Invited paper **Zbigniew HANZELKA, Krzysztof CHMIELOWIEC, Andrzej FIRLIT, Bogusław ŚWIĄTEK**

AGH University of Science and Technology, Department of Power Electronics and Energy Control Systems

New Challenges for Voltage Quality Studies

Streszczenie. *Artykuł przedstawia cztery problemy z dziedziny jakości dostawy energii elektrycznej, które nadal są nierozwiązane, a mają zasadnicze znaczenie dla praktyki inżynierskiej. Są to: (a) wiarygodny pomiar miar liczbowych wskaźników jakości; (b) lokalizacji źródła zaburzenia elektromagnetycznego oraz ocena indywidualnej emisji; (c) rozproszone monitorowanie on-line stanu jakości napięcia, oraz (d) szacowanie kosztów złej jakości energii elektrycznej. Każdy z tych problemów został zilustrowany wybranym przykładem.* ***Nowe wyzwania w dziedzinie jakości dostawy energii elektrycznej***

Abstract*. The paper presents four unsolved problems in the area of power quality having the particular significance for the engineering practice. These are: (a) credible measurement of the voltage quality numerical measures of the voltage quality indices; (b) location of electromagnetic interference source and evaluation of individual load emission; (c) distributed on-line monitoring of the voltage quality in a power system, and (d) evaluation of poor power quality costs.*

Słowa kluczowe: jakość dostawy energii elektrycznej, wskaźniki jakości, lokalizacja zaburzenia, regulacja jakości
Keywords: quality of electric power delivery, power quality factors, disturbance source location, quality control system

Introduction

The quality of power delivery becomes one of the most important issues of the contemporary electrical engineering. Presently, and most certainly in the near future, the majority of electricity consumers will be facing problems associated with electrical power quality either benefiting from it, in both the professional an financial terms, or experiencing adverse impact of its deterioration.

Over the last decade an interest in this rapidly developing area of science and engineering has grown significantly. Among numerous reasons for this interest is the fact that the world economic growth and the quality of our life are presently determined by the quality of power delivery. Another reason that should be mentioned is the growing penetration of distributed energy sources.

Despite of great interest in these issues and an extensive research carried out in this field, still many problems remain unresolved and their list is surprisingly long. The authors do not undertake the task of compiling a list of such problems. They confine their presentation to four selected problems of particular significance for the engineering practice. These are: (a) credible measurement of the voltage quality numerical measures of the voltage quality indices; (b) location of electromagnetic interference source and evaluation of individual load emission; (c) distributed on-line monitoring of the voltage quality in a power system, and (d) evaluation of poor power quality costs. Each of these problems will be illustrated by a representative example.

Measurement of power quality factors

One of the challenges in the power quality (PQ) domain is currently the preparation of procedures for verification of the trueness of measurements performed by means of instruments used for PQ assessment. The issue is apparently obvious - power quality analysers have been utilized for almost two decades, and their share in the power measurements is rapidly growing over last years. New companies are joining the group of these instruments manufacturers seeking for opportunities to extend the range of their offer in this field. Nevertheless different PQ analysers of class A [1.], connected at the same point, yield divergent results whose uncertainty exceeds the limits laid down in relevant standards [1.][2.][3.]. These standards define measurement algorithms and permissible measurement uncertainty, but they do not define procedures for verification of both: the measuring instruments indications trueness and the conformity with a specified accuracy class. In the absence of such information there is no formal and legal basis for PQ analysers certification according to the requirements of the measurement class A. That means no laboratory can formally issue the class of measurement certificate, as a matter of fact, the legal value of already issued certificates is dubious. The practice shows that the lack of standardisation may also result in erroneous indications of commercially available class A instruments [4.][5.][6.]. In order to illustrate this thesis have been compared voltage quality indices recorded by means of selected PQ analysers (Table 1) connected to the same programmable voltage source. The conducted research shows that the results of power quality indices measurement from some class A analysers differ from the values set at the generator. The most frequently occurring discrepancy resulted from erroneous measurement algorithms or incorrect interpretation of standards provisions.

Table 1. List of the class A PQ analysers used in the comparative research

Manufacturer	PQ Analyser
A-eberle	PQBox-100
Fluke	Fluke 435
Lem (Fluke)	Topas 1000
Mikronika	SO-52v11-eME
Procom System	Certan PQ-100
PSL	PQube
Schneider	ION7650
Siemens	Siemas Q80
Sonel	PQM-701
Q-Wave Qualitrol	PowerQuality RTV
Unipower	Unilyzer 902C
Elspec	G3500

Example 2.1: Verified factor was the total harmonic voltage distortion THD factor of a square-wave voltage applied to the inputs of ten selected instruments, listed in Table 1. It was found that three instruments indicated THD = 41 %, whereas the other seven instruments indicated THD = 45 % (Table 2) [5.]. This discrepancy resulted from differences in the employed THD measurement formula – the relation (1).

$$(1)\qquad THD=\sqrt{\sum_{n=2}^{H}\left(\frac{G_n}{G_1}\right)^2}\quad THD=\sqrt{\sum_{n=2}^{H}\left(\frac{G_n}{G_{RMS}}\right)^2}$$

Example 2.2: The purpose of this test was to verify the uncertainty of the voltage asymmetry indices measurement under large harmonic content conditions, and at the fundamental harmonic frequency f = 57.5 Hz. At the inputs of PQ analysers were applied distorted voltages (Table 3) with rms values: L1 – 35.40 V; L2 – 38.04 V and L3 – 40.92 V. Angular symmetry of phase voltages was maintained for the fundamental harmonic. The test results are provided in Table 4. The measurement is deemed correct if the measurement result is contained in the interval (+/-0.15%) around the computed expected value [1.].

Table 2. The results of THD measurement

PQ Analyser No.	THD_U [%]
1	41.00
2	45.32
3	44.91
4	45.05
5	45.00
6	41,03
7	44.99
8	41.08
9	44.86
10	45.10

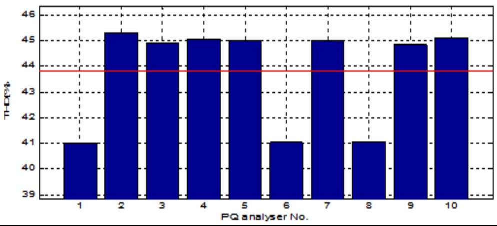


Table 3. Values of harmonics in the distorted voltage waveform

Harmonic No.	3	7	11	15	19	23
Harmonic value related to U_{rms} [%]	10	10	10	4	5	5
Phase-shift angle with respect to the fundamental [°]	180	180	180	180	180	180

Table 4. The results of the voltage asymmetry factor measurement

PQ Analyser No.	Asymmetry indices for	
	zero sequence component [%]	negative sequence component [%]
1	-	4.19
2	4.18	4.19
3	4,18	4.21
4	5.8 +/- 0.2*	4,05 +/- 0.35*
5	4.19	4.20
Expected value	4.18	4,18
Interval of variation	-0.01/ +0.01	-0.00 / +0.03
*The instrument indications were varying during the measurement.		

Example 2.3: A voltage dip with the depth 11% U_{din} and duration of 200 ms was produced at the measuring inputs of seven class A PQ analysers. The numerical measures of the disturbance should be determined using $U_{rms(1/2)}$ values, i.e. the values averaged in 20 ms intervals and actualised every 10 ms [1.]. That means the measured voltage dip duration should always be a multiple of 10 ms. Example test results are shown in Fig. 1. Differences may be the consequence of different interpretations of the standard provisions defining the method for determining the dip start/end. It is difficult to provide an explanation for instances where the dip duration is not a multiple of 10 ms.

Example 2.4: Results of the measurement performed for five synchronised PQ analysers exhibit discrepancies in the measurement data aggregation method [5.]. In this test a voltage with a step change in the harmonic voltage distortion THD: from ≈ 0% (almost sinusoidal) to 45% (square-wave), was applied to the instruments inputs. The sequence of these changes in 10-minute time intervals is shown in Fig. 2.

The waveform changes in each 10-minute interval were chosen so that in each case the time ratio between the sinusoidal and rectangular waveform was 50/50. The intention of this test was to check the subsequent data compression to 10-minute intervals. The measurement results are summarized in Table 5.

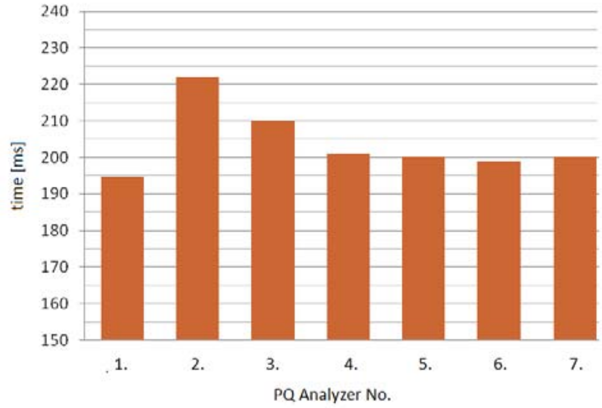


Fig. 1. The results of measurement of voltage dip duration

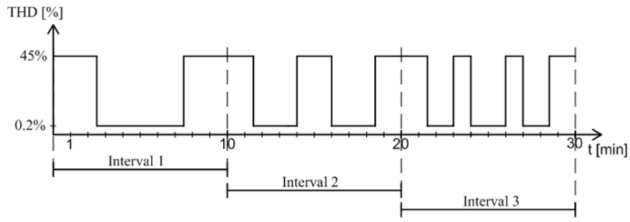


Fig. 2. Aggregation 200 ms samples – presentation of the test

Table 5. Verification of the correctness of sample aggregation 200 ms with 10-minute synchronisation

PQ Analyzer No.	Interval 1 THD_U [%]	Interval 1 THD_U [%]	Interval 1 THD_U [%]
1.	30.12	30.30	30.48
2.	29.72	20.84	29.88
3.	22.23	22.61	22.86
4.	45.05	45.05	45.05
5.	30.06	30.20	30.25

Analysis of the obtained results led to the following conclusions:

i Instruments No. 1, 2 and 5 determined the THD value in a proper way. The value of approximately 30 % was expected in each interval.

ii Instrument No. 3 calculated 10 minute values of THD incorrectly, i.e. as a mean value, whereas, according to [1.], it should be performed using the square root of the arithmetic mean of the squared input values (3).

iii Instrument No. 4 did not perform any aggregation, and as a 10-minute THD value, gave probably 200 ms value registered at the beginning of each 10-minute interval. This was confirmed in another measurement in which the specified waveform was rectangular for almost the entire 10-minute interval except for the first few seconds when sinusoidal waveform was applied. THD indication of the instrument in that case was 0.2 %.

Only several selected examples are presented to illustrate the thesis about errors occurring in measurements of power quality indices that are the consequence of ambiguously formulated measurement procedures and the lack of verification procedures.

Methods for location the sources of electromagnetic disturbances and assessment of individual emission

The old model in which the problem of power quality (PQ) involved two partners – the electricity supplier and the customer – is replaced by a new configuration where at least four, mutually dependent parties participate: the customer, supplier of electric power, manufacturer of equipment and electrical installation contractor. The supplier often insists that sources of disturbances are located at the customer's side, whereas the latter complains about causes located in the supply network. It happens that their discussion leads to the conclusion, shared by both parties, that the equipment is not properly installed or adequately designed, to be operated in the given electromagnetic environment.

Often, in the case of a significant level of a disturbance in electrical power system, at the customer's supply terminals, there is a need for locating the source of harmonics (e.g. [7.]- [21.]), voltage fluctuations (e.g. [22.]-[29.]), voltage dips (e.g. [14.][30.]-[38.]), occasionally also asymmetry. With the deregulation of power industry, utilities have become increasingly interested in quantifying the responsibilities for power quality problems. This issue gains particular meaning when formulating contracts for electric power supply and enforcing, by means of tariff rates, extra charges for worsening the power quality.

There are two, sometimes separate problems which can be stated as follows (Fig. 3). First details concerning the location of disturbance source. A power quality monitor captures disturbance-containing voltage and current waveforms at PCC. It is required to determine if the disturbance comes from the upstream or the downstream. As a result, both the supply utility and customer can obtain a list of disturbances, their severity and directions. Such information will greatly facilitate the resolution of disputes between the two parties if a disturbance results in financial losses to either party.

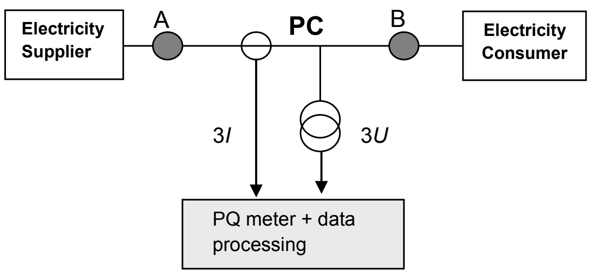


Fig. 3. Problem of locating the voltage disturbance sources

The second is to assess the emission level of the particular considered load or supplier in order to quantitative evaluation of the both parts contribution to the total disturbance level measured at the point of power delivery. The goal is to check the fulfilment of standard or contract requirements.

Solution for both problems posed above is not a trivial task. Works focused on this subject have been carried out for many years. Numerous methods have been proposed and published, only a part of them having practical significance. They differ in the probability of inference correctness (e.g. locating a disturbance source), the value of error made (e.g. determining an individual customer's share in the total disturbance level), the time required to carry out measurements, the number and complexity of equipment needed, etc.

IEC published three documents giving guidelines for the assessment of emission limits, respectively for harmonics (IEC 61000-3-6 [39.]), voltage fluctuations (IEC 61000-3-7 [41.]), and unbalance (IEC 61000-3-13 [42.]). They provide guidance on principles which can be used as the basis for determining the requirements for the connection of distorting installations to MV, HV and EHV public power systems. This documents define emission level as: *the level of a given electromagnetic disturbance emitted from a particular device, equipment, system or disturbing installation as a whole, assessed and measured in a specified manner*; and emission limit as: *the maximum emission level for a particular device, equipment, system or disturbing installation as a whole*. Complementary to the specification of disturbances emission limits, network operators must be in state of verifying if these limits are well respected or not. They should actually be able to identify and - as much as possible - quantify the individual responsibilities of disturbing consumers.

Example 3.1 [43.] The basis for locating the asymmetry source in a power system can be the sign of the negative-sequence component active power measured at the PCC. The positive sign of active power means the dominant asymmetry source is at the supplier side, the negative sign of active power means the dominant asymmetry source is at the consumer' side.

A circuit used to demonstrate the correctness of inference, shown in Fig. 4, enables simulation, at the supplier side, of asymmetry of source voltages rms values, phase shift angles between them, and series and parallel equivalent impedances of the supply source. The load is represented by three phase *RL* impedances with equal or different values.

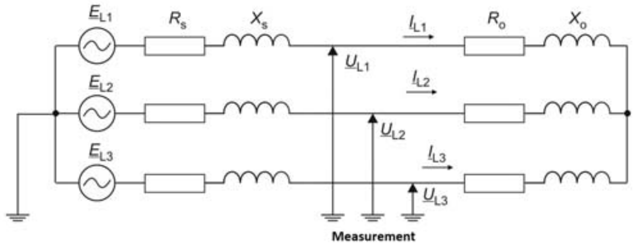


Fig. 4. Circuit diagram for asymmetry source location and identification

The following parameters of the considered circuit are taken in this example (in per unit values): E = 100; $R_s = R$ = 3.536 and $X_s = X$ = 3.536. Then, for symmetrical conditions at both the supplier and consumer side: I = 10 and U_{L1} = 50. The following asymmetry sources were considered:

- unbalanced load side parameters:

$R_{0,L1} = 0{,}1R$, $R_{0,L2} = R$, $R_{0,L3} = 2R$,
$X_{0,L1} = 0{,}1X$, $X_{0,L2} = X$, $X_{0,L3} = 2X$

- unbalanced system side parameters:

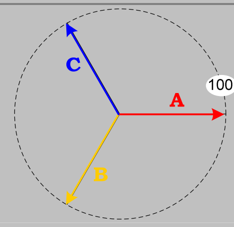
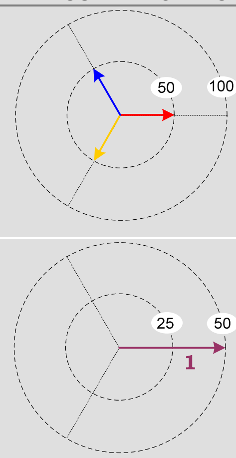
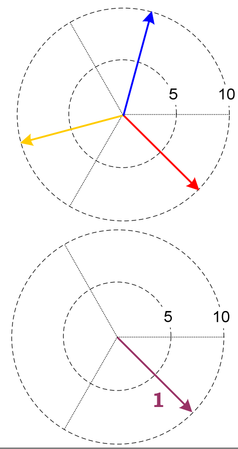
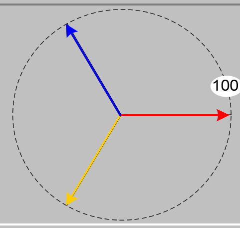
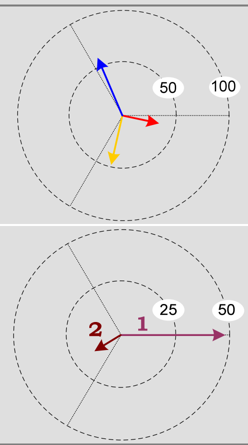
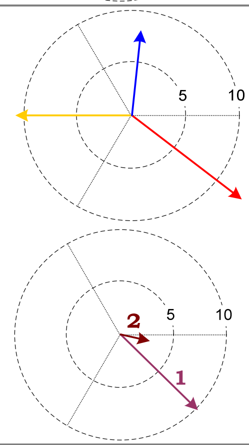
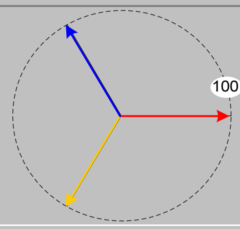
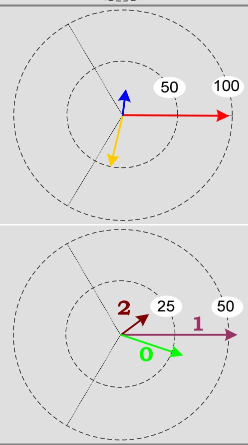
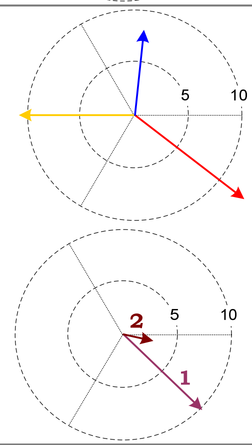
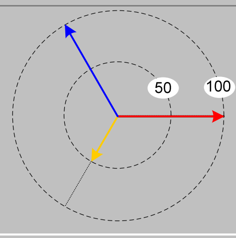
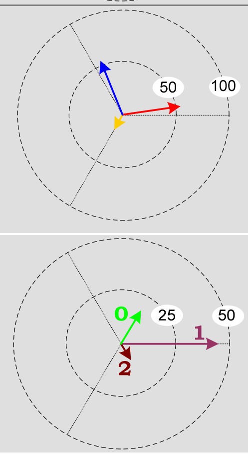
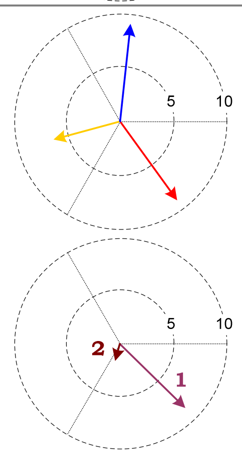
$R_{S,L1} = 0{,}1R$, $R_{S,L2} = R$, $R_{S,L3} = 2R$,
$X_{S,L1} = 0{,}1X$, $X_{S,L2} = X$, $X_{S,L3} = 2X$

- unbalanced system phase voltages:

$$\underline{E}_{L1} = E\mathrm{e}^{\mathrm{j}0^0},\ \underline{E}_{L2} = 0.5E\mathrm{e}^{-\mathrm{j}120^0},\ \underline{E}_{L3} = E\mathrm{e}^{\mathrm{j}120^0}$$

The analysed cases were categorized into three groups: (a) symmetrical source – unbalanced load; (b) asymmetrical source – balanced load; (c) asymmetrical source – unbalanced load. Symmetrical source is understood as the condition in which series impedances and phase voltages' amplitudes are equal to each other and phase-shifted by 120°. Table 6 provides the example simulation results.

Table 6. Results of simulation of various locations of the asymmetry source at the supplier and/or consumer side (P_1, P_2 – active power of positive-sequence and negative-sequence symmetrical component, respectively) [43.]

CIRCUIT CONDITIONS	SOURCE VOLTAGE	MEASURED VOLTAGE	MEASURED CURRENT
<u>Symmetrical condition</u> Load active power: $P_{L1,L2,L3}$ = 1060,5 Active powers of symmetrical components: P_1 = 353,5 P_2 = 0 $P = 3(P_1+P_2)$= 1060,5	 Symmetrical components		
<u>Unbalanced load side parameters</u> (balanced system side parameters and phase voltages) Load active power: $P_{L1,L2,L3}$ = 969,6 Active powers of symmetrical components: P_1 = 352,2 P_2 = -29,0 $P = 3(P_1+P_2)$= 969,6	 Symmetrical components		
<u>Unbalanced system side parameters</u> (balanced load side parameters and phase voltages) Load active power: $P_{L1,L2,L3}$ = 1280,4 Active powers of symmetrical components: P_1 = 397,8 P_2 = 29,0 $P = 3(P_1+P_2)$=1280,4	 Symmetrical components		
<u>Unbalanced system phase voltages</u> (balanced system side parameters and load side parameters) Load active power: $P_{L1,L2,L3}$ = 765,9 Active powers of symmetrical components: P_1 = 245,5 P_2 = 9,8 $P = 3(P_1+P_2)$=765,9	 Symmetrical components		

Distributed systems for monitoring electrical power quality

The popular notion of smart metering acquires its technical sense also in the field of the quality of power delivery. This refers to distributed systems for continuous and synchronous monitoring of selected electric power systems. The measurement data processed into useful information to be used by the system power supply system operator is a strong incentive to implementation of distributed monitoring systems [1.]. Developing of such systems is a complex task in the engineering, organisational and legal terms. Fig. 5 shows a general structure of a distributed monitoring system comprised of four components .

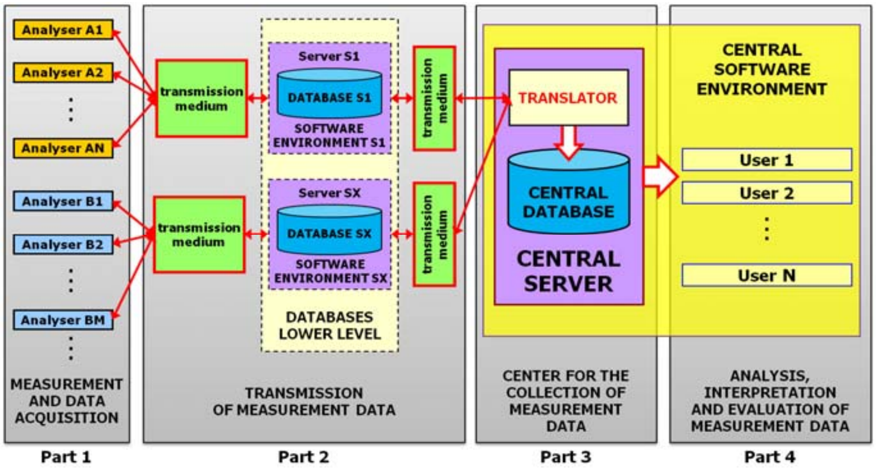


Fig. 5. A general structure of a distributed power quality monitoring system

Part 1 – The measurement and data acquisition by means of analysers of power delivery quality. This poses two questions:

(i) How to locate a limited number of instruments at the network nodes, considering their installation and subsequent operation costs, and to acquire maximum of useful information, e.g. [44.]-[46.]. Solving the optimisation task formulated in that way requires defining a quality index, e.g.: total installation cost, estimate error or its variance, voltage dip detection at the specified sensitivity threshold, etc. In addition, constrains are imposed on the optimisation task, e.g. maintaining the system observability or the measurement accuracy. The methods proposed until now are most often dedicated for the specific measuring purpose.

(ii) How the frequency characteristics of voltage and current transformers that are not fully known, influence the credibility of measurement results.

Part 2 - Automatic data acquisition, synchronisation and transfer through selected transmission media. The most convenient form of data transfer is their transmission through the Internet. Where the Internet is not accessible, a GPRS transmission, cellular telephony networks, radio transmission or power line communication (PLC) can be used. In such systems the synchronisation in time domain of PQ analysers is the necessary functionality, without which the analysis of disturbances in a power grid is impracticable. The PQ analysers can synchronise either with the monitoring system servers or by means of GPS synchronisers.

Extensive monitoring system may incorporate intermediate databases dedicated for handling a part of analysers (e.g. those of the same manufacturer) or other measuring equipment where measuring quality indices is one of their functionalities.

Part 3 - The measurement data collection centre comprising the main server and the central database. In the majority of European countries the basis for power quality evaluation is standard EN 50160 [47.]. This document defines the basic set of quantities that shall be analysed, the required aggregation time and minimum time of voltage quality evaluation. Considering three phases and the number of voltage and current harmonics taken into account, the number of quantities that shall be analysed is about 170, that yields almost 9 million recordings over a year for a single measurement point. The problem of managing such a huge number of data can be exclusive solved using a professional database.

The measurement results acquired from numerous commercially available PQ analysers differ in their data format and the method of measured quantities aggregation. For instance, data can be made available in 3 s, 1 min, 3 min, 10 min or 2 h time intervals. In the simplest case, data are accessed by means of text files or CSV files. These files are written to an indicated directory and the information contained in them is directly accessible. Access to data from PQ analysers by means of PQDIF (Power Quality Data Interchange Format) or COMTRADE files becomes a standard. The PQDIF files are binary, usually compressed, files in the format compliant with IEEE standard P1159.3. Data are accessible by means of specialist software. Similarly, data in the form of COMTRADE files are written in the IEEE Std. C37.111 [48.] compliant format. They also require specialist software. Data are written in four files with different file extensions. Each file contains relevant information: a file with extension CFG is a configuration file and contains information about recordings, DAT – contains data, INF – data for applications, and HDR data for the user. The last two are optional. The most convenient, and the fastest, way of data acquisition is the access to an analyser database by means of SQL query. This form is supported by PQ analyser provided with their own data acquisition system.

The monitoring system requires normalisation of acquired data. This concerns both: the names of measured quantities (each analyser remembers a given quantity under a different name) and the aggregation method. Moreover, this module shall be equipped with a function of data unpacking from these types of files (and/or others the data formats applied by the manufacturers) or directly from database by means of SQL query.

Part 4 – The central software environment that enables visualization, analysis, interpretation and evaluation of measurement data. Developing of a system that fulfils these functions requires several fundamental assumptions. The system shall have a layered and modular architecture and should be open. A layered architecture means an allotment of certain functionalities and development of protocols for information exchange between them. The openness is the possibility of the system extension, not necessarily by the system's author, that means, first of all, the database structure and database access protocol should be made available. The following components can be distinguishes in the system: a server, management application, data scanner, and an application that makes results available via the Internet. In this context the server means both: a computer which because of a huge number of data and its functions (24hrs/day operation and multi-user access) should be sufficiently fast and suitable for continuous operation, and database software with relevant licences. The management application enables the system configuring (e.g. adding new measurements points, analysers, etc.) as well as report generation and data visualisation. A data scanner is an application that allows automatic data collection from PQ analysers. An important functionality is creation of tools that enables to automate the database scanning, e.g. for voltage events, and their remote classification.

Here another concept of the voltage quality evaluation should be noted. Numerical evaluation of voltage quality shows a currently dominant tendency towards separate measuring of quality indices for selected disturbances. In many cases a misoperation of electrical loads is caused by supply voltages whose waveshapes differ from the sinusoidal with nominal parameters. Thus the numerical measures of power quality that are based on waveforms would have a property of universality (i.e. summing-up diverse disturbances) and, by reducing memory resources necessary for measurement data storing, would also facilitate the benchmarking process (labelling the measurement points). The global voltage quality indices can be assigned to one of the three categories: (i) indices based on the evaluation of the actual and ideal voltage waveforms, (ii) indices based on the evaluation of the cost of poor power quality, (iii) aggregated indices determined form the set of classical numerical measures of individual disturbances. The latter, by means of assigning weighting coefficients to classical numerical measures of individual disturbances, would facilitate the operator's efforts aimed at the voltage quality improvement [49.].

An example global voltage quality factor CWJ_U can be determined from per unit values of numerical measures of disturbances referred to their limit levels. If all disturbance indices are smaller than 1, the CWJ_U factor equals the maximum value from the set of individual disturbances indices ($W_{1...4}$).

(2) $$CWJ_U = \max(W_1, W_2, W_3, W_4)$$

If one or more of indices exceeds 1, the CWJ_U factor equals 1 plus the sum of each excess over the limit level (ΔW). Where N disturbances exceeds limit levels, the CWJ_U value is:

(3) $$CWJ_U = 1 + \sum_{i=1}^{N} k_i \Delta W_i$$

The fact, that adverse impact of disturbances depends on both the type of the disturbance and the affected loads, can be accounted for by means of a weighting coefficient k_i assigned to given excess. Each weighting coefficient can take a value from the interval from 0 to 1 and can be negotiated between the supplier and customer. The value of CWJ_U factor is the basis for determining the voltage quality class at the considered measurement point: class S (satisfactory, CWJ_U<1) or class US (unsatisfactory, CWJ_U > 1).

Consideration should also be given to a more complex classification of the voltage quality at the supply point by introducing an additional voltage quality class for points at which the CWJ_U value is close to the limit level but yet not require immediate remedy measures. In such a case a special procedure for that supply point would be adopted, e.g. more frequently performed check measurements of voltage quality.

Example 4.1. The application of the global voltage quality factor CWJ_U using one-week measurements carried out at the Station X 400/110 kV at the primary side of transformer TR2 is presented as the example. Figure 6 shows schematic diagram of the station X power supply system with indicated point of connection of the PQ analyser. Necessary data for determining the total voltage quality factor CWJ_U are provided in Table 7.

The overall value of the global voltage quality factor CWJ_U at the given measurement point is:

$$CWJ_U = 1 + \sum_{i=1}^{N=4} k_i \,\Delta I_i = 1 + (1 \cdot 0 + 1 \cdot 0{,}258 + 1 \cdot 0 + 1 \cdot 1{,}528) = 2{,}787$$

Thus, it can be concluded that the considered measurement point belongs to the voltage class US (unsatisfactory).

Figure 7 shows example measurement results of disturbances numerical measures exceeding limit levels, i.e. voltage fluctuations and the 5th harmonic (in phase L1).

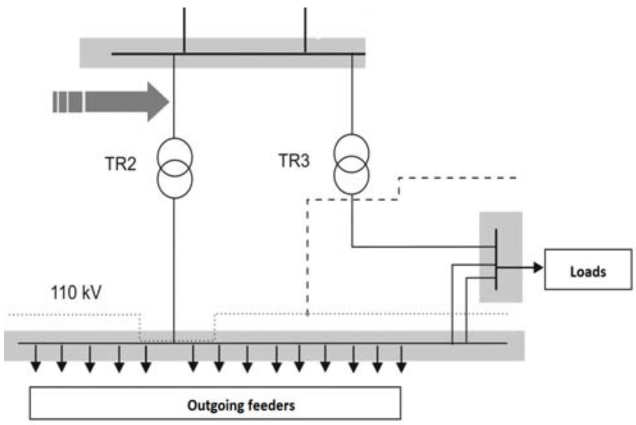


Fig. 6. Schematic diagram of the station X power supply system with the point of the PQ analyser connection indicated with arrow

Costs of poor power quality and the quality control systems

Whereas formerly the issue of supply quality was almost exclusively considered in terms of warranties provided at the state level, it currently evolves toward commercial relations between the supplier and consumer of electric power. As a consequence, a product or service in the power engineering domain is more and more often supplied under a contract concluded between the interested parties that specify the product or service quality characteristics, its value and price.

In the market environment precedes a natural evolution in which failure to comply with agreed standards entails business discussion between the parties and potential financial consequences. This results in transition to an increasing extent from the two-dimensional to tri-dimensional market (Fig. 8).

Table 7. Voltage quality indices and the CWJ_U factor

VOLTAGE QUALITY INDEX	INDEX VALUE	INCREASE	WEIGHTING COEFFICIENT	ASSESSMENT
Slow voltage changes index $W_1 = W_U$	ΔT > 95% $W_1 = 0.825$	$\Delta W_1 = 0$	$k_1 = 1$	✓ positive
Voltage distortion index $W_2 = W_H$	$W_2 = 1.258$	$\Delta W_2 = 0.258$	$k_2 = 1$	× negative
Voltage asymmetry index $W_3 = W_{ASY}$	$W_3 = 0.670$	$\Delta W_3 = 0$	$k_3 = 1$	✓ positive
Voltage fluctuation index $W_4 = W_{Plt}$	$W_4 = 2.528$	$\Delta W_4 = 1.528$	$k_4 = 1$	× negative

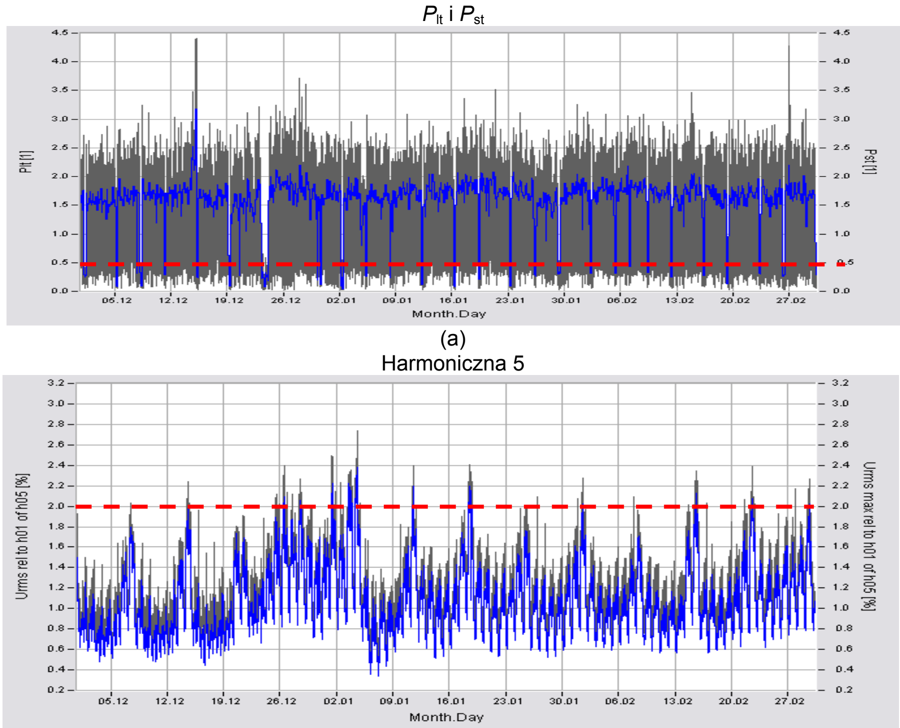


Fig. 7. Example characteristics (phase L1) of flicker severity indices P_{st} and P_{lt} and the 5th harmonic measured over the whole measurement period. The dashed line marks limit values.

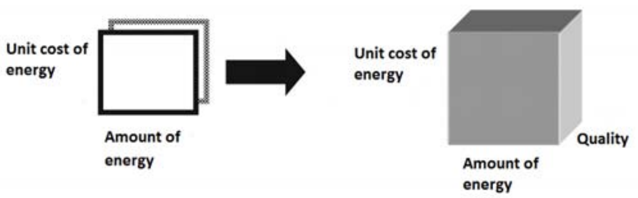


Fig. 8. Evolution of electricity market in result of restructuring processes in the electricity sector

In the area of power quality three different relations between main players in the electricity market and resulting mutual commitments are created in this process: *system operator - consumer; consumer - equipment provider; system operator - equipment provider*. These relations shall be regulated according to defined and accepted rules. The European Union, however, lacks harmonised regulations in this area and the existent solutions cannot be deemed final.

In order to improve the quality of supply, the regulators employ a wide spectrum of incentive mechanisms. The most common are: (a) monitoring the quality of power delivery; (b) minimum standards for power supply; (c) incentive mechanisms: penalties and rewards; (d) "quality" contracts. A necessary component of a regulatory mechanism is acquisition and archiving of data concerning diverse aspects of power delivery. These schemes are necessary for yet another reason: the need for evaluation of poor voltage quality costs.

An interesting phenomenon is the growing number of research projects concerning economic aspects of electrical power quality carried out in many countries, e.g. [50.]-[52.]. These researches are particularly important for a regulator because they indicate the necessity of employing consumer protection measures and also determine the regulation strategy, in chiefly in the areas where the regulatory instruments have not been widely implemented yet, as in the case of voltage quality. As yet, the majority of research focuses on the cost of supply interruptions and voltage dips costs; only a very few of them deal with other types of disturbances, e.g.: [1.][53.]-[57.]. Historically, the costs of poor voltage quality are considered mainly with reference to industrial consumers, with particular regard to the most costly technologies. Costs in the residential sector are deemed difficult to evaluate, chiefly due to consumer's subjective factors, the lack of precise data about the duration and frequency of supply interruptions, types of loads whose operation was interrupted, etc. This situation will certainly change because business activity is more and more often conducted in the residential area environment and it basically utilizes sensitive IT and office equipment.

Questionnaire-based surveys show that consumers estimate the cost of poor quality of supply on the per-disturbance basis whereas the supplier estimates it on the per-kWh basis. That means the concept of the non-supplied energy cost is still dominant in this milieu.

The most often employed scheme of the connection between the quality and costs can be expressed in the form of several simple rules: (a) For each quality index is determined the tolerance interval without consequences; this approach reduces the risk of erroneously positive or erroneously negative assessment. (b) If the index value exceeds the upper limit, the operator's performance is deemed poorer than assumed; in such a case the operator is penalized (in various forms, sometimes only by publication of results). (c) If the index value is lower than the assumed minimum, the operator's performance is deemed better than assumed, and consequently, the operator can be rewarded. It can be observed in the example concerning voltage fluctuations.

Example 5.1. In the event of exceeding the voltage fluctuation limit level the penalty fee can be determined from the relation [58.]:

$$P_{\mathrm{WN}} = \sum_{k\in\Omega_1} C \cdot W^2_{k,\mathrm{P_{st}}} \cdot E_k + \sum_{k\in\Omega_2} C \cdot E_k \tag{4}$$

where E_k is the energy supplied in the time interval with the ordinal index *k*, and $W_{k,\mathrm{P_{st}}}$ is the voltage fluctuation liable to penalty:

$$W_{k,\mathrm{P_{st}}} = \max\left[0, \frac{P_{\mathrm{st},k} - P_{\mathrm{st,\,limit}}}{P_{\mathrm{st,\,limit}}}\right] \tag{5}$$

Ω_1 is the set of intervals in which $W_{k,\mathrm{P_{st}}} \le 1$, and Ω_2 is the set of intervals in which $W_{k,\mathrm{P_{st}}} \rangle 1$. $P_{\mathrm{st},k}$ is the short-term flicker severity index in the *k*-th interval, and $P_{\mathrm{st,\,limit}}$ is its permissible level. W_k is determined for each 10-minute interval during one-week measurement period (*k*=1,2…,1008) and takes non-zero value only when the permissible level is exceeded.

As follows from relation (3), each *k*-th interval in which an excessive voltage fluctuation occurs will entail a penalty fee in the amount of:

$C \cdot W^2_{k,\mathrm{P_{st}}}$ [EUR/kW·h] when $0 \langle W_{k,\mathrm{P_{st}}} \langle 1$ and

C [EUR/kW·h] when $W_{k,\mathrm{P_{st}}} \ge 1$.

In practice the value C can be taken at the level of supply interruptions. It means that intervals in which $W_{k,\mathrm{P_{st}}} \ge 1$ are considered as unacceptable supply conditions. Where exceeding of the voltage fluctuation limit level is according to the adopted schedule of the voltage quality improvement in subsequent years, the penalty fee can be reduced, e.g. according to the formula $P^*_{\mathrm{WN}} = R \cdot P_{\mathrm{WN}}$, where *R* is a rebate factor with constant value (e.g. 0.5), or depending on the duration of the voltage quality improvement process, e.g. $R = (1 - m/M)$, where *M* is the assumed time (in months/years) required to achieve the voltage class S at the given point of grid, and *m* = 0, 1, 2 … are subsequent months/years counted from the start of the quality improvement process. This rule can be applied to all other voltage quality indices.

Conclusion

The presented set of issues is certainly not an exhaustive list of problems that should be solved in the quality of power delivery field. The authors presented only those out the problems that, in their opinion, belong to the most important for both: the power sector and final users.

The work has been accomplished under the grant scheme: "A distributed system for monitoring and evaluation of the quality of power delivery", Project number N511 314340.

REFERENCES

[1.] 1st (2001), 2nd (2003), 3rd (2005), 4th (2008), 5th (2012) Benchmarking Reports on Quality of Electricity Supply. CEER Reports.
[2.] EN 61000-4-15: Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Section 15: Flickermeter – Functional and design specifications.
[3.] EN 61000-4-7: Electromagnetic compatibility (EMC) Part 4: Testing and measurement techniques Section 7: General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto.
[4.] Balawender P., Chmielowiec K., Firlit A., Piątek K. Szkoda R., Ziętek M.: Comparative measurements of power quality recorders - voltage fluctuations (in Polish), 5th National Conference on Power Quality and Energy Efficiency in Polish Power System, Polskie Towarzystwo Przesyłu i Rozdziału Energii Elektrycznej (2012).
[5.] Chmielowiec K., Ziętek M., Piątek K., Firlit A., Szkoda R., Balawender P.: Comparative tests of power quality analyzers - harmonic distortion, 15th IEEE International Conference on Harmonic and Quality of Power, 17–20 June 2011, Hong Kong.
[6.] Szlosek M., Piekarz M., Hanzelka Z., Bień A. etc.: Comparative tests of flickermeters, CIRED, 17th international conference and exhibition on Electricity distribution, Barcelona, 12 – 15 May 2003.
[7.] Chang G. W., Chen C. I, Teng Y. F.: An application of radial basis function neural network for harmonics detection, 978-1-4244-1770-4/08,2008 IEEE.
[8.] Chen C., Liu X, Koval D.,, Xu W., Tayjasanant T.: Critical impedance method - a new detecting harmonic sources method in distribution systems, *IEEE Transactions on Power Delivery*, 19 (2004), No. 1.
[9.] Cristaldi L., Ferrero A.: Harmonic power flow analysis for the measurement of the electric power quality, *IEEE Tran. Instrum. Meas*, 44 (1995), No. 6, 683-685.
[10.] Emanuel A. E.: On the assessment of harmonic pollution, *IEEE Trans. on Power Delivery*, 10 (1995), No. 3.
[11.] Li C., Xu W., Tayjasanant T.: A critical impedance based method for identifying harmonic sources, *IEEE Transaction on Power Delivery*, 19 (2004), No. 1.
[12.] Pfajfar T., Blažić B., Papić I.: Methods for estimating customer voltage harmonic emission levels, 978-1-4244-1 770-4/08 IEEE.
[13.] Review of methods for measurement and evaluation of the harmonic emission level from an individual distorting load, CIGRE 36.05/CIRED 2 Joint WG CCO2, 1998.
[14.] Tayjasanant, T., Li C., Xu W.: A resistance sign-based method for voltage sag source detection, *IEEE Transaction on Power Delivery*, 20 (2005), No. 4,. 2554-2551.
[15.] Technical specification, 1133A Power Sentinel™, Arbiter Systems.
[16.] Tsukamoto M., Kouda I., Natsuda Y., Minowa Y., Nishimura S.: Advanced method to identify harmonics characteristic between utility grid and harmonic current sources, 8th ICHQP, Athens, Greece, Oct. 14-16, 1998.
[17.] Wilkosz K.: A generalized approach to localization of sources of harmonics in a power system, 13th ICHQP, Australia, 2008.
[18.] Hanzelka Z., Słupski P. Piatek K. etc. Single-point methods for location of distortion, unbalance, voltage fluctuation and dips sources in a power system, *INTECH, Power Quality – modelling, analysis and enhancement*, 2001, 157-198.
[19.] Pyzalski T.: Localization of harmonic sources in a power system, Ph.D. dissertation, Wroclaw University of Technology, 2006.
[20.] Xu W., Liu Y.: A method for determining customer and utility harmonic contributions at the point of common coupling, *IEEE Trans. on Power Delivery*, 15 (2000), No. 2.
[21.] Xu W., Liu X., Liu Y.: An investigation on the validity of power direction method for harmonic source determination, *IEEE Trans. Power Delivery*, 18 (2003), No. 1, 2003, 214-219.
[22.] Dán A.M.: Identification of flicker sources, 8th ICHQP '98, Athens, Greece, Oct. 14-16, 1998.
[23.] De Jaeger E.: Measurement of flicker transfer coefficient from HV to MV and LV systems. UIEPQ-9630.

[24.] De Jaeger E.: Measurement and evaluation of the flicker emission level from a particular fluctuating load, CIGRE/CIRED Joint Task Force C4.109, Oct. 2007.
[25.] De Jaeger E.: Disturbances emission levels assessment techniques (CIGRE/CIRED Joint Working Group C4-109).
[26.] Sakulin M.: Flicker measurement - theory and practice. SONT '95 Croatia.
[27.] Sakulin M., Renner H., Bergeron R., Hey T., Nastasi D.: International recommendation for universal use of the UIE/IEC flickermeter. UIE/BNCE Birmingham 1996.
[28.] Sakulin M.: Flickermeßtechnik. International Conference on Quality of Power and Standardization, June 4-7, 1996, Lohusalli, Estonia.
[29.] Stade D. etc.: Simultaneous measurements for analysing the flicker dissipation in meshed HV power systems, 8th ICHQP, Athens, Greece, Oct. 14-16, 1998.
[30.] IEEE guide for protective relay applications to transmission lines, IEEE Std. C37.113, 1999.
[31.] Khosrayi A., Melendez J., Colomer J.: A hybrid method for sag source location in power network, 9th International Conference, Electrical Power Quality and Utilization, Barcelona, 9-II, October 2007.
[32.] Li, C., Tayjasanant, T., Xu W., Liu X.: A method for voltage sag source detection by investigating slope of the system trajectory, *IEEE Proceedings on Generation, Transmission & Distribution*, 150 (2003), No. 3, 367-372.
[33.] Nunez V.B., Moliner X.B., Frigola J.M., Jaramillo S.H., Sanchez J., Castro M.: Two methods for voltage sag source location. 13th ICHQP 2008, Australia.
[34.] Parsons A. C., Grady W.M., Powers E.J., Soward J.C.: A direction finder for power quality disturbances based upon disturbance power and energy, *IEEE Trans. Power Delivery*, 15 (2000), No. 3, 1081-1086.
[35.] Prakash K. S., Malik O. P., Hope G. S. Amplitude comparator based algorithm for directional comparison protection of transmission lines, *IEEE Trans. on Power Delivery*, 4 (1989), No. 4, 2032-2041.
[36.] Pradhan A.K. , Routray A.: Applying distance relay for voltage sag source detection, *IEEE Trans. on Power Delivery*, 20 (2005), 529-31.
[37.] Pradhan A.K, Routray A., Madhan S.: Fault direction estimation in radial distribution system using phase change in sequence current, *IEEE Tran. on Power Delivery*, 22 (2007), 2065-2071.
[38.] The 12th ICHQP Tutorial, Portugal, October 1, 2006.
[39.] IEC 61000-3-6: Assessment of emission limits for the connection of distorting instillations to MV, HV and EHV power systems.
[40.] Firlit A.: Continuous monitoring of electric energy quality (in Polish), *Wiadomości Elektrotechniczne*, 80 (2012), No. 2, 6-9.
[41.] IEC 61000-3-7: Assessment of emission limits for the connection of fluctuating installations to MV, HV and EHV power systems.
[42.] IEC 61000-3-13: Assessment of emission limits for the connection of unbalanced installations to MV, HV and EHV power systems.
[43.] Warecki J., Hanzelka Z.: Negative-sequence active power stream as an index of unbalance source, Conference EPQU, Lisbon 2011.
[44.] Madtharad, C.; Premrudeepreechacharn, S.; Watson, N. R.; Saeng-Udom, R.: An optimal measurement placement method for power system harmonic state estimation; *IEEE Trans. on Power Delivery*, 20 (2005), 1514-1521.
[45.] Muscas, C.; Pilo, F.; Pisano, G.; Sulis, S.: Optimal Allocation of Multichannel Measurement Devices for Distribution State Estimation; *IEEE Transactions on Instrumentation and Measurement*, 58 (2009), 1929-1937.
[46.] Muscas, C.; Pilo, F.; Pisano, G.; Sulis, S.: Optimal Placement of Measurement Devices in Electric Distribution Systems; Proc. IEEE Instrumentation and Measurement Technology Conf. IMTC 2006, 2006, 1873-1878.
[47.] EN 50 160 Voltage characteristics of electricity supplied by public electricity networks.
[48.] IEEE Std. C37.111, IEEE Standard Common Format for Transient Data Exchange (COMTRADE) for Power Systems.
[49.] Hanzelka Z., Błajszczak G.: Financial discounts for depreciation of voltage quality – an idea of solution in tariffs (in Polish) *Rynek Energii*, 4 (2011), 76–82.
[50.] Bertazzi A., Fumagalli E., Lo Schiavo L.: The use of customer outage cost surveys in policy decision-making: Italian experience in regulating quality of elasticity supply, 18th CIRED, International Conference on Electricity Distribution, Turin, Italy, June 2005.
[51.] Hofmann M., Seljeseth H., Volden G.H., Kjolle G.H.: Study on estimation of costs due to electricity interruption and voltage disturbances, SINTEF, December 2010, www.sintef.no.
[52.] Samdal K., Kjolle G., Singh B., Trengereid F.: Customers" interruption costs: what is the problem? 17th CIRED, International Conference on Electricity Distribution, Barcelona, Spain, June 2003;
[53.] Economic framework for power quality, CIGRE/CIRED Joint Working Group C4.107, June 2011.
[54.] European Power Quality Survey, 2004, LPQI .
[55.] Survey about the power quality related problems in Portugal, University of Coimbra – Portugal 2001.
[56.] The cost of power disturbances to industrial & digital economy companies, CEIDS 2001.
[57.] Wagner J.P.: The cost of power quality in the ITE industry, Proceedings of 2nd International Conf. on Power Quality - PQA '92, Atlanta, Georgia, Sep. 28-30, 1992.
[58.] Caramia P., Carpinelli G., Verde P.: Power quality indices in liberalized markets, *Wiley*, 2009.

***Authors**: dr hab. eng. Zbigniew Hanzelka, E-mail: hanzel@agh.edu.pl; mgr eng. Krzysztof Chmielowiec, E-mail: kchmielo@agh.edu.pl; dr eng. Andrzej Firlit, E-mail: firlit@kaniup.agh.edu.pl; dr eng. Bogusław Świątek, E-mail: boswiate@agh.edu.pl; Akademia Górniczo-Hutnicza, Katedra Energoelektroniki i Automatyki Systemów Przetwarzania Energii, al. Mickiewicza 30, 30-059 Kraków.*