Yuri SAYENKO[1], Dmitry KALYUZHNIY[2], Viktor BOLGOV[3], Lauri KÜTT[4]

Pryazovskyi State Technical University (1), O. M. Beketov National University of Urban Economy in Kharkiv (2), TUT Estonian Maritime Academy and TTK University of Applied Sciences (3), Tallinn University of Technology (4)

doi:10.15199/48.2019.03.12

Mathematical model for assessment of voltage disturbing sources in networks with distributed power generation

Abstract. *The assessment of voltage disturbing emission sources still lacks adequate models for customer side incorporating mixed loads and distributed power generation. The paper proposes a solution for this challenging task. It includes the determination of topology and parameters of equivalent circuits representing customers' installations with local power sources in three- and four-wire networks. The equivalent circuits are developed on the basis of two-staged transformation, meet requirements of IEC 61000-4-30 and can be used for the on-line assessment of the emission sources of linear voltage disturbances.*

Streszczenie. *W artykule zaproponowano rozwiązanie problemu konkurujących zadań w sieci zawierającej różne obciążenia I rozproszone generatiry. Określono topologię I parametry obwodów zastępczych reprezentujących instalacje klientów w sieci trzy- I czteroprzewodowej. Schematy zastępcze okręslono na bazie dwustopniowej transformacji z uwzględnieniem normy IEC 61000-4-30. Pozwoliło to na okręślanie on-line źródeł emisji zakłóceń.* ***Model matematyczny do określania napię1)ciowych źródeł zakłóceń w sieci z rozproszoną generacją***

Keywords: customer installation, distributed generation, equivalent circuit, point of evaluation, voltage disturbance, voltage unbalance.
Słowa kluczowe: customer installation, distributed generation, equivalent circuit, point of evaluation, voltage disturbance, voltage unbalance.

Introduction

Among other challenging topical problems in modern electrical power systems, there are the identification of disturbing sources (DSs) in network and assessment of their contributions into power quality (PQ) deterioration at a point of evaluation (POE). The proliferation of renewable energy sources like PV panels and wind generators in electrical systems is transforming centralized power supply systems (PSSs) into those with distributed generation (DG) and increasing importance of PQ problems. There are still no enough good methods for modelling customers' installations especially those incorporating generating units.

This paper considers how to identify DSs in such installations and assess their impact on PQ at a random POE that is usually some point of common coupling (PCC). The presented study offers DS topologies and the procedure for defining the parameters of a DS equivalent circuit on the basis of standard measurements [1].

There are presently a lot of methods proposed to find a solution for the problem. The contemporary methods used to identify and assess impact of voltage disturbing sources on PQ at a POE are shortly described below. A more comprehensive review can be found in [2-5].

The list of used abbreviations is provided at the end of the paper.

Review of existing methods

The models based on single-line Thevenin or Norton equivalent circuits (Fig. 1) are the prevailing ones [3-12]. Both a customer's installation (CI) and an upstream power system (PS) are represented as a voltage source in series with impedance for each sequence q and harmonic. Such an assessment of disturbing sources is simple, but it is applicable only for the case with a single POE, a single CI and a single dominating DS on either utility or consumer's side. Another disadvantage explained below is a need to have an equivalent circuit for each symmetrical component.

There are also some methodological problems related to the evaluation of negative and zero sequence impedances and EMFs [13]. They are caused by the fact that there is only one equation linking the POE current $\underline{I}_q$ and voltage $\underline{U}_q$ measured at a POE with the EMF $\underline{E}_q^{CI}$ and impedance $\underline{Z}_q^{CI}$ of the CI equivalent circuit:

(1) $$\underline{U}_q = \underline{I}_q \cdot \underline{Z}_q^{CI} + \underline{E}_q^{CI}.$$

The impedances of an equivalent circuit (Fig. 1) can be found by means of the increments of the currents and voltages measured at a POE $\Delta\underline{U}_q/\Delta\underline{I}_q$ [7-9, 13, 14], where q is the sequence index. The method is valid if only one of impedances varies.

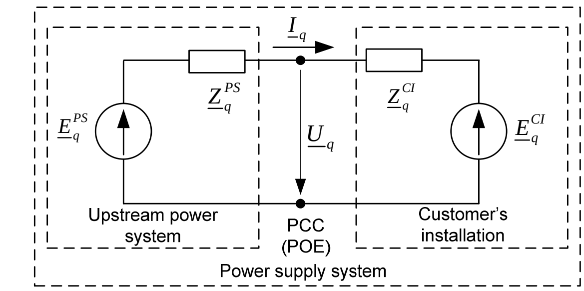

Fig. 1. Thevenin's equivalent circuits of PSS

In addition, the standard PQ measurements require time interval of 10 cycles of industrial frequency for each single measurement [1]. It is practically impossible to define the parameters of the equivalent circuit in Fig. 1 in accordance with this requirement.

The methods based on disturbing power flows use Thevenin and Norton models for identification of a DS [8, 15-21]. Some researchers offer to use only negative reactive power flows [20-21], others demonstrated that correctness of the use of reactive or active power flow sign depends on the nature of load and dominating immittance [10]. The main disadvantage of the method reported already in 1992 [15] that it leads to misleading results under capacitive load phase angles [6, 10, 15, 22, 23]. These methods cannot be used for assessment of disturbing emissions and their contributions into PQ deterioration at a chosen POE. They can only identify on which side prevailing disturbing source is located.

The method of switching the consumer's installation is widely known [4, 24] and even recommended by CIGRE. The method evaluates the contribution of a CI into PQ deterioration by means of measurements performed with the connected and disconnected installation

(2) $$PQC_{load} = PQP_{on} - PQP_{off},$$

where PQC is the CI contribution to the PQ level, $PQP_{on/off}$ is the evaluating PQ parameter measured at a POE with connected/disconnected consumer respectively.

This invasive method is quite simple, but it can generally be implemented to commissioning installations and cannot be used for disturbing emission identification or assessment in continuously operating installations.

The method of transformation of actual 3-phase immittance matrices of power supply system into positive and negative sequence immittance matrices [24, 25]. The solution ignores zero sequence components and implies some other simplifications. It is mainly intended to assess impact of network asymmetry on voltage unbalance.

In conclusion, it should be said that the problem of the identification and assessment of disturbing emissions has still no common solution applicable for an on-line monitoring system.

Major problem with mixed load model

The majority of methods mentioned above use symmetrical components applied to Thevenin and Norton equivalent circuits in order to analyze voltage unbalance (VU). Unfortunately, the direct transformation from three-phase coordinates into symmetrical components leads to insuperable difficulties with the evaluation of the customer's installation equivalent circuit parameters. It can be explained considering evaluation of mixed load (ML) parameters on the basis of measured currents and voltages.

The generalized model of a load (Fig. 2a) being transformed into symmetrical components becomes Thevenin equivalent circuits for positive, negative and zero sequences (Fig. 2b). The state of Thevenin circuits can be described with a set of equations:

(3) $$\begin{cases} \underline{U}_1 = \underline{E}_1 - \underline{I}_1 \cdot \underline{Z}_1; \\ \underline{U}_2 = \underline{E}_2 - \underline{I}_2 \cdot \underline{Z}_2; \\ \underline{U}_0 = \underline{E}_0 - \underline{I}_0 \cdot \underline{Z}_0, \end{cases}$$

where $\underline{U}_q$, $q = 0, 1, 2$, are the qth sequence voltages obtained from the measured voltages $\underline{U}_A$, $\underline{U}_B$, $\underline{U}_C$; $\underline{I}_q$ are the qth sequence currents obtained from the measured currents $\underline{I}_A$, $\underline{I}_B$, $\underline{I}_C$; $\underline{E}_q$ are the qth sequence equivalent EMFs to be calculated; and $\underline{Z}_q$ are the qth sequence impedances to be calculated.

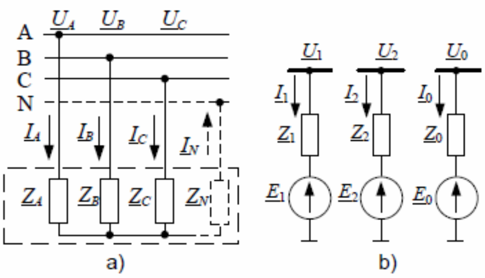

Fig. 2. The model of a mixed load: a) in the phase coordinates, b) Thevenin equivalent circuits for symmetrical components

There are three equations and six unknown quantities in (3), i.e. it cannot be solved without three additional equations. It is impossible to evaluate the parameters of ML equivalent circuits only by means of the measured voltages and currents. That is why the authors discarded direct symmetrical decomposition.

In the previous papers [2, 3], the authors proposed the model in three-phase coordinates based on the phasors of measured voltages and currents, as well as technical specifications of circuit elements as an intermediate stage for the assessment of voltage unbalance emission. This novel method applies the extraction of disturbing parts from three-phase equivalent circuits and their subsequent substitution with disturbing nodal currents. Only in the final stage, the results found in the three-phase coordinates are decomposed into symmetrical components.

A corresponding generalized model for the evaluation of DS impact on PQ at a POE is as follows:

(4) $$\sum_{k=1}^{l} \vec{\mathbf{U}}_{dis}^{DSk} = \mathbf{A}^T \mathbf{Y}_{nondis}^{-1} \left(\sum_{i=1}^{n} \vec{\mathbf{J}}_{dis}^{DSi} + \sum_{j=1}^{m} \vec{\mathbf{I}}_{dis}^{DSj} \right),$$

where $\mathbf{A}^T$ is the transposed incidence matrix, $\mathbf{Y}_{nondis}$ is the nodal admittance matrix for nondisturbing elements of the power supply system (PSS) equivalent circuit, $\vec{\mathbf{J}}_{dis}^{DSi}$ is the column vector of nodal currents of the disturbing passive elements of the disturbing source i; $\vec{\mathbf{I}}_{dis}^{DSj}$ is the column vector of nodal currents of the disturbing active elements of the disturbing source j; $l=m+n$ is the total number of DSs in the PSS.

The determination of a topology and parameters for the equivalent circuit of a generalized passive load without DG sources is curried out on the basis of mathematical model (4) and POE currents and voltages measured over the basic measurement time interval of 10 cycles [26, 27]. The main advantage of this group of methods is that they can be practically implemented even in an on-line monitoring system in contrast to the existing methods. The current paper expands the customer's side models onto distributed generation units.

Modelling of a customer's installation with generating units

Let us consider a linear circuit with sinusoidal state parameters. It requires an idealized linear model of a PSS or taking into account only fundamental components of voltages and currents if the PSS is not linear. We will consider in our study those customers' installations with DG units that cause only sinusoidal disturbances like unbalance, voltage variations and voltage sags. Such an installation will be referred further as a linear customer's installation incorporating distributed generating units (CIDG).

A. Determination of equivalent circuit topology

The modelled power supply system includes a PCC between an upstream power system and a customer's installation incorporating distributed generating units (Fig 3).

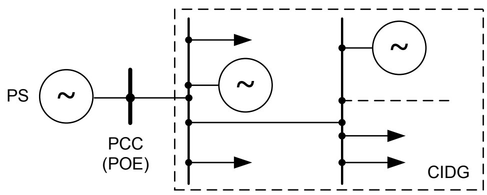

Fig. 3. A topology of a modelled PSS

The equivalent circuit of this PSS incorporates combinations of active and passive components. The general diagram of the three-phase four-wire network is given in Fig. 4.

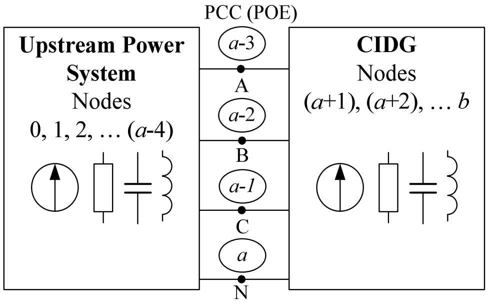

Fig. 4. The general equivalent circuit of a power supply system with separately presented PCC nodes

Let us define the topology of a CIDG equivalent circuit on the basis of the matrix transformation of electrical circuits. The list of nodal index numbers will start from PS nodes and finish with CIDG nodes. Then the node potential equations in a matrix form will be as follows:

$$\begin{Vmatrix}\mathbf{Y}_{aa} & \mathbf{Y}_{ab}\\ \mathbf{Y}_{ba} & \mathbf{Y}_{bb}\end{Vmatrix}\cdot\begin{Vmatrix}\vec{\mathbf{V}}_a\\ \vec{\mathbf{V}}_b\end{Vmatrix}=\begin{Vmatrix}\vec{\mathbf{I}}_a\\ \vec{\mathbf{I}}_b\end{Vmatrix}, \tag{5}$$

where $\mathbf{Y}_{aa}$ is the square submatrix with dimensions $[a\times a]$, which entries correspond to the passive elements of the PS equivalent circuit; $\mathbf{Y}_{bb}$ is the square submatrix with dimensions $[(b\text{-}a)\times(b\text{-}a)]$, which entries correspond to the passive elements of the CIDG equivalent circuit; $\mathbf{Y}_{ab}$ and $\mathbf{Y}_{ba}$ are square submatrices that are transposes of each other with dimensions $[a\times(b\text{-}a)]$ and $[(b\text{-}a)\times a]$, which entries correspond to the CIDG passive elements connecting the CIDGs to the PS; $\vec{\mathbf{I}}_a$ is the column vector of nodal currents with dimensions $[a\times 1]$, which corresponds to the active elements of the PS equivalent circuit; $\vec{\mathbf{I}}_b$ is the column vector of nodal currents with dimensions $[(b\text{-}a)\times 1]$, which corresponds to the active elements of the CIDG equivalent circuit; $\vec{\mathbf{V}}_a$ and $\vec{\mathbf{V}}_b$ are column vectors of node potentials of the PS and CIDG.

After multiplying matrices in the left part of (5) and solving obtained system of equations in relation to the node potential submatrix $\vec{\mathbf{V}}_a$, one obtains

$$\vec{\mathbf{V}}_a=\left(\mathbf{Y}_{aa}+\mathbf{Y}_{ekv}\right)^{-1}\cdot\left(\vec{\mathbf{I}}_a+\vec{\mathbf{I}}_{ekv}\right), \tag{6}$$

where $\mathbf{Y}_{ekv}$ is the square matrix with dimensions $[a\times a]$, which entries correspond to the passive elements of the CIDG equivalent circuit; $\vec{\mathbf{I}}_{ekv}$ is the column vector with dimensions $[a\times 1]$, which entries correspond to the active elements of the CIDG equivalent circuit. They defined as follows:

$$\mathbf{Y}_{ekv}=-\mathbf{Y}_{ab}\mathbf{Y}_{bb}^{-1}\mathbf{Y}_{ba}; \tag{7}$$

$$\vec{\mathbf{I}}_{ekv}=-\mathbf{Y}_{ab}\mathbf{Y}_{bb}^{-1}\vec{\mathbf{I}}_b. \tag{8}$$

Since, there are four nodes between the PS and CIDG sides of the equivalent circuit labelled as a-3, a-2, a-1 and a (Fig. 4) the matrices $\mathbf{Y}_{ekv}$ and $\vec{\mathbf{I}}_{ekv}$ have the following layout:

$$\mathbf{Y}_{ekv}=\begin{Vmatrix}\mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{Y}'_{ekv}\end{Vmatrix};\ \vec{\mathbf{I}}_{ekv}=\begin{vmatrix}\mathbf{0}\\ \vec{\mathbf{I}}'_{ekv}\end{vmatrix}. \tag{9}$$

All nonzero entries of these matrices form submatrices $\mathbf{Y}'_{ekv}$ with dimensions $[4\times 4]$ and $\vec{\mathbf{I}}'_{ekv}$ with dimensions $[4\times 1]$. The dimensions of submatrices demonstrate that the CIDG equivalent circuit for three-phase four-wire network contains four independent nodes and six branches with passive and active elements (Fig. 5).

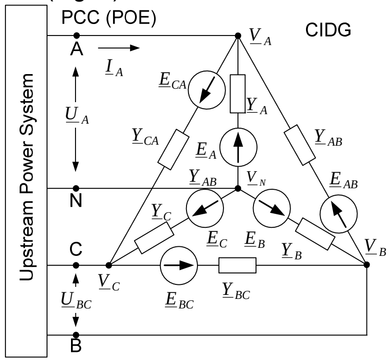

Fig. 5. The equivalent circuit of a customer's installation with distributed generating units for three-phase four-wire network

The equivalent circuit for three-phase three-wire network contains three nodes between the PS and CIDG sides of a PSS. That means the submatricies $\mathbf{Y}'_{ekv}$ and $\vec{\mathbf{I}}'_{ekv}$ have dimensions $[3\times 3]$ and $[3\times 1]$ correspondingly. Therefore, the CIDG equivalent circuit is to include three independent nodes and three branches with active and passive elements (Fig. 6).

B. Determination of equivalent circuit parameters

Let us define the parameters of the CIDG equivalent circuits (Figs. 5, 6). The input data for this task include fundamental values of phase-to-phase and phase-to ground voltages, as well as phase currents of each installation connected to the POE. The basic measurement time interval i is 10 cycles of industrial frequency. Within the interval, the values of PS and CIDG state parameter are supposed to be constant and they alter as compared to the previous interval i-1 and following one i+1. The state parameters on both the PS and CIDG sides can change between time intervals i and i+1 simultaneously. An observer is not to be informed about the events and their locations on the PS and CIDG sides.

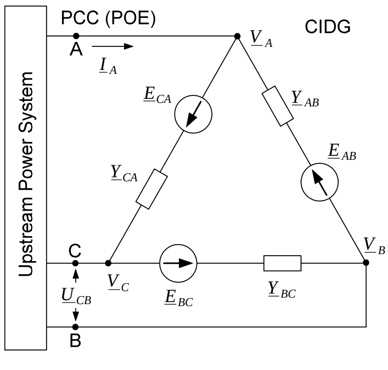

Fig. 6. The equivalent circuit of customer's installation with distributed generating units for three-phase three-wire network

In the three-phase four-wire network, there can be measured three phase-to-phase voltages $\underline{U}_A$, $\underline{U}_B$ and $\underline{U}_C$, three phase-to-ground voltages $\underline{U}_{AB}$, $\underline{U}_{BC}$ and $\underline{U}_{CA}$, as well as three phase currents $\underline{I}_A$, $\underline{I}_B$ and $\underline{I}_C$. The following matrix equation relates these state parameters to the equivalent circuit parameters

$$\mathbf{I} = \left\| \mathbf{U}^Y \quad \mathbf{U}^\Delta \right\| \cdot \left\| \begin{matrix} \mathbf{Y}^Y \\ \mathbf{Y}^\Delta \end{matrix} \right\| + \mathbf{J} \,. \tag{10}$$

The diagonal matrices $\mathbf{I}$, $\mathbf{U}^Y$ and $\mathbf{U}^\Delta$ in (10) include measured currents and voltages, thus they are known terms of the equation (10) and defined as

$$\mathbf{I} = \left\| \begin{matrix} \underline{I}_A & 0 & 0 \\ 0 & \underline{I}_B & 0 \\ 0 & 0 & \underline{I}_C \end{matrix} \right\| ; \tag{11}$$

$$\mathbf{U}^Y = \left\| \begin{matrix} \underline{U}_A & 0 & 0 \\ 0 & \underline{U}_B & 0 \\ 0 & 0 & \underline{U}_C \end{matrix} \right\| ; \; \mathbf{U}^\Delta = \left\| \begin{matrix} \underline{U}_{AB} & 0 & -\underline{U}_{CA} \\ -\underline{U}_{AB} & \underline{U}_{BC} & 0 \\ 0 & -\underline{U}_{BC} & \underline{U}_{CA} \end{matrix} \right\| .$$

The unknown terms in (10) are the admittance diagonal matricies $\mathbf{Y}^Y$ and $\mathbf{Y}^\Delta$, as well as the matrix of nodal currents $\mathbf{J}$ of the CIDG equivalent circuit

$$\mathbf{Y}^Y = \left\| \begin{matrix} \underline{Y}_A & 0 & 0 \\ 0 & \underline{Y}_B & 0 \\ 0 & 0 & \underline{Y}_C \end{matrix} \right\| ; \tag{12}$$

$$\mathbf{Y}^\Delta = \left\| \begin{matrix} \underline{Y}_{AB} & \underline{Y}_{AB} & 0 \\ 0 & \underline{Y}_{BC} & \underline{Y}_{BC} \\ \underline{Y}_{CA} & 0 & \underline{Y}_{CA} \end{matrix} \right\| ; \mathbf{J} = \left\| \begin{matrix} \underline{J}_A & 0 & 0 \\ 0 & \underline{J}_B & 0 \\ 0 & 0 & \underline{J}_C \end{matrix} \right\| .$$

The most of MV networks in former USSR countries equipped only with two sets of measuring transformers obtaining two phase-to-phase voltages $\underline{U}_{AB}$ and $\underline{U}_{CB}$, as well as two phase currents $\underline{I}_A$ and $\underline{I}_C$. That is why (10) has to be rewritten for a three-phase three-wire network as follows:

$$\mathbf{I} = \mathbf{U} \cdot \mathbf{Y} + \mathbf{J} \,, \tag{13}$$

where the known terms are the matrices $\mathbf{I} = \left\| \begin{matrix} \underline{I}_A & 0 \\ 0 & \underline{I}_C \end{matrix} \right\|$ and $\mathbf{U} = \left\| \begin{matrix} \underline{U}_{AB} & -\underline{U}_{CA} \\ \underline{U}_{CA} & \underline{U}_{CB} \end{matrix} \right\|$; the unknown terms are the matricies $\mathbf{J} = \left\| \begin{matrix} \underline{J}_A & 0 \\ 0 & \underline{J}_C \end{matrix} \right\|$ and $\mathbf{Y} = \left\| \begin{matrix} \underline{Y}_{AB} & \underline{Y}_{CA} \\ \underline{Y}_{CA} & \underline{Y}_{BC} \end{matrix} \right\|$.

Both matrix equations (10) and (13) include two unknown terms that means they do not have a solution. Therefore, it is impossible to find the parameters of CIDG equivalent circuits (Figs. 5, 6) on the basis of the PCC measured currents and voltages. The solution can be found by the transformation of the complete equivalent circuits of a CIDG according to (7) and (8). To perform such a transformation we need to know a CIDG configuration and technical specification of all elements. Besides, it is necessary to know modules and phase angles of EMFs generated by power sources and this data must be synchronized with PCC measurements. Collecting such data for technical implementation is a complex task. It requires approaches and technologies of Smart Grid concept [28, 29].

Conclusion

The paper offers a conceptually new approach for assessment of disturbing emission sources and their contributions into PQ deterioration at an arbitrary chosen point of evaluation. It allows modelling multiple mixed loads even incorporating distributed generation units. The proposed solution is applicable for the on-line monitoring of disturbing emissions from multiple customers and an upstream electrical network.

There are remarkable advantages of the method as compared to the existing methods evaluating contribution of disturbing emission sources. Most of them are not applicable for the on-line assessment of the consumers' impact on PQ at a POE, some can evaluate only impact of a single dominating disturbing source, and almost all of them lack proper models for asymmetrical consumers' installations. Those disadvantages have been overcome in the proposed study.

The approach is restricted to linear disturbances (voltage unbalance, voltage variations, voltage sags). The key feature of the method is a brand new model for customers' installations proposed instead of Thevenin and Norton equivalent circuits. It also incorporates distributed generation units. In the case of three-phase four-wire network, the equivalent circuit of a customer's installation contains four nodes and six branches with passive and active elements. In the case of three-phase three-wire network, the customer's installation equivalent circuit contains three nodes and three branches with passive and active elements. It is not generally enough to have measured POE voltages and currents in order to determine the equivalent circuit parameters. That is why the solution is based on two-staged transformation of electric circuits and requires data about the customer installations and upstream power network.

List of abbreviations

CI – customer's installation
CIDG – distributed generating units
DG – distributed generation
DS – disturbing source
ML – mixed load
PCC – point of common coupling
POE – point of evaluation
PQ – power quality
PS – upstream power system
PSS – power supply systems
VU – voltage unbalance

Authors: *prof., PhD Yuri Sayenko, Pryazovskyi State Technical University, Department of Industrial Electrical Power Supply, Ukraine, 87500, Mariupol, 7 Universytets'ka, E-mail: sayenko_y_l@pstu.edu; ass. prof., PhD Dmitry Kalyuzhniy, O. M. Beketov National University of Urban Economy in Kharkiv, Department of Cities Electrical Power Supply, Ukraine, 61002, Kharkiv, 12 Revolutsii, E-mail: KalyuzhniyDN@gmail.comd, DSc Viktor Bolgov, TUT Estonian Maritime Academy, Centre for General and Basic Studies, Kopli 101, 11712 Tallinn, Estonia, and TKK University of Applied Sciences, Department of Electrical Engineering, Pärnu mnt 62, 10135 Tallinn, Estonia, E-mail: victor_bolgov@yahoo.com, prof., PhD Lauri Kütt, Tallinn University of Technology, Department of Electrical Power Engineering and Mechatronics, Ehitajate tee 5, 19086 Tallinn, Estonia, E-mail: lauri.kutt@ttu.ee.*

REFERENCES

[1] IEC 61000-4-30:2015 Electromagnetic compatibility (EMC). Testing and measurement techniques. Power quality measurement methods.
[2] Sayenko Yu., Sukhonos M., Kalyuzhniy D., Bolgov V., Mathematical Model for Real-Time Assessment of Contributions of Disturbing Sources to Power Quality Level at a Point of Common Coupling, *10th International Electric Power*

Quality and Supply Reliability Conference, Tallinn, Estonia, 29-31 August, 2016, 29-35
[3] Sayenko Yu., Kalyuzhniy D., Analytical methods for determination of the factual contributions impact of the objects connected to power system on the distortion of symmetry and sinusoidal waveform of voltages, *Przegląd Elektrotechniczny*, 15 (2005), 81–85
[4] De Jaeger E., Disturbance emission level assessment techniques, *20th Int. Conf. and Exhibition on Elect. Distribution CIRED*, Prague, Czech Republic, June 8–11, 2009, vol. 2, 1–2.
[5] CIGRE report 468, Review of Disturbance Emission Assessment Techniques, CIGRE/CIRED working group C4.109, 2011
[6] Perera S., Gosbell V. J., Sneddon B., A study on the identification of major harmonic sources in power systems, *Australian Universities Power Eng. Conf.*, Melbourne, Australia, Sept. 29–Oct. 2, 2002
[7] Gopalakrishnana C., Prabhub S. G., Kumara K. U., Practical implementation of CIGRE 36.05/CIRED 2 Joint WG CC02 for assessment of harmonic emission level of AC arc furnaces connected to the Tamil Nadu distribution network, *Int. J. Elect. Power & Energy Syst.*, vol. 29 (2007), 275–279
[8] Tulsky V. N., Kartashev I. I., Shamonov R. G., Assessing of impact of disturbing load on power quality, *17th Int. Conf. Electricity Distribution CIRED*, Barcelona, May 12–15, 2003
[9] Seritan G. C., Cepişcă C., Guerin P., The analysis of separating harmonics from supplier and consumer, *Electrotehnică, Electronică, Automatică (EEA)*, vol. 55 (2007), no. 1, 14–18
[10] Wilsun Xu, Xian Liu, Yilu Liu, An investigation on the validity of power-direction method for harmonic source determination, *IEEE Trans. Power Del.*, vol. 18 (2003), 214–219
[11] Mayer V. Ya., Zeniya, A technique of determining share impacts of consumers and power supplying utility into distortion of electric power quality (in Russian), *Electricity (Электричество)*, No 9 (1994), 19–24
[12] Sun Y., Li P., Li, S., Zhang, L., Contribution determination for multiple unbalanced sources at the point of common coupling, *Energies*, 10 (2) (2017), 171
[13] CIGRE 36.05/ CIRED 2 Joint WG CC02 (Voltage Quality), Review of methods for measurement and evaluation of harmonic emission level from an individual distorting load, CIGRE, 1999
[14] Gamazin S. I., Petrovich V. A., Determining the actual contribution of the consumer in the distortion of the quality parameters of electric energy (in Russian), *Ind. Power Eng.*, no. 1 (2003), 32–38
[15] Zykin F. A., Finding the extent loads participate in reducing the quality of electric power (in Russian), Electricity, no. 11 (1992), 13–19
[16] Tanaka T., Akagi H., A new method of harmonic power detection based on the instantaneous active power in three-phase circuits, *IEEE Trans. Power Del.*, vol. 10 (1995), 1737–1742
[17] Schau H., Novitskiy A., Identification of the dominant harmonic source in the LV network on the base of anomalous power flows considerations, *IEEE Russia Power Tech 2005*, St. Petersburg, Russia, June 27–30, 2005, 1–5
[18] Seiphetlho T. E., Rens A. P. J., On the assessment of voltage unbalance, *14th Int. Conf. Harmonics and Quality of Power ICHQP*, Bergamo, Sept. 26–29, 2010, 1–6
[19] Aiello M., Cataliotti A., Cosentino V., Nuccio S., Time domain method to detect harmonic sources in unbalanced power systems, *XVII IMEKO World Congr.*, Dubrovnik, Croatia, June 22–27, 2003, 496–501
[20] Smirnov S. S., Kovernikova L. I., Customer's contribution to high-harmonic voltage levels in electric network nodes (in Russian*), Electricity (Электричество)*, no. 1 (1996), 32–38
[21] Chun Li, Wilsun Xu, T. Tayjasanant, A "Critical Impedance"-based method for identifying harmonic sources, *IEEE Trans. Power Del.*, vol. 19 (2004), 671–678
[22] Rens A. P. J., Swart P. H., On techniques for the localisation of multiple distortion sources in three-phase networks: Time domain verification, *European Trans. Elect. Power*, vol. 11 (2001), 317–322
[23] Emanuel A. E., On the assessment of harmonic pollution, *IEEE Trans. Power Del.*, vol.10 (1995), no. 3, 1693–1698
[24] Jayatunga U., Perera S., Ciufo P., Voltage unbalance emission assessment in radial power systems, *IEEE Trans. Power Del.*, vol. 27 (2012), 1653–1661
[25] Jayatunga U., Perera S., Ciufo P., Agalgaonkar A. P., Voltage Unbalance Emission Assessment in Interconnected Power Systems, *IEEE Trans. Power Del.*, vol. 28 (2013), 2383–2393
[26] Sayenko Yu. L., Kalyuzhniy D. M., Identification of a linear generalized load in a three-phase three-wire network for the task of apportioning factual contributions at a point of common coupling (in Russian), *Electrical Engineering and Electromechanics (Электротехника и электромеханика)*, nr 6 (2016), 65–69
[27] Sayenko Yu. L., Kalyuzhniy D. M., Svergunenko S. V., Identification of a linear generalized load for the task of apportioning factual contributions in three-phase four-wire grids (in Russian), *Technical Electrodynamics (Технічна електродинаміка)*, nr 2 (2018), 67-74
[28] S. D., Ghita O. M., Cepisca C., Vintea A. S., Power quality monitoring systems for smart grid networks, *8th International Symposium on Advanced Topics in Electrical Engineering*, Bucharest, Romania, May 23-25, 2013
[29] Shafiuzzaman Kh., Basu M., Conlon M., UPQC for Power Quality Improvement in DG Integrated Smart Grid Network: a Review, *Int. J. Emerging Elect. Power Syst.*, vol.13 (2012), no.1, 1-13