

INSTRUMENTATION
AND MEASUREMENT

A PUBLICATION OF THE IEEE INSTRUMENTATION AND MEASUREMENT SOCIETY

APRIL 1996

VOLUME 45

NUMBER 2

IEIMAO

(ISSN 0018-9456)

SPECIAL ISSUE ON SELECTED PAPERS IMTC/95

GUEST EDITORIAL	E. W. Richter	351
-----------------------	---------------	-----

PAPERS

Invited Tutorials

Statistical Theory of Quantization	B. Widrow, I. Kollár, and M.-C. Liu	353
Periodic Signals for Measuring Nonlinear Volterra Kernels	C. Evans, D. Rees, L. Jones, and M. Weiss	362

Standards and Calibration

Methods for Aligning the NIST Watt-Balance	G. N. Stenbakken, R. Steiner, P. T. Olsen, and E. Williams	372
Bounds on Frequency Response Estimates Derived from Uncertain Step Response Data	J. P. Deyst and T. M. Souders	378
Effects of Nonmodel Errors on Model-Based Testing	G. N. Stenbakken	384
Static Calibration of Transducers Using Gauss-Function-Based Approximation	S. Huang, R. Z. Morawski, and A. Barwicz	389

Measurement and Control Systems

A Hadamard-Multiplexed Spectrometer Based on an Acousto-Optic Tunable Filter	A. N. Mortensen, S. A. Dyer, R. M. Hammaker, and W. G. Fateley	394
Analysis of Optical Surfaces by Means of Surface Plasmon Spectroscopy	E. Fontana	399
Systematic Design of Instrumentation Architecture for Control of Mechanical Systems	M. E. Stieber, E. M. Petriu, and G. Vukovich	406
A Novel Differential Synchronous Demodulator for AC Signals	R. Pallás-Areny and Ó. Casas	413

Signal Processing

Multiparameter Optimization of Inverse Filtering Algorithms	T. Dabóczy and I. Kollár	417
Performance Enhancement of Scan Converter-Based Transient Digitizers by Digital Image Processing	P. Arpaia, F. Cennamo, P. Daponte, and M. D'Apuzzo	422
Digital Filtering for Robust 50/60 Hz Zero-Crossing Detectors	O. Vainio and S. J. Ovaska	426
Discrete-Time Method for Signal-to-Noise Power Ratio Measurement	Y.-C. Jenq	431
Performance of Stochastic Quantizers Employing Nonlinear Processing	P. Carbone, C. Narduzzi, and D. Petri	435

Power Measurement

A 100 A, 100 kHz Transconductance Amplifier	O. B. Laug	440
A Highly Accurate, Hand-Held Clamp-on Current Transformer	J. D. Ramboz	445

(Continued on page 349)

Measuring Equipment for the Electric Quantities at the Terminals of an Inverter-Fed Induction Motor	<i>L. Cristaldi, A. Ferrero, and R. Ottoboni</i>	449
Calibration and Testing Facility for Resistance Welding Current Monitors	<i>D. E. Destefan</i>	453
Nonintrusive Sensing Techniques for the Discrimination of Energized Electric Cables	<i>A. V. Mamishev, S. X. Short, T.-W. Kao, and B. D. Russell</i>	457
Real-Time Algorithms for Active Power Measurements on PWM-Based Electric Drives	<i>P. Arpaia, F. Avallone, A. Baccigalupi, and C. De Capua</i>	462
On-Line Measurement of Equivalent Parameters for Harmonic Frequencies of a Power Distribution System and Load	<i>L. S. Czarnecki and Z. Staroszczyk</i>	467

Various Other Measurements

Simultaneous Measurement of Electric and Magnetic Properties of a Spherical Sample	<i>S. Yamazaki, T. Negishi, H. Nakane, and A. Tanaka</i>	473
A Double Coil Method for Simultaneously Measuring the Resistivity, Permeability, and Thickness of a Moving Metal Sheet.....	<i>Y. Nonaka</i>	478
Instantaneous Measurement of Electrical Parameters in Palm During Electrodermal Activity	<i>Y. Yamamoto, H. Isshiki, and T. Nakamura</i>	483
Electrostatic Modelling and Measurement of Airborne Particle Concentration	<i>S. N. Murnane, R. N. Barnes, S. R. Woodhead, and J. E. Amadi-Echendu</i>	488
Metrological Characterization of a Contactless Smart Thrust and Speed Sensor for Linear Induction Motor Testing	<i>G. Bucci and C. Landi</i>	493
Laser Speckle Velocimeter Using Self-Mixing Laser Diode	<i>T. Shibata, S. Shinohara, H. Ikeda, H. Yoshida, T. Sawaki, and M. Sumi</i>	499
Measuring On-Wafer High-Frequency Modulation Response Characteristics of Optical Transmitters and Detectors	<i>P. Debie and L. Martens</i>	504
Machinable Rogowski Coil, Design, and Calibration	<i>J. D. Ramboz</i>	511

Sensors

An Accurate Low-Cost Capacitive Absolute Angular-Position Sensor with a Full-Circle Range	<i>X. Li, G. C. M. Meijer, G. W. de Jong, and J. W. Spronck</i>	516
An Integrated Capacitive Position Sensor	<i>H. U. Meyer</i>	521
A Low-Cost, Stable Reference Capacitor for Capacitive Sensor Systems.....	<i>F. N. Toth, D. Bertels, G. C. M. Meijer</i>	526
A Very Accurate Measurement System for Multielectrode Capacitive Sensors	<i>F. N. Toth, G. C. M. Meijer, and H. M. M. Kerkvliet</i>	531
A Novel Low-Cost Capacitive-Sensor Interface	<i>F. M. L. van der Goes and G. C. M. Meijer</i>	536
Distributed-Force Recovery for a Planar Photoelastic Tactile Sensor	<i>R. E. Saad, A. Bonen, K. C. Smith, and B. Benhabib,</i>	541
Monitoring Screws Under Tensile Load Using Acoustic Emission Analysis.....	<i>V. Hänel and W. Thelen</i>	547
A Digital Liquid Level Transducer Based on Optical Fiber	<i>G. Betta, A. Pietrosanto, and A. Scaglione</i>	551
Performance Analysis of Fiber-Optic Transducer for Measuring Low Pressures.....	<i>W. J. Bock, W. Urbanczyk, and A. Barwicz</i>	556
Sensor for High-Air-Humidity Measurement.....	<i>V. Matko and D. Donlagic</i>	561
A Digital Hygrometer Using a Polyimide Film Relative Humidity Sensor	<i>H. Shibata, M. Ito, M. Asakura, and K. Watanabe</i>	564
Improved Micro Thermal Shear-Stress Sensor	<i>J.-B. Huang, S. Tung, C.-M. Ho, C. Liu, and Y.-C. Tai</i>	570
A Novel High-Impedance Probe for Multi-Gigahertz Signal Measurement	<i>M. Shinagawa and T. Nagatsuma</i>	575
A Novel Optoelectronic Interface-Circuit Design for Sensing Applications.....	<i>A. Bonen, R. E. Saad, K. C. Smith, and B. Benhabib</i>	580
Detection of Environmental Ultraviolet Radiation by the Induced Electroluminescence in a Ceramic Detector	<i>C.-S. Su and L.-C. Wei</i>	585

On-Line Measurement of Equivalent Parameters for Harmonic Frequencies of a Power Distribution System and Load

Leszek S. Czarnecki, *Fellow, IEEE*, and Zbigniew Staroszczyk, *Member, IEEE*

Abstract—A method is discussed for on-line measurements of parameters of a power distribution system and its associated load. Four parameters are measured: the complex impedances of the distribution system and the load for harmonic frequencies; the complex rms (crms) values J_n of the harmonics of the load current j and the crms values E_n of the harmonics of the distribution system voltage e . The measurements are performed on two states of the system before and after it is disturbed by either connecting to it a capacitor or a harmonic generating device. The results of physical measurements are compared with those calculated from a model.

I. INTRODUCTION

A concern regarding waveform distortion caused by nonlinear loads increases the need to reduce harmonics in distribution systems. The performance of the harmonic-suppressing equipment depends, however, on the parameters of the distribution system and on those of the load. These parameters at the point where this equipment is installed are of a major importance [1]–[5] for compensator design. The measurement of these parameters is the subject of the paper.

It is assumed that the system tested is linear around the working point determined by the rated voltage. The discussion is confined, moreover, to single-phase systems. The equivalent circuit of the system and the load is shown for the n -th order harmonic in Fig. 1. The parameter identification has to be performed at the working point, since the harmonic generating loads are nonlinear. It requires an "on-line measurement." A high power generator of a harmonic voltage [3] is usually needed for such a measurement. However, since harmonics are almost always present in distribution system voltages, it is possible [1] to use their presence for parameter identification. Use of a device that loads the system with a current with a dense harmonic spectrum to disturb the system is another alternative. The issue of whether or not an existing waveform distortion in a distribution system could be utilized for measuring its equivalent parameters is the subject of the paper. The results of such a measurement are compared with those obtained by disturbing the system with a harmonic generating device.

Manuscript received April 24, 1995; revised January 10, 1996.

The authors are with the Department of Electrical and Computer Engineering, Louisiana State University, Baton Rouge, LA 70803 USA.

Publisher Item Identifier S 0018-9456(96)03505-X.

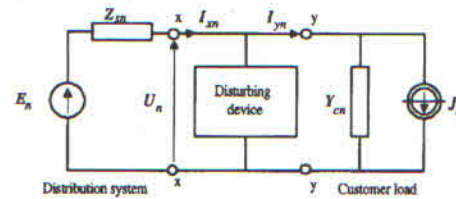


Fig. 1. Equivalent circuit with a disturbing device.

II. FUNDAMENTALS

Considerations in the paper are confined to single-phase systems but could also be applied to three-phase systems that can be analyzed phase by phase. If the symbols U_n and I_n denote the complex rms (crms) values of the n -th order voltage and current harmonics, u_n and i_n , in the circuit shown in Fig. 1, then, they can be related to the crms values E_n of the supply voltage harmonics e_n and the crms values J_n of the load-generated current harmonics j_n as follows:

$$U_n = \frac{1}{1 + Y_{cn}Z_{sn}} E_n - \frac{Z_{sn}}{1 + Y_{cn}Z_{sn}} J_n \quad (1)$$

$$I_n = \frac{Y_{cn}}{1 + Y_{cn}Z_{sn}} E_n + \frac{1}{1 + Y_{cn}Z_{sn}} J_n \quad (2)$$

The system state for the n -th order harmonic is determined by four parameters E_n , J_n , Z_{sn} , and Y_{cn} . These parameters should be understood to be equivalent parameters of a linear approximation of the supply source and the load around the working point. They cannot be calculated, however, since there are only two equations [(1) and (2)]. Measurements in two states of the system, perturbed with a disturbing device as shown in Fig. 1, are needed for that. If the crms values of the voltage and current harmonics in cross sections x and y after the system is disturbed are denoted by U'_n , I'_{xn} , and I'_{yn} , then parameters E_n , J_n , Z_{sn} , and Y_{cn} can be calculated as follows:

$$E_n = \frac{U_n I'_{xn} - U'_n I_{xn}}{I'_{xn} - I_{xn}} \quad (3)$$

$$J_n = \frac{U_n I'_{yn} - U'_n I_{yn}}{U_n - U'_n} \quad (4)$$

$$Z_{sn} = \frac{U_n - U'_n}{I'_{xn} - I_{xn}} \quad (5)$$

$$Y_{cn} = \frac{I_{yn} - I'_{yn}}{U_n - U'_n} \quad (6)$$

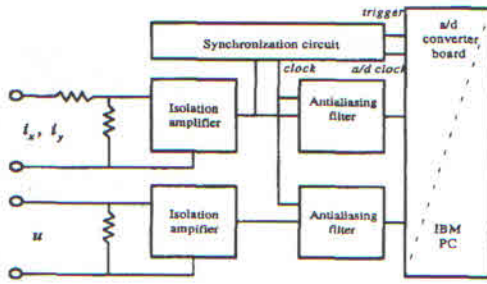


Fig. 2. Measurement and signal processing system configuration.

All parameters in (3)–(6) are expressed in terms of increments of the voltage and current harmonic crms values. Because of that, the following question occurs: "Can the accuracy of the measurement of U_n and I_n be sufficient at the present state of the digital signal processing to calculate the equivalent parameters with an acceptable accuracy?"

III. MEASUREMENT AND SIGNAL PROCESSING SYSTEM

The measurement and signal processing system (M & SPS) has been built with a microcomputer equipped with a 12-bit a/d conversion card with simultaneous sampling, signal isolating and conditioning circuits, antialiasing filters, and a synchronizing circuit. The M & SPS structure is shown in Fig. 2. The input signals were filtered by switched capacitor (SC) low-pass, antialiasing filters with a common, crystal controlled clock with a cut-off frequency chosen to be $f_0 = 1.7$ kHz. To provide coherent sampling of 64 samples per period of the fundamental frequency, the a/d converter was triggered every second period. The samples were processed in the microcomputer with a 64-point FFT algorithm to calculate the crms values of the waveform harmonics. Resistive input circuits, symmetry of the isolation amplifiers and antialiasing filters in the voltage and current channels of the M & SPS made it possible to match their complex transmittances. Therefore, the calculated crms values have provided, with some error, the rms values of the voltage and current harmonics in the system tested and their relative phase shift. A signal record of one period duration, and a coherent sampling made it possible to process the signal almost in real-time, every second cycle, allowing one to observe the variability of the tested system parameters.

The power supply of a power electronics lab, equipped with a 150 kVA transformer, was considered as the test system for experiments. The voltage was distorted by various nonlinear loads in the building of the Department, and possibly, also by the supply of the building. It was verified that the system tested was nonvarying, even for observation intervals of a few minutes.

IV. CALCULATION ERRORS

The circuit parameters are expressed in the approach discussed as ratios of increments ($U_n - U'_n$), ($I_n - I'_n$), and ($U_n I'_n - U'_n I_n$), calculated from measurement data in two slightly different states of the system. The crms values of the

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

Dropping the n -subscript for simplicity, the crms values of the voltage and current harmonics are denoted by U and I and respectively, the admittance and impedance are denoted by Y_c and Z_s .

Let us denote the calculated value of the voltage n -th order harmonic increment by ΔU . It differs from the true value of this increment $U - U'$ by a systematic error ξ_u and a random error ρ_u , i.e.

$$U - U' = \Delta U + \xi_u + \rho_u \quad (7)$$

where ξ_u and ρ_u are complex numbers. Similarly, for the n -th order current harmonic increment

$$I - I' = \Delta I + \xi_i + \rho_i \quad (8)$$

where ΔI denotes the calculated value of this increment, obtained with systematic and random errors, ξ_i and ρ_i . As a consequence, the source impedance Z_s differs from the measured value

$$Z_{sm} = -\Delta U / \Delta I_x \quad (9)$$

by the error ϵ_z , i.e.

$$Z_s = Z_{sm}(1 + \epsilon_z). \quad (10)$$

If magnitudes of relative errors $\xi_u / \Delta U$, $\rho_u / \Delta U$, $\xi_i / \Delta I_x$, and $\rho_i / \Delta I_x$ are much less than one, then the magnitude of the error ϵ_z is limited by

$$\epsilon_z \approx \left| \frac{\xi_u}{\Delta U} - \frac{\xi_i}{\Delta I_x} \right| + \frac{\rho_u}{\Delta U} + \frac{\rho_i}{\Delta I_x} \quad (11)$$

where ρ_u and ρ_i are the magnitudes of the random errors ρ_u and ρ_i . For a large number of repeated measurements, the expected value of the resultant random error is usually calculated as the mean square value of the individual errors. Only two measurements with random errors ρ_u and ρ_i , are used, however, for the impedance calculation in the situation considered. Therefore, these errors may magnify the random component of the impedance determination. Equation (11) represents the worst case situation.

By analogy, the load admittance Y_c differs from the measured value $Y_{cm} = \Delta I_y / \Delta U$, by an error ϵ_Y

$$Y_c = Y_{cm}(1 + \epsilon_Y) \quad (12)$$

with the magnitude limited by

$$\epsilon_Y \approx \left| \frac{\xi_i}{\Delta I_y} - \frac{\xi_u}{\Delta U} \right| + \frac{\rho_u}{\Delta U} + \frac{\rho_i}{\Delta I_y}. \quad (13)$$

This formula provides, similarly as (11), the worst case error.

The crms values of the internal voltage harmonics of the distribution system are, according to (10), equal to

$$E = U \frac{I'_x - I_x \left(\frac{U'}{U} \right)}{I'_x - I_x} \quad (14)$$

since, according to (7)

$$\frac{U'}{U} = 1 - \frac{\Delta U + \xi_u + \rho_u}{U} \quad (15)$$

we obtain

$$E = U - \frac{\Delta U}{\Delta I_x} \frac{1 + \frac{\xi_u + \rho_u}{\Delta U}}{1 + \frac{\xi_i + \rho_i}{\Delta I_x}} I_x = U + Z_{sm} I_x (1 + \epsilon_z). \quad (16)$$

Thus, the crms value of the distribution system internal voltage harmonics E_n can be measured with the measurement accuracy of the terminal voltage harmonic crms value U_n , affected by the accuracy of the supply current and the source impedance measurement. By analogy,

$$J = I_y - \frac{\Delta I_y}{\Delta U} \frac{1 + \frac{\xi_i + \rho_i}{\Delta I_y}}{1 + \frac{\xi_u + \rho_u}{\Delta U}} U = I_y - Y_{cm} U (1 + \epsilon_Y). \quad (17)$$

V. ERRORS CAUSED BY NOISE AND NONLINEARITY

The accuracy in this incremental approach is affected by three types of measurement errors.

- 1) Systematic errors ξ_u and ξ_i which do not change at each measurement in the same conditions. The differential measurements eliminate many common components of these errors, such as temperature, aging or electromagnetic interference at harmonic frequencies. The values ξ_u and ξ_i specify the errors of measuring and calculating the crms values of harmonics of the voltage and current increments in the two different states of the system. The disturbance of the tested system changes the measured voltage and current. Thus, this disturbance also changes the state of the measurement system. The measurement system nonlinearity is the source of systematic errors ξ_u and ξ_i , which cannot be reduced by repeated measurement.
- 2) Random errors ρ_u and ρ_i caused by noise in the tested system and in the measurement system. Under the condition that the system is unchanged, these errors can be reduced relatively easily by repeating the measurement.
- 3) Total errors that occur when measuring the crms values U_n and I_n . The effect of total errors of the crms values U_n and I_n measurement on the accuracy of E_n and J_n calculation depends, according to (16) and (17), 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, the isolation amplifiers, and the SC antialiasing filters. It also contains the quantization noise of the a/d converter.

The time-domain noise is transformed to a harmonic spectrum according to Parseval's theorem. Namely, if σ denotes the standard deviation of the input signal noise with zero mean value, and N is the number of DFT samples, then due to a uniform distribution of the noise energy over all spectral components, the rms values of the signal harmonics are calculated with a random error of the standard deviation σ_s , equal to

$$\sigma_s = \frac{\sigma}{\sqrt{N}}. \quad (18)$$

This formula is valid under the assumption that the rms values of harmonics are much lower than those of the fundamental, which is true in the situation considered. Also, a truncation error caused by the computer is neglected. At a standard precision of real numbers in the Matlab/Simulink program, its value is lower by a few orders than that caused by the random value of the lowest bit of the a/d converter.

Due to weighted additions during DFT calculations, the spectrum noise is Gaussian for any type of noise in the time domain, i.e., the uniformly distributed a/d conversion noise. 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. The standard deviation of random errors for a 12-bit a/d converter, 64-point FFT which reduces the standard deviation according to (18) by 18 dB, and a full conversion range amounts to -83 dB with respect to the fundamental harmonic rms value assumed to be 0 dB. This error results from the random value of the lowest bit of the a/d converter. This value for a 12-bit converter and 64-point FFT should be of the order of -86 dB. The measurement has shown, however, that this deviation is approximately -83 dB. Random 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.

Isolation amplifiers and antialiasing SC filters are the main sources of nonlinearity in the M & SPS. This nonlinearity results in the generation of harmonics of unpredictable value. Consequently, these harmonics affect the accuracy of the rms value measurements, but they are difficult to describe and even to simulate. The standard nonlinearity of an isolation amplifier of order of 0.01-0.02% is equivalent to the spurious-free dynamic range (SFDR) of -100 dB, while integrated analog and switched capacitor filters generate harmonics at a level of the order of -70 dB, so that the filter appears to be the most distorting element of the signal conditioning circuit.

VI. SYSTEM DISTURBANCE

The increments Δu_n and ΔI_n in the crms value of the voltage and current harmonics can be obtained by changing the state of the system with a disturbing device. Obtaining sufficient magnitudes of these increments is the main difficulty in an on-line measurement of the system parameters. This is important, since according to (11) and (13), systematic and random errors, ξ and ρ , contribute to the calculation error because the quantities are referenced to increments ΔU_n or ΔI_n . At low distribution-system impedance, high current is needed to affect the voltage. Such a disturbing device should not be annoying to the customer, however. A single disturbance should not change the rms value of the load voltage by more than a few percent. This value should be even less, if the disturbances repeat, since these disturbances could cause some harmful effects; for example, light flickering may occur.

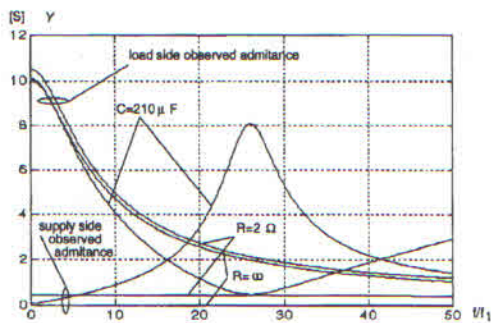
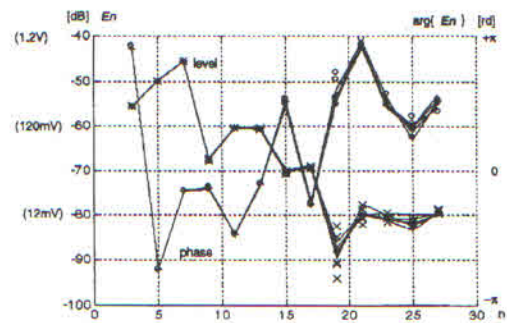


Fig. 3. Plots of admittances versus frequency.

A capacitor can be used as a disturbing device, since its admittance increases with harmonic order. Thus, disturbances are stronger for higher harmonics than for the fundamental. Since the impedance of distribution systems is usually inductive, the change in the admittance as observed from the distribution system can be magnified by a series resonance, while the change in admittance as observed from the load terminals can be magnified by a parallel resonance. The difference between the effects of disturbing the tested system ($R_s = 0.1\Omega$, $L_s = 50\mu\text{H}$) with resistance $R = 2\Omega$ and with capacitance $C = 210\mu\text{F}$, is illustrated in Fig. 3, where the admittances as seen from the distribution system and from the load are plotted versus relative frequency f/f_1 , with $f_1 = 60\text{ Hz}$. Disturbing the tested system with a capacitor made it possible to obtain the voltage increment ΔU_n in the vicinity of a resonance frequency approximately 50 times higher than increments obtained with a resistive device. The resonance frequency can be moved, moreover, by changing capacitance, to a frequency band where the measurement accuracy should be improved. Thus, disturbing the tested system with a capacitor increases the accuracy of the parameter identification substantially. A capacitor bank installed for the power factor improvement could be applied for that purpose. Switching a capacitor results in transients, however. Thus, a sufficiently long time delay is required for the measurement. To eliminate transients at repeated disturbances, a fast power electronic switch was used. It switched the capacitor ON when the instantaneous value of the supply voltage was equal to the capacitor voltage, and it switched the capacitor OFF at its current zero value.

By repeating the measurement for a sufficiently long time, the random error ρ can be reduced below the systematic error ξ . At a low harmonic content, this error may still be too high to enable parameter identification with an acceptable accuracy. A source of harmonic distortion is needed in the circuit in such a case to increase this accuracy.

A thyristor switch connected across the load terminals was used as a source of harmonic currents. One of two thyristors was fired every half cycle, just before voltage zero-crossing, producing narrow current spikes of 0.25 ms duration and the value limited by a small resistance. These current spikes result in a minor voltage distortion in the range of the zero crossing, not harmful for the load performance, but with harmonics sufficient for the parameter identification. This disturbing

Fig. 4. Results of identification of distribution system voltage harmonic crms value E_n .

device is referred to as the "harmonic generating device", or HG device in this paper.

VII. COMPUTER SIMULATION

The method discussed was verified with a computer model of the system under test, along with the disturbing circuit and the M & SPS. The Matlab/Simulab simulation program was used for that purpose.

To verify the method discussed, it was applied to a distribution system and a load with known parameters: $L_s = 50\mu\text{H}$, $R_s = 100\text{ m}\Omega$, $G_c = 100\text{ mS}$, and $B_c = 0$, which were also used in the computer model. Harmonics of the supply voltage in the computer model were assumed to have rms values as observed in the lab at the open terminals of the supply, with the fundamental $E_l = 120\text{ V}$. The load generated current j was set to zero.

The structure of the tested system, its parameters, and waveform distortion were modeled along with the structure and parameters of the M & SPS. The parameters of the M & SPS and its nonlinearity were set up as close as possible to the catalog data and measured values. A uniform distribution noise, equivalent to a 12-bit a/d conversion was added to the samples obtained with coherent sampling of the signals modeled, proportional to the voltage and currents at cross sections xx and yy. Figs. 4–6 show the results of the identification with a $210\mu\text{F}$ disturbing capacitor and the HG device. These figures show the results only for the odd-order harmonics since only odd harmonics were generated by the HG device. Fig. 4 shows the results of five simulations of the measurement of the crms value E_n . The rms values E_n calculated for a capacitive disturbance are marked with "x" and their phase with "o." The results obtained for the system disturbed with the HG device are connected with lines.

It can be seen from Fig. 4, that both methods provide almost the same results for harmonic content up to -70 dB (0.03%). Figs. 5 and 6 show the results of identifying the supply source impedance equal to $Z_s = (0.1 + j5 \cdot 10^{-5}\omega)\Omega$ and the load impedance equal to $R_c = 10\Omega$, with the real part of the admittance or impedance marked with "x" and the imaginary part with "o." The results obtained for disturbances with the HG device are connected with lines. Disturbance with the

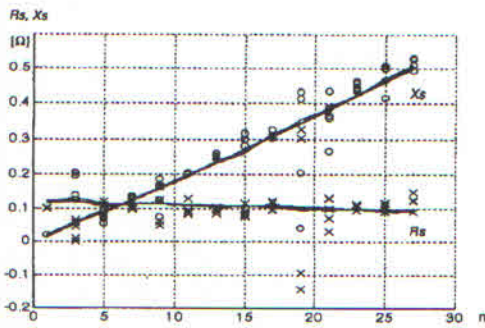


Fig. 5. Results of identifying the distribution system impedance.

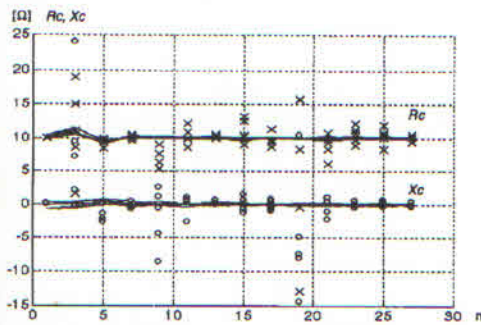
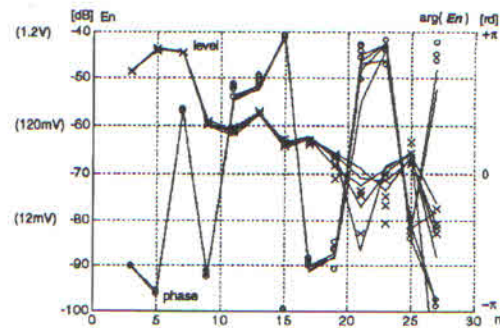
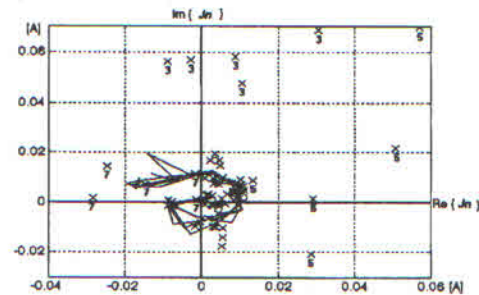


Fig. 6. Results of identifying the load impedance.

HG device now provides results superior to those obtained with a capacitive disturbance. Observe, however, that the test was performed at very low voltage distortion of the order of 0.6%. For example, the values of impedance Z_s calculated for the 23rd harmonic under capacitive disturbance are widely scattered, they were obtained, however, with a content of only 0.01% of this harmonic in the supply voltage.

Though the results shown in Figs. 4–6, are more scattered for the capacitive disturbance than for the disturbance with the HG device, it does not mean that such a disturbance is inferior as compared with that using the HG device. Harmonic filters are installed in systems with waveform distortion much higher than the distortion assumed for the computer simulation. Therefore, when system parameters are needed for a harmonic filter design, then due to the higher distortion, the measurement accuracy at the capacitive disturbance would increase substantially. It is worth observing, that due to a resonance amplification of the harmonic content by the capacitive disturbance, the measurement accuracy remains approximately at the same level, despite, as can be seen from Fig. 6, the harmonic content declining with the frequency. Simulating the measurement of the load generated current harmonics crms values J_n , it was found that at the load current rms value of 12 A, the highest error magnitude at a capacitive disturbance was of the order of 15 mA, i.e., 0.12%. Disturbing the system with an HG device reduces this error approximately by a factor of three. These results indicate that parameters of even weakly polluted systems could be identified with a capacitive disturbance. Identification is more reliable, however, if the tested system is disturbed by an HG device.

Fig. 7. Complex rms values E_n measured at the lab supply.Fig. 8. Error of the load generated harmonic currents crms value J_n measurement.

VIII. PHYSICAL EXPERIMENT

Physical experiments were performed at the supply of a power electronics lab in the department building with a 150 kVA, three-phase transformer. The noise in the system tested and also in the signal conditioning circuits dramatically reduces the identification accuracy as compared with that obtained from the computer model described in the previous Section. It appears, that such single period records in a physical experiment provide a voltage harmonic crms value identification with approximately 30 times less accuracy, which is equivalent to that obtained from simulation with only a 7-bit a/d conversion. The random components ρ_u and ρ_i of the measurement errors are responsible for this. On the condition that the system tested is unchanged, the accuracy can be enhanced by averaging the results obtained by repeated measurements. According to (18), the test has to be repeated approximately 900 times to decrease the random error to its level at a simulation with a 12-bit a/d converter. It means that signal records of approximately 15 s duration are needed to recover the identification accuracy obtained with the simulation. The results of the identification of the harmonics crms values E_n of the internal voltage of the supply for 500 measurement repetitions are shown in Fig. 7. Similarly, as in the case of Fig. 4, the rms values E_n calculated for a capacitive disturbance are marked with "x" and their phase with "o". The results obtained for the system disturbed with the HG device are connected with lines. The distribution of the results does not differ substantially from the simulation results. The scatter of the results for the phase ϕ_n of the

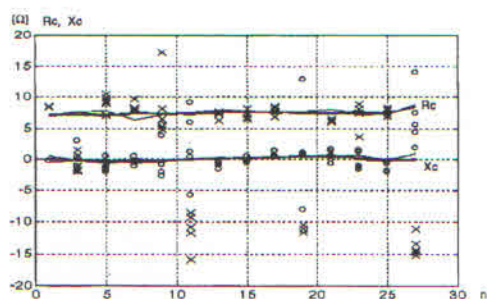


Fig. 9. Results of load impedance measurement.

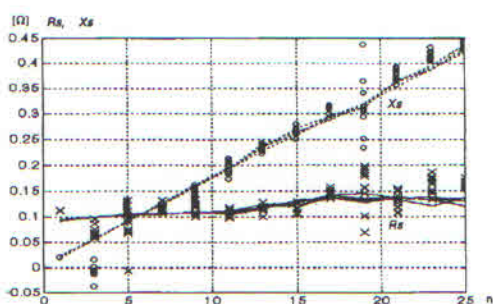


Fig. 10. Results of impedance measurement at the lab supply for signal records of 166 s duration.

15th and the 27th order harmonics is only apparent since it is calculated as $\phi_n \bmod(2\pi)$. There were no sources of harmonic currents of substantial power in the lab, so that, the results of the crms value J_n measurement, as shown in Fig. 8, provide directly the error in its measurement. The measurement was performed at 16 A load current. Thus, even with the capacitive disturbance the relative error is of the order of only 0.5%. When disturbing with the HG device the accuracy is approximately 10 times higher. The accuracy of the source impedance and the load admittance measurement at harmonic levels of the order 0.3% and the records of 15 s duration was substantially lower compared with simulation. This is visible in Fig. 9 for the load impedance measurement, based on 500 repetitions. Longer records are needed to increase the accuracy. This is demonstrated in Fig. 10 which shows the results of the supply source impedance identification using ten times longer signal records. At such long signal records the question could be asked whether the system is sufficiently unchanged for that. Variability of the voltage distortion, is usually high. This distortion changes with a change of all distant harmonic generating loads in the distribution system. The distribution system impedance is not, however, a rapidly varying parameter.

IX. CONCLUSIONS

Computer modeling and physical measurements discussed in the paper show that it is possible to determine the equivalent circuit parameters for harmonic frequencies at the junction of a distribution system and the load by on-line measurements

of the original and the disturbed systems. At high waveform distortion a capacitor bank could be used to disturb the system, on condition however, that it is equipped with a power electronic switch that can enable multiple switching without harmful transients. If this is not possible, a harmonic generating device is needed. At presently available thyristor ratings, such a device with a peak power of several MVA could easily be built using a single thyristor. High resolution in the a/d conversion is not particularly important. Much more important is a low level of nonlinear distortion in the signal conditioning circuits and a low level of noise. The level of the system disturbance is critical for the measurement accuracy. This level is a matter of a trade off between the level that could be tolerated by a customer and that required to obtain the needed measurement accuracy. It was demonstrated that it is possible to disturb the system to a level that enables parameter identification without annoying side effects.

REFERENCES

- [1] D. Crevier and A. Mercier, "Estimation of higher frequency network equivalent impedances by harmonic analysis of natural waveforms," *IEEE Trans.*, vol. PAS-97, no. 2, pp. 424-431, March/April 1978.
- [2] M. F. McGranaghan, "Instrumentation and methodology for power system harmonic measurement," in *Proc. Int. Conf. Harmonics Power Syst.*, Worcester, MA, 1984.
- [3] L. E. Benta and A. P. Meliopoulos, "Distribution system impedance measurement techniques," in *Proc. Int. Conf. Harmonics Power Syst.*, Worcester, MA, 1984.
- [4] J. J. Toth III and D. J. Velazquez, "Benefits of automated on-line harmonic measurement systems," *IEEE Trans. Ind. Applicat.*, vol. IA-22, no. 5, pp. 952-963, Sept./Oct. 1986.
- [5] K. Mikolajuk and Z. Staroszczyk, "Measurement aspects of the voltage distortion compensation," *Europ. Trans. Electric Power Eng.*, vol. 4, no. 5, pp. 403-410, Sept./Oct. 1994.



Leszek S. Czarnecki (SM'85-F'95) received the M.S. and Ph.D. degrees in electrical engineering, and the D.Sc. degree from Silesian Technical University, Poland, in 1963, 1969, and 1984, respectively, where he was employed as an Assistant and Assistant Professor.

From 1984 to 1986, he was a Visiting Research Officer, National Research Council of Canada, Power Engineering Section, Division of Electrical Engineering. From 1987 to 1989, he was an Associate Professor, Department of Electrical Engineering, Zielona Gora Technical University. Since 1989, he has been a Visiting Associate Professor, Department of Electrical and Computer Engineering, Louisiana State University, Baton Rouge. His research interests include power phenomena in systems with nonsinusoidal waveforms and compensation in such systems, network synthesis, power electronics, instrumentation and measurements in nonsinusoidal systems.



Zbigniew Staroszczyk (M'95) received the M.S. and Ph.D. degrees in electrical engineering from Warsaw Technical University, Poland, in 1974 and 1984, respectively, where he was employed as an Assistant and Assistant Professor.

Since 1994 he has been a Visiting Research Associate, Department of Electrical and Computer Engineering, Louisiana State University, Baton Rouge. His research interests include signal processing, instrumentation, and digital measurements.