DETERMINATION OF HARMONIC EMISSION OF AN INDUSTRIAL INSTALLATION

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ABSTRACT

The performance of two harmonic emissions assessment methods was tested on field measurements – the harmonic current vector method and the multiplication of harmonic current magnitudes with network harmonic impedance. With the comparison of obtained emissions with expected steel production plant's harmonic pollution profile and characteristic harmonic voltage levels in distribution power network the validity of both methods has been confirmed. The method's sensibility on harmonic phasors angle inaccuracy and other input parameters has also been examined.

INTRODUCTION

Harmonic emissions assessment is gaining importance due to the growing numbers of non-linear loads in customers' facilities. As high levels of harmonic pollution in power system can cause problems with electromagnetic compatibility, increased losses in transmission and tripping of induction motors torque, the determination and assessment of customer's contribution to harmonic pollution has been the goal of research for many years.

The first methods of customer's harmonic emissions determination were based on harmonic power flow, but were found misleading and unsuitable. A breakthrough has been made with harmonic current vector method [1], which modeled utility and customer side at the point of common coupling (PCC) with reference impedances and represented harmonic emissions as scalar projections on harmonic phasors measured at PCC. The method was further developed in [2] where resistance at fundamental frequency, obtained from measurements, was taken as customer reference impedance.

The joint CIRED/CIGRE working group C 4.109 [3] has introduced some harmonic emissions assessment methods based on the IEC report 61000-3-6. In this paper, the method which determines harmonic emissions based on current and voltage phasor measurements [2] is tested. Results are compared with the "conventional" way, by simply multiplying magnitudes of harmonic current with reference network harmonic impedance.

ASSESSMENT METHOD

The harmonic current vector method according to [2] is based on harmonic voltage and current phasors $\underline{U}_{Ph}$ and $\underline{I}_{Ph}$, obtained from measurements at PCC with Fast Fourier analysis.

The utility and customer side are modeled as harmonic voltage sources and impedances, as is shown in Figure 1.

As utility impedance, the reference impedance calculated from short circuit power was used. Customer's reference impedance is modeled as a resistance, calculated from fundamental frequency voltage and current magnitudes $|\underline{U}_{P1}|$ and $|\underline{I}_{P1}|$ and angle φ_{P1} between these two phasors:

$$\underline{Z}_{Ch-ref} = R_{C1} = \frac{|\underline{U}_{P1}| \cdot \cos\varphi_{P1}}{|\underline{I}_{P1}|} \tag{1}$$

$$\varphi_{P1} = \varphi_{U_{P1}} - \varphi_{I_{P1}} \tag{2}$$

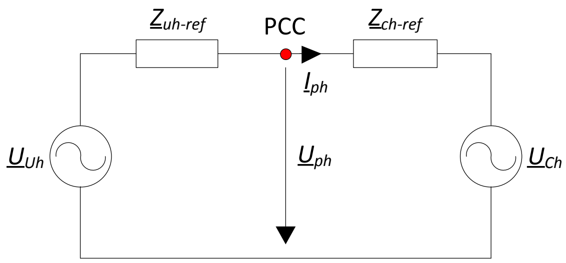

Figure 1: Thevenin circuit used for calculating emissions

Harmonic current sources are calculated using:

$$\underline{U}_{Ch} = \underline{U}_{Ph} - \underline{I}_{Ph} \cdot R_{C1} \tag{3}$$

$$\underline{U}_{Uh} = \underline{U}_{Ph} + \underline{I}_{Ph} \cdot \underline{Z}_{Uh-ref} \tag{4}$$

Then, the phasor contributions to PCC harmonic voltage are calculated using superposition principle:

$$\underline{U}_{C-Ph} = \frac{\underline{Z}_{Uh-ref}}{\underline{Z}_{Uh-ref} + R_{C1}} \cdot \underline{U}_{Ch} \tag{5}$$

$$\underline{U}_{U-Ph} = \frac{R_{C1}}{\underline{Z}_{Uh-ref} + R_{C1}} \cdot \underline{U}_{Uh} \tag{6}$$

Finally, the scalar contributions to PCC harmonic voltage magnitude (emissions) are calculated from phasor contribution magnitudes and its arguments:

$$U_{Chs} = |\underline{U}_{C-Ph}| \cdot \cos(\delta_{C-Ph} - \delta_{Ph}) \tag{7}$$

$$U_{Uhs} = |\underline{U}_{U-Ph}| \cdot \cos(\delta_{U-Ph} - \delta_{Ph}) \tag{8}$$

δ_{Ph} is the argument of PCC harmonic voltage.

Harmonic Phasor Angle Accuracy

Fundamental frequency of power system fluctuates around 50 Hz and causes problems with FFT analysis using fixed FFT window length, leading to significant errors in amplitude and phase. They are most noticeable at 2nd and 3rd harmonic voltage due to the spectral leakage. Therefore, the time window length must be varied according to zero-crossing positions. However, the angle inaccuracy at low order harmonics persists. To solve this problem, an innovative method of processing discrete values in FFT time window [5] has been tested. With linear interpolation

between zero-crossing points a fine fundamental frequency is calculated and subtracted from time spectrum in FFT time window, which considerably improves harmonic voltage angle accuracy. The comparison of phasor magnitude and angle time courses for 2nd harmonic, obtained with varied time window (upper two graphs) and fine frequency subtraction (lower two graphs) can be seen on Figure 2.
The impact of this new approach on harmonic emissions calculations can be seen on Figure 3. Customer's harmonic contributions decrease and utility's contributions increase. Overall, the total level of harmonic voltage is also higher. For example, 2nd harmonic voltage total level and utility emissions are around 0.1-0.2 % p.u. higher when using fine frequency subtraction; on the other hand, customer emissions are up to 0.1 % p.u. lower. Such effect can be observed at all harmonic orders.
This new method using fine frequency subtraction was used to calculate phasors from field measurements.

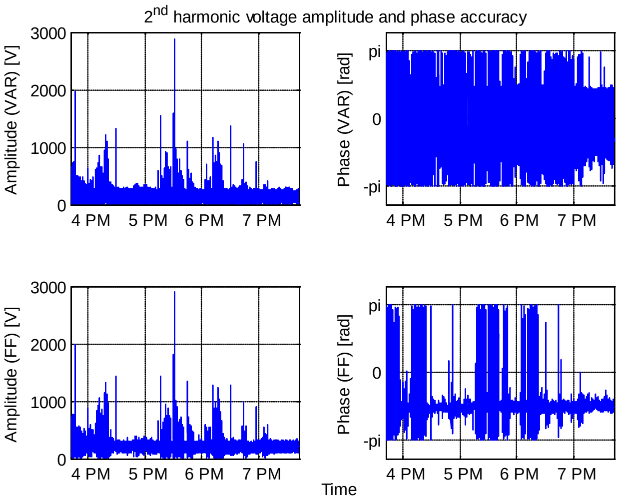

Figure 2: 2nd harmonic voltage amplitude and phase obtained with varied time window (VAR) compared to fine frequency subtraction (FF)

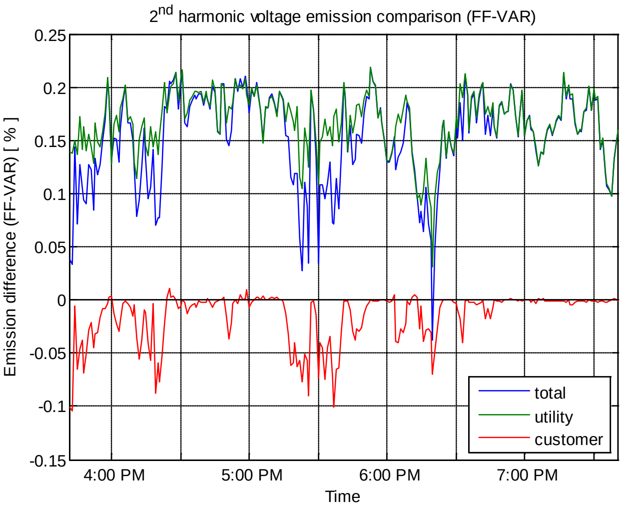

Figure 3: 2nd harmonic voltage emission differences calculated from phasors obtained with fine frequency subtraction compared with emissions calculated from phasors obtained with varied time window

FIELD MEASUREMENT TESTS

Field measurements were carried out at two steel production plants in Austria and Slovenia. Both plants are connected to utility network via 110/20 kV transformers. The Austrian plant is also equipped with an SVC device on MV level (Figure 4). The PCC is in both cases at the 110 kV bus.
The measurement data includes voltage measurements at both sides of feeding transformers and current measurement. The discrete samples are transformed to frequency domain by Fast Fourier analysis with 200 ms time window to provide harmonic voltage and current phasors through time. These phasors together with utility reference impedance are the input parameters to the tested harmonic current vector method which provides emission levels in each 200 ms window. Emission levels are then averaged to provide better observability.

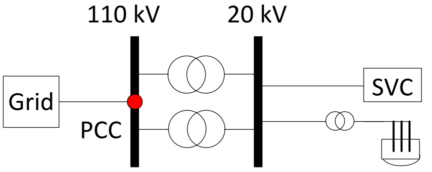

Figure 4: Network scheme for Austrian steel production plant

Case 1: Austrian steel production plant

The measurements at Austrian steel production plant lasted for 4 hours with the sampling frequency of 2000 Hz. The emissions were calculated for 2nd, 3rd, 5th and 7th harmonic voltages and currents and mean emission values were calculated in 1 minute intervals.
Figure 5 presents 2nd harmonic voltage emission levels. It can be observed, that utility contribution level is relatively constant from 0.2 to 0.3 % p.u. whereas the customer emissions coincide with harmonic level peaks and operating state of the arc furnace.

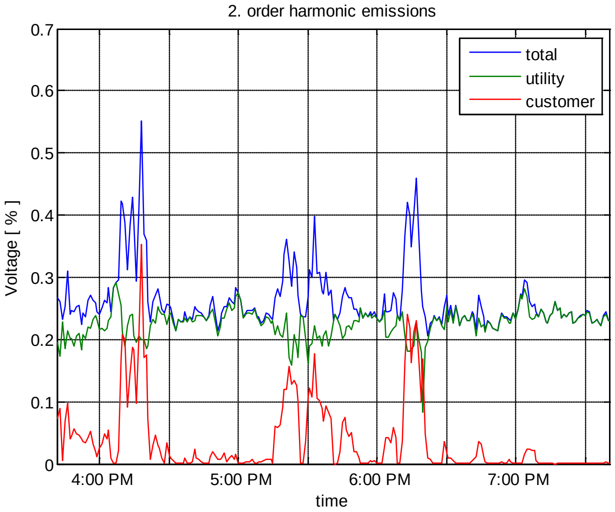

Figure 5: 2nd harmonic order voltage emissions

In Figure 6 time courses of harmonic voltage emissions from the customer installation are shown. The harmonic emissions follow the typical steel production plant operation pattern: with begin of melting cycle, 2nd and 3rd harmonic emissions increase while 5th harmonic level is relatively low. In liquid steel bath phase, 2nd and 3rd harmonic emissions decline, while 5th harmonic emission rises. Also, the 3rd harmonic customer emissions are very low due to the installed SVC.

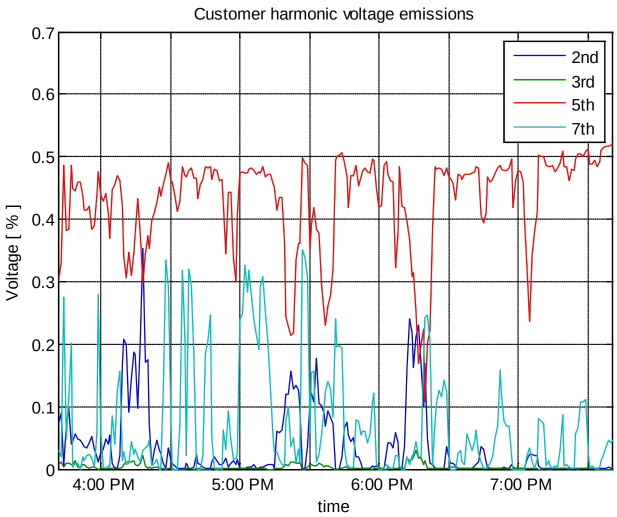

Figure 6: Customer harmonic voltage contributions

Considering utility emissions, the trends through time are shown in Figure 7. 2nd and 3rd order utility voltage emissions are relatively constant, while 5th and 7th harmonics show noticeable downward and upward trends respectively. Since utility emissions represent harmonic contributions from all other loads in network outside the steel plant, one can assign the downward trend of 5th harmonic from 5-6pm to late working hours; later on the emission level increases which is most likely the credit of the household electronic devices turned on after work. The same reason could be applied to upward trend of 7th harmonic after 6pm.

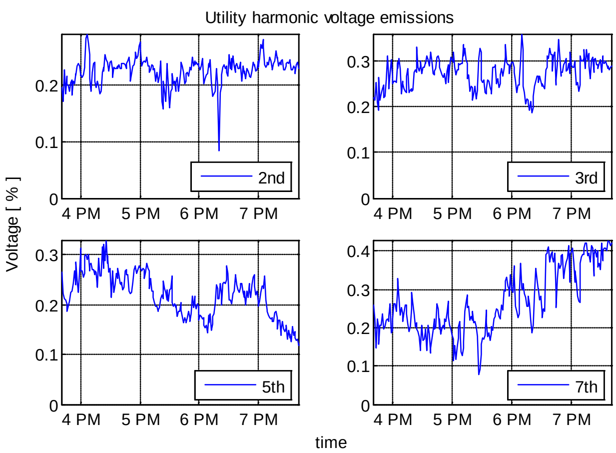

Figure 7: Utility harmonic voltage contributions

Harmonic current emissions are more or less one-sided. Almost 100 % of the harmonic current levels can be credited to the customer side. It is significant to note that the customer harmonic current emissions have similar time patterns as voltage emissions. However, that is not the case by utility current emissions.

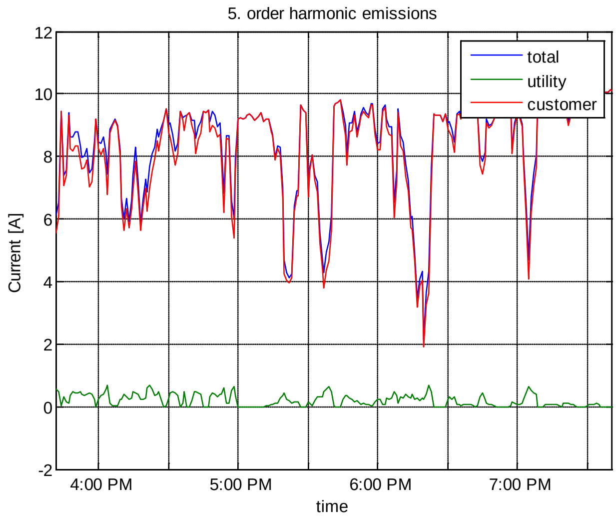

Figure 8: 5th order harmonic current contributions

Case 2: Slovenian steel production plant

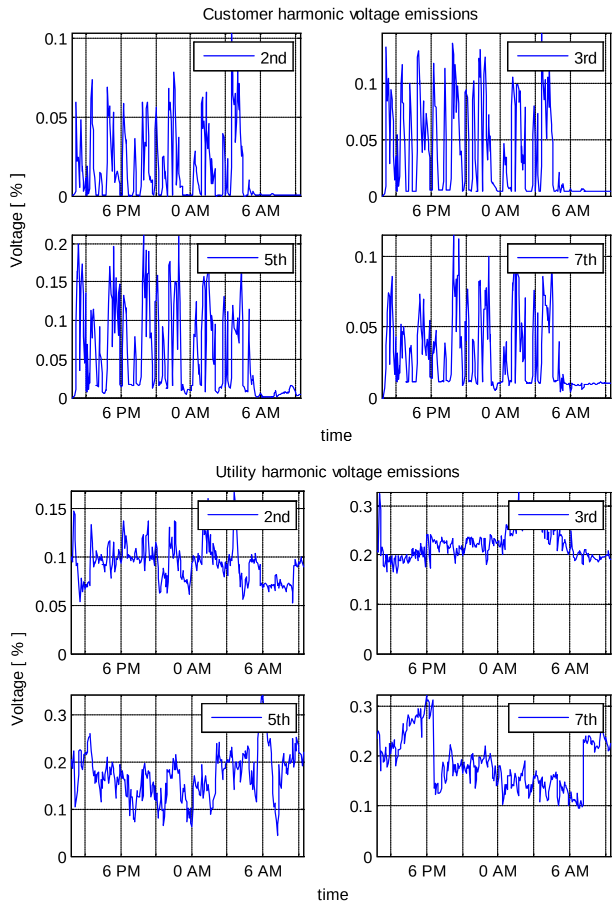

Figure 9: Emissions at Slovenian steel plant

In Slovenia, the measurements lasted for approximately 20 hours with the sampling frequency of 6400 Hz.

The results, displayed on Figure 9, are as expected: utility harmonic contributions are relatively constant and "calmer" as the contributions from customer. Utility's 5th and 7th harmonic are low in sleeping hours with rapid rise in the morning around 7 am. The customer is on the other hand responsible for all the peaks in harmonic voltage levels as its power demand is very strong and turbulent. Although after 6am it can be noted that electric arc furnace operation has stopped.

On the basis of stated tests and observations, the presented emission assessment results appear plausible and suggest that harmonic current vector method is suitable for determination of load's harmonic voltage contributions to the total pollution levels and successfully isolates the influence of already present harmonic emissions in the public network.

CONVENTIONAL METHOD

In C4.109 group report [3], a simple method for determining customer harmonic voltage emissions was proposed by simply multiplying harmonic current magnitude with reference utility harmonic impedance:

$$\left|\underline{U}_{hc}\right| = \left|\underline{I}_{h}\right| \cdot \left|\underline{Z}_{h-ref}\right| \tag{1}$$

Figure 10 shows the difference between emissions calculated using conventional method compared with harmonic current vector method with phasors obtained with fine frequency subtraction. It can be noted that conventional method produces more restrictive results for the customer as its emission levels are always higher, especially at 7th harmonic order, where high difference is probably the consequence of low network impedance at 7th harmonic due to resonance.

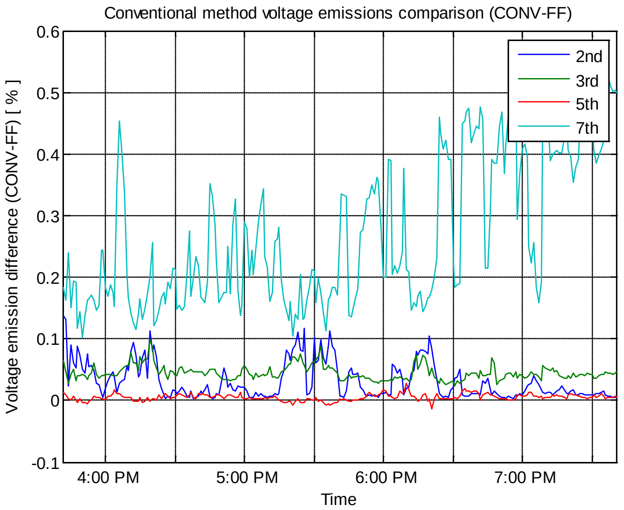

Figure 10: Harmonic voltage emissions, obtained with conventional method, compared with emissions obtained with harmonic current vector method

CONCLUSIONS

This paper examines the performance of two harmonic emission assessment methods: harmonic current vector method and the conventional method using harmonic current magnitudes. The obtained results were verified according to typical harmonic pollution profiles of steel production plants and harmonic levels expected in usual distribution network. Both methods provide results, where melting cycles can be clearly recognized from customer harmonic emissions as harmonic voltage peaks are contributed to the customer. Utility emission levels are relatively constant with characteristic trends in working and sleeping hours.

These tests confirm harmonic current vector method as suitable and practically useful method of assessing harmonic pollution in power grids. However, its downside is relative sensitivity on harmonic phasors' angle accuracy. This issue can be resolved using synchronized measurement sampling frequencies and/or advanced FFT time windowing.

The simpler conventional harmonic assessment method with multiplication of harmonic current magnitudes yields valid results, as harmonic current phasors' time pattern is equal to customer's harmonic voltage emissions time pattern obtained with harmonic current vector method. However, the emission levels obtained with conventional method are considerably higher and thus more restrictive to the customer. The method also provides no information about utility's harmonic pollution and produces too high emission levels in resonance conditions.

The future work with harmonic emissions assessment is the further testing of assessment methods and their final implementation in power quality meters.

REFERENCES

[1] W. Xu, Y. Liu, "A Method for determining Customer and Utility Harmonic Contributions at the Point of Common Coupling", *IEEE Trans. Power Del.*, vol. 15, no. 2, 2000, 804-811.

[2] T. Pfajfar, B. Blažič, I. Papič, "Harmonic Contributions Evaluation with the Harmonic Current Vector Method", *IEEE Trans. Power Del.*, vol. 23, no. 1, 2008, 425-433.

[3] E. De Jaeger et. al., 2010, "Emission Assessment Techniques", Technical report, CIGRE-CIRED Working Group C4.109, April 2010.

[4] IEC/TR 61000-3-6, "Electromagnetic compatibility (EMC) –Part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems", Edition 2, 2008

[5] D. Matvoz, I. Papič, M. Maksić, *Analysis of low-frequency interharmonics in the transmission electric power network*, Elektroinštitut Milan Vidmar, Ljubljana, Slovenia, 2009, 35-41.