Experimental Value of Network Harmonic Impedance

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Abstract: - Experimental study allows for a direct evaluation of the harmonic impedance as seen from a network node or for the identification of the equivalent circuits harmonic parameters followed by a computation of the harmonic impedance using one of the methods implied in more accurate models. The two problems mentioned above seem to have distinct targets, but they have still a common aim, considering that when one is interested in the value of the harmonic impedance the problem to be solved is in fact to identify the transversal impedance of the equivalent circuit of an entire network as seen from the chosen node.

Key words: - harmonic impedance, harmonic currents, Fast Fourier Transform

1 Introduction

Experimental study allows for a direct evaluation of the harmonic impedance as seen from a network node or for the identification of the equivalent circuits harmonic parameters followed by a computation of the harmonic impedance using one of the methods implied in more accurate models. The two problems mentioned above seem to have distinct targets, but they have still a common aim, considering that when one is interested in the value of the harmonic impedance the problem to be solved is in fact to identify the transversal impedance of the equivalent circuit of an entire network as seen from the chosen node.

2 Non-linear Loads as Harmonic Current Sources

Non-linear loads within the power system can be grouped into two categories, according to the source of the harmonic regime: harmonic voltage source, and harmonic current source. The first group includes: inductances, saturated-core transformers, and synchronous generators.

The second group includes: converters, electric arc ovens, electric welding units, gas-discharge and metallic-vapour lamps, and corona discharge. Special attention will be devoted to converters [1], [2], [3]. Considering the harmonic regime, they are characterised by the following:

- The order of current and voltage harmonic is determined by:

  $$k = np \pm 1 \ ,$$

  where

  p = number of pulses,

  n = 1, 2, 3, … for circuits with $p \geq 2$,

  n = 1, 3, 5, 7,… for circuits with p = 1.
- Converter non-linearity increases while p is lower;
- Due to manufacturing inaccuracies, converters with p>12 generate non-specific harmonics, typical for lower p converters; controlled converters are characterised by the existence of the sub-harmonics;
- Neglecting switching process, the magnitude of the current harmonics can be computed as:

  $$I_k = \frac{I_1}{I_k} \qquad (1)$$

  while otherwise they can be computed as:

  $$I_k = \frac{I_1}{\left(k - 5/k\right)\cdot 1.2} \qquad (2)$$
- For a given circuit, increasing the angle α leads to the decreasing of the rectified current, while the frequency spectrum for the network current is negatively affected;
- Thyristor non-symmetric control leads to even-order harmonics to be present within the network (p=2, 6, 12, 18 and 24) for circuits where they do not normally exists and for p=3 they are more severe;
- For single polarity circuits (p=1, 3, 6, 12 etc) the indirect harmonic influence of the uncompensated e.m.f. on the network transformers can be traced when they are equipped with free-flux cores. In this case a strong saturation is present, which strongly distorts the e.m.f. induced into the two windings, so terminal voltage presents high order harmonics;
- The magnitude of the converter generated currents depends on the eddy reactance of the network transformer, as well as on the transformer connection group.

3 Measuring Methods for the Harmonic Impedance

Considering the methods [4] employed to obtain the harmonic currents $\underline{I}_k$ injected into the network, three methods can be identified as using: 1) the harmonic currents of the existed installation, 2) the transient regime triggered by switching certain network elements or 3) the harmonic current injection. A synthesis of these methods is presented in Table 1. Problems related to the methods presented within Table 1 will be mentioned bellow.

Table 1 Methods for obtaining harmonic currents

Method	Means	Advantage	Disadvantage
Harmonic currents injected by the real installation	• rectifiers • converters • electric arc oven • induction ovens	• no supplementary sources • network operation is unaffected • correspondence to the actual operation regime • can supply high harmonic currents	• frequency domain is relatively narrow • interharmonics are liable to appear
Transient regime triggered by switching in and out certain network elements	• condenser banks • saturated-core transformers	• wide frequency spectrum • usual operations, that require no special • relatively high harmonic currents, as compared to the usual situation • harmonics of 700 Hz to 1000 Hz are possible to appear	• short time harmonic regime • condenser banks are used to compensate the network reactive power • strongly unbalanced currents • harmonic current amplitudes depend on the switching instant
Direct injection of the harmonic currents	• electrified rail roads	• high level harmonic currents are generated • harmonic spectrum extending up to 1000 Hz • correspondence to real situation	• high level noise • short time registering time
	• saturated-core transformers, using a DC current injected into the neutral point	• harmonic spectrum extending up to 1000 Hz • harmonic current level can be adjusted • long duration harmonic currents can be granted	• need of special transformers (transformer unit, five-column transformers) • unbalanced harmonic currents • consideration of the previous harmonic currents
	• use of the inter-harmonic current generators	• harmonic spectrum extending up to 2500 Hz • existent harmonics not affected by the appearance of the inter-harmonics	• powerful signal generators are needed • low reactance transformers are needed for connection • non-symmetrical injected currents

4 Determination of the Harmonic Impedance

Absorbed power variation according to the load curve leads to modifications of the nodal voltages and of the currents injected into the network nodes. Such variations can be exploited when evaluating the harmonic impedances. The estimation principle can be traced in Fig. 1.

A supply line is characterised by the admittance $\underline{Y}_k$ and by the source of the harmonic current $\underline{J}_k$ connected to the rest of the network via the harmonic impedance $\underline{Z}_k$ and a harmonic voltage source $\underline{E}_k$. The resulted voltage $\underline{U}_k(t)$ and the injected current $\underline{I}_k(t)$ can be sampled at regularly spaced instants e.g. equal to one minute.

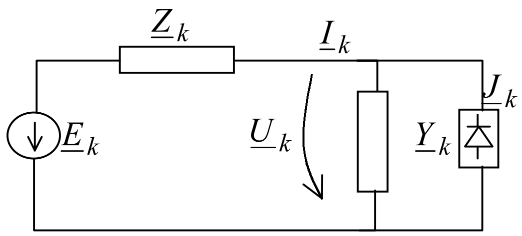

Fig. 1 Equivalent circuit for a line and the rest of the network.

Considering a stable operation and a weak correlation between the network harmonic voltage $\underline{E}_k$ and the input signal $\underline{I}_k(t)$, the output signal $\underline{U}_k(t)$ is sensibly affected by $\underline{I}_k(t)$. Under such circumstances, the time dependence of the network harmonic impedance $\underline{Z}_k(t)$ can be obtained using the inverse Fourier transform [5], [6] starting with the equation:

$$\underline{Z}_k(\omega) = |\underline{Z}_k(\omega)| \exp[j\varphi(\omega)] = \frac{G_{kiu}(\omega)}{G_{kii}(\omega)} \quad (4)$$

where:

$G_{kiu}(\omega)$ is the spectrum of the complex auto-correlation function of the input signal $\underline{I}_k(t)$,

$G_{kii}(\omega)$ is the spectrum of the complex inter-correlation function between the input $\underline{I}_k(t)$ and the output $\underline{U}_k(t)$ signals

The auto-correlation function:

$$g_{kii}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} I_k(t) I_k(t+\tau) dt \quad (5)$$

is approximated by a discrete sum of N terms, where –for instance– N can be even equal to 60. As a result a sampling rate of 1/Δt=1/min is sufficient for the sum to cover an interval of one hour.

Numerical computation can use an equation of the form:

$$g_{kii}(\tau) = g_{kii}(\mu\Delta t) =$$
$$= \frac{1}{N} \sum_{\nu=-N/2}^{N/2} I_k(\nu\Delta t) \cdot I_k[(\nu+\mu)\Delta t] =$$
$$= \frac{1}{N} \sum_{\nu=1}^{N-\mu} I_k(\nu\Delta t) \cdot I_k[(\nu+\mu)\Delta t] \quad (6)$$

Putting $U_k[(\nu+\mu)\Delta t]$ in Eq. (6), the inter-correlation function is obtained:

$$g_{kiu}(\tau) = \frac{1}{N} \sum_{\nu=-N/2}^{N/2} I_k(\nu\Delta t) \cdot U_k[(\nu+\mu)\Delta t] =$$
$$\frac{1}{N} \sum_{\nu=1}^{N-\mu} I_k(\nu\Delta t) \cdot U_k[(\nu+\mu)\Delta t] \quad (7)$$

To obtain the spectral densities $G_{kiu}(\omega)$ and $G_{kii}(\omega)$ to be used in Eq. (4) the discrete Fourier transform can be applied to the sum in Eq. (6) or Eq. (7). It is to be noted that for each harmonic component k a correlation function and respectively a inter-correlation function can be obtained, so $\underline{Z}_k(\omega)$ does not represent the frequency-dependent network impedance, but the variation of the impedance $\underline{Z}_k$ over a time interval. The inverse transform of $\underline{Z}_k(\omega)$ offers the time-domain image for $\underline{Z}_k$, this is $\underline{Z}_k(\omega)$.

5 Harmonic Measurements in Electrical Railroad Systems

Semiconductor converters placed on electric railroad engines, fed via 110kV/27kV transformers, induce harmonic voltages and currents into the supply network, acting as genuine non-sinusoidal regime sources for the 110 kV network. This current injection offers a simple way to identify the harmonic impedances within 110 kV network, for k<20 [1, 2, 7] (Figs. 2–5). Fig. 3 presents the spectrum of the maximum relative harmonic currents specific to electric railroad system. The results have been obtained within the Bucharest–Chitila Substation feeding the railroads running into the North Railroad Station of the city.

Table 2 Experimental results

Measured	Minimum	Maximum	Average
L1N Volts	114.3 k	122.7 k	119.0 k
L1 Amps	0.000	6.371	1.474
L1 PF	0.000 L	1.000 C	0.948
L1 Watts	0.000	527.9 k	165.5 k
L2N Volts	116.1 k	124.5 k	120.9 k

For experimental work the ACE-2000 device has been used. It has processing facilities for power signals, as well as facilities for a harmonic analysis of such signals.

The device can handle single-phase as well as three-phase signals in networks of 3 or 4 conductors. The high registering speed, storage and alarming facilities, its efficient interactive interface with digital display recommend it as a particularly useful device in studying the energy quality problems. It is provided with 6 to 8 analogue input channels, completely insulated (3 to 4 current inputs and 3 to 4 voltage inputs) and 4 numerical channels (2 input channels and 2 output channels).

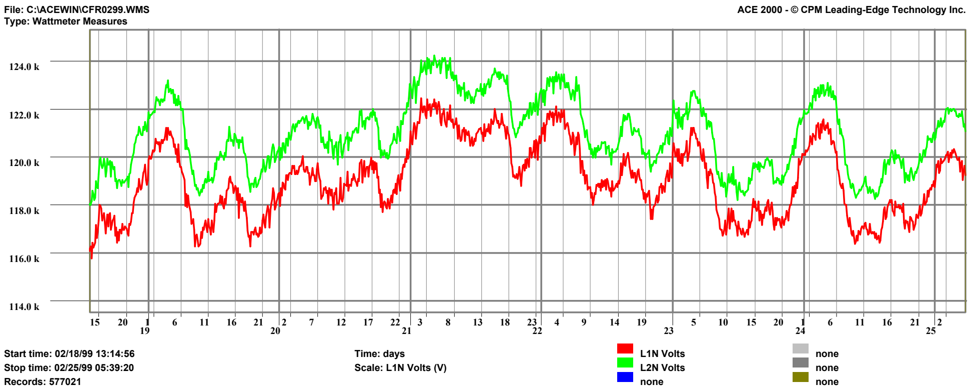

Fig. 2 Phase voltage curve

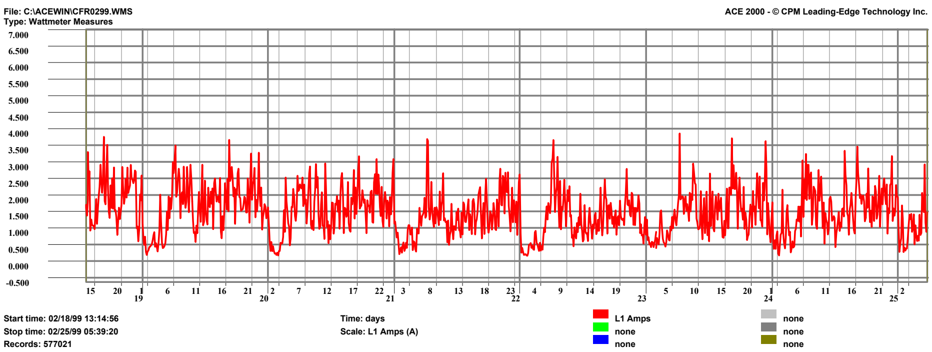

Fig. 3 Current curve

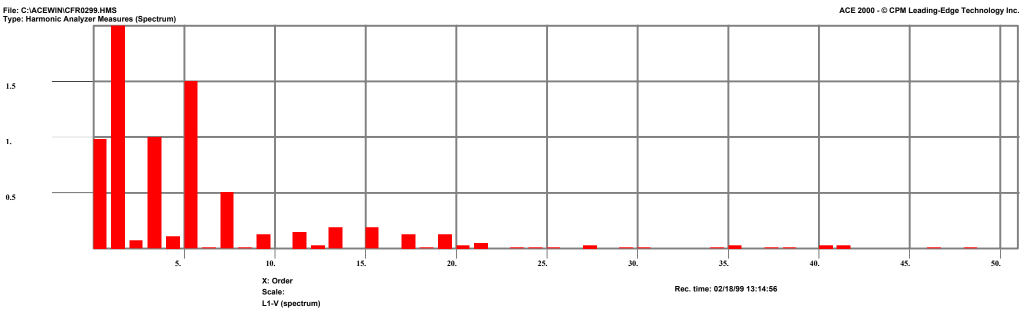

Fig. 4 Harmonic spectrum of Line 1 Voltage: THD:1.92% RMS: 117.9 kV , 3^{rd}:1.00% 5^{th}:1.50%.

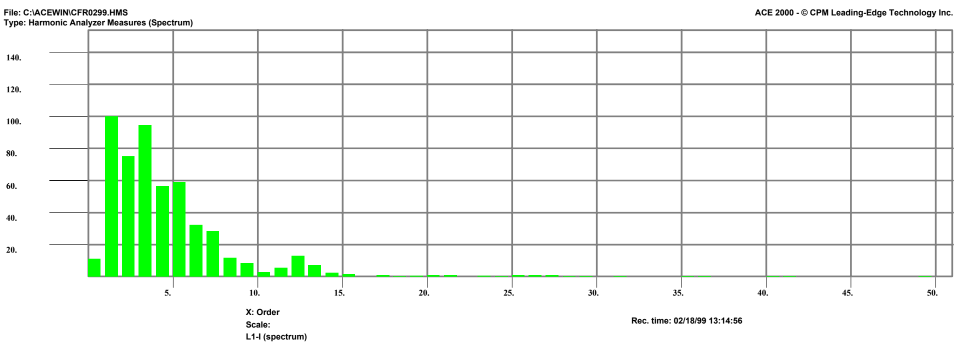

Fig. 5 Harmonic spectrum of Line 1 Current: THD:153.70%, RMS: 0.493 A, 3^{rd}: 94.71% 5^{th}: 58.94%.

The high resolution and simultaneous samplings of the voltage and current channels, together with facility for a numerical processing of these data allow for a cycle-by-cycle analysis within power frequency networks. The dual architecture of its microprocessor grants the high precision, even in case of the highly distorted wave shapes; it also provides a real-time, high-level, numerical data processing and the digital display of the results.

The device allows for the measurement and for the describing all absorbed power problems. It can detect r.m.s values for voltages and currents, the actual values for power factor, frequency, and active and reactive energy.

Measurements are repeated each cycle. For the time interval selected by the user (from 1s up to 9 999s) the device can identify the extreme (maximum and minimum) values for each quantity it is monitoring. A more flexible study could make use of data stored in different time modes.

Measured values of the absorbed powers and for the identified harmonics are compared against set levels to check these are not violated, so the user could easily identify the dangerous harmonics. The start and the end of the measuring session can be decided upon by the user for time intervals of 20 ms up to 1 hour. Special events can be registered along with the extreme values and their initiation moments and the due duration.

The sampling frequency is equal to 12.5 kHz, while the highest order for the monitored harmonics is 50. For graphic processing and display of the registered values the device makes use of automatic amplifiers granting scaling factors of 0.01…20000 (in case an external voltage transformer is used) or up to 10000 (with an external current transformer).

6 Accuracy of the Experimental Data

The network harmonic impedances (namely numerical discrete values of the impedance $\underline{Z}_k$) are given by the ratio of harmonic voltages $\underline{U}_k$ to the harmonic currents $\underline{I}_k$, which are values obtained converting the time variation of the measured voltages and currents into harmonic spectra using Fourier transform.

Experimental data are obtained using data logging and processing systems according to the adopted measuring scheme. Possible error sources in obtaining the measured data that are specific to the adopted measuring method are:

- The inconsistency between measuring scheme characteristics and the ones of the data logging system transducers.
- The signal affected by noise that under certain circumstances can be of magnitude of the same order.
- The method employed for harmonic analysis.

Regarding the way the harmonic analysis is performed, it is to be mentioned that indirect, as well as direct methods can be employed [8]. Indirect methods proceed to the sampling of the acquired signals followed by an appropriate numerical method (equal-distance co-ordinates, selected co-ordinates or Krug-Roth) to compute Fourier series coefficients. Large errors are introduced by these methods, due to the limited number of attainable samples. The direct methods use compensation procedures and selecting and translating techniques, recently completed with digital facilities to apply FFT algorithm.

An important role during the process of harmonic analysis by the aid of the data logging and processing systems is played by the sampling & storage circuit characteristics, as well as by the characteristics of the analogue-to-digital converter.

A typical example of an E/M circuit is offered by the circuit HS11 having a sampling & storage time less than 5μs, a low rate of stored signal decaying of 50μV/ms and a good linearity.

The analogue-to-numerical converter (ANC) has to comply with the following main characteristics:

- to grant a linear dependence of the output signal on the input signal. Integrated converters present nonlinearities of at most ± 0.5 LSB;
- to grant a resolution as high as possible. Integrated converters have resolutions of 8, 10, 12 and even 16 bits, so the signal could be described by 2^8=256 points, 2^{10}=1024 points, 2^{12}=4096 points, or 2^{16}=65536 points;
- to grant a lower converting time e.g. usual 8-bit ANCs have converting times lower than 20μs.
- to grant a strong rejection of the input noise, a property that is described by the ANC capacity to provide an output signal proportional to the input signal only.
- to have a high precision, characterised by the sampling error. Expressed in p.u. the sampling error is defined by the number of bits of the converter and by the maximum interval of the input signal variation. For unipolar and bipolar conversion, the standardised values for this interval are respectively: 0…5V; 0…10V and –0.5V…+2.5V; -5V…+5V; -10V…+10V. An 8-bit converter can have an error of 0,2% for an input signal variation of -10V…+10V.

As for the sampling frequency, it should be selected according to Shanon's theorem, so it would be at least two times the maximum frequency within the frequency spectrum of the input signal. In practice the adopted sampling frequencies are at least 5 to 10 times higher than the maximum frequency of the spectrum.

The errors caused by the presence of the noise or by the low level of the input signal could be drastically reduced using correlation techniques. Thus, for U_k and I_k representing appropriate samples of harmonic voltages and currents, the correlation technique allows for the elimination of non-periodical components and for noise rejection. To this aim the inter-correlation function R_{UkIk} and the voltage sample auto-correlation function R_{UkUk} are to be estimated. Then using Fourier transform for R_{UkIk} will provide the power spectral density S_{UkIk}, value characterised by its magnitude and phase angle. The equation relating the two transformed functions S_{UkUk} and S_{UkIk} provides the network impedance for each harmonic, the coherence function offering the very value of the network harmonic impedance:

$$\underline{Z}_k = \frac{S_{\underline{U}_k^* \underline{U}_k}}{S_{\underline{U}_k^* \underline{I}_k}} \quad (9)$$

A thorough analysis of the error sources when identifying the harmonic impedance process leads to the overall image presented in Fig. 6.

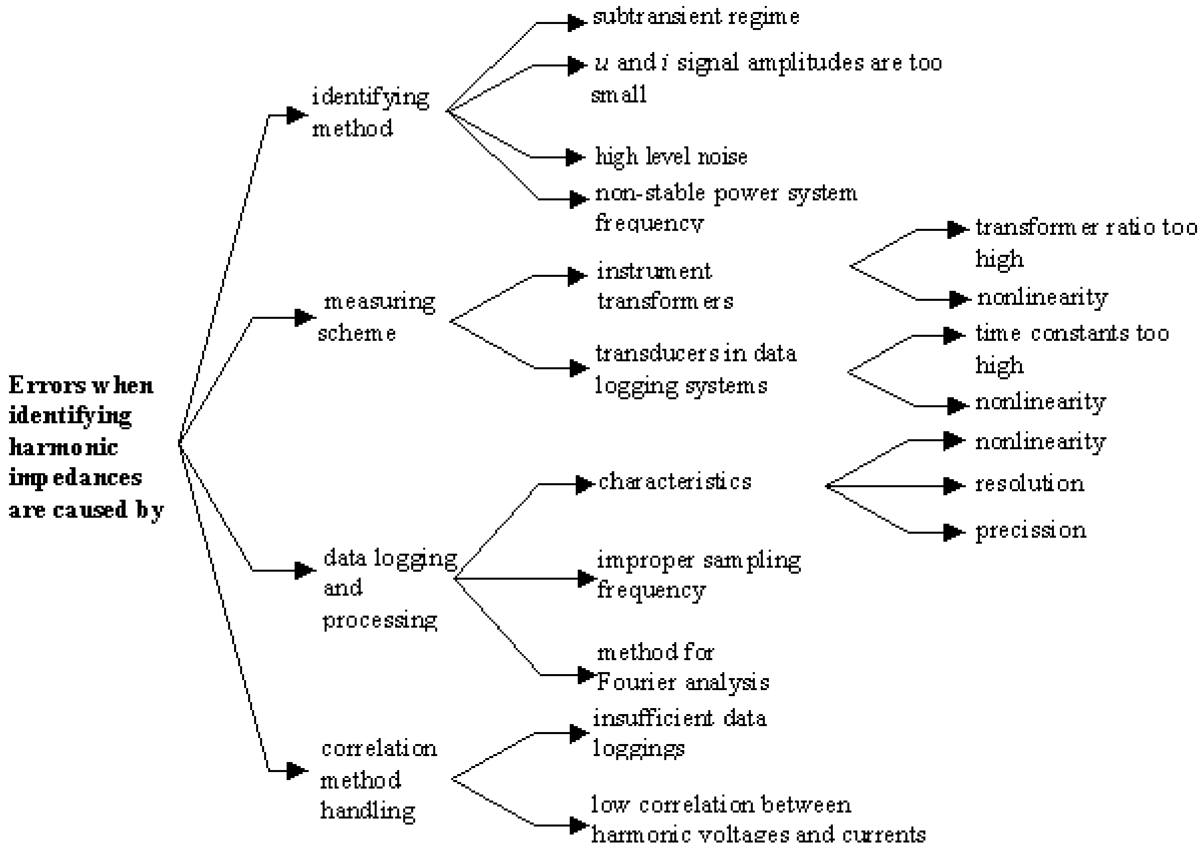

Fig. 6 Error sources when identifying network harmonic impedances

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