor and the reactance. The current through the reactance is transformed into an additional current harmonic source [6]. Since customer facilities usually do not include active power generation, the customer reference impedance can be calculated from the measured fundamental frequency active power P and voltage U_{P1}.

$$\underline{Z}_{Ch-ref} = R_{C1p} = \frac{|\underline{U}_{P1}|^2}{P} = \frac{|\underline{U}_{P1}|}{|\underline{I}_{P1}| \cdot \cos\gamma_{P1}} . \qquad (1)$$

In (1) the γ_{P1} represents the phase angle between the measured fundamental frequency current and voltage with the corresponding magnitudes U_{P1} and I_{P1}. The customer harmonic current source is calculated with (2).

$$\underline{I}_{Ch} = \frac{\underline{U}_{Ph}}{R_{C1p}} - \underline{I}_{Ph} . \qquad (2)$$

With the determination of utility reference impedance (sum of the short circuit network impedance and the last transformer impedance before the connection point) the utility harmonic current source is calculated according to (3).

$$\underline{I}_{Uh} = \frac{\underline{U}_{Ph}}{\underline{Z}_{Uh-ref}} + \underline{I}_{Ph} . \qquad (3)$$

The utility and customer harmonic contributions to measured current $\underline{I}_{Ph}$ can be determined with the superposition principle [5-7]. The utility ($\underline{I}_{U\text{-}Ph}$) and the customer ($\underline{I}_{C\text{-}Ph}$) harmonic current contributions or harmonic emission levels at PCC are determined with (4) and (5).

$$\underline{I}_{U-Ph} = \frac{\underline{Z}_{Uh-ref}}{\underline{Z}_{Uh-ref} + R_{C1p}} \cdot \underline{I}_{Uh} , \qquad (4)$$

$$\underline{I}_{C-Ph} = -\frac{R_{C1p}}{\underline{Z}_{Uh-ref} + R_{C1p}} \cdot \underline{I}_{Ch} . \qquad (5)$$

The calculation of the utility (I_{Uhs}) and customer (I_{Chs}) scalar harmonic current contributions at PCC are explained in [5, 6]. The scalar harmonic current contributions can have either a positive or a negative sign. The negative sign component actually compensates the positive sign component, i.e. reduces a particular harmonic at PCC.

2.2 Harmonic Voltage Contributions

The Thevenin equivalent circuit is used to determine the harmonic voltage contributions. The Thevenin equivalent circuit with reference impedances is shown in Fig. 2.

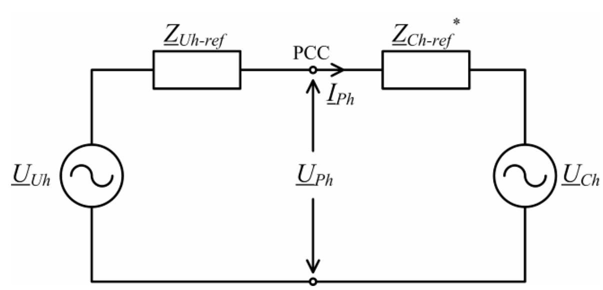

Figure 2. Thevenin equivalent circuit with reference impedances.

The circuit is composed of the customer and the utility voltage harmonic sources ($\underline{U}_{Ch}$ and $\underline{U}_{Uh}$) and reference impedances $\underline{Z}_{Ch\text{-}ref}$* and $\underline{Z}_{Uh\text{-}ref}$ respectively. The customer reference impedance is calculated with (6).

$$\underline{Z}_{Ch-ref}{}^* = R_{C1s} = \frac{P}{|\underline{I}_{P1}|^2} = \frac{|\underline{U}_{P1}| \cdot \cos\gamma_{P1}}{|\underline{I}_{P1}|} . \qquad (6)$$

In (6) γ_{P1} represents the phase angle between the measured fundamental frequency current and voltage. The customer and utility voltage harmonic source can be calculated with (7) and (8).

$$\underline{U}_{Ch} = \underline{U}_{Ph} - \underline{I}_{Ph} \cdot R_{C1s} \,, \tag{7}$$

$$\underline{U}_{Uh} = \underline{U}_{Ph} + \underline{I}_{Ph} \cdot \underline{Z}_{Uh-ref} \,. \tag{8}$$

The utility ($\underline{U}_{U\text{-}Ph}$) and customer ($\underline{U}_{C\text{-}Ph}$) harmonic contributions to measured voltage $\underline{U}_{Ph}$ (harmonic voltage emissions) are calculated with (9) and (10).

$$\underline{U}_{U-Ph} = \frac{R_{C1s}}{\underline{Z}_{Uh-ref} + R_{C1s}} \cdot \underline{U}_{Uh} \,, \tag{9}$$

$$\underline{U}_{C-Ph} = \frac{\underline{Z}_{Uh-ref}}{\underline{Z}_{Uh-ref} + R_{C1s}} \cdot \underline{U}_{Ch} \,. \tag{10}$$

The calculation of the scalar harmonic voltage contributions (U_{Uhs}, U_{Chs}) is explained in [5, 6]. The scalar harmonic voltage contributions can have either a positive or a negative sign. The component negative sing represents the compensation of a particular harmonic at PCC.

3. Simulation Study

A simulation study of harmonic emission level estimation with the HVCM with reference impedances was performed with the PSCAD simulation software. The simulation study included two cases where different customer loads were connected to the network. To study the customer influence on the power system, the customer was simulated as a linear load with a capacitor bank for reactive power compensation and as a nonlinear load. To simulate the harmonic distortion from other loads in the network the harmonic source was added on the utility side. As the most problematic conditions appear around the resonance frequency, special attention was paid to the harmonics near this frequency.
The simulated network model with the harmonic source on the utility side is presented in Fig. 3.

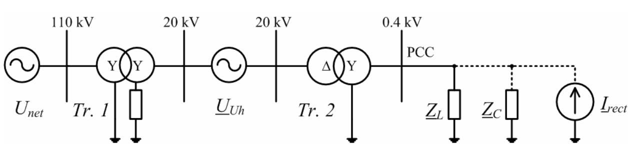

Figure 3. Single-phase diagram of the network model.

The utility side network is modeled as a stiff voltage source (U_{net}) feeding the customer over a 110/20 kV transformer (Tr. 1) and a 20/0.4 kV transformer (Tr. 2). The harmonic voltage source on the utility side ($\underline{U}_{uh}$) injects the 5th and the 13th order harmonics. The customer in the first case includes a linear *R-L* load ($\underline{Z}_L$) and a nonlinear load. Nonlinear load is simulated with a 3-phase rectifier feeding a dc load. In the second case the customer load consists of a linear *R-L* load and a capacitor bank ($\underline{Z}_C$) for reactive power compensation. The values of individual network components are given in Table I.

TABLE I
VALUES OF INDIVIDUAL NETWORK COMPONENTS

Component	Parameter	Value
Stiff voltage source	U_N	110 kV
	S_k''	1500 MVA
	R/X	0,1
Tr. 1, 110/20 kV	S_N	31,5 MVA
	u_k	14 %
	R/X	0,1
Tr. 2, 20/0,4 kV	S_N	0,4 MVA
	u_k	6 %
	R/X	0,2
$\underline{Z}_L$	P_L	100 kW
	$\cos\varphi$	0,9
$\underline{Z}_C$	Q_C	40 kVAr
	R/X_C	0,01
$\underline{U}_{Uh}$	$\underline{U}_{U5}$	115,5 V∟0°
	$\underline{U}_{U13}$	11,5 V∟0°
3-phase rectifier	S_{rect}	100 kVA

The results of harmonic emission levels obtained with the HVCM using reference impedances were compared with the results where switching manoeuvres of the considered load were used. The method for customer harmonic emission levels estimation with switching of the customer distorting load is explained in [3].

3.1 Customer: nonlinear load

In the first case the customer is represented with a linear *R-L* load and a nonlinear load which can be switched on or off. Simulation results of voltage and current at PCC are presented in Table II where measured current $\underline{I}_{Ph}$, voltage $\underline{U}_{Ph}$ and phase angle γ_{Ph} are given. Due to symmetrical conditions in the network only the results of phase L1 are presented in the paper.

TABLE II
SIMULATION RESULTS AT PCC – CUSTOMER NONLINEAR LOAD

	Nonlinear load OFF			Nonlinear load ON		
Harm. order	$\underline{U}_{Ph}$ (V)	$\underline{I}_{Ph}$ (A)	γ_{Ph} (°)	$\underline{U}_{Ph}$ (V)	$\underline{I}_{Ph}$ (A)	γ_{Ph} (°)
1	228,5	158,6	-25,9	227,3	299,4	-16,2
5	2,23	0,66	-67,6	2,71	28,5	-307,4
13	0,22	0,03	-80,5	3,16	9,25	-264,1

It can be seen from the results that the harmonics at PCC increase when the customer nonlinear load is connected to the network.
The comparison of the customer load switching method and the HVCM with reference impedances is presented in

Table III and Table IV. In Table III angle $\varphi_{C\text{-}Phsw}$ is the argument of the customer harmonic current emissions $\underline{I}_{C\text{-}Phsw}$ determined with the switching method, and angle $\varphi_{C\text{-}Ph}$ the argument of the customer current emissions $\underline{I}_{C\text{-}Ph}$ determined with the HCVM with reference impedances. In Table IV angles $\delta_{C\text{-}Phsw}$ and $\delta_{C\text{-}Ph}$ are the arguments of the customer harmonics voltage emissions determined with load switching method ($\underline{U}_{C\text{-}Phsw}$) and with HCVM with reference impedances ($\underline{U}_{C\text{-}Ph}$).

TABLE III
CUSTOMER HARMONIC CURRENT EMISSIONS - COMPARISON OF A SWITCHING LOAD METHOD AND HCVM WITH REFERENCE IMPEDANCES

	Switching load		**HCVM with ref. imp.**	
Harm. order	$\underline{I}_{C\_Phsw}$ **(A)**	$\varphi_{C\text{-}Phsw}$ **(°)**	$\underline{I}_{C\text{-}Ph}$ **(A)**	$\varphi_{C\text{-}Ph}$ **(°)**
5	27,8	-158,7	26,1	-161,5
13	9,6	-159,1	9,69	-155,6

TABLE IV
CUSTOMER HARMONIC VOLTAGE EMISSIONS - COMPARISON OF A SWITCHING LOAD METHOD AND HCVM WITH REFERENCE IMPEDANCES

	Switching load		**HCVM with ref. imp.**	
Harm. order	$\underline{U}_{C\_Phsw}$ **(V)**	$\delta_{C\text{-}Phsw}$ **(°)**	$\underline{U}_{C\text{-}Ph}$ **(V)**	$\delta_{C\text{-}Ph}$ **(°)**
5	3,39	109,1	3,1	106,1
13	3,03	110,1	2,98	113,5

It can be seen from results in Table III and Table IV that both methods give similar results for customer harmonic emission levels. However the HCVM with reference impedances require only measurements at PCC and does not require any load switching manoeuvres. Also the HCVM with reference impedances enables the evaluation of the responsibility for harmonic distortion at PCC. The results of responsibility for harmonic distortion at PCC are given in Table V where U_{Uhs} and I_{Uhs} present the utility and U_{Chs} and I_{Chs} the customer contribution to voltage and current harmonic at PCC.

TABLE V
CUSTOMER AND UTILITY SCALAR CONTRIBUTIONS TO HARMONIC DISTORTION AT PCC

	Nonlinear load OFF		**Nonlinear load ON**	
Harm. order	5	13	5	13
I_{Uhs} **(A)**	0,66	0,05	2,4	-0,44
I_{Chs} **(A)**	0	-0,02	26,1	9,69
U_{Uhs} **(V)**	2,28	0,22	0,46	0,2
U_{Chs} **(V)**	-0,05	0	2,25	2,96

The results show that the customer contributions to harmonic distortion increase when the customer nonlinear load is switched on. When nonlinear load is not connected to the network the customer indicates a negative or a zero contribution to harmonic distortion. A negative sign component actually indicates the compensation of the positive sign component, i.e. mitigation of a particular harmonic at PCC.

3.2 Customer: linear load

The customer consists of a linear *R-L* load and a capacitor bank which can be switched on or off. Simulation results of voltage and current at PCC are presented in Table VI where measured current $\underline{I}_{Ph}$, voltage $\underline{U}_{Ph}$ and phase angle γ_{Ph} are given.

TABLE VI
SIMULATION RESULTS AT PCC – CUSTOMER LINEAR LOAD

	Capacitor bank OFF			**Capacitor bank ON**		
Harmonic order	$\underline{U}_{Ph}$ **(V)**	$\underline{I}_{Ph}$ **(A)**	γ_{Ph} **(°)**	$\underline{U}_{Ph}$ **(V)**	$\underline{I}_{Ph}$ **(A)**	γ_{Ph} **(°)**
1	228,5	158,6	-25,9	229,9	144,7	-4,8
5	2,23	0,66	-67,6	2,62	2,6	79,8
13	0,22	0,03	-80,5	1,48	4,61	81,9

It can be seen from the results that the harmonic voltages at PCC increase when the customer capacitor bank is connected to the network. Although the customer does not have any harmonic source on his side, the harmonic amplification is clearly a consequence of unsuitable customer impedance. As a series resonance appears around 13th harmonic order (650 Hz) especially large 13th harmonic amplification can be seen when the customer capacitor bank is switched on. The comparison of the customer load switching method and the HVCM with reference impedances is presented in Table VII and Table VIII. The variables are explained with Table III and Table IV in previous section.

TABLE VII
CUSTOMER HARMONIC CURRENT EMISSIONS - COMPARISON OF A SWITCHING LOAD METHOD AND HCVM WITH REFERENCE IMPEDANCES

	Switching load		**HCVM with ref. imp.**	
Harm. order	$\underline{I}_{C\_Phsw}$ **(A)**	$\varphi_{C\text{-}Phsw}$ **(°)**	$\underline{I}_{C\text{-}Ph}$ **(A)**	$\varphi_{C\text{-}Ph}$ **(°)**
5	3,16	-35,2	2,8	-11,1
13	4,59	55,0	4,48	55,4

TABLE VIII
CUSTOMER HARMONIC VOLTAGE EMISSIONS - COMPARISON OF A SWITCHING LOAD METHOD AND HCVM WITH REFERENCE IMPEDANCES

	Switching load		**HCVM with ref. imp.**	
Harm. order	$\underline{U}_{C\_Phsw}$ **(V)**	δ_{C-Phsw} **(°)**	$\underline{U}_{C-Ph}$ **(V)**	δ_{C-Ph} **(°)**
5	0,39	-127,4	0,33	-103,2
13	1,48	-35,9	1,37	-35,5

Again both methods produce similar results therefore it can be concluded that HCVM using reference impedances properly indicates the customer harmonic emission level. It should be pointed out that both methods present an estimation of the harmonic emission levels therefore small deviations are expected. The results of responsibility for harmonic distortion are presented in Table IX.

TABLE IX
CUSTOMER AND UTILITY SCALAR CONTRIBUTIONS TO HARMONIC DISTORTION AT PCC

	Capacitor bank OFF		**Capacitor bank ON**	
Harm. order	5	13	5	13
I_{Uhs} **(A)**	0,66	0,05	0,19	0,13
I_{Chs} **(A)**	0	-0,02	2,41	4,48
U_{Uhs} **(V)**	2,28	0,22	2,31	0,12
U_{Chs} **(V)**	-0,05	0	0,31	1,36

As expected the whole responsibility for the 5th and the 13th harmonic is on the utility side when the capacitor bank is switched off. A negative sign in case of customer contributions indicates that some harmonics are mitigated by the customer. When the customer capacitor bank is switched on, the responsibility for the 5th voltage harmonic stays almost fully on the utility side, although the customer responsibility for the 5th voltage harmonic increases. This seems reasonable as the 5th voltage harmonic at PCC increases as a consequence of the 5th harmonic current amplification caused by the load side. The customer with the capacitor bank switched on demonstrates series resonance around the 13th harmonic order. Regardless of the fact that the customer does not have a harmonic source on its side the method shows almost full customer responsibility for the 13th harmonic distortion. This is sensible regarding the customer responsibility for harmonic amplification as the consequence of series resonance. It should be pointed out that in case of resonance conditions the HCVM where actual impedances are used would not show any customer responsibility for harmonic distortion at PCC therefore the customer would not be responsible for any harmonic amplification.

5. Conclusion

This paper presents a method for estimation of customer harmonic emission levels at the point of common coupling. The proposed method is based on the harmonic current vector method where reference impedances are used. The main advantage of this method is that it does not require the knowledge of customer impedances or any switching manoeuvres of distorting customer loads. The customer harmonic emission levels can be calculated directly from the measurement data at PCC. The proposed method can also evaluate the responsibility for harmonic distortion at the point of common coupling. It also enables the evaluation of customer and utility harmonic contributions in resonance conditions.
Although the determination of the responsibility for harmonic distortion and harmonic emission levels is very important the determination should be simple due to practical reasons. The presented method indicates the right approach but practical implementation of the method remains to be realized.

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