Dynamic On-Line Measurement of Equivalent Parameters of Three-Phase Systems for Harmonic Frequencies

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Abstract.

A method of an on-line measurement of equivalent parameters for harmonic frequencies of a three-phase distribution system with harmonic generating loads is discussed in the paper. The impedances of the supply and the load, the complex RMS (CRMS) values of the load generated current harmonics, and the CRMS values of the distribution voltage harmonics are the subject of the measurement. It is shown that the on-line measurement of these parameters requires that the line voltages and currents are measured at least in three different states of the system. These states of the tested system are changed by disturbing the system with a current harmonics generating device, built in a form of a fast thyristor switch. The method is illustrated with measurements in a physical system.

1 Introduction

If the voltage or current harmonics are observed at a load terminal, we are not capable of concluding whether the supply voltage, the load or both are responsible for this.

There may be several reasons for identifying the equivalent parameters of a distribution system and its load for harmonic frequencies. First of all, these parameters affect the performance of the resonant harmonic filters. Moreover, the knowledge of these parameters enables us to predict the system response to new sources of the waveform distortion. Also, it makes it possible to identify the sources of the power-quality degradation. Though, as it was demonstrated in [4] and [5, 6], the direction of the harmonic active power flow P_n enables us to identify the dominating cause of harmonic distortion, nonetheless, according to [8], equivalent parameters of the system are needed for a full identification of the power phenomena in electrical systems and a series/shunt compensator control.

The equivalent parameters of a distribution system for harmonic frequencies can be found with a computer simulation, and various software is available for that, but such a simulation is usually a time-consuming process. Identification of these parameters by a measurement could be considered, therefore, as an important alternative [1, 2, 3, 7] to a computer simulation. A direct measurement can provide, moreover, a validation for the simulation results.

There are several general issues related to an identification of the distribution-system parameters for harmonic frequencies by an on-line measurement. To measure these parameters, the voltages and currents of these frequencies have to be present in the system. They are present, usually, due to the waveform distortion, but may not have the magnitudes sufficient for the measurement purposes. An additional source of the waveform distortion could be used in such a case. Such a source should be sufficiently strong to provide signals for a measurement, without disturbing, however, the customer or protective equipment. An on-line measurement of the system parameters requires that the voltage and current measurements are performed at different states of the system. The information on the system parameters is contained in the difference of such states. To change the system state, the tested system has to be somehow disturbed. The measured difference is affected, however, by the distribution system and the measuring system noise. At usually very low level of harmonic contents and a low level of the acceptable disturbance, obtaining a sufficient signal-to-noise ratio is a real metrological challenge.

2 Assumptions

The method of a dynamic on-line measurement is confined in this paper to three-phase, three-wire system at its junction with the single-phase distribution systems. These single-phase systems may cause the load imbalance and asymmetry of the voltage and current, but mutual coupling between system phases can be neglected. On the other hand, the impedance symmetry and mutual coupling are usually a dominating feature of three-phase supply systems, though they can be asymmetrical as to the supply voltage. Therefore, such a model is assumed for the three-phase supply system. It is assumed, moreover, that the distribution system is supplied from an infinite power bus, so that the positive and negative sequence impedances of the distribution system at the point of its parameters measurement are the same. There is no need to measure the zero sequence voltage, since a zero-sequence current cannot occur.

Harmonic distortion in distribution systems is caused mainly by the load time-variance and its non-linearity. To describe it in terms of admittances, to apply the superposition principle, and to analyse the system harmonic by harmonic, it is assumed in this paper that the system is linear in some range around the working point specified by the working voltage and the working current of the equipment. Most symbols used in the paper relate to harmonics or to parameters for harmonic frequencies. A particular harmonic order is irrelevant for the discussion, however. Therefore, to simplify the used symbols, the index of harmonic order is neglected.

3 Measurement of Linear Unbalanced Load Admittances

Each linear unbalanced load has an equivalent circuit of the structure shown in **Fig. 1**. As it has been proven in [10], there is an infinite number of such circuits equivalent to the original load at a symmetrical supply voltage, but only one if this voltages is asymmetrical. To identify such a load means to find the line-to-line admittances $\underline{Y}_{L2L3}$, $\underline{Y}_{L3L1}$ and $\underline{Y}_{L1L2}$ for harmonic frequencies based on the voltage and current measurement at the load terminals L1, L2 and L3. The complex RMS (CRMS) value of the supply current n-order harmonic of a linear unbalanced load can be expressed in terms of the equivalent admittance, $\underline{Y}_e$, unbalanced admittance for a positive sequence voltage, $\underline{A}$, and unbalanced admittance for a negative sequence voltage, $\underline{F}$. They are equal to

$$\begin{bmatrix}\underline{Y}_e\\ -\underline{A}\\ -\underline{F}\end{bmatrix}=\begin{bmatrix}1 & 1 & 1\\ 1 & \underline{\alpha} & \underline{\alpha}^*\\ 1 & \underline{\alpha}^* & \underline{\alpha}\end{bmatrix}\begin{bmatrix}\underline{Y}_{L2L3}\\ \underline{Y}_{L3L1}\\ \underline{Y}_{L1L2}\end{bmatrix}, \tag{1}$$

where $\underline{\alpha}=e^{j2\pi/3}$ and $\underline{\alpha}^*$ is complex conjugate of $\underline{\alpha}$.

Let the symbols $\underline{I}_p$ and $\underline{U}_p$ denote the CRMS values of the positive sequence components of the n-order harmonic of the voltage and current at the load terminals, and similarly, $\underline{I}_n$ and $\underline{U}_n$ denote the CRMS values of the negative sequence of the voltage and current harmonic. They can be calculated based on the measurement and calculation of the CRMS values of the voltage and current harmonics at the load terminals. These CRMS values are related mutually as follows:

$$\underline{I}_p=\underline{Y}_e\,\underline{U}_p+\underline{F}\,\underline{U}_n, \tag{2}$$

$$\underline{I}_n=\underline{A}\,\underline{U}_p+\underline{Y}_e\,\underline{U}_n. \tag{3}$$

Eq. (1) has the determinant of non-zero value, thus, admittances $\underline{Y}_e$, $\underline{A}$ and $\underline{F}$ are mutually independent. The third of them cannot be calculated if the remaining two are known. Thus, these admittances cannot be calculated from eqs. (2) and (3). There is the lack of one equation. Consequently, an unbalanced load cannot be identified based on a single measurement of voltages and currents. The measurement has to be repeated at a different supply voltage. Let different states of the system be denoted by [1] and [2]. From four equations of the form of eqs. (2) and (3) three can be chosen for example, the following:

$$\underline{I}_p[1]=\underline{Y}_e\,\underline{U}_p[1]+\underline{F}\,\underline{U}_n[1], \tag{4}$$

$$\underline{I}_n[1]=\underline{A}\,\underline{U}_p[1]+\underline{Y}_e\,\underline{U}_n[1], \tag{5}$$

$$\underline{I}_p[2]=\underline{Y}_e\,\underline{U}_p[2]+\underline{F}\,\underline{U}_n[2]. \tag{6}$$

The third eq. (6) is independent of the first eq. (4) on the condition, however, that

$$\frac{\underline{U}_p[2]}{\underline{U}_p[1]}\neq\frac{\underline{U}_n[2]}{\underline{U}_n[1]}, \tag{7}$$

and in such a case the admittances $\underline{Y}_e$, $\underline{F}$ and $\underline{A}$ can be expressed as

$$\underline{Y}_e=\frac{\underline{I}_p[1]\,\underline{U}_n[2]-\underline{I}_p[2]\,\underline{U}_n[1]}{\underline{U}_p[1]\underline{U}_n[2]-\underline{U}_p[2]\underline{U}_n[1]}, \tag{8}$$

$$\underline{F}=\frac{\underline{I}_p[2]\,\underline{U}_p[1]-\underline{I}_p[1]\,\underline{U}_p[2]}{\underline{U}_p[1]\underline{U}_n[2]-\underline{U}_p[2]\underline{U}_n[1]}, \tag{9}$$

$$\underline{A}=\frac{\underline{U}_n[1]\,\underline{I}_n[2]-\underline{U}_n[2]\,\underline{I}_n[1]}{\underline{U}_p[2]\underline{U}_n[1]-\underline{U}_p[1]\underline{U}_n[2]}, \tag{10}$$

and hence, eq. (1) results in line-to-line admittances of the load equivalent circuit, namely

$$\begin{bmatrix}\underline{Y}_{L2L3}\\ \underline{Y}_{L3L1}\\ \underline{Y}_{L1L2}\end{bmatrix}=-\frac{1}{3}\begin{bmatrix}-1 & 1 & 1\\ -1 & \underline{\alpha}^* & \underline{\alpha}\\ -1 & \underline{\alpha} & \underline{\alpha}^*\end{bmatrix}\begin{bmatrix}\underline{Y}_e\\ \underline{A}\\ \underline{F}\end{bmatrix}. \tag{11}$$

One might notice, that admittances $\underline{Y}_e$, $\underline{A}$ and $\underline{F}$ could be easily eliminated from the procedure of the line-to-line admittances $\underline{Y}_{L2L3}$, $\underline{Y}_{L3L1}$ and $\underline{Y}_{L1L2}$ calculation. The same relates to the voltage and current symmetrical components. If the line quantities are used for calculating the load equivalent parameters, it is not directly visible, however, that the supply voltage has to be asymmetrical, since at a symmetrical supply voltage there is an infinite number of circuits equivalent to a three-phase load. Moreover, admittances $\underline{Y}_e$, $\underline{A}$ and $\underline{F}$ provide with eqs. (2) and (3) a deeper insight into the behaviour of a three-phase load as an entity at asymmetrical supply than the line-to-line admittances.

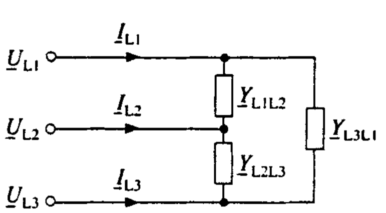

Fig. 1. Equivalent circuit of a three-phase load

4 Measurement of the Parameters of an Unbalanced, Harmonic Generating Load

Harmonic generating loads are usually non-linear. According to Section 2, the load is linear in some range around the working point. i.e. for each harmonic frequency, apart from the fundamental, there is an equivalent circuit as shown in **Fig. 2**. The symbols $\underline{J}_{L1L2}$, $\underline{J}_{L2L3}$ and $\underline{J}_{L3L1}$ represent the CRMS values of the line-to-line

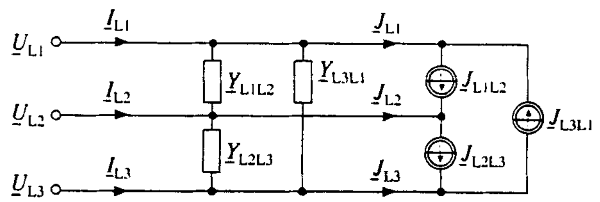

Fig. 2. Equivalent circuit of a non-linear load around a working point

current harmonics generated by the load, and $\underline{Y}_{L2L3}$, $\underline{Y}_{L3L1}$ and $\underline{Y}_{L1L2}$ represent admittances for incremental voltage changes around the load working point.

Even if the CRMS values of the line current harmonics, $\underline{J}_{L1}$, $\underline{J}_{L2}$ and $\underline{J}_{L3}$ are known, one equation is missing to calculate $\underline{J}_{L1L2}$, $\underline{J}_{L2L3}$ and $\underline{J}_{L3L1}$ values from *Kirchoff's* equations for nodes L1', L2' and L3', since

$$\underline{J}_{L1}+\underline{J}_{L2}+\underline{J}_{L3}=0. \tag{12}$$

Thus, there is an infinite number of different CRMS values $\underline{J}_{L1L2}$, $\underline{J}_{L2L3}$ and $\underline{J}_{L3L1}$ equivalent with respect to the line current CRMS values $\underline{J}_{L1}$, $\underline{J}_{L2}$ and $\underline{J}_{L3}$. One of them can be chosen arbitrarily without affecting the line current harmonics CRMS values $\underline{J}_{L1}$, $\underline{J}_{L2}$ and $\underline{J}_{L3}$, so that, also without affecting the terminal current harmonics CRMS values $\underline{I}_{L1}$, $\underline{I}_{L2}$ and $\underline{I}_{L3}$. Let us assume that $\underline{J}_{L1L2}=0$. In such a case, $\underline{J}_{L2L3}=\underline{J}_{L2}$, $\underline{J}_{L3L1}=-\underline{J}_{L1}$, and the load equivalent circuit for a harmonic frequency has the form shown in **Fig. 3**.

Let $\underline{J}_p$ and $\underline{J}_n$ denote the CRMS values of the positive and negative sequence of the current harmonics generated by the load. The superposition principle results in:

$$\underline{I}_p=\underline{Y}_e\underline{U}_p+\underline{F}\,\underline{U}_n+\underline{J}_p, \tag{13}$$

$$\underline{I}_n=\underline{A}\,\underline{U}_p+\underline{Y}_e\underline{U}_n+\underline{J}_n. \tag{14}$$

The CRMS values $\underline{U}_p$, $\underline{U}_n$, $\underline{I}_p$ and $\underline{I}_n$ can be calculated based on the measurement at the load terminals. They are known variables of eqs. (13) and (14). The values $\underline{Y}_e$, $\underline{F}$, $\underline{A}$, $\underline{J}_p$ and $\underline{J}_n$ are unknown. Five equations are required for their calculation while a single measurement at the load terminals provides only two equations. Measurements in three different states, denoted by [1], [2] and [3], of the load are needed, therefore, to identify the load equivalent circuit, i. e., the values $\underline{Y}_e$, $\underline{F}$, $\underline{A}$, $\underline{J}_p$ and $\underline{J}_n$.

Since the matrix of eqs. (13) and (14) written for three different states of the load is a sparse matrix, i. e. with a number of zero entries, it may be convenient to solve first a subset of these equations, for example, with only unknown variables $\underline{Y}_e$, $\underline{A}$ and $\underline{J}_n$. It may simplify the measurement-error analysis, as well as it may enable to draw conclusions regarding disturbances of the system needed for this error reduction:

$$\begin{bmatrix}\underline{I}_n[1]\\ \underline{I}_n[2]\\ \underline{I}_n[3]\end{bmatrix}=\begin{bmatrix}\underline{U}_p[1] & \underline{U}_n[1] & 1\\ \underline{U}_p[2] & \underline{U}_n[2] & 1\\ \underline{U}_p[3] & \underline{U}_n[3] & 1\end{bmatrix}\begin{bmatrix}\underline{A}\\ \underline{Y}_e\\ \underline{J}_n\end{bmatrix}=T\begin{bmatrix}\underline{A}\\ \underline{Y}_e\\ \underline{J}_n\end{bmatrix},$$

$$\text{so that}\quad\begin{bmatrix}\underline{A}\\ \underline{Y}_e\\ \underline{J}_n\end{bmatrix}=T^{-1}\begin{bmatrix}\underline{I}_n[1]\\ \underline{I}_n[2]\\ \underline{I}_n[3]\end{bmatrix}. \tag{15}$$

After the equivalent admittance $\underline{Y}_e$ is calculated, parameters $\underline{F}$, $\underline{J}_p$ of the load equivalent circuit can be found from eq. (13) for two different states, namely:

$$\begin{aligned}&\underline{I}_p[1]-\underline{Y}_e\underline{U}_p[1]=\underline{F}\,\underline{U}_n[1]+\underline{J}_p,\\ &\underline{I}_p[2]-\underline{Y}_e\underline{U}_p[2]=\underline{F}\,\underline{U}_n[2]+\underline{J}_p.\end{aligned} \tag{16}$$

There is a number of different options regarding the choice of the circuit equations, different than eqs. (15) and (16). The choice of other option may affect some practical aspects of the measurement and the solution accuracy, but the discussion of such options is beyond the scope of this paper.

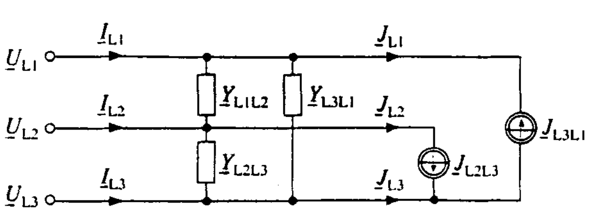

Fig. 3. Modified equivalent circuit of a non-linear load

5 Measurement of the Three-Phase Supply Parameters

According to the assumptions made in Section 2, the equivalent circuit of a supply three-phase system may have the form shown in **Fig. 4**. The circuit is symmetrical as to internal impedances but can be asymmetrical with respect to the internal voltages e_{L1}, e_{L2} and e_{L3}. At such assumptions:

$$\begin{aligned}&\underline{U}_p=\underline{E}_p-\underline{Z}_p\underline{I}_p,\\ &\underline{U}_n=\underline{E}_n-\underline{Z}_n\underline{I}_n,\end{aligned} \tag{17}$$

with $\underline{Z}_p=\underline{Z}_n:=\underline{Z}_s$. Thus, there are only two eqs. (17) for three unknown variables $\underline{E}_p$, $\underline{E}_n$ and $\underline{Z}_s$ calculation. Measurements in two different states of the source are needed for the supply source parameters measurement. The following set of equations can be chosen, for example, for the parameters calculation:

$$\begin{aligned}&\underline{U}_p[1]=\underline{E}_p-\underline{Z}_s\underline{I}_p[1],\\ &\underline{U}_n[1]=\underline{E}_n-\underline{Z}_s\underline{I}_n[1],\\ &\underline{U}_p[2]=\underline{E}_p-\underline{Z}_s\underline{I}_p[2],\end{aligned} \tag{18}$$

so that, for each harmonic

$$\underline{Z}_s=\frac{\underline{U}_p[2]-\underline{U}_p[1]}{\underline{I}_p[1]-\underline{I}_p[2]}, \tag{19}$$

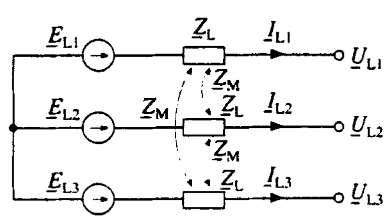

Fig. 4. Equivalent structure of a three-phase supply

and the CRMS values of $\underline{E}_p$, $\underline{E}_n$ for each harmonic can be calculated with eqs. (18). Such a measurement does not enable us to calculate, however, the phase and mutual impedances of the supply source. The impedance for symmetrical components of both sequences is equal to

$$\underline{Z}_s = \underline{Z}_L - \underline{Z}_M, \tag{20}$$

thus, there is no possibility to separate impedances $\underline{Z}_L$ and $\underline{Z}_M$ if only impedance $\underline{Z}_s$ is known. To calculate impedances $\underline{Z}_L$ and $\underline{Z}_M$ the impedance for the zero-sequence component has to be calculated which is possible only in a four-wire system. Fortunately, there is no need to know the line and mutual impedances of the source in three-wire systems. Such a system can be described entirely in terms of only three parameters $\underline{E}_p$, $\underline{E}_n$ and $\underline{Z}_s$ at any working conditions.

6 Tested System and its Disturbance

To draw conclusions on practical aspects of the method presented, it was applied for the on-line measurement of the equivalent parameters for harmonic frequencies of the power electronic laboratory and its supply in a building with a 150 kVA transformer. The grid in the laboratory was rated for 100 A with 70 A fuses.

Though any disturbance of the identified system with distorted waveforms may provide information sufficient for measuring the system equivalent parameters, nonetheless, when the system is disturbed with a linear device then the measurement accuracy depends strongly [9] on the harmonic level in the tested system. Having the tested system disturbed with a harmonic generating device (HGD), the measurement becomes independent of the harmonics existing in the system.

An HGD built of a thyristor switch was used for changing the tested system states. By periodic short circuit of two chosen supply lines for a time of few 100 µs at the line-to-line voltage near to its zero crossing, the HGD has created current pulses of peak value of 60 A in the supply lines. Such pulses have disturbed the supply voltage sufficiently for the parameters measurement, but without any harmful observable effects on the equipment installed in the laboratory. The tested system was not disturbed in the reference state [1], disturbed with the HGD connected between phases L1L3 in the second state [2], and connected between phases L2L3 in the third state [3]. Phase L3 was used as the reference phase for the voltage measurements. Only currents in phases L1 and L2 were sampled in experiments. A wide frequency spectrum of disturbing current spikes made it possible to measure harmonic CRMS values up to the 25th order.

To produce jitter-free testing waveforms with a repeatable spectrum and to synchronize the measurement with the line waveforms of the tested system, a computer-controlled synchronizing system was developed. The synchronization made it possible to use 128 or 64 point, two period long signal records for signal processing. *Hamming*'s window with 256-point record was used in experiments to protect the measurement results from the leakage due to a drift of the fundamental frequency.

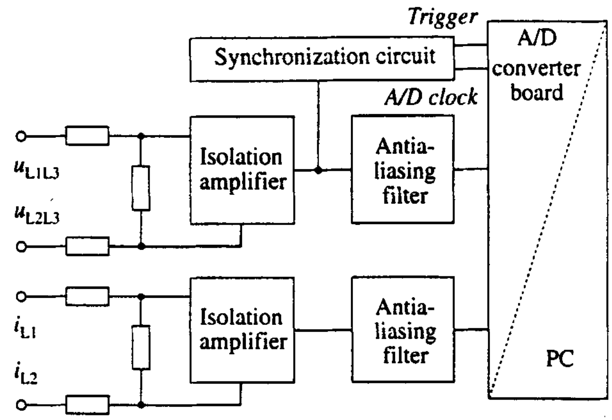

Fig. 5. Measurement and signal-processing system

7 Measurement and Signal Processing

To verify experimentally the discussed method a measurement and signal processing system (M&SPS), of the structure shown in **Fig. 5**, has been assembled. It has been built of a microcomputer equipped with a 12 bit A/D conversion card with simultaneous sampling in four channels, resistive voltage/current sensors, isolation amplifier and antialiasing filters. Signals were processed with LabWindows CVI.

The measuring channels were affected by the electromagnetic interference, noise, non-linearity, and mutual coupling. The noise properties were tested by observing the spectrum noise for coherent input signals. The noise was found to be equivalent to 1 bit at 10 bit quantization. The level of the electromagnetic interference occurred to be of the order of −60 dB for the line frequency, and below −70 dB for higher harmonics. The non-linearity was tested by averaging the channel output spectrum for the input signal of a frequency different from the line frequency. **Fig. 6** shows that the output signal has been distorted with the second harmonic of the order of −60 dB and with higher harmonics below −70 dB of the fundamental.

8 Comments on Calculation Errors

The system parameters are expressed in the discussed approach with increments of the CRMS values of the voltage and current harmonic in states [a] and [b] of

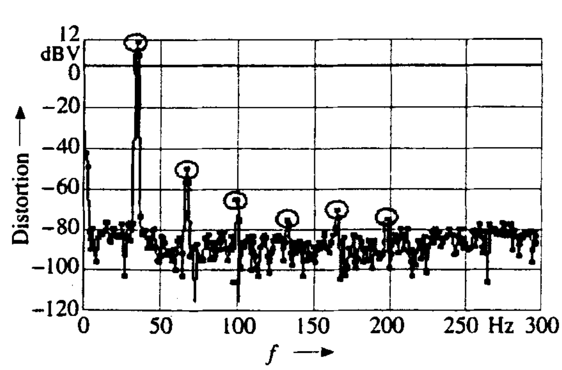

Fig. 6. Harmonic distortion of measuring channel

the system. The CRMS values of the voltage and current harmonics in these states are very close, usually, to one another, so that, the increments are measured with a reduced systematic error but with a doubled random error. These two errors affect the accuracy of the system parameters calculation with an error, referred to as a *calculation error*.

Let us denote the calculated value of the voltage n-order harmonic increment by $\Delta \underline{U}$. It differs from the true value of this increment $\underline{U}[a] - \underline{U}[b]$ by systematic error $\underline{\xi}_u$ and by random error $\underline{\rho}_u$, i.e.

$$\underline{U}[a] - \underline{U}[b] = \Delta \underline{U} + \underline{\xi}_u + \underline{\rho}_u, \qquad (21)$$

where $\underline{\xi}_u$ and $\underline{\rho}_u$ are complex numbers. Similarly, for the n-order current harmonic increment

$$\underline{I}[a] - \underline{I}[b] = \Delta \underline{I} + \underline{\xi}_i + \underline{\rho}_i, \qquad (22)$$

where $\Delta \underline{I}$ denotes the calculated value of increment, obtained with systematic and random errors, $\underline{\xi}_i$ and $\underline{\rho}_i$.

The calculation accuracy in such an approach is affected by three types of measurement errors:

- Systematic errors $\underline{\xi}_u$ and $\underline{\xi}_i$ which do not change at each measurement in the same conditions. The incremental measurement eliminates many common components of these errors, such as temperature, aging or electromagnetic interference. The values $\underline{\xi}_u$ and $\underline{\xi}_i$ specify the errors of measuring and calculating the CRMS values of harmonics of the voltage and current increments in two different states of the system. The change of the system tested, so that also the measurement system state, is the source of these errors, caused by measurement system non-linearity. Their values were evaluated in Section 7.
- Random errors $\underline{\rho}_u$ and $\underline{\rho}_i$ caused by noise in the tested and in the measurement system. Assuming that the system is stationary, these errors are relatively easy to be damped by repeating the measurement.
- Total errors of measuring the CRMS values of the voltage and current harmonics. Their effect on the accuracy of values $\underline{E}$ and $\underline{J}$ calculation depends on the supply impedance and the load admittance.

The measurement noise comes from the tested system itself, as well as from the signal conditioning circuits, isolation amplifiers, from antialiasing filters, and from the quantization noise of the A/D converter. The time-domain noise is transformed to harmonic spectrum according to *Parseval*'s theorem. If σ is the standard deviation of the input signal noise with zero mean value, and N is the number of DFT samples, then harmonics RMS values are calculated with the random error of the standard deviation σ_s, equal to

$$\sigma_s = \frac{\sigma}{\sqrt{N}}. \qquad (23)$$

Due to weighted additions during DFT calculations, the spectrum noise is *Gaussian* for any type of noise in the time-domain. This allows us to treat equally all components of the random noise which occur in the tested and measurement systems, independently of their source and properties. Random spectral errors in physical experiments were estimated to be of the order of −60 dB, mainly due to the noise in the system tested. Fortunately, this error can be reduced by repeating measurements and averaging the results until the required signal/noise ratio is obtained, at the cost, however, of increased measurement time.

9 Experimental Results

The experimental on-line identification of the load and supply parameters was performed to validate the method in the power electronic laboratory supplied with a 150 kVA transformer and the known load parameters.

– *Measurement of Load Admittances*

Fig. 7 and **Fig. 8** show the results of the experiment aimed at measuring the admittances of a passive unbalanced load, composed of a resistor of R = 13 Ω with a parallel capacitor of C = 70 µF, connected between phases L2 and L3. According to eq. (1), $\underline{Y}_e = -\underline{A} = -\underline{F} = \underline{Y}_{L2L3}$ for such a load at each harmonic frequency. Fig. 7 shows the waveform distortion generated by the HGD. Fig. 8 shows the frequency plots of admittances, calculated with eqs. (8) to (10) and averaged over ten measurements. As it can be seen from the plot in Fig. 8, the accuracy declines above the 15th harmonic, mainly due to a decline in the harmonic contents. Nonetheless, all admittances change similarly with the frequency; their real part varies around the same constant value while the imaginary part increases linearly with the frequency in-

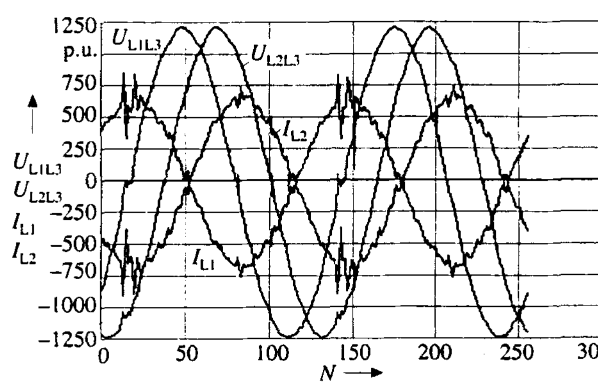

Fig. 7. Waveform distortion caused by HGD

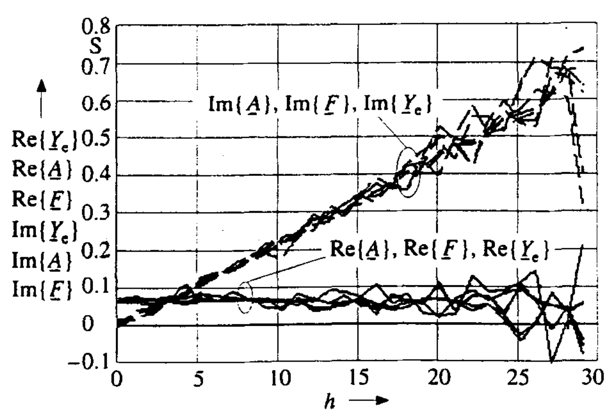

Fig. 8. Plots of equivalent and unbalanced admittances

crease. Though the measurement accuracy is not high, one could observe, however, that the measurement was performed at a relatively low voltage distortion and the results were averaged over only ten measurements. Similar accuracy was obtained also for other loads.

– *Measurement of Load-Generated Harmonics*

A three-phase AC/DC rectifier was used as the source of the load harmonics in this experiment. Since the harmonic spectrum of the converter supply current is known, it was considered as a kind of a reference for the measurement of the load-generated current harmonics. The small circles in **Fig. 9** mark the CRMS values in the polar coordinates of the positive-sequence harmonics measured in the supply lines at various linear loads, symmetrical and asymmetrical, but at the same AC/DC rectifier. The asterisks mark the CRMS values of the load-generated current harmonics calculated with eqs. (16) for the measurement ten repetitions. Fig. 9 shows that independently of the load conditions, the calculated values of the load-generated current harmonics converge to clusters confined by circles.

Harmonics of the order different than $n = 6k \pm 1$ were not visible. Taking into account that the RMS value of the fundamental harmonic in the experiment was in the range of 15 A to 35 A, and the RMS value of the calculated current harmonics are below 0.08 A, the method provides relatively high measuring resolution with respect to the load-generated current harmonics. This resolution can be enhanced by repeated measurements

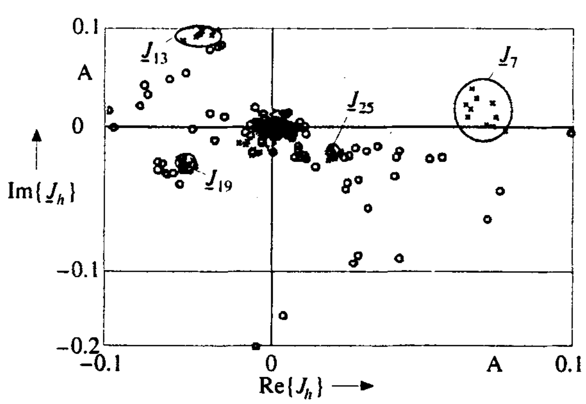

Fig. 9. Measured CRMS values of the load-generated current harmonics of positive sequence

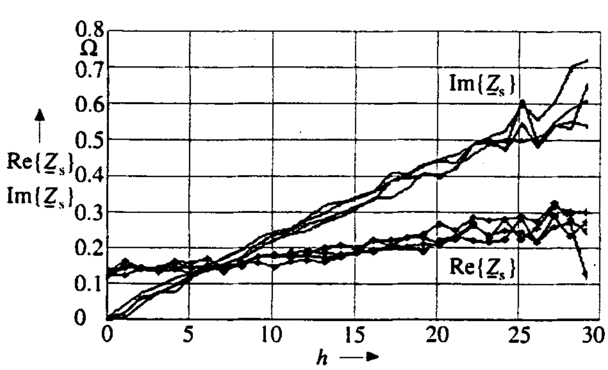

Fig. 10. Plots of the supply source impedance for symmetrical components versus harmonic order

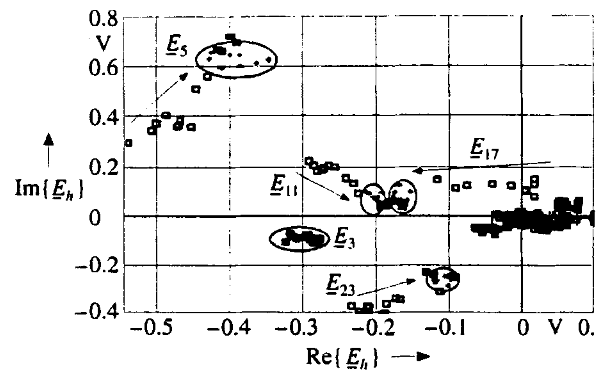

Fig. 11. CRMS values of the internal voltage harmonics of the supply source

which increases the signal-to-noise ratio. The results of the measurement of the negative-sequence harmonics do not differ from that presented above for the positive-sequence harmonics.

– *Measurement of Supply Source Impedance*

The results of a measurement of the supply source impedance for the symmetrical components are shown in **Fig. 10**. Since the reduction in the number of the calculated parameters has provided more information from the measurement than needed, the supply source impedance was calculated using different voltage and current sequences and different disturbances. Unfortunately, the true values of the supply source impedance for harmonic frequencies were not known.

– *Measurement of Supply Source Harmonics*

The CRMS values of the supply source internal voltage harmonics e_h were measured in the system with a harmonic generating load. Thus, the line voltage harmonics CRMS values u_h were affected both by the supply and the load. The measurement and calculation results are shown for some harmonics in **Fig. 11**. Small squares mark the CRMS values of the voltage harmonics at the supply source terminals at various load conditions. The asterisks mark the CRMS values of the supply source internal voltage harmonics e_h calculated with formulas (18). The calculated values converge to clusters confined by ellipses. Though apparently the calculated values are substantially scattered, one should observe, however, that the calculated RMS values of the supply voltage harmonics are well below 1 % of the fundamental, equal to 120 V.

10 Conclusions

The common measurements of the voltage and current harmonic contents in power systems do not provide, usually, information on the load-generated current harmonics and on the distribution system internal voltage harmonics. The effects of these sources of the waveform distortion are superimposed mutually and depend on the distribution system and the load impedances. The sources of the waveform distortion could be identified, along with the admittances for harmonic frequencies by the voltage and current measurements in three different states of the system and by a digital signal processing of the obtained samples. It seems that the digital hardware available on the market has the quality that enables us to identify the equivalent parameters of the distribution system and the loads for harmonic frequency with accuracy which can be considered as satisfactory for various technical purposes.

11 List of Symbols and Abbreviations

11.1 Symbols

$\underline{Y}_{L2L3}, \underline{Y}_{L3L1}, \underline{Y}_{L1L2}$	line-to-line admittances of the load for harmonic frequencies
$\underline{\alpha}, \underline{\alpha}^*$	$e^{j2\pi/3}$ and its conjugate
$\underline{U}_p, \underline{I}_p$	CRMS values of the positive-sequence components of the voltage and current harmonics
$\underline{U}_n, \underline{I}_n$	CRMS values of the negative-sequence components of the voltage and current harmonics
$\underline{Y}_e$	load equivalent admittance for harmonic frequency
$\underline{A}, \underline{F}$	unbalanced admittances for positive and for negative-sequence voltage harmonics
$\underline{J}_{L1L2}, \underline{J}_{L2L3}, \underline{J}_{L3L1}$	CRMS values of the load-generated current harmonics
$\underline{I}_{L1L2}, \underline{I}_{L2L3}, \underline{I}_{L3L1}$	CRMS values of the line current harmonics
$\underline{J}_p, \underline{J}_n$	CRMS values of the positive- and negative-sequence components of the load-generated current harmonics
$\underline{E}_p, \underline{E}_n$	CRMS values of the positive- and negative-sequence components of the supply voltage harmonics
$\underline{Z}_s$	source impedance for symmetrical current harmonics
$\underline{Z}_L, \underline{Z}_M$	line and mutual impedance of the supply for harmonic frequency
$\underline{\xi}_u, \underline{\rho}_u$	systematic and random errors of the measurement of the voltage harmonic increment
$\underline{\xi}_i, \underline{\rho}_i$	systematic and random errors of the measurement of the current harmonic increment
σ	standard deviation of the input signal noise
σ_s	standard deviation of the random error of the harmonic CRMS value calculation
N	number of samples used for the Discrete *Fourier* Transform calculation

11.2 Abbreviations

AC/DC	Alternating Current/Direct Current
A/D	Analog/Digital
CRMS	Complex RMS value
DFT	Discrete *Fourier* Transform
HGD	Harmonic Generating Device
L1, L2, L3	load terminals

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Discussion by *J. L. Willems*
(Univ. of Gent/Belgium):

In Section 3 of the paper the authors discuss the possibility of identifying the impedance or admittance description of a load at a given frequency (fundamental or harmonic) from the measurements of the line voltages and the line currents in a three-phase three-wire power system in sinusoidal steady state. They state "... there is an infinite number of such circuits equivalent to the original load at a symmetrical supply voltage, but only one if the voltage is asymmetrical". This statement also appears in [10] of the paper. This statement is misleading. To formulate it exactly, for *any* three-phase voltage there is an infinite number of equivalent circuits (where equivalent means that they correspond to the same current for a given voltage). A unique load representation in sinusoidal steady state can only be found if the current is measured for *two* independent voltages, where independent means that the voltage phasors are not proportional (as complex numbers). This implies that a unique load representation can be found from the currents for one symmetrical supply voltage and one asymmetrical supply voltage, or from the currents for *two* unsymmetrical supply voltages.

Reply by *L. S. Czarnecki*:

I appreciate very much the interest and comments by Prof. *J. L. Willems*. I cannot agree, however, with the conclusion expressed in the sentence: "To formulate it exactly, for *any* three-phase voltage there is an infinite number of equivalent circuits ...". Just opposite, it was proven in [10], that an infinite number of equivalent circuits exist not for *any* three-phase voltage, but only for *symmetrical* three-phase voltages. It was also proven there, that there is *only one* equivalent circuit for asymmetrical voltages. Trivial reconfigurations have to be excluded, of course.