Jakość i Użytkowanie Energii Elektrycznej
Tom IX Zeszyt 2 Rok 2003

MODERN MEASUREMENT OF ELECTRICAL ENERGY QUALITY INDICES

Współczesny Pomiar Wskaźników Jakości Energii Elektrycznej

Andrzej Bień
AGH — University of Science and Technology
Kraków

Summary: **Recent power networks provide electrical nergy to consumers of different characteristics. The way the power is supplied and the behaviour of the consumers generate various complex phenomena in power networks. From the electrical energy consumers' point of view, these phenomena cause changes of electrical energy quality parameters. These changes are felt as worsening electrical energy quality. The electrical energy quality assessment is connected with measuring quality indices and, further, with comparing the indices obtained with limiting values specified in standardising documents. Indices definitions are based on physical phenomena connected with electrical energy transmission and with the influence exerted by the perturbed electrical energy on the consumers. The electrical energy quality assessment requires therefore using such instruments that measure the indices according to the adopted definitions and with inaccuracy as small as possible. Most electrical energy measurement definitions are implemented approximately. The approximation results from the adopted definitions, their descriptions and the method the measurement is implemented.**
The definitions of electrical energy indices and descriptions of their measurement implementations allow to construct measuring instruments based on different technologies of which digital measurement system are most widely used recently. The design of such measurement systems requires digital algorithms to be applied to measure signals specified in definition descriptions as analog operations. To make measuring instrument indications reliable, verification procedures are used. They shall reflect real working conditions of the measuring instrument. This is one of the essential reasons of substantial differences between the measurement results of the reliable measuring instruments. Recent measurement methods based on fast signal processing by means of signal processors and programmable structures will be better base for developing the definitions of the measured quantities, i.e. indices. Newly developed digital measuring instruments should take into account the real properties of power network and conditions of measurement.

Streszczenie: **Współczesne sieci energetyczne dostarczają energię elektryczną do odbiorników o różnych właściwościach. Sposób dostarczania energii i zachowanie się odbiorników prowadzi do powstawania różnych złożonych zjawisk w sieciach energetycznych. Zjawiska te z punktu widzenia odbiorców energii elektrycznej prowadzą do zmian jej parametrów. Zmiany parametrów energii elektrycznej są odczuwane jako pogorszenie jej jakości. Ocena jakości energii elektrycznej jest związana z pomiarem wskaźników jakości i dalej porównaniem otrzymanych wyników z wartościami granicznymi podawanymi przez dokumenty normatywne. Wskaźniki te są definiowane w oparciu o zjawiska fizyczne związane z przesyłaniem energii elektrycznej i zjawiska związane z oddziaływaniem zaburzonej energii elektrycznej na odbiorców. Ocena jakości energii elektrycznej wymaga więc stosowania przyrządów pomiarowych realizujących pomiar wskaźników zgodnie z przyjętymi definicjami i możliwie małą niedokładnością. Większość definicji pomiarowych wskaźników jakości energii elektrycznej jest realizowana w sposób przybliżony. Przybliżenie to jest skutkiem przyjętych definicji, ich opisu i zastosowanego sposobu realizacji pomiaru.**
Definicje wskaźników jakości energii elektrycznej i opisy realizacji ich pomiarów umożliwiają konstruowanie przyrządów pomiarowych w oparciu o różne techniki, przy czym należy zauważyć, że realizacja pomiaru w oparciu o cyfrowe systemy pomiarowe aktualnie jest najszerzej stosowaną. Konstrukcje takich systemów pomiarowych wymagają stosowania cyfrowych algorytmów wykonywania operacji na sygnałach pomiarowych, często podawanych w opisach definicyjnych jako operacje analogowe. W celu uwiarygodnienia wskazań przyrządów pomiarowych stosowane są procedury sprawdzające. Powinny one odzwierciedlać rzeczywiste warunki pracy przyrządu pomiarowego. Jest to jeden z podstawowych powodów sprawiających, że wyniki pomiarów pomiędzy uwiarygodnionymi przyrządami pomiarowymi mogą się znacznie różnić. Współczesne techniki pomiarowe oparte na szybkim przetwarzaniu sygnałów za pomocą procesorów sygnałowych i struktur programowalnych będą lepszą podstawą dla opracowania definicji wielkości mierzonych – wskaźników. Nowo opracowywane cyfrowe przyrządy pomiarowe powinny uwzględniać rzeczywiste właściwości sieci energetycznej i warunki pomiarów.

Key words: measurement power quality indexes, accuracy and limitation of measurements
Słowa kluczowe: pomiar wskaźników jakości, dokładność i ograniczenia pomiarów

1. INTRODUCTION

Power systems are essential elements and important condition of functioning of our civilisation. As the purest carrier, electrical energy is in common use by various consumers under different conditions. Electrical energy is supplied to non-turbulent, turbulent, linear, nonlinear, low and high power loads. In spite of this, all energy consumers require the parameters and quality indices to be kept at specified levels. The definition of electrical energy quality covers broad spectrum of notions, from physical quantities to legal matters. The electrical energy quality is rather widely understood through specifying a set of indices which should not change more than is laid down in the relevant standards. For quantities defined as current and voltage signals, a notion of electrical energy indices measurement is introduced. The RMS (root mean square) voltage may serve as the example: according to the valid standards, the RMS voltage in the low-voltage network is 230 V and may undergo changes within an interval specified by the relevant legal document. Because of obvious connections between the electrical energy suppliers and consumers, the electrical energy quality indices are the quantities set out in legal documents and standards. Also specified are the allowable ranges of these indices changes. To assess electrical energy quality, it is necessary that these indices are measured, recorded and analysed.

2. ELECTRICAL ENERGY QUALITY INDEX: DEFINITIONS AND DESCRIPTIONS

The values of measurable quantities with indirect and complex definitions (such as the electrical energy quality index) can be determined by indirect measurements only. The quantities that are directly measurable are defined with the use of laws of physics and are described in SI units. When defining measurable quantities the relevant laws are employed concerning this theoretical discipline where the defined quantity occurs. Electrical engineering is such relevant discipline for electric quantities.

Mathematical relationships are the most commonly met forms used for description of the quantities that may be measured and their origin comes from theoretical description of phenomena occurring in electric circuits. A description of signal processing to obtain a value of the measured quantity is used primarily where the measured quantity is of diagnostic character or serves the purpose of quantitative assessment of a highly complicated phenomenon. Such an approach prevails in descriptions of standards. Successive steps of a described procedure are formulated as mathematical relationships or are related to the quantities previously defined by mathematical relationships.

To define measured quantities practically all mathematical operations from the area of function analysis are used. As they must be practically implemented in measurement systems, it always should be expected that certain relevant errors occur. Regarding to the electric signals application and research area, the following mathematical operations can be distinguished for defining complex measured quantities:

- simple operations: summation, subtraction, multiplication, division,
- nonlinear operations: power, logarithmic, exponential operations,
- analytical expressions: differentiation, integration,
- non-analytical expressions: discontinuities, delta distribution.

Definitions of complex quantities are in general expressed by a few various mathematical operations. Measurement implementation of basic definitions of electrical quantities measured directly is difficult or even impossible. The reason is that it is impossible to met infinitely large or infinitesimal values for both observation time and the quantities. This can be seen for the definition of the current unit according to SI or definitions of active power or RMS value. A value resulting from the measurement of the quantity whose signals met the definition assumptions only approximately cannot be adequate to the phenomena relevant to the measurement. The electrical energy manuals omit interpretation of the results such a way obtained. The variations of a quantity simplified when measurement is implemented influences the measurement result in such a way that it is impossible to decide whether it is the measured quantity that changed or the above mentioned limitations influenced the result. The problems of interpreting such measurements are discussed in [8, 9].

The definitions of electrical energy quality parameters have been formulated since it was observed that the nonlinear and turbulent load generate problems to power network operation. Recent possibilities of construction of measurement systems based on the digital processing of a signal allowed to define several quantities describing electrical energy quality [1, 6, 7]. The following parameters can be included into the group of parameters most frequently cited and informing on the electrical energy quality:

- *power-line frequency,* rated voltage frequency, specified for networks operated synchronously with electric power system, or without synchronisation (i.e. autonomically),
- *RMS supply voltage value*, defined for observation period ranging from ″ of the basic period to 10 minutes,
- *fast voltage changes,* individual changes during a 24-hour period that do not exceed the relevant allowable values,
- *severity of flickering* (a term related to voltage fluctuations),
- *voltage drops,* defined as short-time voltage decreases
- *short breaks in supply,* the duration of such breaks can be compared with multiples of basic periods
- *long breaks in supply,* lasting longer than e.g. 3 minutes; an allowable number of such breaks per year is specified,
- *short-time overvoltages,*
- *temporary overvoltages between the live line and earth,*
- *supply voltage asymmetry,* important for multiphase networks,
- *harmonic voltages*, certain values of selected harmonics of the network voltage and the THD coefficient are specified,
- *interharmonic voltages.*

The definitions of the given quantities—electrical energy quality indices—are expressed as mathematical formulas and measurement methods. The list of the quantities has not been yet closed; new definitions of complex measurable quantities or modifications to the existing ones can be expected. This conclusion can be drawn from the discussions carried out in the related literature or at the electrical energy quality conferences. The papers [12, 13, 14, 16, 17] show that the direction of the research now is connected with changing power network operation and new solutions used for constructing the new measurement systems.

The analyses of the definitions given suggests selecting of a basic group of quantities which can be used as a base for defining other quantities. The basic group of quantities includes:

— *basic power-line frequency,* specified as the base frequency of voltage signal, 50 Hz in Europe
— *RMS voltage value,*

$$U = \sqrt{\frac{1}{T} \int_{t_0}^{t_0+T} u^2(t)dt} \tag{1}$$

This definition applies to periodic signals,

— *light flickering perception indices,* P_{ST} and P_{LT}, specifying the discomfort of a user of light sources supplied by the power network voltage,
— *harmonics contents,*
— *specific powers and energies* as the quantities influencing the electrical energy quality indices.

3. APPLIED MEASUREMENT METHODS

The recent state of knowledge on measurements and low-frequency disturbances in the power network voltages includes:

— analysis of influence of "turbulent" loads on the network where network properties are taken into consideration; the problems of disturbance propagation in networks are of the special interest,
— determination of the properties of measured signals, i.e. characteristic forms of time runs, their variation intervals as well as the properties of their frequency spectra,
— adaptation of algorithms used for analysis of stationary and nonstationary signals to the results of measured signal disturbances occurring in power networks,
— definitions of electrical energy quality index measures and their relevant measuring methods.

The tools presented in the published standard documents and scientific papers can be grouped according to various criteria. The author considers methods connected with Fourier frequency analysis the leading elements of every criterion.

Nonstationarity of signal voltages and currents is often connected with the occurrence of pulse (transitional) disturbances. Such signals are often analysed by wavelet transformation.

Another interesting approach is shown in papers on application of non-Fourier analysis to the power network signals. These methods are high-resolution methods and are often applied if a short record of noised sine signal is available. In [17] these methods are called parametric methods.

The parametric methods were applied in the system for measuring power network voltage basic frequency. The main reason of their application is the measurement time, considerably shorter when compared with the period counting based methods. For an inaccuracy below 1%, the measurement time is more that ten times shorter.

Measurement implementation methods approximate the way the quantities defined by the mathematical formula or description are determined. The applied approximations and their influence on the measurement result depend on the measurement implementation. The known measurement implementation methods can be divide into the following groups:

— analog implementations,
— digital implementations,
— mixed implementations.

An **analog implementation** of a signal processing method means that the processing uses physical phenomena for which such intermediate quantities and processing method exist that enable signals and signal processing to be described with continuous functions in time domain. Examples of such processing include scale change with a voltage divider, voltage amplifying by a amplifier with logarithmic characteristic.

In the case of a **digital implementation,** both processing method applied and the intermediate quantities are discrete. Most often, the quantities of digital-discrete character both in output values (resolution of analog-to-digital converters) and in arguments (sampling in time or distance domain) are used. A series of samples produced by reading out indications of digital voltmeter at selected time instants serves an example.

Mixed implementations employ both mentioned above methods and the order the block implementing given method occurs depends on the implemented definition of a complex quantities and the constructor of an instrument implementing the measurement. A measurement system where input signals are filtered with analog filters, converted into digital form and further processed in digital form is an example. The results are available in both analog and digital form. An interesting implementation is using systems with switchable capacitances whose dynamic properties are similar to those of digital systems while discretization does not occur here.

The necessity for using approximations in measurement implementations for quantities according to their definitions results from carrying out the following operations:

— arithmetic operations on signals and measurement parameters,
— scale change,
— signal summation, subtraction,
— signal multiplication, division,
— calculation of functional relationships and functionals,
— signal integration, differentiation
— determination of nonlinear function values,
— diving or limiting functionals into time segments,

and

— limited observation time of input signals,
— limited resolution of signal observation value and time (sampling).

Arithmetic operations carried out for signal values and measurement parameters in analog systems are approximated with nonlinear blocks, as e.g. logarithmic systems, or linear blocks as instrumentation amplifiers. In digital systems, the implementation of the above operations is based on approximating functions and functionals by operations on time series. Representation of numbers used during calculations is an additional limiting element resulting in result truncation or rounding.

The analog solutions approximate definitional operation of integration with constraints. Of the most importance are here finite values of the amplification and input and output resistances. Also, the drifts of these values and drifts zero of occur. This list is longer and the discussion on the problems connected with construction of such systems and methods for correcting operating parameters can be found in information materials of designers and manufacturers of recent integrated circuits.

The operation of integration in digital systems is realised by summation with use of composite quadrature formulas. The requirement that integration operation must be carried out in real time, i.e. during sampling the input signal, considerably limits the choice of the quadrature and its operating time. Replacing integration by summation is the most common solution. An example of implementation of RMS value and active power measurements, where such a solution is applied is discussed in the further parts of the paper. Time differentiation is the next operation used on measurement signals. It is obvious that the differentiation methods presented (like integration methods) approximate differentiation operation. More complex structures with better properties are also available, but all the time the limitations connected with the approximation of differentiation and the class of signals for which a given solutions exists.

Digital methods compete here effectively with the analog methods. Two groups of methods can be defined that may be applied in real-time systems. The first one is based on an expansion i.e. on approximation of definition formula, the second one is based on the properties of digital filters with finite pulse response. A lot of papers exists on the both groups. From point of view of real-time measurement systems, data processing methods with equidistant arguments are very interesting. This results from the utilisation of constant frequencies of sampling observed signals. For several measurement data sufficiently differentiable, method based on differential tables are most often used:

$$\frac{d^r u}{dt^r} = \frac{1}{(\Delta t)^r}\left(\Delta - \frac{1}{2}\Delta^2 + \frac{1}{3}\Delta^3 - \ldots\right) \qquad (2)$$

Assuming: $t_k = t_0 + k \cdot \Delta t \quad k = 0, 1, 2\ldots$ and using interpolation formulas, useful relationships may be derived for differentiating measurement data in real time. A typical 3-point relationship is:

$$u'_{-2} = \frac{1}{2\Delta t}\left(-3u_{-2} + 4u_{-1} - u_0\right) + \xi \qquad (3)$$

where is an error estimate.

The indexes at signal samples u_k denote respectively: 0 – current time moment, i.e. the sample taken lately, –1 —before last sample, –2 —the sample taken as the first to determine the derivative u'_{-2}. This means that the value of the determine derivative corresponds to the –2 time moment. Also, several relationships exist based on the other relationships or other sample number required to determine the derivative. Commercial information on the measurement systems recently available on the market and the relevant papers on signal processing suggest that the methods of differentiating with the finite pulse response digital filters are the most popular.

The coefficients of a filter that implements the differentiation operation can be selected so that the filtration of a selected fragment of the differentiated signal spectrum be possible. The methods for the determination of the coefficients are described in several papers and available as ready-to-use software or procedures. These methods are based on the best possible approximation carried out according to a prefixed amplitude and phase criterion of the designed filter so that it can implemented the differentiation operation with a known error.

Basic statistical operations are the next specific group of operations. They include comparing operations used for making histograms, cumulated probability functions or threshold detectors. Except for the last ones, these operations are implemented in digital way only.

Apart from the discussed operation of integration and differentiation, also nonlinear operations and basic arithmetic operations are used: scale change (multiplication by a constant), signal multiplication, division (indeterminacy of division operation should be taken into account), summation and subtraction of signals.

Based on the mentioned implementation methods, complex operations are created that describe definitions of such complex quantities as: spectrum analysis (Fourier transformation, wavelet transformation), convolution, nonlinear integration operators (Hamerstein, Wiener operators), statistical operations. Also, the measurements are implemented that use optimisation methods, especially for estimating parameters of complex models of phenomena and objects.

4. ACCURACY LIMITATIONS OF THE ELECTRICAL ENERGY QUALITY INDEX MEASUREMENTS

The parameter values determined by the measurement and used for the electrical energy quality assessment should be measured with measuring instruments whose structures and operation algorithms are specified in the normative documents, i.e. the definitions of the measured parameters and their implementation are imposed by the relevant standards. Following this way it makes it possible to comparise the measurement results obtained with different instruments, and the results obtained during a longer time periods. It can be seen that certain quantities can be measured both by the analog and digital methods, while the other quantities can be measured by digital methods only. Those quantities that can be measured by the digital methods only are connected with phenomena and definitions of "grainy" character and being complex regarding to their processing e.g. in the frequency domain. The remaining quantities are measured with instruments that implement the measurement with analog methods, mixed analog-digital methods or by fast analog-digital processing and further processing by digital systems. This last method is applied to measure the quantities based on the definitions connected with Fourier spectrum of the analysed signals, e.g. THD. Typical solutions from the mixed analog-digital group include a light flickering severity meter where the flickering severity signal is determined by an analog method, and its statistical analysis is made by a digital method (a solution presented in normative documents). The limitations and difficulties of the current measurement implementations according to the given definitions of quality measures are connected to the changing parameters of the measuring signals: distortion from sine wave, nearly-periodicity, non-harmonic spectrum, time variability of the amplitude, frequency and phase angle, i.e. variability of the signal spectrum. The properties of the measurement systems used are a next limitation.

These include:

— limitations of the ranges by the accumulated nonlinearity errors,
— measurement frequency band signal,
— static instability (e.g. influence of the temperature and component aging) of components,
— dynamic instability (e.g. oscillations of the filter used),
— internal noise of the instruments resulting from e.g. quantisation in the A/D converters,
— sampling frequency,
— length of words used in the data processing algorithms,
— errors and rounding in calculation algorithms.

Essential limitations result from the difficulties in the calibration of the designed measuring instruments. Complex and multi-stage calibration procedures are the limitation. The reference signals used, are described as periodic signals and, until now, no reference signals exists with random signal characteristics, described by the statistical parameters. A discrepancy between the reference signals and the signals for which a measurement is carried out is clearly visible in the documents on the light flickering severity meter [1, 2, 3] where statistical properties of the tested signal are analysed, and testing signals are sine or rectangular signals. In [8] it is shown that such an approach to the measurement increases the measurement uncertainty and may generate problems of measurement result interpretation.

The construction of the high accuracy instruments will be based on digital or mixed analog-digital processing with a tendency for displacing the mixed analog-digital solutions. The great technological progress in the manufactury of components for constructing such systems (improved is operation speed, resolutions and accuracy, implementation capacity of arithmetic and logic operations) is the second reason for introducing solutions based on the fast analog-digital processing and further digital processing. Economical effects are not without importance here.

5. MEASURING INSTRUMENTS

Digital instruments to measure the electrical energy quality parameters are a sub-group of the existing digital measurement systems. Regarding their hardware, these instruments can be divided into the following groups:

— microcontroller based instruments,
— instruments based on the standard computer systems adapted to real-time systems, industrial version of IBM PC, PC104,
— instruments based on the DSP processors,
— instruments based on programmable logic structures,
— instruments based on mixed solutions.

A choice of the method comes from the requirements for the processing speed, accuracy, user's interface, capabilities of the used design tools and, of course, from the economic reasons. Mixed solutions prevail with the critical (with regard to speed) parts of instruments are implemented by the programmable logic structures or signal processors, while measurement results recording, presentation or transmission trough interfaces are performed by an instrument part built from microcontrollers or IBM PC, VME or VXI systems. The possibility of changing the instrument's operation variability, i.e., the modernization of the instrument without its rebuilding is an additional property of such construction of the instrument. A typical general structure of the instrument is shown in Fig. 1.

The input voltage and current signals are measured and assessed on their quality. In multiphase power systems, they can be treated as voltage and current vectors. Input circuits are a block of analog elements used to scale inputs and provide galvanic separation required to secure the safety of personnel and instrument. Because the signal sampling frequency of the A/D converter block is specified, the input circuits contain also the filters that limit the highest frequency in the sampling signal band so that the requirements of the sampling theorem are met (antialiasing filters). If the input signal sign changes and its constant component is not analysed, A/D converters with lower parameters (zero drift) and band-pass filters can be used. In a A/D block, the signals are converted into digital form. The character of the observed signals (distorted signals of the basic frequency of 50 Hz) and their analysis connected with instantaneous values cause that the fast and high resolution converters are used (ads and catalogues say that converters with are used have resolution of at least 16 bits and operating at sampling frequency of 5 kHz or more). The problem of ensuring sufficient amplitude frequency is two-aspect: the resolution of the A/D converter used and the transmission of common (parallel) disturbances by the input system. Because of the additive disturbances, the utilization of high-quality A/D converters is often not very efficient. Moreover, the spectra of these disturbances cover a band frequency similar to the measuring signal band spectrum. For this reason, a method of effective galvanic separation from the network, of high CMMR coefficient, good measurement signal transmission with low internal noise is used. A digital system implementing transmission of signal to determine quantities characterising electrical energy quality is designed in such a way that it can operate correctly at the given sampling frequencies, i.e. that the servicing times of the external events and calculations do not exceed the calculation power of the means applied. The measurement results are exported by the user's interface understood more widely as visualisation devices, and the interfaces to other digital systems. This interface allows to control the measurement. An autocalibration block is an essential element for controlling of the analog part and the correction of certain deviations in operation of these blocks. The block is controlled by a digital system and is used for generating testing signals of known parameters. The testing signals are transmitted to the input and A/D converters blocks. Through multiplexers, the signals are used to test the state of

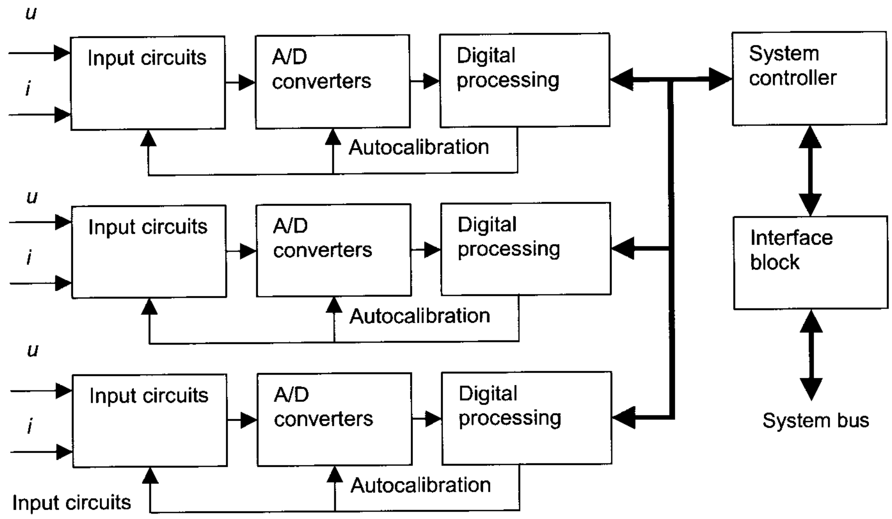


Fig. 1. Block diagram of a system for measuring quality indices in three-phase network

the instrument before measurements starts, or can be treated as additional element of the input data vector and enable current control to be made.

A diagram of the typical system with signal processors, one per each phase, with fast internal bus and specialised controller is presented in Fig. 1. Such a structure is typical for the VXI and VME standard solutions and for fast dedicated constructions.

6. CALIBRATION IN MEASUREMENT SYSTEMS

The systems measuring complex quantities through complicated processing of signals, require the verification of the correctness of the results obtained. This process is necessary for assessing whether the measurement is sensitive to the changes of the measured quantities, and possibly not sensitive to the disturbing quantities. The designed and manufactured measurement system requires after the operational tests that its calibration is made in order to ensure its reliability. The calibration is process that should be standardised. Reference and standardisation papers describing the instrument construction give usually a method for instrument verification and calibration. If complex quantities are measured than this process is usually multi-stage. In the first stage of making the measurement system, the instrument, operational, signal values at some selected points of its characteristic curve are determined. These values are mainly the values of the frequency characteristics and measurement scales. The values of the measured quantities, treated as input values, are selected so that the operational range of the MS (measurement system) can be verified. Sine signals or rectangular signals suitably modulated are the testing signals. Selection of such signals is connected with the knowledge on their parameter values and easiness in their generation. In further stages, the measurement results obtained by the tested MS are compared with the reference instrument. Also, basing on the testing signals specified in the standardization documents, the ready instrument is tested. Based on these signals, their parameter are determined as well as the measurement results these signals. The differences between the measurement results and the expected values give the basis for determining the operational correctness of the MS. The application of procedures with complicated relationships, great number of tests and verifications gives the instruments of similar properties. However, the problem arises of how these checked instruments will work with signals that have more complex spectrum and nonstationarity. Solving this problem, a proposal is put to carry out verification with a reference instrument for selected operating conditions of the MS. The performance of such a task would consist in selecting a group of consumers generating characteristic signals, and verifying the MS during its operation. Systems with dynamically changing load are the examples of the consumers influencing the electrical energy quality. With such a test a problem is connected of nonrepeatability of the conditions under which the MS was tested. On the other hand, complicated tests and limited operational range of the MS worsen its usability, and its economic costs increase. The considerations presented define in fact a problem of calibration of instruments working with random signals. As it was found, such instruments are mostly calibrated by determined signals which results in occurrence of differences difficult to interpret. A way to solve this problem is searching for such measurement methods and defining such quantities that have the same properties for random and determined signals.

7. INTERNATIONAL COOPERATION ON SCIENCE AND TECHNOLOGY

The complexity and importance of the electrical energy quality problems in power networks of various countries and the commercial exchange of electrical energy contribute to developing many standardization documents. Recently, standardization documents lay down the definitions of indices being the quality criteria, and the recommended method for their measurement. In most cases, a general method of measurement is given and also the method for verifying its correctness. Measuring instruments used for quantitative assessment of electrical energy quality by measuring selected quality indices are important elements of the quality improvement. The problem of developing and standardizing methods for measuring the effects of network voltage variability within the 0.5 Hz – 2 kHz band has been intensively investigated for more than 10 years by the International Union for Electrotechnology and the International Electrotechnical Commission. These activities are focused on determining uniform measurement methods (implemented in various ways, though), adopting certain measures for quantitative assessment of measured quantities and standardising the form of measurement results. Not without an importance in these activities is the dissemination of the opinion that the work carried out in this discipline is purposeful and is the condition for improving electrical energy quality. The "Leonardo" programme under the European Union may be an example of such activities.

The measurements of electrical energy quality-connected quantities were initially based on the valid national standards and guidance manuals, as a rule different in different countries where tests were carried out. In 1980s, when the problem of disturbances in power networks intensified, the access to intense work on developing correct and uniformed methods was declared by such organizations as UIE, IEC, CENELEC (European Committee for Electrotechnical Standardisation) and IEEE. They published several reports and standardisation documents that were accepted in groups of power network constructors and operators. Now, under the accession obligation, several documents are being translated into Polish. Observing new documents, old updated ones and discussions in standardisation committees and professional journals suggests that this is a problem in a developing state and new changes are to be expected forced by the progress in measuring technique and the changing operational conditions of power networks.

8. RESEARCH AND PRACTICAL PROBLEMS—THE PROSPECTS

The area of problem connected with the widely understood control over the electrical energy distribution is vast. On the one hand, it covers all stages of electrical energy transmission, on the other hand, it covers the multiplicity and complexity of the measuremend of the quality parameters of the transmitted electrical energy. Journals (national: Quality and utilisation of electrical energy) and many scientific conferences are dedicated to these problems. Also the relevant research work is carried out. The recent stat of art of the technology clearly augment these problems. The analysis of document and papers show that both research work and development of standardisation documents continues and nothing points the end is nearby.

From the metrological point of view, two directions of work can be distinguished: the first one concerns developing definitions for electrical energy quality indices, the second one covers the problems of designing the instruments measuring the electrical energy quality indices. These works converge and aim to such a description of problems on measuring instruments and methods that the resulting standardisation documents could be used for practical implementing of measurements employing mostly digital method for processing measuring signals. Several research and technology problems can be defined for measurement methods, circuit solutions and metrological properties of the devices for determining quality parameters of the supplied electrical energy. Of special interest is the measurement of the quantities connected with the physiological effects of light source flickering.

Basic problems include certainly the problems with definitions and with making measurement conditions more precise, especially those subjective. An example can be presented the problem of the influence of physiological factors during designing a flickering severity meter, i.e., flickermeter. Low band and the way voltage changes, mostly nonstationary, but approximately described by statistical parameters is another important problem.

Definition problems are beeing solved by creating definitions based on natural measures. Examples are: voltage instantaneous value, RMS value, average, frequency. More complex, "arbitral" measures are also used, e.g. such that give the influence of light flickering on man's physiology. Solutions to the definition problems are carried out based on the following premises:

- — using the measurement as a functional over the measured variables. Required: measure uniqueness and boundedness, i.e. the existence of a measure for real signals.
- — obtaining such properties of the measures that enable the efficient interpretation of the described phenomena to be made
- — high measure sensibility to the variability of parameters connected with the measured quantity.
- — low sensibility to unwanted factors because each "ideal" definition is implemented under real conditions and with concrete technical means.

Finally, the definition problems are solved first of all by international agreements on the definition formula and on the manner the mentioned above factors are taken into account in the measurement method with application of recent technical capabilities. Such capabilities consist, first of all, in application of fast digital technique to implement algorithms of complex voltage processing and in spectral and statistical analyses. The usability of the defined electrical energy parameter verifies the whole work.

The second group of research and technology problems is connected with the implementation of measurement and the assessment of metrological properties of measuring instruments. The basic idea of a digital instrument consists in the fast high-resolution A/D processing of the measured network voltage, and then in digital implementation of the definition of measured quantities in a signal processor or other system processing signal in a digital way. The rate of processing results from the nonstationarity of the voltage of 20 ms period and spectrum covering the band up to the 40th harmonic while the high resolution results from the measurement signal variability, i.e. generally small (of order of percent of fraction of percent) "components" of this voltage against a constant large value. This implies stronger requirements on the measuring instrument, especially on the quality of its input circuits. Certain problems arise then of processing quality assessing and measuring instrument testing.

The scope of work concerning building, calibrating and then utilising an instrument for measuring the electrical energy quality index, i.e., light flickering severity, covers two parts.

The first one contains research on algorithms implementing definitions of measured quantities where the amplitude and voltage frequency nonstationarity is taken into account. This research includes:

- presentation of a model for network voltage conversion into a quantity measured in a form of a linear on nonlinear dynamic operation, producing a nonstationary signal connected with the measured quantity
- spectrum analysis of this signal to find objective measures connected with the measured quantity,
- investigating the parameters (random and non-random) of these measures, with the nonstationarity character of the investigated signal taken into account.

Such stating of the problem of measured quantity representation means that the signal processing models should be separated in the measurement path into the models that can be assessed objectively and the models whose assessment is to considerable extent subjective. In the second case, it is necessary to accept the settlements following from the up-to-date experiences or valid documents.

The second part includes the verification of the conception of circuit and program solutions of an instrument for measuring electrical energy quality. The conception foresees the application of the modern and available technological solutions. The constructions of such instruments have full galvanic separation and autocalibration features. Also it is planned that the instruments may be connected to computers that are provided with standard interfaces (e.g. RS232, RS485, eternet and modem connections) to record in long time periods the selected measurement results and to operate with computer networks. Such recording can be used to determine the quantities that describe changes in voltage parameters in normal operation during long time period, e.g., frequency and the range of voltage changes, flicker, harmonic content and other changes occurring in large power systems. These quantities may be used to analyse the power system operation, so such an instrument may also be applied to diagnose power systems.

It is proposed that measuring instruments be built in two classes of measuring quality: reference instruments with their parameters strictly specified by the standards relating to instrument construction and measurement method, and indicators with allowable greater measurement errors that can result from a simplification of the measurement method. Relatively large differences (of order of a few percent) between the results of measurements made by these instruments are allowable.

The directions or work carried out in several research centres, and the problems the users of the recently manufactured measuring instruments encounter are related with the large differences between indications of measuring instruments considered as reference ones, and with their interpretation. Following changes in the standardization documents, it can be noted that attempts made by ICE aim at defining the parameters of measuring instruments more precise, so that these differences be removed. The differences between the measurement results are the effects of measurement signal properties and differences in the constructions of various instruments that meet the requirements of the relevant standards, which leads to the problems of interpreting of results. The work of standardisation committees aim at adopting more stringent testing of the manufactured instruments by developing a rather complicated multi-stage instrument calibration procedure. It is assumed that introducing simpler methods for processing measurement signals postulated in this paper will significantly reduce such differences. Introducing the digital processing method and placing in a document the parameters of this processing will eliminate the differences between the manufactured instruments. Application of digital methods for processing measurement signals results in better approximation of the model of the described processing methods and an evaluation of this approximation as early as in the stage of the design of a MS, and, in consequence, improving the quality of measuring instruments. Comparing the recent state of technology, especially the parameters of instruments with digital signal processors (fast digital systems with a 150 MHz clock or better, fixed and floating point arithmetic) or programmable logic structures, with the parameters of measurement signals connected with the electrical energy quality (the band of usable signals smaller than 10 kHz), it can be stated that the digital implementations of measurement methods are technological feasible and may have measurement characteristics much better than their analog equivalents. However, implementations of measurements by digital systems generate hardware and software problems because measuring according to an accepted definition requires adopting certain approximations of the operations used on signals, and must take into account the properties of the technological means used for measurement implementation.

Solving of the problems, presented in this paper, is based on the available technological means and is often limited for economic reasons. Pursuing the greatest accuracy possible usually results in an increase of calculation capacity (e.g. filtration by filters with a greater number of coefficients); also data word length increases and the number of arithmetic operations. It is, therefore, necessary to have more time for the measurement, or a faster and more efficient digital system. To this end, signal processors are introduced (with their structure adjusted to the measurement type), and programmable logic structures. The digital system type and its calculation capacity are, in turn, limited for economic reasons. It can be noted that digital technology is preferred in standardisation documents. At the recent stage, this technology only replaces analog solutions, modelling their operation. It may be presumed that new capabilities of digital technology allow to employ new definitions of measured quantities and more accurate representation of defined quantities that are feasible to be implemented not only in this technology.

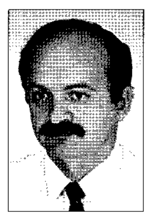
The presented problems of measuring parameters, indices of electrical energy quality, refers especially to signals connected with the part of spectrum close to the basic power network frequencies and called nonstationarity. The consideration presented are a starting point for defining new electrical energy quality indices and designing measuring instruments to determine their values.

9. CONLUSIONS

The problem of defining the measured quantities describing the electrical energy quality is an important side of the problems discussed. Analysing the relevant papers and discussions, it can be noted that such a quantity is searched for, that it measurement will more synthetically represent the state of voltage at an testing point of the power network. To determine more accurately disturbances and predict their propagation, this quantity should meet the conditions necessary for determining a rational scale, and especially the postulate of additivity of measurement results. The lack of solution to this question results in developing new and new quantities assessing the electrical energy quality with regard to particular groups of power system users. Certain difficulties occur with unique interpretation of measurement results, which produces some attempts to make definitions their implementations more precise through more and more complicated procedures of design and calibration of measuring instruments. A turning point in measurement of quantities connected with electrical energy quality has not occurred yet. In the author's opinion, the development of a definition of a quantity being an electrical energy quality index in low frequency disturbances of power network and that does not have measurement and utility disadvantages is feasible.

REFERENCES

1. *Guide to Quality of Electrical Supply for Industrial Installations, Part 5, Flicker and Voltage Fluctuations*, "Power Quality" Working Group WG2, 2000.
2. IEC 60868, *Flickermeter, Functional and design specifications*, 1986.
3. IEC 60868-0. *Amendment 1, Flickermeter, Functional and design specifications*, 1990.
4. IEC 61000-4-15 A1 Ed.1, *Amendment to IEC 61000-4-15, Electromagnetic compatibility (EMC) – Part 4-15: Testing and measurement techniques – Flickermeter – Functional and design specifications*, 2002-09-20.
5. IEC 61000-4-15:1997, *Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Section 15: Flickermeter – Functional and design specifications.*
6. *Power Quality Measurements for Contract Applications*, DRAFT, SC 77A,WG9, TF1, 1998.
7. Arrillaga J., Watson N.R., Chen S.: *Power system quality assessment.* John Wiley & Sons, LTD 2000.
8. Bień A., Szyper M., Rozkrut A.: *Correctness of flickermeters calibration.* IMEKO 2000 International Confederation XVI IMEKO World Congress, Hofburg Wien Austria, September 25–28, 2000.
9. Bień A., Rozkrut A.: *A measurement scale for the light flickering phenomenon.* procedigs 6th International Conference, Electrical Power Quality and Utilisation, September 19-21, Kraków, 2001, str. 231–239.
10. Bucci G., Landi C.: *On-Line Digital Measurement for the Quality Analysis of Power Systems Under Nonsinusoidal Conditions.* IEEE Transactions on Instrumentation and Measurement, Vol. 48, No. 4, August 2001.
11. Caldara S., Nuccio S., Spataro C.: *Digital Techniques for Flicker Measurement: Algorithms and Implementations Analysis.* Proceedings of the 16th IEEE Instrumentation and Measurement Technology Conference, Volume 2, Venice Italy 24–26 V 1999.
12. Chen M.T.: *Digital algorithms for measurement of voltage flicker.* IEE Proc.-Gener. Transm. Distrib., Vol 144, No. 2, March 1997.
13. Daponte P., Di Penta M., Mercurio G.: *Transientmeter: a distributed measurement system for power quality monitoring.* Ninth International Conference on harmonics and quality of power Proceedings, Vol. II, Orlando, Florida USA, October 1–4, 2000.
14. Dash P.K., Mishra S., Salama M.M., Liew A.C.: *Classification of power system Disturbances Using a fuzzy expert system and a Fourier linear combiner,* IEEE Transactions on Power Delivery, Vol. 15 No 2, April 2000.
15. Hanzelka Z., Bień A.: *Voltage Fluctuation.* International Workshop on Power Quality, Organized by Carlos III University, Electrical Engineering Department, Session 2: Perturbations, 21 May, Madrid Spain 2003.
16. Lakshimikanth A., Morcos M.M.: *A power quality Monitoring System: a case study in DSP—Based Solutions for power electronics.* IEEE Transactions on Instrumentation and Measurement, vol. 50 number 3, June 2001.
17. Łobos T.: *Advanced spectrum estimation methods for signal analysis in power electronics and systems.* Electrical Power Quality and Utilisation, Kraków, Polska, September 19–21, 2001.



Andrzej Bień

Was born in 1954 in Warsaw, Poland. He received M.Sc. and Ph.D. degrees from the University of Mining and Metallurgy in Cracow. At present he is Researcher in the AGH University of Science and Technology in Cracow, Department of Meseurement and Instrumentation. His field of interest is digital instrumentation based on DSP for electricity property measurement (especially power quality).

Mailling address:
Andrzej Bień
AGH University of Science and Technology
Department of Meseurement and Instrumentation
Al. Mickiewicza 30, 30-059 Kraków
Poland
phone: (+48 12) 617 28 73, fax: (+48 12) 633 85 65
e-mail: abien@uci.agh.edu.pl