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Control of electric power quality indicators in distribution networks comprising a high share of solar photovoltaic and wind power stations

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Abstract

Mass-scale integration of renewable power stations into distribution power networks is a main trend of power industry development aimed at its decarbonation. All solar photovoltaic (SPVS) and wind power (WPS) stations are connected to the existing medium- and high-voltage distribution networks, excluding large capacity wind power and photoelectric fields. Modern SPVS and WPS are integrated into energy systems with the use of inverters/converters into which control algorithms for output power and protection have to be included. Critical deviations of electric power quality indicator (EPQI) from their normal operation values may occur, in networks, in these inverters/converters low-load conditions. Such deviation appears in low irradiance conditions in SPVS and low wind speed in WPS. It has to be noted that various electric loads of industrial consumers can be connected to the distribution networks for which such EPQI deviations are critical. This article deals with the newly developed method and device for EPQI sampling control enabling to automatically detect EPQI deviations including short-term ones. Results of preliminary simulation modeling, in various operation conditions, of distribution network including SPVS and WPS are used in the newly developed device. Besides, the device implements automatic Wald's sequential analysis procedure on the basis of a multiple-choice indicator distributed in accordance with the binomial law. The effectiveness of EPQI sampling control based on the mathematical statistics methods has been demonstrated. It has been proposed to apply an integrated indicator, i.e. the absolute value of intercorrelation coefficient, for current and voltage signals, in order to take account of the complex effect of EPQI on the electric loads. Implementing the developed method and device for sample-based EPQI control makes it possible to prevent considerable and long-term EPQI deviations, in order to ensure reliable operation of consumers' electric receivers, in distribution networks comprising a high share of SPVS and WPS.

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Keywords: Solar photovoltaic stations; Wind power stations; Inverters; Converters; Electric power quality indicator; Space-vector; Cross-correlation coefficient for current and voltage signals; Simulation modeling

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1. Introduction

Today, the intensive works are in progress, in a large number of countries, in the field of digital decentralized low-carbon energy infrastructure. The major role in this process belongs to the renewable power stations (first of all solar photovoltaic stations (SPVS) and wind power stations(WPS)), which integrated into the medium- and high-voltage distribution networks, on a massive scale, excluding those of large-capacity wind and solar power fields. In the recent decade, the worldwide renewable power stations (RPS) capacity put into operation exceeded that of all conventional energy sources. This trend will reasonably retain, on both short- and long-term horizon making its contribution to the decarbonization of global power industry (Dong et al. 2020 [1]; Zhang, 2021 [2]; Cheng et al. 2021 [3]; Juan et al. 2021 [4]).

SPVS and WPS became active once they have been connected to the corresponding distribution networks. In such systems, power flows may change their direction and amplitude several times during a day depending on the generation conditions and energy consumption, in multiple network nods. It means that such distribution networks represent complicated heterogeneous objects that, as a rule, are controlled on a decentralized basis. These comprise power consumers with load control, SPVS and WPS, distributed generation systems and electric energy accumulation systems (Liu, 2019 [5]; Ilyushin et al. 2021a [6]).

Modern SPVS and WPS are integrated into distribution networks with the use of inverters/converters in which certain algorithms of output power and protection control are applied. In low load operation conditions of such inverters/converters, critical deviation of electric power quality indicators (EPQI) from their rated values may occur, in the corresponding networks (Praiselin and Edward, 2018 [7]; Rylov et al. 2021 [8]). This situation may take place for low irradiance conditions in SPVS and low wind speed in WPS (Burmeyster et al. 2020 [9]). The duration of short-term EPQI deviations vary from some fractions of a second to several minutes while that of long-term ones is in the range from dozens of minutes to several hours.

In distribution networks with SPVS and WPS, electric loads of industrial consumers operate that are critically sensitive to EPQI deviations. Simultaneous disturbances of multiple EPQI may occur leading to protection shutdowns of electric circuits followed by technological processes disruption. It is associated with material damage experienced by industrial consumers due to possible product defects and underproduction (Suslov et al. 2013 [10]; Papkov et al. 2015 [11]. Detecting short-term EPQI disturbances (such as voltage drop, transient process, etc.) that cause the maximum damage is essentially important (Mishra et al. 2020 [12]).

The existing EPQI visual control methods using discrete Fourier transformation followed by the simplified statistical analysis do not comply with the up-to-date requirements. Recently, EPQI control systems have been developed on the base of neural networks (Huang et al. 2002 [13]; Ghosh and Lubkeman, 1990 [14]), expert system (Styvaktakis et al. 2002 [15]), machine learning method (Balouji and O. Salor, 2017 [16]; Ma et al. 2017 [17]), decision 'trees' (Zhao and Rengang, 2007 [18]), support vector methods (Axelberg et al. 2007 [19]), k-nearest neighbors, linear logistic regression (Bagheri et al. 2018 [20]) and so on (Rönnberg, and Bollen, 2017 [21]).

In parallel, there is the problem of correctly assessing the output parameters of the RPS generating equipment, especially for SPVS, in combination with the influence of environmental conditions on them and differences in different types of generating equipment. For example, for SPVS, these differences are the functioning of photovoltaic modules made using different technologies, the absence or presence of solar radiation concentrators, etc. (Shepovalova, 2019 [22]; Shepovalova, 2018 [23]; Arbuzov et al. 2015a [24]; Strebkov et al. 2019 [25]; Arbuzov et al. 2015b [26]).

Depending on particular problems to solve, either continuous or sampling-mode EPQI control based on the up-to-date digital signal processing and machine learning methods can be implemented, in EPQI control systems (Ribeiro et al. 2014 [27]). Modern EPQI control systems perform processing of large amount of data on measuring both currents in the branches and voltages in the nods of power distribution networks comprising SPVS and WPS and analyze transient processes in such networks.

The main objective of EPQI control system implementation is to ensure early detection of EPQI deviation from their standard values and to perform technical operations aimed at the recovering their rated values, in automatic mode (Ilyushin and Pazderin, 2018 [28]; Ilyushin, 2017 [29]).

The purpose of the studies described in this article was to develop an effective EPQI sampling control method, for distribution networks comprising SPVS and WPS. Simulation modeling and statistical data analysis methods are applied for EPQI control. Control operations in inverters/converters included into SPVS and WPS and/or harmonic filters are performed automatically.

2. Data analysis principles applied in EPQI control systems

Data analysis, in EPQI control systems, involves operations in which measurement results for currents and voltages, in the network branches and mods, respectively, have to be processed with the aim to deduce regularities and various relationships in order to obtain useful information for decision making.

The following problems to be solved in modern EPQI control systems based on the data analysis are essential for distribution networks comprising SPVS and WPS:

– detecting the sources of EPQI disturbance,

– analysis of the reasons of EPQI deviation from their standard values,

– monitoring both periodicity and duration of each EPQI deviation, as well as those of each EPQI group,

– defining the relationships between deviations of particular EPQI (groups of EPQI) and between the operation conditions of distribution networks, SPVS or WPS, as well as defining the limiting conditions leading to damages,

– evaluating negative effects of EPQI disturbance with the account of specific technological features of electric loads functioning,

– deducing the trends in EPQI change in case of connection new consumers, SPVS and WPS, distributed power generation, etc.

Three major methods for primary data processing are known: data streaming, real-time (RT) data processing and batch-mode processing (Grus, 2015 [30]).

Data flows are generated by various devices such as, for example, EPQI control equipment transferring these data into EPQI control system in form of small fractions. Application of data streaming may be reasonable when events take place frequently and in adjacent time intervals in which case prompt reactions on the received data are initiated.

While processing data on the RT basis, operations with the data are performed and the relevant decisions are taken in the same rate as that of physical processes. With respect to the EPQI control, such time intervals may be in the range from several milliseconds to several seconds. RT data processing makes it possible to detect sharp EPQI deviations, on an operational basis, in order to timely generate control signals and implement control actions aimed to recover EPQI normal values.

In case of batch-mode processing, large amounts of data have to be treated simultaneously. This data processing mode is applicable when the problems of clustering and classification of information and events implemented on the basis of processes monitoring have to be solved within sufficiently long time intervals.

In EPQI control systems of distribution networks comprising SPVS and WPS, the following two types of numeric values for currents and voltages, respectively, in their branches and nods can be applied:

1. Continuous time-dependent series of numeric values, for both short- and long-time intervals that describe such power quality parameters as the waveform and phase symmetry in the three-phase current/voltage system. These include, for instance, root-mean-square (rms) voltages, flicker amplitude, harmonic distortions factor (THD), amplitudes of particular harmonic components, interharmonic amplitudes and frequencies and asymmetry coefficient.

2. Series of short-term intervals within which parameters of currents/voltages deviate substantially from their standard values, normally defined for a single utility frequency period. Such EPQI deviations are qualified as 'events' with reference to EPQI (GOST 32144-2013 [31]).

EPQI deviations result in distortion of the current and voltage sinewave. That is why the following parameters are mainly used for EPQI calculations:

– rms voltage (calculations made for each of the three phases make it possible to obtain a whole parameter population corresponding to a particular voltage measurement channel),

– voltage complex values (digital processing devices with higher performance rate are required for these calculations in order to apply other EPQI calculation methods),

– spatial vector (SV) (methods enabling to substitute three phase voltages by one integrated complex value changing in time to be applied in calculations (Ignatova et al. 2009 [32]). In devices using this method, specific digital signal processing algorithms have to be used in order to detect all EPQI deviations, on a real-time basis).

In terms of ensuring most effective sampling-mode EPQI control, in distribution networks comprising SPVS and WPS, the SV method is of principal interest.

3. EPQI analysis methods employing spatial vector

While using SV, it is assumed that its mathematical model enables to describe all potential dynamic external factors affecting three-phase voltage in both stationary conditions and fast transient processes with fluctuations. SV method is the essence of the integrated approach to the description of EPQI deviation from their rated values, in three-phase systems.

In the absence of filtration, SV components contain all exhaustive information related to the sinewave distortion of voltage signals. It is generally accepted that SV may serve as a visualization tool for EPQI deviation, in the complex numbers plane, while its absolute value can be used for detecting short-term voltage drops (see Fig. 1 and description see Eqs. (1)–(4)) (Ignatova et al. 2009 [32]; Wang et al. 2017 [33]).

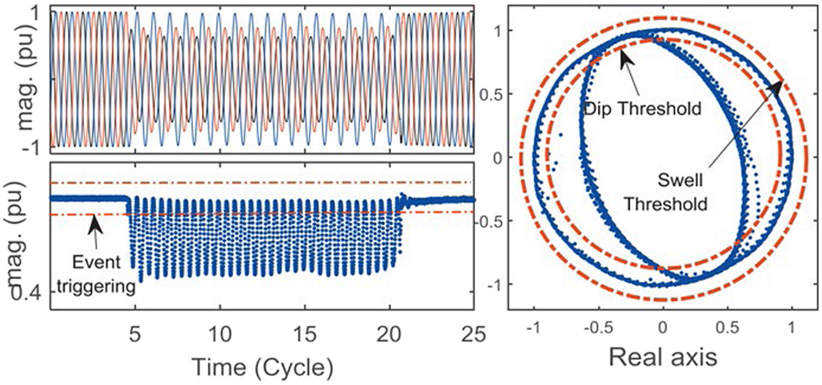

Fig. 1. Application of spatial vector for detecting voltage drops (Wang et al. 2017 [33]).

For a three-phase system of quantified voltage values $\underline{u}_a(n)$, $\underline{u}_b(n)$, $\underline{u}_c(n)$, SV is given in the following form:

$$\underline{u_s}(n) = \frac{2}{3}\left[\underline{u_a}(n) + a \cdot \underline{u_b}(n) + a^2 \cdot \underline{u_c}(n)\right], \tag{1}$$

where $a = \{j2\pi/3\}$, n – moment (step) of the EPQI control process (step of electric energy quality analysis).

The real and imaginary components of SV value correspond to those of Clarke's transformation:

$$\underline{u_s}(n) = \frac{\sqrt{2}}{3}\left[\underline{u_\alpha}(n) + j \cdot \underline{u_\beta}(n)\right] \tag{2}$$

$$\begin{bmatrix} u_\alpha(n) \\ u_\beta(n) \\ u_0(n) \end{bmatrix} = \frac{\sqrt{2}}{3} \cdot \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \cdot \begin{bmatrix} u_a(n) \\ u_b(n) \\ u_c(n) \end{bmatrix}, \tag{3}$$

These are linked with quadrature components $u_p(n)$, $u_q(n)$ of Park–Gorev transformation via the following vector–matrix relationship (Wang et al. 2017 [33]):

$$\begin{bmatrix} u_p(n) \\ u_q(n) \end{bmatrix} = \begin{bmatrix} \cos(2\pi f n) & \sin(2\pi f n) \\ -\sin(2\pi f n) & \cos(2\pi f n) \end{bmatrix} \cdot \begin{bmatrix} u_\alpha(n) \\ u_\beta(n) \end{bmatrix}. \tag{4}$$

Since SV presents transformation of quantified voltage values, for three phases in relation to the neutral, in particular time intervals, any change of voltage wave appears immediately in the SV complex components. Whenever voltage retains its constant rated value, SV circumscribes periodically a circle about the neutral while its absolute value remains unchanged. Any change in voltage amplitude leads to deviating SV absolute value. This property of SV serves as the trigger for EPQI disturbance detection.

As far as there is no time delay in the cause of digital voltage sampled values processing in accordance with Eqs. (2)–(4) it is advisable to use SV for detecting the starting and the final moments of EPQI disturbance, as well as its duration (see Fig. 1).

Studies dedicated to the analysis of EPQI disturbances based on the change of SV components underlined the newly developed EPQI sampling control method and the corresponding device for distribution networks comprising RPS. Let us review some most indicative of those studies (Hao Liu et al. 2008 [34]; Leprette et al. 2017 [35]; Bagheri et al. 2018 [36]).

Block diagram of an EPQI disturbance analysis device is shown in Fig. 2 (Hao Liu et al. 2008 [34]). This device was designed to calculate coefficients A_1, A_2, A_3, used for EPQI deviations classification by measuring SV components.

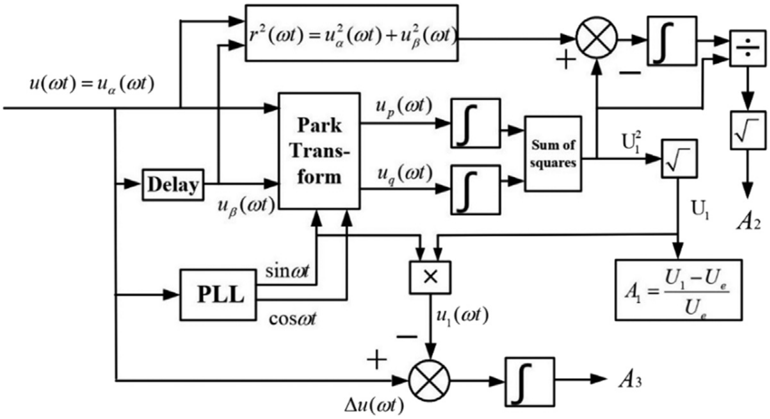

Fig. 2. Block diagram of the device for EPQI disturbances analysis with EPQI deviations classification function (Hao Liu et al. 2008 [34]).

Such equipment makes it possible to specify 5 types of single EPQI disturbance (voltage drops, voltage deviation and flicker, transient voltage oscillations, voltage harmonic distortion, notch-shaped distortion), as well as 5 types of combined EPQI disturbances (harmonic distortion & voltage drop, notch-shaped distortion & voltage drop, harmonic distortion & transient voltage oscillations. notch-shaped distortion & transient voltage oscillations, voltage deviation & harmonic distortion).

One more EPQI analysis device option, for three-phase power distribution networks, comprises data sampling unit, SV components calculation unit, EPQI calculation unit and display unit for calculation results (Leprette et al. 2017 [35]). The following five EPQI are calculated in this device: three-phase harmonic distortion coefficient characterizing 'contamination' of the voltage/current waveform, three-phase imbalance coefficient characterizing asymmetry of the three-phase voltage/current system, indicator of three-phase voltage/current drop/fall, indicates three-phase overvoltage/overcurrent and indicator of flicker level (IEC 61000-4-30:2015 [37]). Each EPQI deviation is calculated with the use of SV components, while for calculating coefficient k_H zero phase-sequence component is additionally required.

The EPQI disturbance analysis method mentioned above and the equipment for its implementation involve visual indication of EPQI deviation analysis results and, therefore, its application in automatic control systems is essentially limited.

In a number of technical solutions, the use of two-dimensional convolution-type neural networks has been suggested in order to overcome this disadvantage. In these devices, three-phase input voltage signals get transformed into two-dimensional representations of SV (Eq. (1)), then their images are encoded with the use of relevant arrays. Specialized arrays of size 22 × 22 are applied as the input data for two-dimensional convolution-type neural network processing (Bagheri et al. 2018 [36]). An example of SV image transformation into two-dimensional array structure is shown in Fig. 3.

The two-dimensional neural network architecture suggested in (Bagheri et al. 2018 [36]) includes four convolution-type and three fully-connected layers. Convolution-type layers serve to automatically obtain parameters of voltage drops, while fully-connected layers are used for their classification in accordance with the following seven voltage drop types:

– C_a, C_b and C_c indicate three types of unbalanced voltage drop characterized by substantial amplitude of two or three phase voltages and insignificant (if any) undervoltage in the third phasee (subindex indicates the phase with insignificant voltage drop),

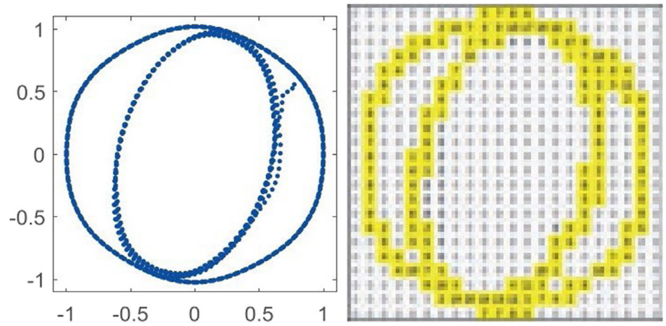

Fig. 3. Representation of spatial vector image in form of array of size 22 × 22 (Bagheri et al. 2018 [36]).

– D_a, D_b and D_c indicate three types of unbalanced voltage drop characterized by substantial undervoltage in one of the three phases and insignificant (if any) undervoltage in the two other phases (subindex indicates the phase with substantial voltage drop),

– A indicates symmetrical voltage drop.

The two-dimensional SV representation described above enables to encode voltage drops (undervoltages) within one and the same array independently on their duration and frequency. Results obtained during testing this method have demonstrated rather high accuracy of the automated voltage drops (undervoltages) classification, as well as the effectiveness of neural networks application for identification of images characterizing the change of SV rotation trajectory (Bagheri et al. 2018 [36]).

4. EPQI sampling control method for distribution networks comprising SPVS and WPS

For the sake of simplicity, a new EPQI control method has been developed applied to the automatic EPQI deviations classification procedure by introducing generalized EPQI parameter which made it possible to avoid visual control of SV images. In this case, sample monitoring is performed with the use of spatial vector, while the absolute value of intercorrelation coefficient for signals representing the coherence of voltages and currents serves as the generalized EPQI parameter.

Coherence of the voltage and current signals belongs to principal conditions of this EPQI control method. Oscillations have to be considered as coherent if their phase difference remains constant in time determining the amplitude of oscillations superposition. Two harmonic (sinewave) unifrequent oscillations are always coherent. That is why the electric energy quality can be evaluated with the application of correlation coefficient characterizing the extent of sinewave signal distortion, as well as to define noncompliance with the coherence requirement (Shirman et al. 20007 [38]).

The higher is the real component value of the correlation coefficient the closer is the shape identity of the corresponding signals. In case of coincidence of the complex quantified signals under comparison intercorrelation coefficient attains its maximum and equals to their energy. The absolute value of the maximum intercorrelation coefficient can be achieved only in case that the analyzed quantified signal has absolutely the same shape as the reference one.

If the three-phase voltage/current signal has a sinewave form, corresponds to 50 Hz frequency and is symmetrical (in relation to the neutral) the combination of SV sampled values may be considered as the reference complex signal. And the EPQI deterioration of the SV sampled values combination, for the signal subject to the analysis, has to be evaluated in relation to this voltage/current signal.

If the signal under consideration has been normalized and corresponds to the reference one the absolute value of intercorrelation coefficient equals to unity. Therefore, the intercorrelation coefficient absolute value of the analyzed and reference signals can be used as the generalized indicator, while defining the requirement to EPQI in a certain connection point of industrial consumer electric loads.

In the course of simulation modeling, the permissible deviation of the absolute value of the intercorrelation coefficient, for SV reference and analyzed signals, has to be determined with the account of electric loads specificity, in their connection pints. The estimated deviation value has to be applied as the setting point, while exceeding this value shall be qualified as a quantified indicator of the generalized EPQI parameter deviation outside the permissible range.

In order to ensure effective application of the newly designed EPQI control method, in power distribution networks comprising SPVS and WPS, preliminary simulation modeling has to be carried out to meet the following targets:

– defining operation conditions of distribution networks comprising SPVS and WPS, in various schematic and load-related environments including repair and maintenance conditions (Ilyushin et al. 2021b [39]),

– specifying schematic and load-related situations and electric loads connection points in which critical EPQI distortion may occur requiring actions on recovering normal operation of distribution networks comprising SPVS and WPS,

– establishing permissible deviation ranges for the generalized EPQI parameter (particular EPQI) in order to perform EPQI sampling control procedure, in analyzed operation conditions and connection points, with the account of specific properties of particular industrial consumer' electric loads.

The equipment for implementing the suggested EPQI control method (see Fig. 4) includes a number of series-connected units (i.e. those of data sampling, three-dimension transformation, normalization, correlation, detection, comparison and sequential analysis) and storage unit for simulation modeling results.

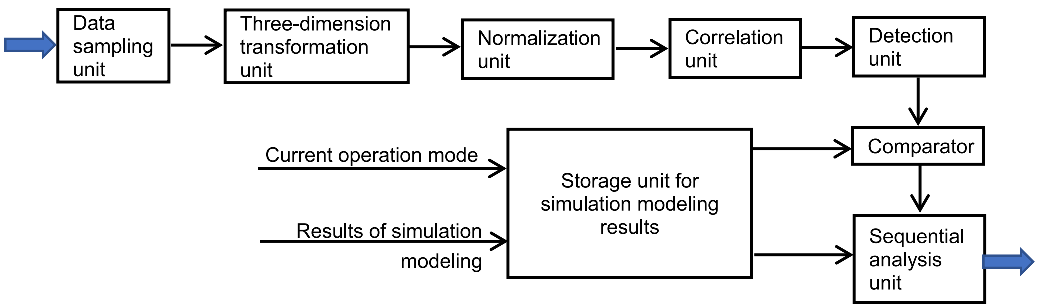

Fig. 4. Block diagram of the equipment implementing the EPQI control method for power distribution networks comprising SPVS and WPS.

Results of simulation modeling (permissible deviation ranges of the generalized EPQI, particular EPQIs for sampling control procedure implementing) are loaded into the memory of the storage unit (Leprette et al. 2017 [35]).

Let us consider the principle of signal digital processing, taking the three-phase voltage signal as an example. For this purpose, we will use voltage signal on the time interval of six periods of the utility frequency ($T = 120$ ms) in the assumption that the sampling frequency is $f_s = 1/t_s = 1$ kHz (i.e. twenty cycles for one period of the utility frequency).

Fig. 5a shows the phase voltages $u_a(n)$, $u_b(n)$, $u_c(n)$ of the three-phase system defined on the utility frequency $f = 50$ Hz. These graphs correspond to the secondary voltage signals with the amplitude of 100 V, on the output of the voltage measuring transformer, measured in the electric loads connection point. Let us take this signal as the reference (non-distorted) one. Therefore, all EPQI deviations will be analyzed in comparison with this signal.

If in the connection point, at the time moment $t = 40$ ms (the 40th sampling cycle of the quantified signal, in Fig. 5a, three-phase voltage started to be disturbed by the third and fifth harmonics having the amplitudes equal to 20 % of the fundamental harmonic ($f = 50$ Hz) amplitude due to certain operation conditions of inverters/converters included in SPVS or WPS we will observe distorted voltage signals as shown in Fig. 5b. The results of Clarke's transformation and the diagram of the calculated $u_\alpha(n)$ and $u_\beta(n)$ components are shown in Fig. 6.

As a result of transition from SV quadrature components (see Fig. 6) to the sinewave voltage with the help of calculation of instantaneous amplitude and phase (of the complex vector) we obtain the signal shown in Fig. 7.

Current values of the complex vector are transferred from the three-dimension transformation unit into the normalization unit. In the normalization unit, in the sliding data screen containing N sampled SV complex values, they are reduced to the normalized form relating to energy. For this purpose, the energy of the combination of N SV complex values, in the current sliding data screen, and each SV complex of instantaneous values get normalized to the calculated energy value.

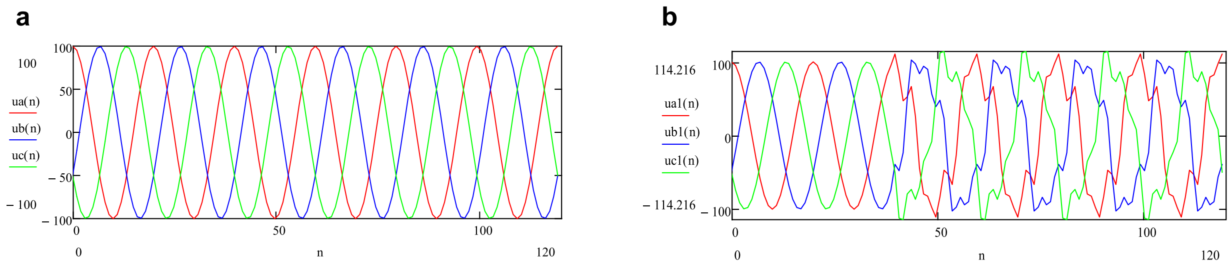

Fig. 5. (a) Diagram of the reference three-phase quantified voltages system, (b) diagram of distorted three-phase quantified voltages system.

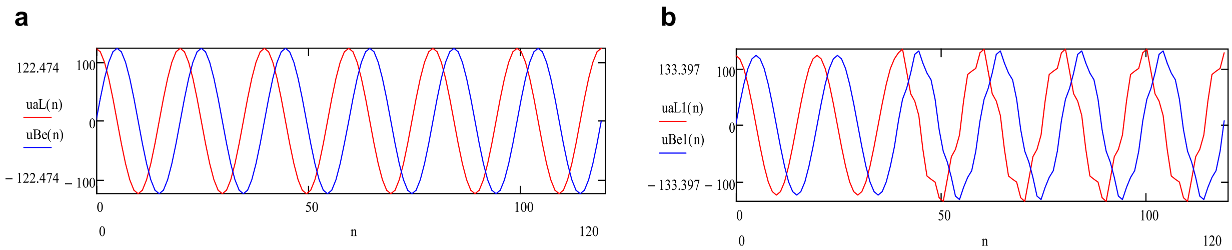

Fig. 6. Quadrature components of the spatial vector for non-distorted signal (a) and for distorted signal (b).

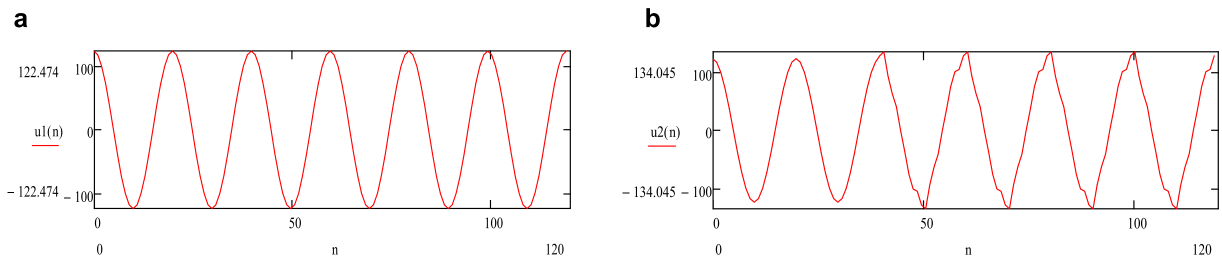

Fig. 7. Representation of the spatial vector in form of sinewave signal, for non-distorted signal (a) and distorted signal (b).

Normalized combinations of SV complex of instantaneous values is directed from the normalization unit into the correlation unit. In this unit, generalized EPQI is calculated whose role plays intercorrelation coefficient associated with the term ‘coherency’.

In the correlation unit, SV intercorrelation coefficient is calculated (see Fig. 4). The functions of correlation unit can be performed by a digital filtration device (digital filter) whose impulse characteristics correspond to the SV reference signal (Falshina and Kulikov, 2012 [40]).

Current values of the intercorrelation coefficienta are transferred into the detection unit where their absolute values are derived. These absolute values are transferred from the output of the detection unit onto the first input of the comparator while on its second input the set value from the storage unit for simulation modeling results enters. This set value corresponds to the permissible absolute deviation value of the intercorrelation coefficient, for the considered electric loads connection point and current operation mode. The results of comparison are used to generate a quantified binary signal (‘0’ or ‘1’) for further mathematic operations, in the EPQI sampling control process.

In the normalization, detection and correlation units, digital signals processing operations are performed in order to calculate the absolute values of the normalized coefficient of intercorrelation between the distorted $u_2(n)$ and non-distorted signals $u_1(n)$ (see Fig. 7) in the following form (Shirman et al. 20007 [38])

$$|\rho_{12}(n)| = \frac{\left|\sum_{i=1}^{N} u_1(i+n) \cdot u_2(i+n)\right|}{sqrt\left(\sum_{i=1}^{N} u_1^2(i+n) \cdot \sum_{i=1}^{N} u_2^2(i+n)\right)}. \tag{5}$$

In this case, in the normalization unit, current values of the distorted signal $u_2(n)$ are divided on coefficient $k_n(n)$, corresponding to the denominator of the following Eq. (5)

$$k_n(n) = \frac{1}{sqrt\left(\sum_{i=1}^{N} u_1^2(i+n) \cdot \sum_{i=1}^{N} u_2^2(i+n)\right)}. \tag{6}$$

Normalizing coefficient $k_n(n)$ is calculated for each current value, in the analysis screen, on the basis of N sampled values. Let us assume $N = 20$ in which case, the averaging interval will correspond to one period of the utility frequency.

In the correlation unit of the device, intercorrelation coefficient $\rho_{12}(n)$ is calculated from the following equation

$$\rho_{12}(n) = \frac{\left|\sum_{i=1}^{N} u_1(i+n) \cdot u_2(i+n)\right|}{sqrt\left(\sum_{i=1}^{N} u_1^2(i+n) \cdot \sum_{i=1}^{N} u_2^2(i+n)\right)}. \tag{7}$$

The absolute value of the normalized coefficient of intercorrelation between the distorted $u_2(n)$ and non-distorted $u_1(n)$ signals is calculated in the detection unit. Dependence $|\rho_{12}(n)|$, corresponding to the voltage signals $u_2(n)$ and $u_1(n)$ is shown in Fig. 8.

In Fig. 8, the set value for $|\rho_{12}(n)|$ is shown calculated based on the simulation modeling results. This value corresponds to that of permissible intercorrelation coefficient deviation, for the analyzed connection point and current operation mode. It is seen from Fig. 8 that situations may occur when the set value corresponding to that of quantified random value ξ is exceed or becomes lower in which case $\xi_n \in \{0, 1\}$.

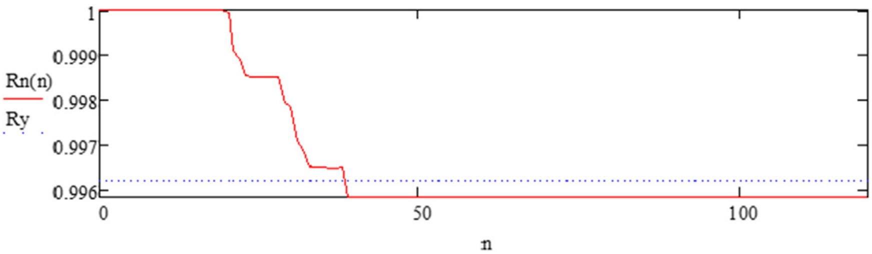

Fig. 8. Dependence of the normalized value of the intercorrelation coefficient ρ_{12} $(n)|$ on quantified time n.

In the storage unit for simulation modeling results (see Fig. 4), information related to the current operation conditions is taken into account such, for example, as the number of operation mode. This information can be received, for instance, from SCADA-systems of distribution networks.

The number of operation mode defines the current combination of the set values transmitted from the output of the storage unit for simulation modeling results into the comparison unit, in the course of analysis of the electric loads connection point under control. Additionally, the values of parameters k_1, k_2, a, b are transferred from the storage unit for simulation modeling results onto the second input of the sequential analysis unit, for each operation mode and connection point. Calculation method for k_1, k_2, a, b will be further described (see Eqs. (12), (13)).

A sequence of random values ξ_1, $\xi_{2,\ ...,}$ $\xi_n, \ldots$,inters the first input of the sequential analysis unit from the output of the comparison unit. Here ξ_{n} is quantified parameter whose value characterizes EPQI deviation and corresponds to the results of EPQI sampling control, at the current time moment. Let us denote as q the probability of the event when ξ_n is equal to 1. Besides, we will reduce the problem of generalized EPQI control to that of testing the hypothesis that q does not exceed a certain specified value q'.

While controlling EPQI with the application of digital signals processing (see Fig. 4), on a selected time interval, we have a large array of sampled values of the generalized EPQI registered one by one on the input of the detection unit. Values of the generalized EPQI, in each moment, may either exceed or not the permissible range (quantified signal ξ_n on the output of the comparison unit). Therefore, the quality of electric energy, in each time moment, may be qualified as either corresponding or not to the requirements, in particular electric loads connection point, for the current operation conditions of a particular distribution network. Let us assume $\xi_n = 0$ if, in the current time moment, the requirements for EPQI correspond to the standard ones. And vice versa, $\xi_n = 1$ if the requirements for EPQI have not been complied with. Let us assume that variable q represents the relative number of time moments when deviations of EPQI from the standard values takes place.

As applied to the device (see Fig. 4) variable ξ_n equals to either 0 or 1 with probability values of $R\{\xi_n = 0\} = (1 - q)$ and $R\{\xi_n = 1\} = q$ where q is the probability of the event when the absolute value of intercorrelation coefficient occurs to be lower than the set value for the current distribution network operation conditions.

It will be expedient to select such value of q' that corresponds to the situation when, for $q \geq q'$, the quality of electric energy is assumed to comply with the standard requirements, over the entire selected observation interval. And contrariwise, the quality of electric energy would be considered as failed to comply with the standard requirements when $q > q'$.

The check of the sampled values combination of the generalized EPQI, in all connection points of electric loads to the consumer's distribution network on the permanent basis would be rather expensive which requires extensive assets. Moreover, it may occur not expedient, in many cases, taking into consideration specific schematic and load-related conditions. In order to organize a rational EPQI sampling control it is necessary to define the risks associated with wrong decisions.

For $q = q'$, electric energy quality corresponds to the limiting permissible level and, in this case, it does not matter which solution to choose. When $q > q'$ it is advisable to state a failure to comply with the established requirements for the electric energy quality. The higher is q the higher is the degree of such advisability. In case that $q < q'$, we will suppose that the electric energy quality is within the permissible range and the confidence level grows with the decreasing q.

If q differs from q' insignificantly the probability of wrong decision related to the electric energy is not high. We can specify such values q_0 and q_1 ($q_0 < q'$ and $q_1 > q'$) that the electric energy quality has to be considered as not acceptable one (i.e. causing damages for consumers) only in the case when $q \geq q_1$. Accordingly, electric energy quality has to be qualified as acceptable (i.e. there is no risk of damage for consumers) when $q \geq q_0$. If the values of q are in the range from q_0 to q_1 there is no need for any decision.

If values q_0 and q_1 are defined the permissible risk associated with the failure to choose a proper decision can be described as follows:

- probability of EPQI deviation detection shall not exceed preset value α when $q \geq q_0$,
- probability of detection of EPQI correspondence to the requirements shall not exceed preset value β when $q \geq q_1$.

Therefore, the risk of wrong decision will be defined by these four parameters q_0, q_1, α, β. In prior years, the values of these variables were selected with the use of statistical methods, tables, diagrams, etc. (Wald, 1947 [41]). Today, it has become expedient to define values q_0, q_1, α, β on the basis of simulation modeling results, for distribution networks comprising RPS, in various schematic and load-related conditions.

In the sequential analysis unit, a binominal EPQI control algorithm according to the multiple-choice principle is implemented (ISO 2859-1:1999 [42]) in which hypothesis testing is performed on the basis of ξ_n value registration results (Wald, 1947 [41]):

$$H_0 : q = q_0 \text{ and } H_1 : q = q_1, \tag{8}$$

where q_0 and q_1 are the specified critical probability levels, for EPQI control and $q_0 < q_1$.

In each current nth moment of the EPQI control process, we have a random ξ_n value whose distribution law corresponds to the following expression:

$$p(\xi; q) = q^{\xi}(1 - q)^{1-\xi}, \tag{9}$$

where ξ takes either value 0 or 1.

Decisions have to be made based on the results of calculating likelihood ratio η that on the nth step of electric energy quality analysis has the following form:

$$\eta_n(\xi_1, \ldots, \xi_n) = \frac{p(\xi_1; q_1) \cdot p(\xi_2; q_1) \cdot \ldots \cdot p(\xi_n; q_1)}{(p(\xi_1; q_0) \cdot p(\xi_2; q_0) \cdot \ldots \cdot p(\xi_n; q_0))} = \left(\frac{q_1}{q_0}\right)^{D_n} \cdot \left(\frac{(1 - q_1)}{(1 - q_0)}\right)^{n-D_n}, \tag{10}$$

where D_n is random variable describing the aggregate number of deviation instantaneous values of the intercorrelation coefficient absolute value from its standard value, for the current operation mode, $D_n = \xi_1 + \xi_2 + \cdots + \xi_n$.

Let d_n be the value of random variable D_n. Then the interval within which the Wald's procedure of sequential analysis has to be continued is defined by the following in equations:

$$B < \left(\frac{q_1}{q_0}\right)^{d_n} \cdot \left(\frac{(1-q_1)}{(1-q_0)}\right)^{n-d_n} < A\,; \qquad A = \frac{1-\beta}{\alpha}, \quad B = \frac{\beta}{1-\alpha}, \tag{11}$$

where α and β are the first and second type errors (provider's and consumer's risks) (Wald, 1947 [36]; ISO 2859-1:1999 [37]).

After some simple mathematical transformations, Eq. (11) can be reduced to the following form:

$$k_1 \cdot n – k_2 \cdot b < d_n < k_1 \cdot n + k_2 \cdot a, \tag{12}$$

where $a = ln\, A > 0$, $b = -\, ln\, B > 0$ and

$$k_2 = \frac{1}{ln\left(\frac{q_1(1–q_0)}{q_0(1–q_1)}\right)}, \quad k_1 = k_2 \cdot ln\left(\frac{(1–q_0)}{(1–q_1)}\right). \tag{13}$$

Sequential analysis has to be continued until Eq. (12) are satisfied (the both inequations are valid) and has to be completed after the step of EPQI control procedure on which either of these two inequations becomes invalid. Failure to comply with the left inequation leads to the acceptance of hypothesis H_0: $q = q_0$, while the failure to comply with the right one has to be followed by accepting hypothesis H_1: $q = q_1$.

Suppose that the following values are given: $\alpha = 0.1$, $\beta = 0.2$, $q_0 = 0.01$, $q_1 = 0.03$ based on the results of simulation modeling. Let d_n be the value of random variable D_n. Then the interval within which Wald's procedure of sequential analysis has to be continued is defined by Eqs. (11)–(13). Thus, in accordance with the given values of q_0, q_1, α, β we obtain: $k_2 = 0.893$, $k_1 = 0.018$, $a = 2.08$ and $b = 1.6$.

Finally, Eq. (12) can be written in the following form:

$$0.018n – 1.43 < d_n < 0.018n + 1.86. \tag{14}$$

Suppose that EPQI sampling control is performed on the basis of values of the quantified variable ξ_n corresponding to the change of the value of the intercorrelation coefficient starting from the time moment $n = 34$. Let us introduce variable μ counted from this particular time moment. In Table 1, the results of Wald's sequential analysis procedure implementation are represented.

Table 1. Variables describing Wald's sequential analysis procedure implementation applied to the case when EPQI deviate from their standard values.

Variables	$\mu = 1$	$\mu = 2$	$\mu = 3$	$\boldsymbol{\mu = 4}$	$\mu = 5$	$\mu = 6$	$\mu = 7$	$\mu = 8$
ξ_μ	0	0	1	**1**	1	1	1	1
$0.018\mu + 1.86$	1.878	1.896	1.914	**1.932**	1.95	1.968	1.986	2.004
d_μ	0	0	1	**2**	3	4	5	6
$0.018\mu - 1.43$	−1.412	−1.394	−1.376	**−1.358**	−1.34	−1.322	−1.304	−1.286

It is seen from Table 1 that implementing the process for EPQI sampling control method based on Wald's sequential analysis procedure, for the selected example, has been completed on the fourth step ($\mu = 4$), by making the conclusion of unacceptable deviation of the generalized EPQI.

For three-phase voltage signal, when there is no deviation of EPQI (see Fig. 5a) the absolute value of intercorrelation coefficient $|\rho_{12}(\mu)|$ equals to 1, for all μ values, while quantified variable $\xi_\mu = 0$. The results of Wald's sequential analysis procedure application to this case are presented in Table 2.

It is clear from Table 2 that the conclusion about acceptability of EPQI deviations will be made on the 80-th step of sequential analysis which corresponds to the time interval $t = 80$ ms.

Results of EPQI sampling control are expressed in values of quantified signal from the output of the sequential analysis unit (see Fig. 4). Detecting signal '1' on the output of this unit indicates EPQI deviating from their normal values that may cause damage for industrial consumer.

The newly developed method and device for EPQI sampling control with the use of spatial vector make it possible to take account of the complex effect produced by combinations of EPQI deviations on the operation of industrial consumer's electric loads.

Table 2. Variables describing Wald's sequential analysis procedure implementation applied to the case when there is no EPQI deviation.

Variables	$\mu = 1$	$\mu = 2$	$\mu = 3$	...	$\mu = 77$	$\mu = 78$	$\mu = 79$	$\boldsymbol{\mu = 80}$	$\mu = 81$
ξ_μ	0	0	0	...	0	0	0	**0**	0
$0.018\mu + 1.86$	1.878	1.896	1.914	...	3.246	3.264	3.282	**3.3**	3.318
d_n	0	0	0	...	0	0	0	**0**	0
$0.018\mu - 1.43$	−1.412	−1.394	−1.376	...	−0.044	−0.026	−0.008	**0.01**	0.028

Early detection of hazardous EPQI deviations provides the possibility to timely implement control actions on the inverters operating in inverters/converters included in SPVS or WPS or on the harmonic filters in order to recover the quality of electric power thus ensuring reliable operation of electric loads, in distribution networks having a large share of SPVS and WPS.

5. Conclusion

Mass-scale integration of SPVS and WPS into the power distribution networks to which electric loads of industrial consumer are connected may lead to substantial deviations of EPQI from their standard values, in conditions of low load of inverters/converters included in SPVS or WPS. It causes electric loads shutdowns by protection devices and leads to breaking technological processes which is associated with material damage due to defective products and product undersupply.

Early recognition of serious EPQI deviations followed by implementing control operations on the inverters/converters incorporated into SPVS and WPS or on filters helps to recover the quality of electric power EPQI, in power distribution networks comprising SPVS and WPS.

EPQI control systems employing spatial vector commonly applied today feature complicity of current and voltages digital signals processing, as well as the application of image identification method while classifying EPQI deviations.

Application of EPQI sampling control is highly advisable that is based on mathematical statistics method and is used to detect EPQI incompliance with the standard requirements or with those taking account of the specific characteristics of industrial consumer electric loads.

In order to consider the complex effect of EPQI deviations on the electric loads a complex-type indicator has been proposed whose role plays the absolute value of the intercorrelation coefficient. This parameter characterizes the coherence degree between current and voltage signals.

Results of preliminary simulation modeling, in various operation conditions, of distribution network comprising SPVS and WPS are used in the newly developed EPQI sampling control device. Besides, the device implements automatic Wald's sequential analysis procedure on the basis of a multiple-choice indicator distributed in accordance with the binomial law.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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