# An assessment of the share contributions of distortion sources for various load parameters

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## Article Info

## ABSTRACT

The method for assessing the contributions of distortion sources based on measuring consumer currents and calculating their projections onto the supply current vector is considered in the paper. Determination of contributions is carried out on the basis of the developed model of an industrial enterprise in the food industry in MATLAB Simulink software. This study presents various cases of simulation, including variable parameters of linear and non-linear consumer load, changes in parameters of external distortion sources and passive harmonic filters. It is shown that the considered method gives correct results in the absence of external distortions in the electrical grid. The considered criteria for the share contributions make it possible to estimate the most efficient place for installing a passive filter in the absence of external distortions. An indicator for evaluating external distortions has also been developed based on calculating the projection of the harmonic system current onto the harmonic current of the shunt filter at the considered frequency.

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## 1. INTRODUCTION

At present, the problem of improving the power quality is becoming widespread, since electrical equipment with semiconductor energy converters is being intensively introduced at any enterprise. Such equipment, in turn, significantly pollutes the electrical grid with harmonics, which can lead to a number of problems, including stoppage of technological lines and equipment failure [1]–[4]. This is typical not only for consumers with non-linear electrical loads, but also for consumers that do not distort the supply voltage. In this case, it is very important to determine the share contributions of distortion sources in the power quality indicators. A considerable number of developed methods are known for searching and identifying the contribution of consumers to the deterioration of the power quality [5]–[14]. At the same time, there are still no correct and approved methodologies and guidelines that allow identifying such a contribution at operating enterprises, and none of the developed methods is used to solve such problems in practice [15]. For example, the method for determining the consumers` contribution to voltage distortion, approved in 2002 in Russia, was canceled due to incorrect identification of distortion sources based on the method of switching on and off the load [10]. A large number of works are devoted to techniques based on the analysis of harmonic power flows and based on the determination of the phase shift angle between voltage and current at the harmonic

frequency [16]–[19]. A number of works provide a mathematical description of the processes confirming the inoperability of this method [20], [21].

The next fundamental stage in the development of methods for identifying distortion sources is the works based on the analysis of the Norton or Thevenin equivalent circuits [22]–[28]. When implementing this method, the equivalent conductivity of each consumer is determined, which is defined with significant assumptions and can have a significant error on the accuracy of the methods. A large number of works are devoted to improving methods for measuring the conductivity of the power supply system and consumers [29]–[34]. Invasive methods quite accurately estimate the parameters of the system and consumers based on the generation of current harmonics of a certain spectrum into the grid and the subsequent measurement of the harmonic voltage. However, the complexity of the source used to generate the signal into the grid significantly increases the cost of solving the problem.

The principle of some methods for identifying distortion sources is based on the calculation of one or another type of power flow. These methods include the calculation of active power flow, the reactive or inactive power flow, the distortion power flow. However, none of the methods provides accurate information on the percentage contribution of each distortion source to total distortions, but determines only the dominant source [35], [36].

There are also a number of methods, the essence of which is based on the analysis of the current and voltage vectors at the point of common coupling [37]–[42] where the division of responsibility for the generation of harmonic currents is determined by their projections onto the total current vector. In this case, a situation is possible when the current amplitude of the distorting consumer is greater than the current amplitude of the supply current vector of all consumers. Then the sum of the current harmonic projections will be more than 100%, which leads to an incorrect determination of the distortion sources contributions. Shklyarskiy *et al.* [43] developed a method based also on the analysis of current vectors and their projections onto the supply current vector, where the above disadvantages are additionally eliminated, which makes it possible to determine the presence of external distortions, provided that a passive harmonic filter is used. Thus, the purpose of this paper is to assess the share contributions of distortion sources based on the method developed by the authors using the example of modeling the power supply system of a food industry enterprise, which is confirmed for a number of different variations in load parameters.

## 2. RESEARCH METHOD
### 2.1. Method of distortion sources assessment

The method under study has been completely described in [30]. The main idea of the method is that the contribution of each consumer can be calculated as shown in (1).

$$K_D^{(h)} = \frac{I_{pr}^{(h)}}{I_0^{(h)}} \cdot 100\%, \tag{1}$$

Where $I_0^{(h)}$ is the $h$ harmonic current at the point of common coupling (PCC), $I_{pr}^{(h)}$ is projection of the consumer's $h$ harmonic current on $I_0^{(h)}$. It can be illustrated by the vector diagram shown in Figure 1. The case when two consumers are connected at the PCC is considered.
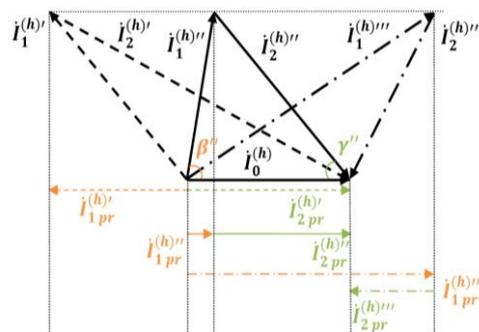


Figure 1. Relative positions of the currents' vectors

There are three different relative positions described in the vector diagram. For all options $I_0^{(h)}$ remains the same but the first and the second consumers current vectors $\dot{I}_1^{(h)}/\dot{I}_2^{(h)}$ are varied and marked as

$I_1^{(h)\prime}/I_1^{(h)\prime\prime}/I_1^{(h)\prime\prime\prime}$ and $I_2^{(h)\prime}/I_2^{(h)\prime\prime}/I_2^{(h)\prime\prime\prime}/I_2^{(h)\prime\prime\prime\prime}$. Consequently, the projections of the consumers' $h$ harmonic currents on $I_0^{(h)}$ are changed, namely, both their amplitudes and signs. Both projections $I_{1\,pr}^{(h)\prime\prime}$ and $I_{2\,pr}^{(h)\prime\prime}$ are positive that means that both of them are the $h$ harmonic current sources. At the same time, $I_{1\,pr}^{(h)\prime}$ is negative that indicates $h$ harmonic current compensation by the first consumer. Similarly, negative $I_{2\,pr}^{(h)\prime\prime\prime}$ shows that the second consumer is the $h$ harmonic current compensator.

## 2.2. Case study

To test the proposed method, the scheme of the power supply system of a food production enterprise with 630 and 1000 kVA input transformers, was considered. The calculations were carried out for one of the sections of a 0.4 kV switchgear, shown in Figure 2. The input of the main distribution panel (MDP), which, in turn, feeds five outgoing power panels, is powered from the said switchgear. The load of the power panels was presented in the form of equivalent loads by the types of electrical equipment, which makes it possible to clearly demonstrate the developed method. Thus, in this case, there are 5 outgoing panels, the load parameters of which are described in Table 1. To simulate the described power supply system in the MATLAB Simulink software environment, the parameters of the equivalent circuit for each element of the system were calculated. The equivalent circuit parameters are presented in Table 2.
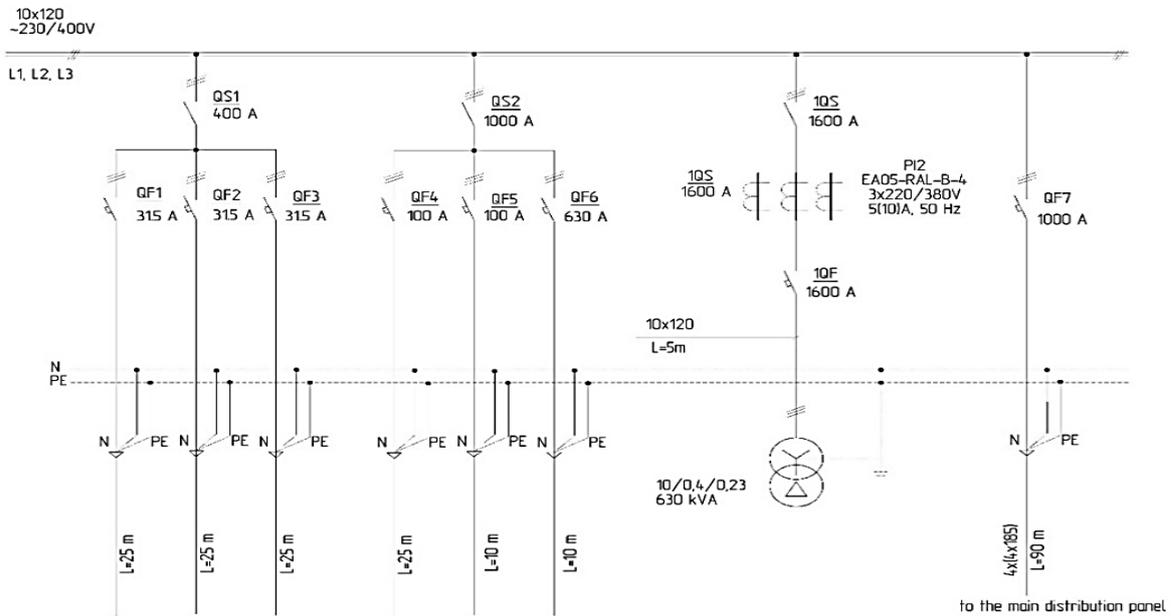


Figure 2. The scheme under study

Table 1. The load`s parameters

| Panel's label | Load's type | Power (kVA) |
|---|---|---|
| LP | LEDs | 40 |
| VP | Ventilation with power converter | 75 |
| EP1 | Process equipment (linear / non-linear load) | 90 / 75 |
| EP2 | Process equipment (linear load) | 37 |
| CP | Compressors | 110 |

Table 2. The parameters of the equivalent circuit

| Elements of the scheme | Parameters and values |
|---|---|
| Energy system | Upss = 0.4 kV, Xpss = 0.002 Ω |
| Transformer | S = 630 kVA, $U_{HV}$ = 10 kV, $U_{LV}$ = 0.4 kV, $\Delta P_{SC}$ = 7.6 kW, $U_{SC}$ = 5.5. % |
| LP power line | $l_1$ = 150 m, $R_{l1}$ = 1.2 Ω/km, $X_{l1}$ = 0.0675 Ω/km |
| VP power line | $l_2$ = 100 m, $R_{l2}$ = 0.54 Ω/km, $X_{l2}$ = 0.0637 Ω/km |
| EP1 power line | $l_3$ = 100 m, $R_{l3}$ = 0.2 Ω/km, $X_{l3}$ = 0.0602 Ω/km |
| EP2 power line | $l_4$ = 150 m, $R_{l4}$ = 0.74 Ω/km, $X_{l4}$ = 0.0662 Ω/km |
| CP power line | $l_5$ = 100 m, $R_{l5}$ = 0.158 Ω/km, $X_{l5}$ = 0.0602 Ω/km |
| Harmonic filter | $Q_F$ = 25 кkvar, $L_F$ = 0.77 mH, $C_F$ = 530 µF, $R_F$ = 0.01 Ω |

Lighting devices, being the load of the lighting panel (LP), are simulated according to the scheme presented in [2], where the authors consider computer models of semiconductor lighting devices. A model of type B LEDs, the current waveform of which coincides with the lighting devices at the enterprise and has the form shown in Figure 3, has been selected.

The load of the ventilation panel (VP) and the compressor panel (CP) is presented in the form of a standard induction motor unit with a frequency power converter (PC) with a scalar pulse-width modulation algorithm (PWM), the power consumption of which is controlled by changing the shaft torque. The non-linear load of the first process equipment panel (EP1) is also simulated by a standard induction motor unit with a thyristor power regulator (TPR). As in the case of scalar PWM, the load is controlled via changing the torque. The linear load of the EP1 and the second process equipment panel (EP2) is replaced by an induction motor with a squirrel cage rotor with a possibility of torque control. The harmonic filter is a shunt filter tuned to a specific frequency.
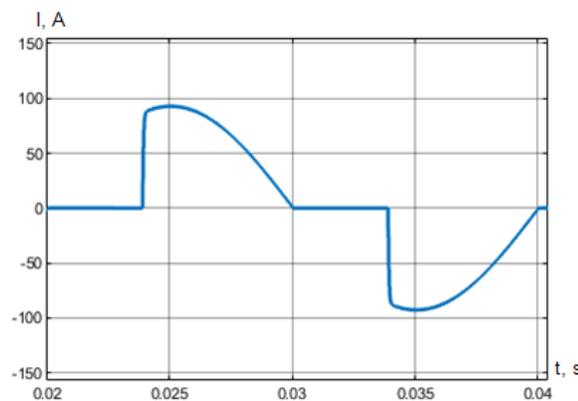


Figure 3. Lighting devices current waveform

## 3.    RESULTS AND DISCUSSION

The power supply system (PSS), built on the MATLAB Simulink platform, was simulated for various parameters of the consumer load, filter connection points and external distortions. All calculations are conditionally divided into 3 blocks. These blocks provide the following modes: i) simulation without filter and external distortions, ii) simulation with a harmonic filter and without external distortions, and iii) simulation with external distortions.

### 3.1.  Block 1: Simulation without filter and external distortions

The single-line equivalent circuit for all experiments in block 1 looks the same, as shown in Figure 4. As can be seen from the scheme, the harmonic filter is not connected to the system, and the presence of external distortions from the grid is not assumed. Within the framework of each simulation, the load of one of the panels varied in relative units relative to the rated capacity of each panel, indicated in Table 1. The load parameters for each simulation are presented in Table 3.
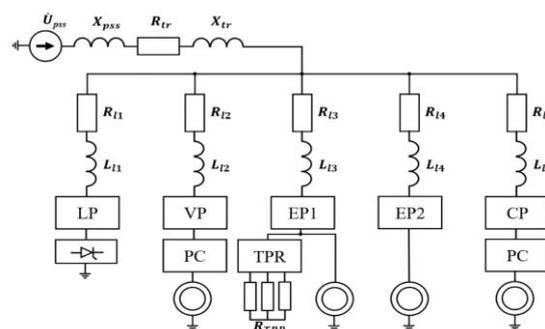


Figure 4. PSS's and enterprise's equivalent circuit for block 1 simulations

Table 3. Loads' parameters for block 1 simulations

| Simulation number | LP's load, p.u. | VP`s load, p.u. | EP1's load (non-linear part), p.u. | EP2's load, p.u. | CP's load, p.u. |
|---|---|---|---|---|---|
| 1 | 1 | 0.5÷1 | 1 | 1 | 1 |
| 2 | 1 | 1 | 0÷1 | 1 | 1 |
| 3 | 1 | 1 | 1 | 0÷1 | 1 |
| 4 | 1 | 1 | 1 | 1 | 0:0.5:1 |

It is assumed that the lighting load does not change, the fans are regulated in the range of 0.5÷1, the non-linear load of technological processes can change the power consumption in a wide range of 0÷1, and the compressors can either be switched off, or operate under the nominal mode or at half of this mode power. Simulation 1 was carried out with a change in the torque of the motor connected to the VP. The results of simulation 1 are presented in Table 4.

Analyzing the simulation results, it is worth noting that the EP2 linear load is characterized by a negative contribution of a small amplitude, slightly varying for different simulated modes from -5.55% to -5.65%. The contribution of the EP1 consumer, which includes both linear and non-linear loads, is characterized by a value close to the contribution of the linear load, since the non-linear consumer, being a part of it, generates such a 5th harmonic current that the projection of this current onto the current at the PCC is small. As a result, the total contribution of the non-linear and linear load of the consumer is closer to the contribution of the linear load. However, the change in this coefficient, depending on the VP loading, from -4.54% to -5.87% indicates that the non-linear load in the consumer of a mixed structure of the EP1 is still present. A similar situation with a small contribution of non-linear load can be observed with respect to the results of calculating the LP ratio. It is also seen that the contribution of the LP decreases from 2.72% to 2.30% and the contribution of the CP decreases from 83.51% to 77.18% with an increase in the load of another non-linear consumer. With an increase in the VP`s load, the contribution of this consumer increased from 23.87% to 32.01%. As a result, the calculated coefficients fully reflect the contributions of consumers depending on the power consumption and, accordingly, the currents generated by them. During simulation 2, the load of the EP1 was changed. The results of simulation 2 are presented in Table 5.

Table 4. Simulation 1 results

| Parameters | VP's load, p.u. | | | | | |
|---|---|---|---|---|---|---|
| | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1 |
| $K_D$(LP), % | 2.72 | 2.62 | 2.50 | 2.43 | 2.36 | 2.30 |
| $K_D$(VP), % | 23.87 | 25.66 | 27.28 | 28.86 | 30.48 | 32.01 |
| $K_D$(EP1), % | -4.54 | -4.85 | -5.14 | -5.40 | -5.62 | -5.84 |
| $K_D$(EP2), % | -5.55 | -5.58 | -5.58 | -5.61 | -5.63 | -5.65 |
| $K_D$(CP), % | 83.51 | 82.15 | 80.94 | 79.72 | 78.41 | 77.18 |
| THDu (PCC), % | 6.33 | 6.50 | 6.66 | 6.82 | 6.99 | 7.16 |
| THDi (PCC), % | 17.41 | 17.37 | 17.28 | 17.23 | 17.19 | 17.14 |
| $I^{(5)}$(PCC), A | 78.87 | 81.15 | 83.37 | 85.64 | 87.96 | 90.25 |
| $I^{(5)}$(VP), A | 23.34 | 25.81 | 28.14 | 30.44 | 32.77 | 35.02 |

Table 5. Simulation 2 results

| Parameters | EP1's load, p.u. | | | | |
|---|---|---|---|---|---|
| | 0 | 0.25 | 0.5 | 0.75 | 1 |
| $K_D$(LP), % | 0.88 | 1.28 | 1.64 | 1.98 | 2.30 |
| $K_D$(VP), % | 37.44 | 36.13 | 34.79 | 33.42 | 32.01 |
| $K_D$(EP1), % | -12.92 | -11.66 | -10.03 | -8.08 | -5.84 |
| $K_D$(EP2), % | -6.04 | -5.93 | -5.83 | -5.74 | -5.65 |
| $K_D$(CP), % | 80.65 | 80.18 | 79.43 | 78.42 | 77.18 |
| THDu (PCC), % | 7.01 | 7.04 | 7.08 | 7.12 | 7.16 |
| THDi (PCC), % | 18.19 | 17.75 | 17.45 | 17.25 | 17.14 |
| $I^{(5)}$(PCC), A | 84.96 | 86.34 | 87.64 | 88.93 | 90.25 |
| $I^{(5)}$(EP1), A | 11.03 | 11.44 | 14.68 | 19.33 | 24.54 |

Unlike the loads of the VP and the CP, the non-linear load of the EP1 is powered by a thyristor power regulator. During the simulation, it was revealed that the contribution of the EP1 increased from -12.92% to -5.84%. Negative values of contributions of a mixed structure consumer were analyzed in the previous simulation. The fact that the non-linear load of EP1 generates a 5th harmonic current, small relative to other consumers, is confirmed by the last line of the Table 5, where it can be seen that when the non-linear load is switched off, the current consumption is 11.03 A, obviously, caused by external sources of distortion, and at full loading the value of this current increases only to 24.54 A. As in the previous case, the contribution of the non-linear load of the EP2 changes slightly, while the contributions of the non-linear consumers of the VP and CP decrease. In this case, it can be noted that the proposed coefficient allows one to quantify the contributions of non-linear consumers, including consumers, which include both linear and non-linear loads. Within the framework of simulation 3, the load of the linear consumer of the EP2 was changed. The results of Simulation 3 are presented in Table 6.

According to the results of calculations, it can be seen that the operating mode of the linear load virtually does not affect the contributions of all consumers connected to the PCC. It can be observed that increasing the linear load decreases the THDi level, but this has virtually no effect on THDu. This effect is achieved by increasing the PCC current at the fundamental frequency with constant harmonic emissions from non-linear consumers. Simulation 4 was carried out with a change in the operating mode of the CP load. At

first, the CP`s load was disconnected, then loaded by 0.5 of the rated power, after which it worked in the nominal mode. The results of Simulation 4 are presented in Table 7.

When the CP`s load is off, the dominant source of the 5th harmonic distortions is the VP`s load. When the compressors are connected at full power and by 0.5 of this value, the contributions are redistributed and the CP`s load becomes the dominant source. As in previous simulations, the contribution of the load with an increase in capacity increases, while the contributions of other non-linear and mixed structure loads decrease. As a result, before connecting passive filters according to the proposed method, it is possible to assess the contributions of consumers with respect to current distortion at the PCC. It can be seen that the contribution directly depends on the amplitude and phase of the current generated directly by the consumer and is also determined by the current in the PCC, i.e. by the total impact of all consumers connected to the PCC. However, such calculations are acceptable only in case of insignificant distortions from the PSS. The case with a dominant source of distortion from the PSS is considered in block 3.

Table 6. Simulation 3 results

| Parameters | EP2's load, p.u. | | | | |
|---|---|---|---|---|---|
| | 0 | 0.25 | 0.5 | 0.75 | 1 |
| $K_D$ (LP), % | 2.07 | 2.13 | 2.18 | 2.24 | 2.30 |
| $K_D$ (VP), % | 32.31 | 32.24 | 32.16 | 32.09 | 32.01 |
| $K_D$ (EP1), % | -6.50 | -6.34 | -6.18 | -6.01 | -5.84 |
| $K_D$ (EP2), % | -5.71 | -5.70 | -5.68 | -5.67 | -5.65 |
| $K_D$ (CP), % | 77.83 | 77.68 | 77.52 | 77.36 | 77.18 |
| THDu (PCC), % | 7.18 | 7.17 | 7.16 | 7.16 | 7.16 |
| THDi (PCC), % | 18.83 | 18.41 | 17.99 | 17.57 | 17.14 |
| $I^{(5)}$ (PCC), A | 89.81 | 89.90 | 90.01 | 90.12 | 90.25 |
| $I^{(5)}$ (EP2), A | 5.13 | 5.13 | 5.12 | 5.12 | 5.10 |

Table 7. Simulation 4 results

| Parameters | CP's load, p.u. | | |
|---|---|---|---|
| | 0 | 0.5 | 1 |
| $K_D$ (LP), % | 2.81 | 2.80 | 2.30 |
| $K_D$ (VP), % | 105.53 | 41.65 | 32.01 |
| $K_D$ (EP1), % | -3.20 | -4.20 | -5.84 |
| $K_D$ (EP2), % | -5.14 | -5.51 | -5.65 |
| $K_D$ (CP), % | 0.00 | 65.25 | 77.18 |
| THDu (PCC), % | 4.25 | 5.86 | 7.16 |
| THDi (PCC), % | 16.49 | 17.32 | 17.14 |
| $I^{(5)}$ (PCC), A | 50.05 | 72.44 | 90.25 |
| $I^{(5)}$ (CP), A | 0.00 | 48.48 | 71.09 |

### 3.2. Block 2: Simulation with a harmonic filter and without external distortions

The single-line equivalent circuit for the simulation of block 2 is shown in Figure 5. It can be seen that the possibility of connecting the 5th harmonic filter to various nodes of the PSS, including the bus, as well as directly to consumers after the power lines, was simulated. During simulation 1 of block 2, a filter was connected to the bus. The contributions of consumers relative to the current at the PCC $K_{D/PCC}$, as well as the contributions of consumers and the power supply system relative to the filter current $K_{D/F}$ were calculated. The calculation results are presented in Table 8. Due to the fact that after installing the filter, the value of the 5th harmonic current in the power supply system tends to zero, the calculated contributions of $K_{D/PCC}$ are not informative, since the denominator of the expression for calculating the said value is too small. As for the contributions relative to the filter current, it is worth noting that the contribution of the power supply system is -1.99%, which fully reflects the source data, which do not provide for distortions from the power supply system. The linear load of the EP2, the non-linear load of the LP, and the mixed load of the EP1 are either not sources of the 5th harmonic current, or their amplitude is small. Therefore, they are characterized by negative contributions of small amplitude, while the contributions of other consumers reflect the distribution of responsibility for the generation of harmonic currents to the same extent as the results of simulations 1-4 of block 1 at the rated load of all consumers.
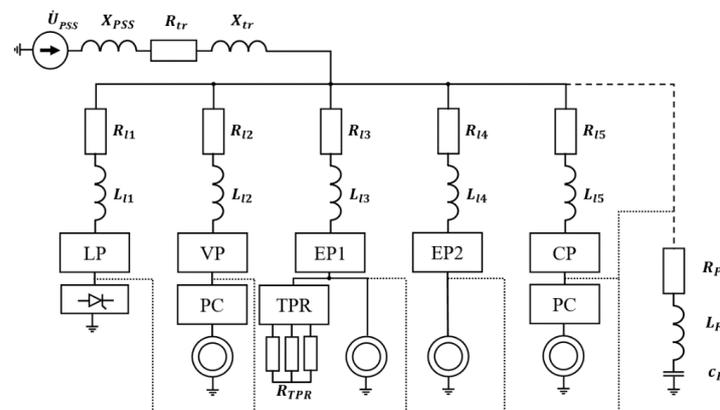


Figure 5. PSS's and enterprise's equivalent circuit for block 2 simulations

During simulation 2, the filter connection point was changed, and the contribution of the external system to the current distortion at the filter connection point was calculated taking into account all other loads connected to the bus. The calculation results are presented in Table 9. The contributions of the power supply system in relation to the filter current for each filter connection point were determined. When filter is connected to the PCC, a value of -1.99% can be observed, which indicates that the distortion sources are located on the consumer`s side. When the filter is connected to the LP, the contribution of the power supply system is 121.62%, while in this case all consumers to which the filter is not connected are included in the power supply system. Similarly, it is worth noting that the impact of the external non-linear load on EP1 and EP2 is more than 100%. The connection of the filter to the PCC is preferable according to the Table 9 data. At the same time, this conclusion can be made based on the calculation of the contribution of $K_{D/F}$, since there is a direct relationship between this indicator and other power quality indicators at the PCC. The second efficient point in this case is the connection of the filter to the CP point with $K_{D/F}$=11.33%.

Table 8. Simulation 1 results of block 2

| Load | Parameters | |
|---|---|---|
| | $K_{D/PCC}$, % | $K_{D/F}$, % |
| LP | 15.67 | -5.42 |
| VP | 5.84 | 41.87 |
| EP1 | 26.50 | -12.83 |
| EP2 | -5.87 | -0.06 |
| CP | 92.82 | 79.58 |
| Filter | -12.93 | --- |
| PSS | --- | -1.99 |

Table 9. Simulation 2 results of block 2

| Filter connection point | Parameters | | | |
|---|---|---|---|---|
| | $K_{D/F}$, % | THDu (PCC), % | THDi (PCC), % | $I^{(5)}$ (PCC), A |
| PCC | -1.99 | 4.75 | 12.50 | 42.13 |
| LP | 121.62 | 6.02 | 15.59 | 76.02 |
| VP | 31.01 | 5.13 | 13.42 | 50.94 |
| EP1 | 116.96 | 5.02 | 13.26 | 49.78 |
| EP2 | 101.04 | 5.70 | 15.18 | 70.78 |
| CP | 11.33 | 4.93 | 12.92 | 43.39 |

### 3.3. Block 3: Simulation with external distortions

The single-line equivalent circuit for the simulation of block 3 is similar to the circuit in Figure 5 with two corrections, the passive filter is connected to the PCC and there is a 5th harmonic voltage with 10% amplitude of the rated voltage. The simulation was carried out with a filter connected to the bus (Case 1 in Table 10) and without a filter (Case 2). Firstly, the contributions of consumers relative to the power supply system are not informative at this level of distortions, but the dominant source can still be identified. As in the simulation of block 2, when the filter is connected, the value of THDu (PCC) decreases from 10.55% to 6.29%. However, the value of THDi (PCC) increases from 21.09% to 22.47%, as does the 5th harmonic current at the PCC. This indicates that effective compensation of harmonics should be carried out in the nodes outside the considered enterprise. To determine the most effective filter connection point, it is possible to use the method of calculating harmonic current projections of the system onto the filter current. If the calculated contribution of $K_{D/F} \approx 0$, as in case when the filter is connected to the PCC in simulation 2 of block 2, then the compensation of harmonics is efficient. With an increase in $K_{D/F}$, the efficiency of harmonic compensation decreases.

Table 10. Simulation results of block 3

| Load | $K_{D/F}$, % | $K_{D/PCC}$, % | THDu (PCC), % | | THDi (PCC), % | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 1 | 2 | 1 | 2 |
| PCC | 44.44 | --- | 6.29 | 10.55 | 22.47 | 21.09 |
| LP | -2.28 | -48.54 | | | | |
| VP | 18.97 | 64.28 | | | | |
| EP1 | -5.33 | -61.28 | | | | |
| EP2 | -0.09 | 26.03 | | | | |
| CP | 45.41 | 119.51 | | | | |

### 4.    CONCLUSION

Thus, the conclusion that can be drawn from this research are: i) The direct dependence of the consumer's contribution on the power of non-linear loads with frequency converters and for LED lighting devices has been confirmed; ii) The constancy of the consumer's contribution with linear load, regardless of the load and operating modes of other consumers, connected to the same PCC, has been confirmed; iii) The considered criteria for the share contributions make it possible to estimate the most efficient place for installing a passive filter in the absence of external distortions; and iv) The efficiency of current distortion compensation decreases in the presence of distortions in power supply voltage. This can be characterized by

the introduced indicator $K_D/_F$ based on calculating harmonic current projections of the system onto the filter current filter, directly indicating which part of distortions will not be compensated for by the filter.

## ACKNOWLEDGEMENTS

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