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Evaluation of three consumers' contribution to the current and voltage distortions at the point of common coupling

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ABSTRACT

The article presents the method to evaluate share responsibility for the generation of harmonic currents between utility and consumer that are connected to the same point of common coupling (PCC). For these purposes, an indicator that evaluates the consumer's contribution to the distortion of current and voltage at the PCC is proposed, based on the previously carried out mathematical modeling of the power supply system (PSS) with two consumers. An evaluation of the distortion caused by three different non-linear loads on the consumers' side is carried out in this study. The approbation of the proposed method was carried out on a laboratory bench, where various operation modes of linear and nonlinear loads were studied. Thus, the results proved that the proposed method could quantify the contribution of voltage and current distortion caused by three and more non-linear loads at the PCC of the consumer's side. Besides, this proposed method can also be used to draw up recommendations for the mitigation of the harmonic currents compensation.

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1. INTRODUCTION

Increasing the energy efficiency of technological equipment and processes is one of the most important issues of modern science. This applies both to increasing the efficiency of all processes from generation to energy consumption, and to reducing CO_2 emissions [1], [2]. Technical measures are proposed to increase energy efficiency in mining industry [3], in gas and oil industry [4], [5], and in metallurgy [6]. The use of renewable energy technologies [7], wind turbines [8], solar panels [9] is also relevant. It is proposed to apply atypical approaches to the efficient distribution of electricity, for example, machine learning [10], as well as algorithms for regulating power consumption [11].

One of the technical measures allowing reducing the energy intensity is the use of variable-frequency drives based on semiconductors [12], [13] with control systems that increase the energy efficiency of an automatic electric drive [14]–[16]. However, highlighting the obvious advantages of this type of equipment [17], [18], it is possible to miss the issues of the electrical energy quality [19]. The negative consequences of the power supply system (PSS) voltage and current distortions are known and widely reported [20]–[22]. Non-sinusoidal current consumed by semiconductor elements [23] leads to a decrease in the quality of electrical energy [24], [25]. At the same time, quality indicators are regulated by international standards (IEEE 1159-2019, IEEE 519-2014), which establish the permissible level of both voltage (THDu) and current distortions (THDi). It should be noted that the standard of the Russian Federation (GOST 32144-2013) regulates only the quality of voltage, but not current.

Thus, in the power quality field of research, the methods developments that allow assessing the impact of each consumer on the voltage quality at the point of common coupling (PCC) have occurred. A few works are devoted to the search for a dominant source of distortions caused by the consumption of harmonic currents. Some of the methods are implemented by calculating any type of power: active power method [26], [27], reactive power method [28], non-active power method [29], and distortion power method [30]. However, the functionality of these methods is limited to determining the dominant source, not providing a quantitative assessment of the impact of distortions sources. Also, it is described in [31]–[33] that, when carrying out calculations according to the above methods, it is possible to obtain opposite results, which casts doubt on the accuracy and applicability of these methods.

Some researchers prefere to change the strategy of calculating the power to the strategy and focus on comparing the currents and voltages vectors at the PCC [34], however, with the approach described, it becomes difficult to interpret the results for the linear loads that include inductance. In addition, the influence of external harmonic sources on the determined load currents should be taken into account [35]–[37]. There is also multi point method [38], however, the technical implementation of such method requires significant costs for measuring equipment, as well as significant computational capability. In addition, studies have been carried out to assess the efficiency and effectiveness of previously proposed methods. For example, in [39] the drawbacks [28], [34], [40] are considered, and in [41] the articles [38], [42], [43] are criticized.

It should be noted that the relevance of research on the development of a method for a reasonable, reliable quantitative assessment of the distortion sources' contributions is confirmed by the fact that, despite the variety of developed methods, none of them is officially approved by the standards regulating electrical power quality. This article is devoted to the approbation of the method developed by the authors for determining the contributions of consumers to voltage and current distortions at the PCC. This approach to the distribution of responsibility for the generation of harmonic currents between consumers powered at the PCC was based on mathematical modeling of a PSS with two consumers, which is described in section 2. As a result, the application of the proposed indicator, which characterizes the consumer's contribution to the distortions of current and voltage at the PCC, was tested on a laboratory bench, where various modes of operation of linear and nonlinear loads were studied in section 3. The main findings and recommendations are presented in section 4.

2. RESEARCH METHOD

2.1. Method of distortion sources assessment

To clarify the essence of the proposed method, it is necessary to consider an equivalent circuit of a PSS with two consumers Figure 1. The diagram is drawn up for harmonics with the introduced coefficients $\dot{n}_1^{(h)}$ and $\dot{n}_2^{(h)}$, showing how many times the consumers' impedances are greater than the PSS impedance $Z_0^{(h)}$. In Figure 1: $\dot{I}_0^{(h)}$ is the harmonic current of the PSS, $Z_0^{(h)}$ is the impedance of the PSS for the harmonic h; $\dot{I}_1^{(h)}/\dot{I}_2^{(h)}$ is the harmonic current of the first/second consumer; $\dot{I}_{1nl}^{(h)}/\dot{I}_{2nl}^{(h)}$ non-sinusoidal current generated by the non-linear load of the first/second consumer; $\dot{I}_{1l}^{(h)}/\dot{I}_{2l}^{(h}$ –non-sinusoidal current consumed by the linear load of the first/second consumer.

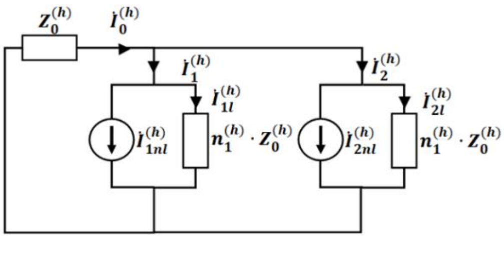

Figure 1. Equivalent circuit of a PSS with two consumers

When developing most of the methods, researchers attempt to separate the components $\dot{I}_{1nl}^{(h)}/\dot{I}_{2nl}^{(h)}$ from the total current $\dot{I}_1^{(h)}/\dot{I}_2^{(h)}$. With this approach to assessing the non-sinusoidality of voltages and currents at the PCC, the contribution of each consumer depends only on the amplitude and phase of the generated harmonic current. However, since the technical method for the reliable separation of these components has not been presented, it is proposed to calculate the contribution of the *j*-th consumer to the deterioration of the quality of current and voltage at the PCC with *n* consumers as the ratio of the projection of the consumer's harmonic current vector on the total harmonic current vector of PSS to the total harmonic current vector of PSS according to (1):

$$K_{Dj}^{(h)} = \frac{I_{\mathrm{j}}^{(h)} cos\varphi_{\mathrm{j0}}^{(h)}}{I_0^{(h)}} \tag{1}$$

where $I_{\mathrm{j}}^{(h)}$ is the *h* harmonic current, flowing in the lines of the *j*-th consumer, $I_0^{(h)}$ is the PSS *h* harmonic current, $cos\varphi_{\mathrm{j0}}^{(h)}$ is the cosine of the angle between the current vectors $\dot{I}_{\mathrm{j}}^{(h)}$ and $\dot{I}_0^{(h)}$.

It can be seen that with this approach the consumer's contribution will also depend on the parameters of the loads connected to the PSS. The magnitude of this influence has been estimated in [44], where the proposed indicator $K_D^{(h)}$was compared with the contribution of consumers to the generation of harmonic currents K_G, calculated based on $\dot{I}_{1nl}^{(h)}/\dot{I}_{2nl}^{(h)}$. Further research is aimed at expanding the scope of the proposed indicator, respectively, laboratory experiments were carried out with three consumers.

2.2. Case study

As part of the research, a laboratory branch was assembled. A circuit diagram is shown in Figure 2. The branch includes: i) three-phase sinusoidal voltage source (L_1, L_2, L_3, *N*); ii) three variable inductance coils L_S; iii) asynchronous motor AIR 90L6 (*M*) with a 1.5 kW rated power, loaded with a 1.1 kW P32M DC motor, operating in the generator mode; iv) thyristor rectifier (*TR*) TVN-3-L-230-125, designed for input line voltage 380 V, output voltage up to 230 V and rated current 125 A; v) single-phase resistance as a 6 kW of electric heating tubes (EHT_1)-*TR* load; vi) three-phase thyristor power controller (TPC) TRM-3M-30 designed for an input line voltage of 380 V, maximum load current of 30 A; and vii) three-phase resistance as a 1.5 kW of electric heating tubes (EHT_2)-*TPC* load.

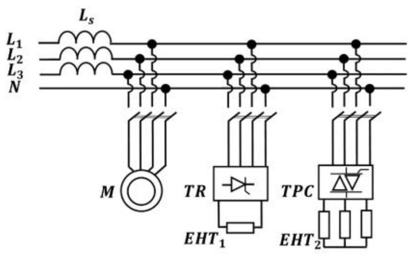

Figure 2. The laboratory branch

An experiment with three loads was carried out in order to study the performance of the proposed method for determining the contribution of consumers to voltage and current distortions at the PCC in the presence of several sources of harmonic currents, while some harmonics are generated by both nonlinear loads (5, 7, and 11), and some are generated by *TPC* (2, 4). The experimental conditions were as follows: the variable load was a *TR*, which a control voltage varied from 5 to 45%. *TPC*'s control voltage was constant and equal 60%, *M* was in no-load mode. In addition, L_S=4 mH were connected in series with the voltage source. Under such conditions, voltage distortions occured at the PCC, exceeding the values established by the standards.

The resource-UF2M power quality analyzer was used as a measuring device, which makes it possible to determine the amplitudes and phases of voltages and currents at harmonics from the 1st to the 40th, as well as the phases between the vectors. Since it was possible to make the assumption that all electricity consumers participating in the experiment are symmetric within the framework of a laboratory experiment, the resource-UF2M quality analyzer was connected to the laboratory stand as follows. Voltage measuring cables were connected to phases A, B, and C at the PCC, current measuring clamps were used to determine the current flowing through each consumer. All measurements of currents were carried out on phase A of the laboratory branch so the current clamp marked with phase A measured the *TR*'s current, phase B measured *TPR's* current, and phase C measured *M*'s current. From the entire data array, the amplitudes of the harmonic currents were selected, which have had the greatest impact on the deterioration of the current and voltage quality. Based on these values, the contributions K_D of each consumer for each harmonic were calculated separately.

3. RESULTS AND DISCUSSION

The experimental results are presented as tables and figures. Figures 3-5 shows the oscillograms of the *TR'*s, *TPC*'s, and *M'*s currents. It can be seen that 5th, 7th, 11th, and 13th. Harmonic currents appear to a large extent in the *TR'*s spectrum. At the same time, *TPC* generates 2nd, 4th, and 8th harmonic currents in addition to the mentioned before. All the above-mentioned harmonics are recorded in the *M* spectrum, however, at lower amplitudes. Based on obtained data, the harmonics most clearly represented in these spectra were selected. Tables 1-3 show the calculations for the 2nd, 5th, and 7th harmonics.

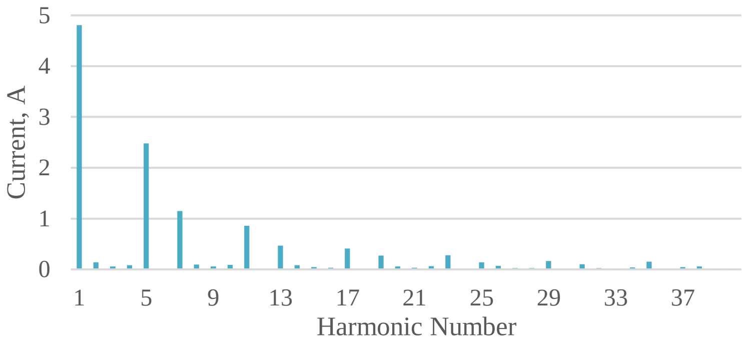

Figure 3. Spectrum of TR current

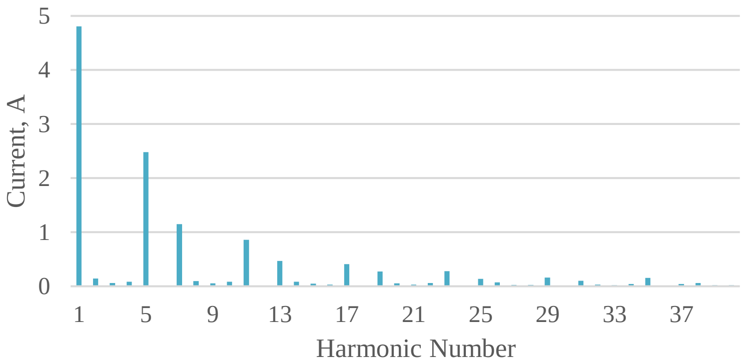

Figure 4. Spectrum of TPC current

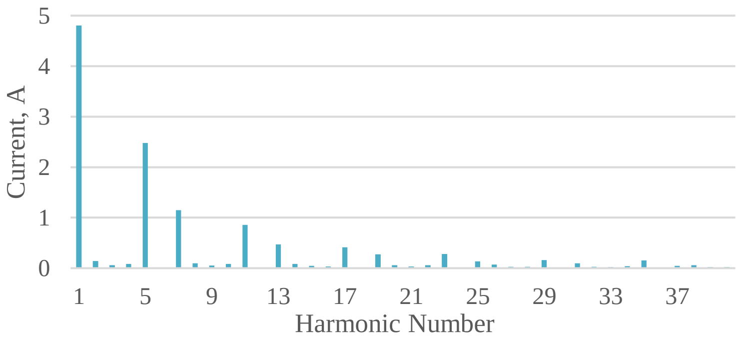

Figure 5. Spectrum of M current

Table 1. Calculation results for the second harmonic

Parameter	Value for the second harmonic					Unit
THDu	8.601	9.784	10.315	11.331	12.843	%
I_{TR}	2.310	2.950	3.642	4.377	5.670	A
$I^{(2)}_{TR}$	0.132	0.144	0.148	0.145	0.142	A
$K_D{}^{(2)}{}_{TR}$	-0.089	-0.097	-0.102	-0.101	-0.101	p.u.
I_{TPC}	2.626	2.650	2.635	2.607	2.568	A
$I^{(2)}_{TPC}$	1.513	1.533	1.515	1.491	1.461	A
$K_D{}^{(2)}{}_{TPC}$	1.021	1.028	1.033	1.032	1.030	p.u.
I_M	2.440	2.423	2.402	2.375	2.325	A
$I^{(2)}_M$	0.201	0.204	0.201	0.197	0.190	A
$K_D{}^{(2)}{}_M$	0.068	0.069	0.069	0.069	0.070	p.u.

According to the 2nd harmonic calculation results, it can be seen that *TPC* is a source of 2nd harmonic current since its contribution $K_D{}^{(2)}{}_{TPC}$ in relative units exceeds 1. Also, the value of the contribution varies around the average value, which is logical, since the *TPC*'s load did not change so the consumed current stayed constant. At the same time, the contributions of *TR* and *M* are close to zero but have different signs, caused by the different resistances of consumers at the 2nd harmonic. The possibility of a negative contribution and a contribution greater than 1 is caused by the fact that the consumer current projection vector can be opposite to the PSS current vector.

Table 2. Calculation results for the fifth harmonic

Parameter	Value for the fifth harmonic					Unit
THDu	8.601	9.784	10.315	11.331	12.843	%
I_{TR}	2.310	2.950	3.642	4.377	5.670	A
$I^{(2)}_{TR}$	1.270	1.592	1.896	2.158	2.478	A
$K_D{}^{(2)}{}_{TR}$	0.699	0.739	0.780	0.821	0.893	p.u.
I_{TPC}	2.626	2.650	2.635	2.607	2.568	A
$I^{(2)}_{TPC}$	0.440	0.459	0.458	0.442	0.384	A
$K_D{}^{(2)}{}_{TPC}$	0.241	0.206	0.171	0.133	0.066	p.u.
I_M	2.440	2.423	2.402	2.375	2.325	A
$I^{(2)}_M$	0.141	0.166	0.190	0.216	0.253	A
$K_D{}^{(2)}{}_M$	0.060	0.055	0.049	0.046	0.040	p.u.

When analyzing the 5th harmonic calculation results, it is worth paying attention to the fact that both *TR* and *TPC* are sources of the 5th harmonic current. Therefore, the responsibility for the generation should be divided between them. As can be seen from Table 2, the contribution of *TR* increases as its load increases, while the contribution of *TPC* decreases. The significant predominance of the *TR* contribution over the *TPC* contribution is explained by the difference in the loads of these consumers. For a more detailed analysis, it is necessary to conduct an experiment with equal loads of non-linear consumers. It is also worth noting the contribution of *M*, which is close to zero as in previous case for the 2nd harmonic.

Table 3. Calculation results for the seventh harmonic

Parameter	Value for the seventh harmonic					Unit
THDu	8.601	9.784	10.315	11.331	12.843	%
I_{TR}	2.310	2.950	3.642	4.377	5.670	A
$I^{(2)}_{TR}$	0.925	1.075	1.174	1.211	1.151	A
$K_D{}^{(2)}{}_{TR}$	0.853	0.860	0.879	0.920	1.115	p.u.
I_{TPC}	2.626	2.650	2.635	2.607	2.568	A
$I^{(2)}_{TPC}$	0.317	0.361	0.408	0.447	0.461	A
$K_D{}^{(2)}{}_{TPC}$	0.291	0.280	0.259	0.214	0.004	p.u.
I_M	2.440	2.423	2.402	2.375	2.325	A
$I^{(2)}_M$	0.157	0.175	0.181	0.168	0.113	A
$K_D{}^{(2)}{}_M$	-0.145	-0.140	-0.138	-0.133	-0.118	p.u.

For the 7th harmonic, results similar to the 5th harmonic are observed, with a notable increase in the *TR* contribution. However, a negative *M* contribution can be observed. The transition of the *M* contribution to the negative diapason is justified by an increase in the complex impedance of the *M* with an increase in the harmonic number. As a result, it can be concluded that for the case with one linear and two nonlinear consumers, it is possible to determine the consumer's contributions at each harmonic separately and to quantify the effect of each of them on voltage and current distortions at the PCC, based on the developed method. Based on the obtained quantitative results, it is possible to determine to the consumer that should connect a specific harmonic filter in the most efficient to way.

4. CONCLUSION

During the research, it was proposed to use the coefficient of the consumer's contribution to the deterioration of the quality of voltage and current at the PCC $K_D^{(h)}$. Previous experiments have confirmed the possibility of applying this approach to two consumers. This work is devoted to expanding the scope of the method. Based on the results of laboratory experiments, it can be concluded that the use of the coefficient when considering the joint work of three consumers is possible, and the obtained results unambiguously indicate the dominant harmonic current source, if this harmonic current is generated only by one of the electricity consumers (in the case of the 2nd harmonic). Also, according to the calculated values, it is possible to divide the responsibility for the generation of the harmonic current when several consumers are the sources of such a harmonic (in the case of the 5th and 7th harmonic). In any of the presented cases, after comparing the calculated contributions of consumers $K_D^{(h)}$, it is possible to conclude that the installation of a filter-compensating device (FCD) is advisable for the consumer whose coefficient $K_D^{(h)}$ is greater. In this case, this conclusion does not have any special engineering viability, since all consumers are connected directly to the PCC, and therefore the filters must be connected to the PCC. However, in real conditions, large consumers can be connected to the PCC through long lines, and in this case, the point of connection of the FCD will already be different from the PCC, and will depend on the $K_D^{(h)}$ of a particular consumer.

Further development of this method should also be carried out in order to expand the scope of application. The issues of connecting non-linear consumers with equal power, the issues of connecting consumers through long lines, the issues of connecting capacitive elements, such as reactive power compensators, and PCD have not been investigated. Obtaining detailed information about such modes of loads operation will give a complete picture of the possibility of applying the proposed method and describe the features of the results interpretation depending on the type of load.

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