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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

Abstract. *One of the main reasons of the significant economic losses of consumers and suppliers of electrical energy is the use of low-quality electricity. In the event of such situation, the solution of financial compensation issue of damages to the injured party is based on determination of factual contributions of entities connected to power network to the deterioration of power quality at the point of common coupling. So far, there are many methods of determination of the factual contributions to the reduction of power quality that are different both in methodology and in technical features of their implementation. The results of analysis of the present methods and their classification are given and the application field of each of them is identified in the article.*

Streszczenie. *Jedną z głównych przyczyn znacznych strat gospodarczych u odbiorców i dostawców energii elektrycznej jest użytkowanie energii elektrycznej o obniżonej jakości. W takiej sytuacji rozwiązaniem powinna być finansowa rekompensata strat dla pokrzywdzonej strony oparta na określeniu udziału podmiotów przyłączonych do sieci elektroenergetycznej w pogorszenia jakości energii elektrycznej w punkcie wspólnego przyłączenia. Istnieje wiele metod określania negatywnego wpływu odbiorców na jakość energii elektrycznej, różniących się zarówno metodologii jak i technicznymi sposobami ich realizacji. W artykule dokonano analizy obecnych metod, podano ich klasyfikację oraz określono zakresy ich stosowania. (**Analityczne metody określania wpływu rzeczywistego udziału obiektów przyłączonych do systemu zasilania na zaburzenia symetrii i sinusoidalnego przebiegu napięć**).*

Keywords: Power quality, the factual contribution, voltage asymmetry, voltage waveform distortion
Słowa kluczowe: jakość energii, rzeczywisty udział, asymetria napięcia, odkształcenie napięcia

Introduction

The distribution and consumption of electrical energy (EE) of lower quality leads to the significant economic damages [1],[2],[3]. According to the data [4], the financial losses of some consumers may reach 6 000 000 € per hour as a result of single event of power quality (PQ) reduction. According to the data [2] the annual losses for the particular countries are in the order of 10-20 billion US dollars. When the question of compensation of economic losses arises, the problem of identification of sources of PQ deterioration appears. It is solved on the basis of factual (equity) contribution (FC) of connected objects to the reduction of PQ at the point of common coupling (PCC), where FC is understood as true value of power quality index share (PQI) that is introduced in PCC by each object [5].

Analysis of recent research and publications

The first publications on this subject appeared after the adoption of the first PQ standard. The first method of FC determination in the reduction of PQ in PCC was the method of "switching on"/"switching off" the consumer which was developed by a group of scientists headed by Yu. S. Zhelezko [6]. A fundamentally different approach to the solution of this problem, which is known as "secondary power balance method", was proposed by F. A. Zykin [7]. His idea about using the method of symmetrical components and linear circuit theory with non-sinusoidal current sources has been used by other authors. As a result, the most general method for the FC determination is a method that has been proposed by V. Ya. Mayer and Zeniya [8]. The next principal stage in the development of FC determination methods is the method of Yang Hong Geng [5],[9],[10],[11],[12]. Its distinguishing feature is the use of several consecutive measurements of voltages and currents. The works of S. I. Gamazin are devoted to the correction of the last method. They suggest using active experiment for FC determination [12],[13]. Recent studies of this problem have been carried out by G. A. Senderovich who offered to determine FC by means of distortions' conductivity [14].

Object of the article

To analyze, classify and define the application field of existing methods of the FC determination of connected objects in the PQ deterioration in PCC in terms of asymmetry and non-sinusoidal waveform of voltages.

Principal materials of research

All existing methods of FC determination in the PQ reduction can be divided into four large groups (table 1) on the basis of used quantity for FC determination. The first group of methods uses PQI itself for FC determination. The second, third and fourth groups use either currents and voltages of reverse and zero sequences, as well as their higher harmonic components, or the relationship between them.

Table 1. Classification of FC determination methods

Group of methods	Quantity used for FC determination
I	PQI
II	Distortion power
III	Distortion voltage
IV	Distortion conductivity

Methods of each group has been considered taking into account the possibilities of their technical implementation in accordance with the PQI measurement procedure and use of additional information.

The method of "switching on/switching off" the consumer. According to this method [6] FC of the consumer (FC_c) in PQ reduction is defined as the difference between the values of PQI in "switched on" (PQI_{on}) and "switched off" (PQI_{off}) states in relation to PCC:

$$FC_c = PQI_{on} - PQI_{off} .$$

It is obvious that this method estimates PQI at two different points of time for which the state of connections and sources of distortion (SD) are independent and unrelated to each other. In addition, the method cannot be implemented within PQI measurement technique, for this reason its use is limited to the cases of preliminary analysis of the effect of the new connection on PQ [5].

Curve method of $PQI = f(S_{load})$.

The basis of this method [5] is the use of statistical, hypothetically linear curve of PQI as a function of power of consumer's switched on equipment S_{load} (fig. 1).

The curve $PQI = f(S_{load})$ obtained on measurements' results allows evaluating FC of the electrical power system of PQI_S as a certain constant value (system background): $PQI_S = PQI(0)$. As a result, FC of the consumer to PQ reduction equals to:

$$FC_c = PQI_{cur} - PQI_c ,$$

where PQI_{cur} is current value of PQI in PCC.

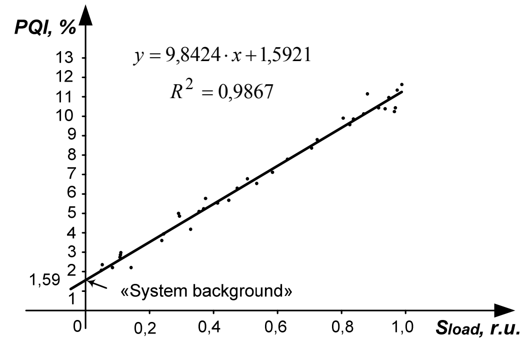

Fig.1. Example of functional curve estimation between load power and value of PQI [5]

Taking into account that PQ in PCC is determined by the mutual influence of all connected objects, the adequacy of $PQI = f(S_{load})$ will depend on the level of each connection noise. Therefore, the usage of this method is limited to the cases when the present consumer has a dominant influence on PQ in PCC [5].

Method of secondary power balance.

The basis of this method [7] is the following representation of the physical processes: distorting PQ load does not spend the part of its input power on the process but converts it and generates back to the electric grid in the form of distortion (fig. 2). The negative value of secondary power defines a source (generator) of EE distortion in the electric network [5],[13],[16],[17].

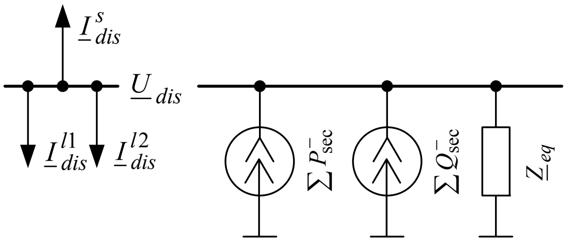

Fig.2. Equivalent circuits of electric network by the method of secondary power balance

Therefore, putting aside the positive secondary active and reactive power, FC of *m*-th connected object to PQ in relation to PCC is equal to:

$$d_m = \frac{P_{sec}^{-(m)} \cdot \sum_{i=1}^{k} P_{sec}^{-(i)} + Q_{sec}^{-(m)} \cdot \sum_{i=1}^{k} Q_{sec}^{-(i)}}{\left[\sum_{i=1}^{k} P_{sec}^{-(i)}\right]^2 + \left[\sum_{i=1}^{k} Q_{sec}^{-(i)}\right]^2} ,$$

where $P_{\sec}^{-(i)}$ and $Q_{\sec}^{-(i)}$ – negative active and reactive components of secondary power of *i*-th connected object.

It should be noted that the main idea of this method is used in approaches of FC and SD determination of other authors [5],[15],[16] as fundamental.

Likewise, in work [15], contribution to the voltage levels of higher harmonics in electrical network nodes is proposed to be determined from the balance of distorting power:

$$U_{nij} = U_{pni} \cdot \left|\underline{D}_{nij}^{g}\right| \Big/ \left(\left|\underline{D}_{ni}^{cs} + \underline{D}_{ni}^{cl}\right|\right) \tag{1}$$

where: U_{pni} – the active component of *n*-th harmonic voltage in node *i*; U_{nij} – contribution of nonlinear voltage of node *j* in *n*-th harmonic voltage of node *i*; $\underline{D}_{nij}^{g}$ – generation of distorting power in node *i* of nonlinear voltage of networks node *j*, $\underline{D}_{ni}^{cs}$ and $\underline{D}_{ni}^{cl}$ – consumption distorting power of power system and load in node *i*.

In [5] the method of FC determination to PQ reduction based on the analysis of only active components of secondary power is described. SD is recognized from the negative sign of the active secondary power among objects connected to PCC. Vector summation of currents is made for them to determine the current value of I_{Σ} equivalent to SD. Other parameters of the equivalent circuit are presented as equivalent passive resistance. The module of input resistance equivalent to SD is determined from the formula:

$$Z_{in} = U_{dis} / I_{\Sigma} ,$$

where: U_{dis} – distortion voltage.

Having known the equivalent input resistance FC of each *k*-th the SD is determined from the following expression:

$$U_{dis\,k}^{FC} = I_{dis\,k} \cdot Z_{in} ,$$

where $I_{dis\,k}$ – distortion current of *k*-th distorting connected object.

In [16] the approach of SD determination in relation to PCC is considered, where total power of *n*-th harmonic component is represented in the form of three components:

$$\underline{S}_n = \underline{S}_n^{(1)} + \underline{S}_n^{(2)} + \underline{S}_n^{(3)} ,$$

where $\underline{S}_n^{(1)}$ and $\underline{S}_n^{(2)}$ – powers generated by current source of *n*-th harmonic component, power system and capacity accordingly, $\underline{S}_n^{(3)}$ – mutual power that exists in the presence of current sources of *n*-th harmonic components both in system and in load.

For $\underline{S}_n^{(1)}$, $\underline{S}_n^{(2)}$ and $\underline{S}_n^{(3)}$ the following mechanisms are defined. Having one of SD there is one of the three components $\underline{S}_n^{(1)}$ or $\underline{S}_n^{(2)}$. The direction of this secondary power for each *n*-th harmonic component is always corresponded to its generation. Having two or more SD there are all three components. The analysis of these components does not allow determining SD clearly and FC of each connected object respectively.

Summing up the methods analysis of FC determination of this group, one can select their main disadvantage: having more than one distorting object in relation to PCC secondary power are the result of the mutual action of all SD which does not allow to identify clearly the guilty party in its direction. In this regard, the use of these methods is limited to the cases when the singular or dominant SD is connected to PCC [5],[13].

The method of FC determination on distortion voltages.

The founders of the present method of FC determination (V. Ya. Mayer and Zeniya) used approximate representation of the real electrical network. Likewise, all passive non-linear elements have been replaced by active SD [8]. This method of representation corresponds to the classical case of linear electric circuits with non-linear current sources [17]. On that basis, the calculation and analysis of network operation mode parameters can be conducted on individual harmonics and sequences.

Under the principle of superimposition (fig. 3) voltages of the individual sequences and harmonics in PCC can be divided into separate components. These components depend on the distortion of each connected objects, and accordingly characterize FC of each object. In the case of two connections (power system and load), we have:

(2) $$\underline{U}_{nq} = \underline{U}^{s}_{nq} + \underline{U}^{l}_{nq},$$

where $\underline{U}_{nq}$ – voltage of *n*-th harmonics and *q*-th sequence.

It should be noted that the authors of this method point out that part of the data ($\underline{Z}^{s}_{nq}$ and $\underline{Z}^{l}_{nq}$ are equivalent resistance of *n*-th harmonic of *q*-th sequence of distorting power supply system and load) should be determined by calculation, taking into account the basic assumptions in the calculation of short-circuit currents [18].

On the basis of (2) FC to the PQ distortion on such PQI as K_{2U}, K_{0U}, K_U and $K_{U(n)}$ are defined in the following manner:

$$\begin{cases} K^{l}_{2U} = \dfrac{U^{l}_{(1)2}}{U_{(1)1}} \cdot 100\%; \\ K^{s}_{2U} = \dfrac{U^{s}_{(1)2}}{U_{(1)1}} \cdot 100\%; \end{cases} \quad \begin{cases} K^{l}_{0U} = \dfrac{U^{l}_{(1)0}}{U_{(1)1}} \cdot 100\%; \\ K^{s}_{0U} = \dfrac{U^{s}_{(1)0}}{U_{(1)1}} \cdot 100\%; \end{cases}$$

$$\begin{cases} K^{l}_{U} = \dfrac{100\%}{U_{(1)}} \sqrt{\sum\limits_{n=2}^{40} \left[U^{l}_{(n)}\right]^2}; \\ K^{s}_{U} = \dfrac{100\%}{U_{(1)}} \sqrt{\sum\limits_{n=2}^{40} \left[U^{s}_{(n)}\right]^2}; \end{cases} \quad \begin{cases} K^{l}_{U(n)} = \dfrac{U^{l}_{(n)}}{U_{(1)}} 100\%; \\ K^{s}_{U(n)} = \dfrac{U^{s}_{(n)}}{U_{(1)}} 100\%. \end{cases}$$

The main disadvantage of this method is the need of obtaining of accurate information about $\underline{Z}^{s}_{nq}$ and $\underline{Z}^{l}_{nq}$.

Elimination of this disadvantage is possible through the use of solution that was offered by Yang Hong Geng [5],[12]. Its distinguishing feature is a way of identification of $\underline{Z}^{s}_{nq}$ and $\underline{Z}^{l}_{nq}$ (fig. 4).

In this modification of FC determination method by distortion voltages it is proposed to determine impedance of $\underline{Z}^{s}_{nq}$ and $\underline{Z}^{l}_{nq}$ by the results of two consecutive measurements of currents and voltages according to the following principles. If the source of current distortion from the system $\underline{J}^{s}_{nq}$ changes onto the value $\Delta\underline{J}^{s}_{nq} = \underline{J}^{s(t_1)}_{nq} - \underline{J}^{s(t_2)}_{nq}$, current $\underline{I}_{nq}$ and voltage $\underline{U}_{nq}$ in PCC will change onto the values $\Delta\underline{I}_{nq} = \underline{I}^{(t_1)}_{nq} - \underline{I}^{(t_2)}_{nq}$ and $\Delta\underline{U}_{nq} = \underline{U}^{(t_1)}_{nq} - \underline{U}^{(t_2)}_{nq}$ respectively. The similar increment of current $\Delta\underline{I}_{nq}$ and voltage $\Delta\underline{U}_{nq}$ will take place if $\underline{J}^{l}_{nq}$ changes. In that case, if $\mathrm{Re}\left(\Delta\underline{U}_{nq}/\Delta\underline{I}_{nq}\right) > 0$, the relation $\Delta\underline{U}_{nq}/\Delta\underline{I}_{nq}$ defines impedance $\underline{Z}^{l}_{nq}$, in case when $\mathrm{Re}\left(\Delta\underline{U}_{nq}/\Delta\underline{I}_{nq}\right) > 0$ the impedance is equal to $\underline{Z}^{s}_{nq}$.

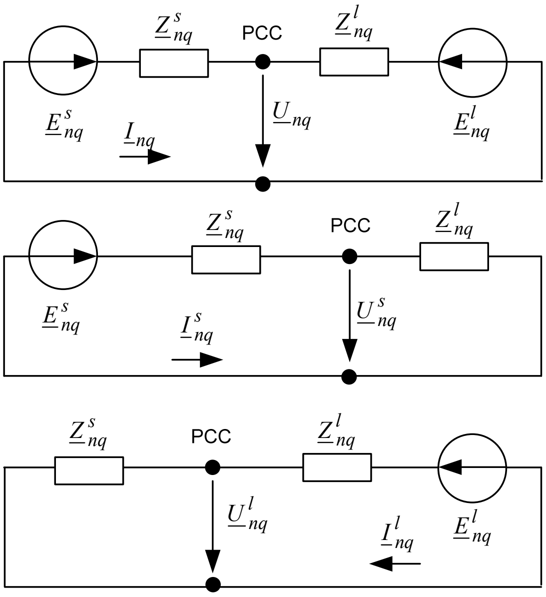

Fig.3. Equivalent circuit of electric network, explaining the principle of power system and consumer participation in the formation of total distortion of EE in PCC

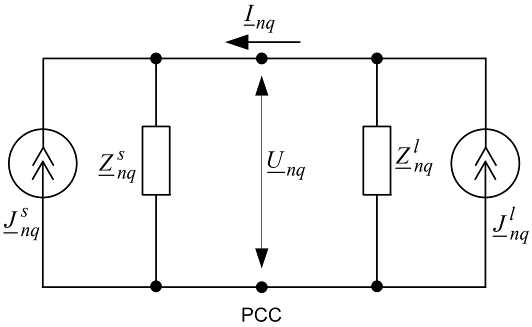

Fig.4. Equivalent circuit of electric network used by Yang Hong Geng

It is obvious that such method of calculation of two unknown quantities $\underline{Z}^{s}_{nq}$ and $\underline{Z}^{l}_{nq}$ at two different points of time is possible provided that: $\underline{Z}^{s}_{nq}$ equals to const, $\underline{Z}^{l}_{nq}$ equals to const, $\underline{J}^{s}_{nq}$ equals to const and $\underline{J}^{l}_{nq}$ equals to var or $\underline{J}^{l}_{nq}$ equals to const and $\underline{J}^{s}_{nq}$ equals to var. This condition is improbable in power system and, therefore, it identifies the main disadvantage of this FC determination method.

In the work [12] it is indicated that calculation error $\underline{Z}^{s}_{nq}$ and $\underline{Z}^{l}_{nq}$ by the method of Yang Hong Geng is within acceptable limits only when the current increment of harmonic component of one of SD is hundreds of times higher than the current increment of another one. In addition, the change of linear (undistorted) part of impedance $\underline{Z}_{nq}^{s}$ and $\underline{Z}_{nq}^{l}$ is possible regardless of currents $\underline{J}_{nq}^{s}$ and $\underline{J}_{nq}^{l}$ of SD. It is offered to eliminate these disadvantages by forcing changes of linear part of impedance $\underline{Z}_{nq}^{s}$ or $\underline{Z}_{nq}^{l}$ during the active experiment (fig. 5) using an automatically switched bank of capacitors (BC). In this case, the measurement and calculation method of FC determination is as follows. 1. Currents $\underline{I}_{nq}^{l1} = \underline{I}_{nq}^{s1} = \underline{I}_{nq}^{1}$ and voltages $\underline{U}_{nq}^{1}$ with switched on BC are measured. 2. Currents $\underline{I}_{nq}^{l2}$, $\underline{I}_{nq}^{s2}$ and voltages $\underline{U}_{nq}^{2}$ at the time (or after) switching on BC are measured. 3. Impedance $\underline{Z}_{nq}^{s}$ is calculated with respect to the change of voltage $\Delta\underline{U}_{nq} = \underline{U}_{nq}^{1} - \underline{U}_{nq}^{2}$ to the change of current $\Delta\underline{I}_{nq}^{l} = \underline{I}_{nq}^{l2} - \underline{I}_{nq}^{1}$. 4. Impedance $\underline{Z}_{nq}^{l}$ is calculated with respect to the change of voltage $\Delta\underline{U}_{nq}$ to the change of current $\Delta\underline{I}_{nq}^{s} = \underline{I}_{nq}^{s2} - \underline{I}_{nq}^{s1}$. 5. Components of voltage $\underline{U}_{nq}$ that characterize the share of power system and consumer in PQ distortion in PCC are defined by the following expressions

$$\underline{U}_{nq}^{s} = \left(\underline{U}_{nq} + \underline{I}_{nq} \cdot \underline{Z}_{nq}^{l}\right) \cdot \underline{Z}_{nq}^{s} \Big/ \left(\underline{Z}_{nq}^{l} + \underline{Z}\right)$$

and

$$\underline{U}_{nq}^{s} = \left(\underline{U}_{nq} + \underline{I}_{nq} \cdot \underline{Z}_{nq}^{s}\right) \cdot \underline{Z}_{nq}^{l} \Big/ \left(\underline{Z}_{nq}^{l} + \underline{Z}\right)$$

The adequacy of the modification of FC determination method on voltages distortion, proposed by S. I. Gamazin similar to the modification of Yang Hong Geng, will depend on the following conditions: $\underline{J}_{nq}^{s}$, $\underline{J}_{nq}^{l}$ and $\underline{Z}_{nq}^{s}$ are constant and $\underline{Z}_{nq}^{l}$ is variable or $\underline{Z}_{nq}^{l}$ is constant and $\underline{Z}_{nq}^{s}$ is variable that in general is also an impossible event in the power system.

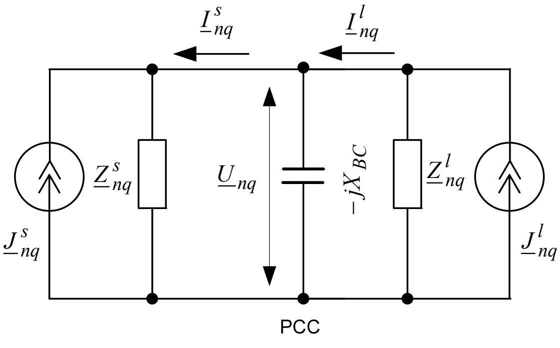

Fig.5. Equivalent circuit of electric networkused by S. I. Gamazin

Therefore, the field of FC determination method on voltages distortion is limited to the cases when several SD with one salient dominant connection are connected to PCC. From the point of view of the technical realization possibility the difficulty arises for the modified method proposed by S. I. Gamazin that requires constant commutation of BC in the intervals of time of PQI measurement.

Method of FC determination on conductivity distortion.

According to this method of FC determination to PQ reduction on voltage asymmetry [16],[19] the following conductivity distortions are proposed to use:

$$\begin{cases} \underline{Y}_{2}^{v\,eq} = \dfrac{1}{3}\left(\underline{Y}_{A}^{v\,eq} + a \cdot \underline{Y}_{B}^{v\,eq} + a^{2} \cdot \underline{Y}_{C}^{н\,eq}\right); \\ \underline{Y}_{0}^{v\,eq} = \dfrac{1}{3}\left(\underline{Y}_{A}^{v\,eq} + a^{2} \cdot \underline{Y}_{B}^{v\,eq} + a \cdot \underline{Y}_{C}^{v\,eq}\right), \end{cases}$$

that can be obtained for the equivalent circuit shown in figure 6, in the assumption of voltage symmetry in PCC.

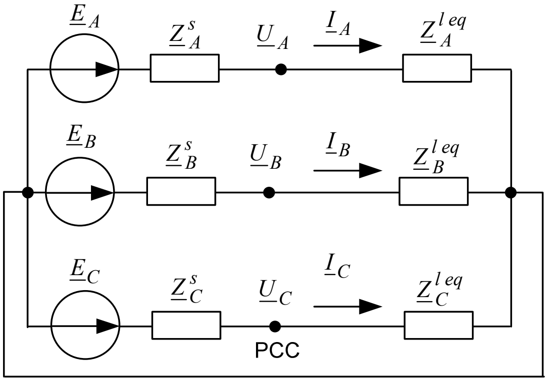

Fig.6. Equivalent circuit of electric network for PQ analysis on voltage asymmetry

On the assumption that the asymmetrical impact of the consumer on network is determined by phase conductivity asymmetry ($\underline{Y}_{2}^{eq}$ and $\underline{Y}_{0}^{eq}$), share participation of *i*-th consumer in the creation of voltage asymmetry on individual sequences can be determined in the following manner:

$$d_{2}^{i} = \underline{Y}_{2}^{i} \Big/ \sum_{i=1}^{n} \left|\underline{Y}_{2}^{i}\right|, \quad d_{0}^{i} = \left|\underline{Y}_{0}^{i}\right| \Big/ \sum_{i=1}^{n} \left|\underline{Y}_{0}^{i}\right|.$$

The analysis of the assumption accepted in this method showed that absolute accuracy of $\underline{Y}_{2}^{v\,eq}$ and $\underline{Y}_{0}^{v\,eq}$ determination is equal to:

$$\begin{cases} \Delta\underline{Y}_{2}^{v\,eq} = -\dfrac{K_{2U}}{100\%} \cdot e^{j\phi_{U_2}} \cdot \dfrac{\left(\underline{S}_{1}^{v\,eq}\right)^{*}}{\left(U_{1}\right)^{2}}; \\ \Delta\underline{Y}_{0}^{v\,eq} = -\dfrac{K_{0U}}{100\%} \cdot e^{j\phi_{U_0}} \cdot \dfrac{\left(\underline{S}_{1}^{v\,eq}\right)^{*}}{\left(U_{1}\right)^{2}}. \end{cases}$$

In this manner inaccuracy of d_2 and d_0 determination are directly proportional to K_{0U} and K_{2U} coefficients as well as $\underline{S}_{1}^{l\,eq}$ load power. Accordingly, the application field of the method is limited to the cases of PCC with low power connections.

Conclusion

The majority of FC determination methods to PQ reduction in PCC are based on the use of linear analyzing of equivalent circuits of electrical network on separate harmonic and symmetrical components in its mathematical models. It defines their main disadvantage, which is neglecting of SD mutual influence on each other. Getting more information about the parameters of electrical network equivalent circuits in the coordinates different from phase can cause difficulties both of methodological and technical character.

The methods of determination of electrical network equivalent circuits parameters which characterize SD by the results of current and voltage measurement are designed for one of the extreme cases when the change of SD states in relation to PCC takes place only in one of them. Existing disadvantages of the discussed methods with no difficulties with technical implementation limit their field of application significantly. It is reduced to the case of PCC with a salient one dominant SD.

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