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Reducing Electric Power Losses in the System of Power Supply Due to Compensation of Higher Harmonics of Currents: Economic and Energy Efficiency Outcomes

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ABSTRACT

The issue of increasing energy efficiency and energy saving is of great importance for the countries with high energy intensity of the gross domestic product, including Russia and the rest of the Commonwealth of Independent States. The measures adopted in Russia on the federal and regional level as part of the State Program on Energy Efficiency and Energy Development are focused on reducing the energy intensity of Russia's gross domestic product and introduce sustainable practices on energy saving in Russia's commercial and budget sectors. This paper presents a case study describing the way to reduce electric power losses in a system of power supply (SPS) of an industrial enterprise. In particular, the case study determines the level of the higher harmonic components of current and voltage at the existing enterprise for the production of reinforced concrete products. The results of the experiment were reproduced using a simulation model of the power supply system in the Matlab/Simulink package. A comparative analysis of using a passive and hybrid filter compensating device to reduce the level of the higher harmonics of current and voltage was carried out by means of modeling. The active losses in the SPS from non-sinusoidal mode are calculated. In addition, the economic effect of using the proposed method is estimated.

Keywords: Energy Efficiency, Industry, Electric Power Losses, Higher Harmonics of Currents.
JEL Classifications: Q29, Q49, L94.

1. INTRODUCTION

The key role in improving economic performance, energy security, and environmental sustainability, as well as mitigating climate change, is played by energy efficiency (Fawcett and Killip, 2019; Foggia, 2018; Ingrao et al., 2018; Dadzie et al., 2018). There is a considerable body developed on energy efficiency of industry in general and in particular industrial enterprises (Malinauskaite et al., 2019; Zheng and Lin, 2018; Pusnik, 2017; Paulo de Lima, et al., 2018; Bhat et al., 2018; Lin and Zheng, 2017; Yanez et al., 2018; Xiong et al., 2019; Quiceno et al., 2019; Zuberia et al., 2017; Haraldsson and Johansson, 2018; Tanaka, 2011; Kohler, 2014; Hea and Wang, 2017). One of the most important factors contributing to energy efficiency is energy and recourse saving (Çay, 2018; Matraeva, et al., 2019; Feng, et al., 2018; Yang et al., 2018; Trotta, 2018). This is achieved through the implementation of energy saving measures, timely transition to new technical solutions, technological processes based on the introduction of the best available and innovative technologies, optimization forms of management, as well as improving product quality, using international experience and other measures. The modern research convincingly shows that the introduction of energy saving technologies not only leads to lower costs and increases product competitiveness, but it also contributes to improving the overall sustainability of the fuel and energy complex and the ecological situation, reducing the cost of introducing additional capacity, and removing barriers to economic development by reducing technological limitations (Kim, 2017; Aslani et al., 2019; Chowdhury et al., 2018).

One of the ways to increase energy efficiency in industrial enterprises is to reduce electricity losses in electrical networks. This is highly topical issue for the energy industry not only in Russia (Sadykova, 2014; Borodin et al., 2015; Savina and Myasoedov, 2017) but in other countries as well (Jamshidieini et al., 2019; Rozali, et al., 2018; Ward and Staffell, 2018). More than that, reducing electricity losses in electrical networks allows to: (1) Reduce the losses of the electric grid organizations due to the reduction of payment for excess losses and accumulate additional funds for a further reduction of losses; (2) unload the electrical networks from the additional power flows and, consequently, ensure the possibility of connecting additional power to the electrical networks; (3) reduce fuel consumption and harmful emissions at power plants by reducing power generation to compensate for losses; (4) reduce the volume of construction of generating capacity for reliable power supply to consumers with the apparent shortage of active capacity; (5) reduce tariffs for electricity transmission services on electric grids and electricity tariffs for end users (Liu et al., 2016; Abeysinghe et al., 2017; Innocent and Francois-Lecompte, 2018; Usman, 2018).

This paper presents a case study of how an industrial enterprise could reduce electric power losses in the system of power supply (SPS) and increase its energy efficiency. In particular, we calculate the level of the higher harmonic components of current and voltage at the existing enterprise for the production of reinforced concrete products (RCP). The results of the experiment were reproduced using a simulation model of the power supply system in the Matlab/Simulink package. A comparative analysis of using a passive and hybrid filter compensating device to reduce the level of the higher harmonics (HH) of current and voltage was carried out by means of modeling. The active losses in the SPS from non-sinusoidal mode are also determined, along with the economic effect of using the proposed method.

The presented case study contributes to the scholarly literature on energy saving and energy efficiency (Davidson, 2002). The model described and calculated in the paper is applicable at any industrial enterprise and demonstrates its effectiveness to reduce energy losses in electric power systems.

2. CASE STUDY

2.1. Introduction

At industrial enterprises, the production of RCP is carried out by a conveyor method in compliance with the requirements of the technological process. To ensure the necessary degree of compaction of concrete, mixture dosing, various vibration frequencies, speeds of belt conveyors and dispensers are used (Averbukh et al., 2016). For this purpose, a frequency-controlled electric drive is used based on a semiconductor frequency converter with an intermediate DC link – an asynchronous motor. Such receivers are the cause of the HH of current and voltage generated in the SPS of the enterprise. The negative influence of the HH is manifested in the violation of the operation of the monitoring and control means, leads to false alarms, to an increase in additional losses of electricity in the elements of the power supply system, etc.

2.2. Materials and Methods

The SPS of the industrial enterprise of the reinforced concrete industry is illustrated in Figure 1. It can be seen from the diagram that the main receivers with a non-linear voltage-voltage characteristic are variable frequency drives (VEDs) of various capacities connected to one section of the bus of the sub-station 630/6/0.4, where the transformer is used as a step-down and matching. To determine the degree of influence of the non-sinusoidal regime on the power supply system for such electric receivers, experimental studies (I_1-I_4) were carried out at the substation of RCP, which showed that the total coefficients of the harmonic current components K_I and the voltage K_U on the low side of the step-down transformer: K_I=22÷45%, K_U=2.5÷9% (Averbukh et al., 2017).

To develop recommendations for achieving the optimum level of electromagnetic compatibility (EMC), a simulation model in Figure 2 based on the actual SPS of the enterprise under investigation was built in the Simulink application of the Matlab software package. The basic elements are modeled in the same sequence as those included in the real scheme with numerical values of the parameters in accordance with the VED passport data. The role of the electric power source in the model is performed by a three-phase source of a sinusoidal voltage (Three-Phase Source). In the adjustment fields, the amplitude of the line voltage, the initial phase of the voltage in degrees, the frequency of the voltage in hertz and the internal parameters of the source (Chernykh, 2008). The cable line (CL) connecting the transformer to the voltage source is represented by the Three-Phase Series RL Branch and the input parameters for the unit is the active, inductive resistance of the CL. The step-down transformer is represented by the Three-phase Reduce Transformer (Two Windings), we indicate the connection schemes of the primary and secondary windings, the parameters of the rated total power and frequency, the voltage, the active and inductive resistance of the windings and the magnetizing circuit. Non-linear receivers are represented by units with VED subsystems connected to the secondary winding of the transformer using a CL unit.

The results of the experimental studies and modeling are shown in Figure 3, in the form of histograms of the fundamental and VG current and voltage with the indication of K_I and K_U.

2.3. Calculation of Electricity Losses in the SPS

The most significant effect due to non-sinusoidal operation is additional losses of active power in CLs and transformers from high-frequency current and voltage components (Averbukh and Zhilin, 2016; Averbukh et al., 2017; Abrokwa et al., 2017; Ahamed et al., 2019).

The total losses of active power in the elements of the SPS can be determined from expression:

$$\Delta P_{\Sigma}=\Delta P_{\Sigma T}+\Delta P_{\Sigma КЛ},$$

where $\Delta P_{\Sigma T}$ - total losses of active power in the transformer, $\Delta P_{\Sigma КЛ}$ - total active power losses in CLs.

The loss of electric power in the KL from non-sinusoidal operation is determined by the formula:

$$\Delta P_{\Sigma_{\hat{E}\hat{Y}\hat{E}}} = 3 \times \sum_{n=2}^{p} I_n^2 \times R_\Sigma \times k_{rn},$$

where R_Σ is the total active resistance of the transmission line at the fundamental frequency; n is the number of the harmonic; I_n is the current of the nth harmonic; k_{rn} is a coefficient that takes into account the effect of the surface effect, it is equal to $\sqrt{n}$.

Additional losses of active power in the transformer windings from non-sinusoidal operating modes can be expressed as the sum of losses of a short circuit and an idling (Costa-Campi et al., 2018; Hollas and Herren, 1982). In addition to additional transformers, there are additional losses due to eddy currents. In normal sinusoidal modes, these losses are small and amount to 5% of the nominal losses of short circuits. However, when the HH currents flow in the transformer, the additional losses increase sharply and can reach 30-50% ΔP_{nc} (Dolinger, 2013):

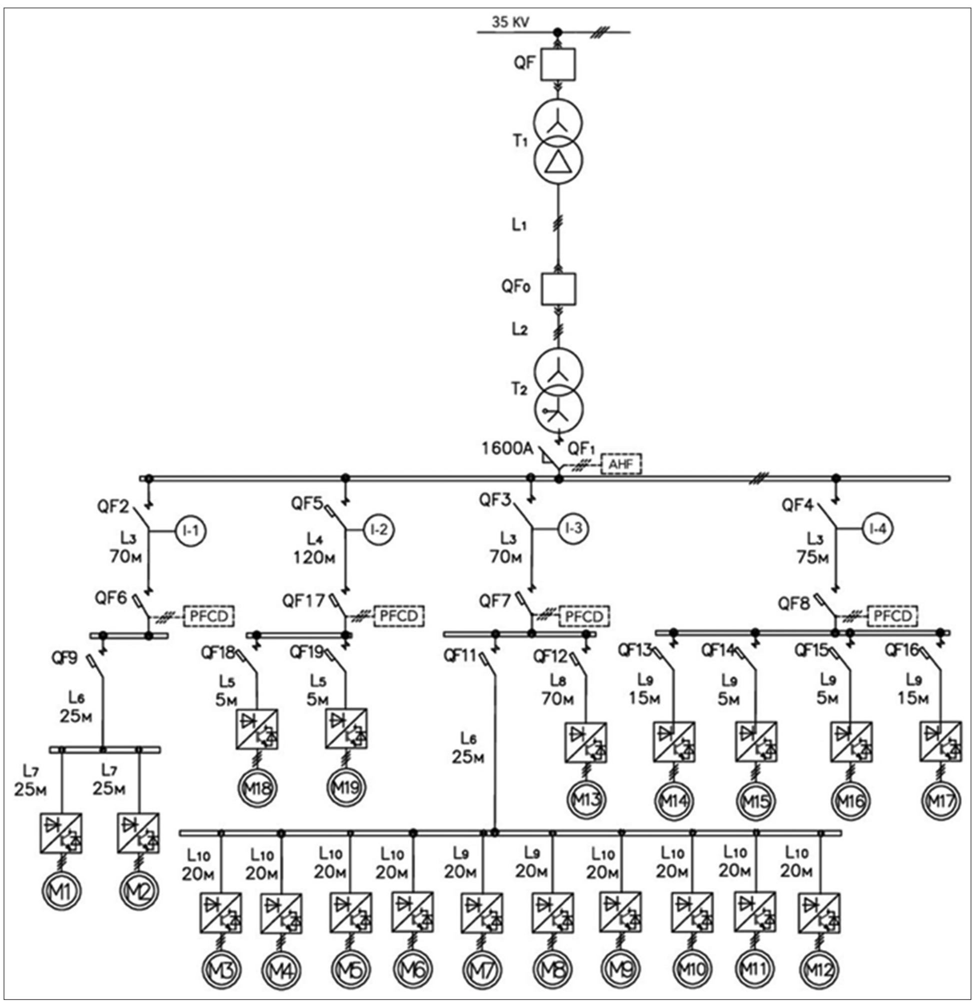
$$\Delta P_{\Sigma_T} = \Delta P_{nc} \times \sum_{n=2}^{p} U_n{}^2 + 0.607 \times \frac{\Delta P_{si}}{u_{si}^2} \times \sum_{n=2}^{p} \frac{1 + 0.05 \times n^2}{n \times \sqrt{n}} \times U_n{}^2.$$

Calculated losses of electricity based on the results of experimental studies in the SPS showed that the total active energy loss per shift (8 h) is 159.6 kWh. Taking into account the fact that the company operates an average of 6120 h a year, the annual power losses amount to 122.1 MWh, with a consumption of 957.44 MWh, hence the share of total additional losses from HH with 12.8%. Therefore, to reduce the influence, high-frequency components of current and voltage, the use of filter compensating devices (FCD) is necessary. In Figure 1, the dashed line indicates the proposed installation site for a passive and active FCD for EMC.

2.4. Passive Filter Compensating Device (PFCD) for Compensation of HH

The filter-feeding network system is a complex resonant voltage circuit caused by a current of frequency equal to or near the resonant frequency ω_p, overcurrent arises in a series circuit on its inductive and capacitive elements (7) (Kartashev, 2006). At the frequency $\omega > \omega p$, the impedance of the PFCD under consideration will be inductive, and if $\omega < \omega p$ it is capacitive, it follows that at the fundamental frequency, the filter generates reactive power; therefore, such devices are able not only to filter out the HH

Figure 1: A scheme of the power supply system



Source: QF-BP35HCM, T[1] – TMH 1000/35/6, L1-AC-70/11 3 × 70 7.5 km. QF[0] – BHA – 10/630 U2, L[2] – ABCbSHv 3 × 120 50 m, T[2] – TMG 630/6/0.4, L[3] – ABBG 4 × 95, L[4] – ABBG 4 × 120, L[5] – BBG 4 × 95, L[6] – ABBG 4 × 50, L[7] – ABBG 4 × 25, L[8] – ABBG 4 × 16, L[9] – BBG 4 × 16, L[10] – BBG 4 × 4, PFCD – passive filter compensating device, AHF – active harmonic filter

Figure 2: Simulation model of the power supply system in Matlab/Simulink

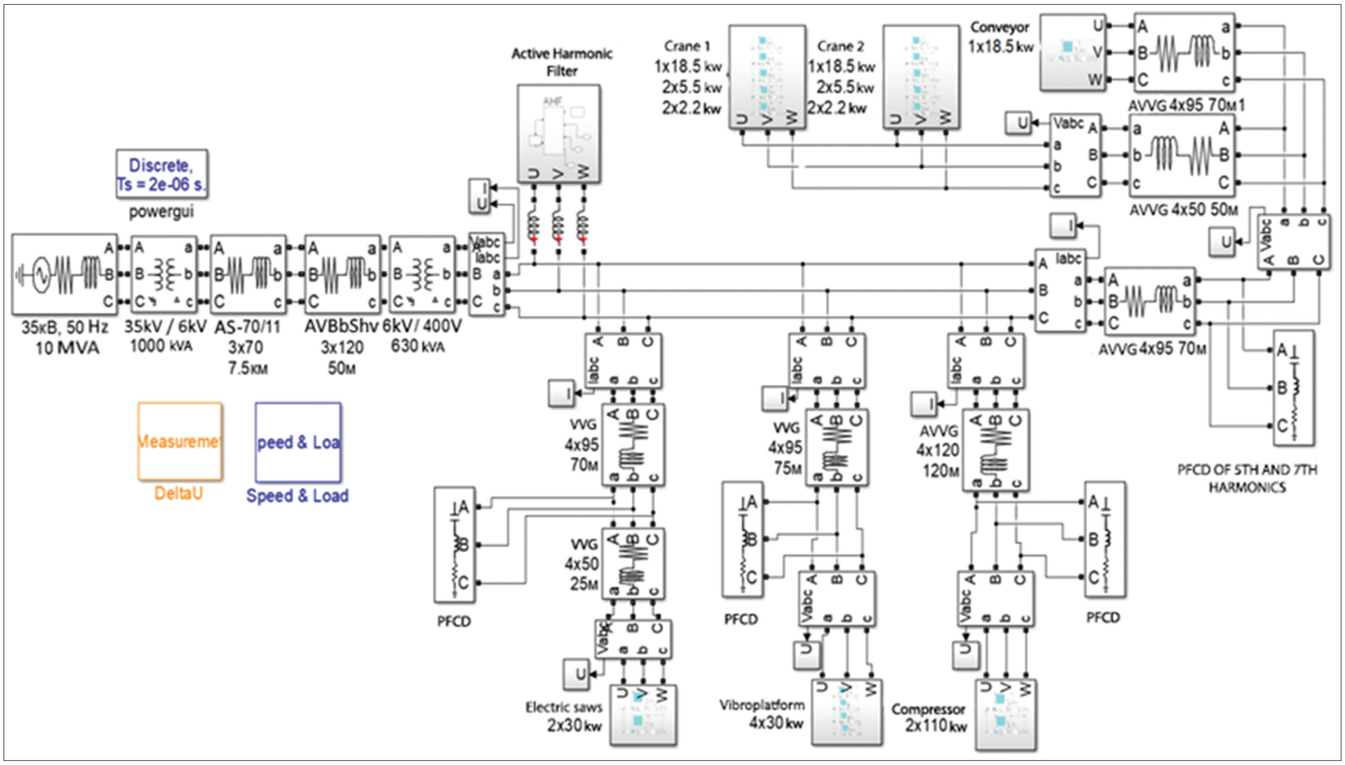
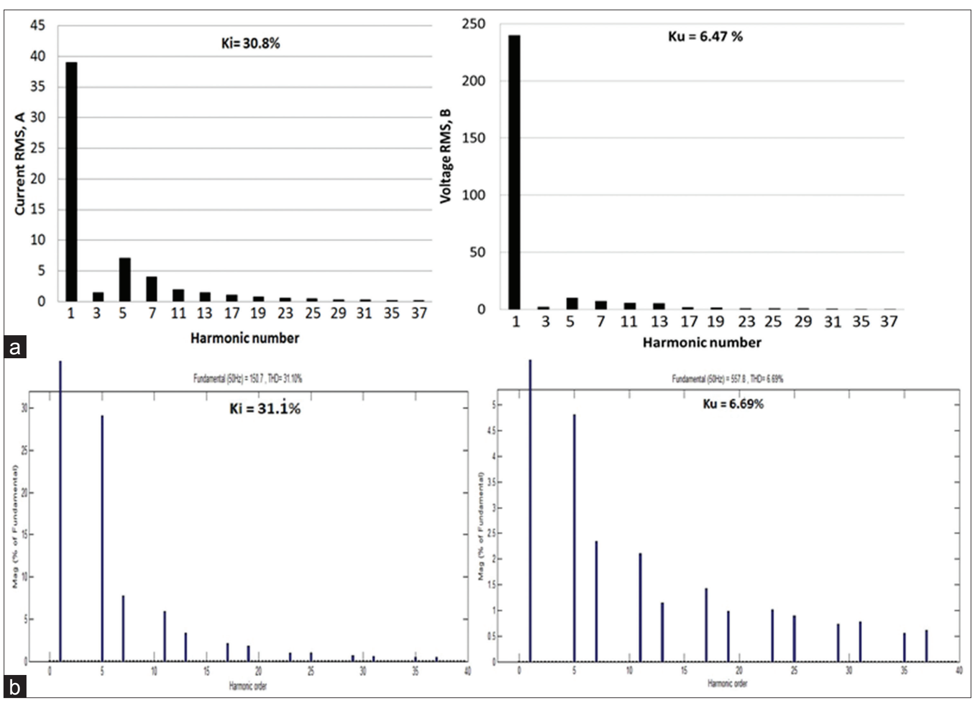


Figure 3: Current and voltage histograms obtained (a) experimentally and (b) in simulation



generated by the RE, but also compensate for the lack of reactive power at the connection point (Das, 2003; Arrilaga et al., 1985). Selecting the power of the capacitor bank that is part of the PFCD Q_n, if the PFCD performs the function of a filter and a reactive power compensator, is performed under the condition $cos\varphi = 0.94$ at the device connection point:

$$Q_n = Q_m - Q_d$$

where Q_m is the reactive power measured by the device during the investigation of the operating conditions of the substation users, Q_d is the design reactive power at which $cos\varphi = 0.94$

The qualitative difference in the characteristics of the UPF and the SPF is due to the fact that their filtering properties are provided by different techniques. If, in the first case, the phenomenon of series resonance is used to allow the main resistance of the filter to shunt the resistance of the system with a low-resistance circuit $R = 0$, thus creating a bypass path for the higher-order current, then in the second case, the shunt resistor $R \to \infty$ filter.

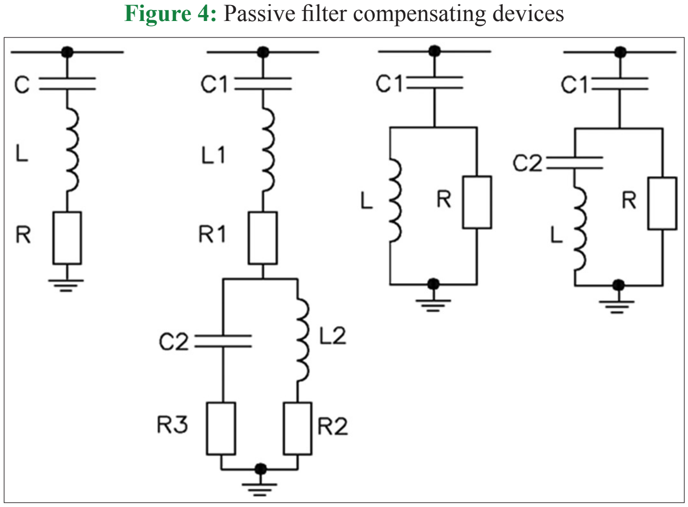
Figure 4 shows the four types of PFCD:

a. A narrowband filter tuned to the frequency of a single harmonic is, in practice, rarely tuned to the harmonic frequency due to a change in the temperature coefficient of capacitance, the frequency of the mains supply and the inductance of the reactor or the capacitance of the capacitor during operation;
b. The double-tuning filter allows to significantly reduce the losses at the fundamental frequency, and the large operating voltage associated with the decrease in the number of inductors under full line voltage is relatively expensive and complicated in tuning;
c. The broadband filter of the second order, are not sensitive to the deviation of temperature and frequency, so the quality factor (0.5 ÷ 5) is chosen from the condition of equi-efficient filtering of the harmonics of the entire band above the resonant one, from disadvantages - the loss in resistance and inductance is higher than in the UPF;
d. A wide-band C-type filter, due to the successively tuned C2 and L, smaller losses are achieved at the fundamental frequency, and the losses at high frequencies are comparable with the filter (c).

As a result of simulation using PFCD Schneider Electric of the Varset series of narrowband and broadband filters tuned to the frequencies of the 5th and 5th, the 7th harmonic respectively, installed on the outgoing sections of electric receivers with nonlinear CEC. The analysis of the total coefficient of harmonic current and voltage components on the secondary winding of the step-down transformer is presented in Table 1.

From the obtained modeling results it follows that the efficiency of HH decrease is greater for filter (b), but its higher cost and complexity of tuning for resonance make the filter (a) a practical-significant option for application, with its lower cost and simple tuning. The use of PFCD in the power supply system has reduced the level of the higher harmonic components, however, in order to completely reduce the HH current and voltage, it is necessary to include harmonics in the SPS of the active filter, which also reduces the losses in the step-down transformer and the 6 kV supply line.

Figure 4: Passive filter compensating devices



2.5. Hybrid FCD for Compensation of HH

Depending on the switching scheme of the active and passive parts, the following hybrid filter configurations exist:

- Serial connection of the active and passive parts, while the active harmonic filter (AHF) is considered as a voltage source;
- Parallel connection of the active and passive parts, while the active filter must have the characteristics of the current source.

It should be noted that PFCD type b (Table 1) sufficiently reduces the levels of harmonic current and voltage components at the point of connection of the most powerful TRE. However, in order to take into account the sharply variable nature of the load of the entire SPS for providing the best parameters of EMC, a simulation model of the system under study with an active filter connected in parallel on the low side of the step-down transformer.

An important element of the structure of the active filter is the block for calculating the reference signal. The accuracy of the calculation of this unit directly affects the efficiency of using the AHF. The existing methods for generating the active filter control signal can be divided into 2 groups:

- Methods for generating reference signals in the frequency domain;
- Methods for generating time-domain reference signals;

The methods for generating the reference signals in the frequency domain are based on the application of the discrete Fourier transform and its modifications, and thus have a long time delay, which is necessary for obtaining a sample of variables and calculating the Fourier coefficients. Despite the fact that these methods are widely used, the above features do not allow them to be used for the real-time control system operation in distribution networks with sharply variable load (Boyarskaya, 2014). Most methods for generating signals in the time domain (for example, the instantaneous power method or p-q theory) differ in the increased complexity of the algorithms (Akagi, 2005; JenoPaul and Raglend, 2010). However, the use of intelligent methods allows you to design a high-speed real-time management system.

Intellectual technologies distinguish, first of all, what exactly is the basis of the concept of intellectuality – either the ability to work with formalized human knowledge (expert systems, fuzzy logic), or the methods of learning and thinking peculiar to man (artificial neural networks and genetic algorithms) (Rubanov and Filatov, 2006; Viegas et al., 2017). The use of fuzzy inference systems allows the creation of high-speed and simple algorithms that can be used to replace objects with a complex mathematical description. Therefore, the use of fuzzy models in active filter management systems is quite effective. However, the structure of the fuzzy inference system does not imply the adjustment of the parameters, i.e., in the case under consideration, which is not envisaged at the design stage of the active filter control system, the load operation mode can negatively affect the level of harmonic current components in the network. Therefore, it becomes necessary to adapt the algorithm of the system for

Figure 5: Current and voltage histograms showing the total level of harmonic components obtained in the simulation of a system with passive filter compensating device

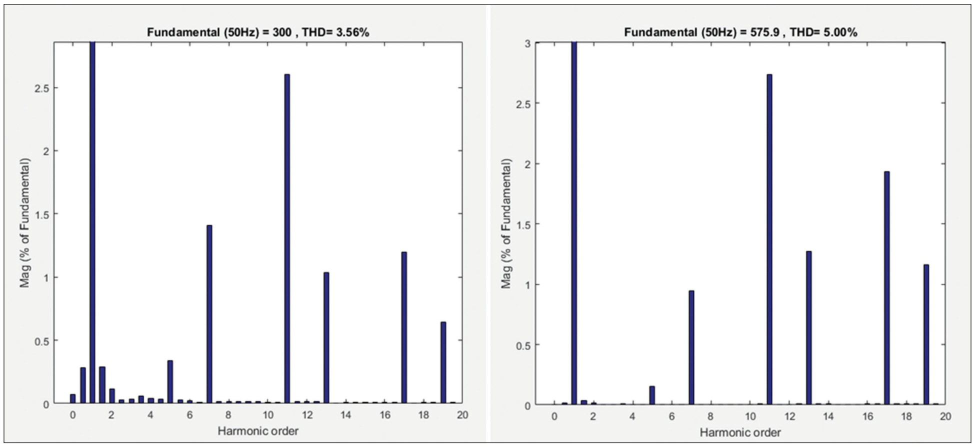


Figure 6: Current and voltage histograms showing the total level of harmonic components obtained during the simulation of a system with a hybrid filter compensating device

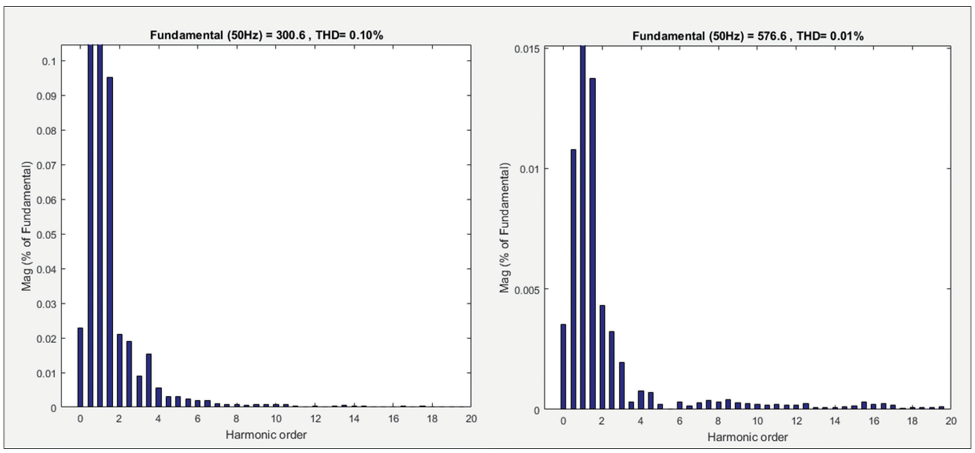


Table 1: Comparison of simulation results

Indicators (%)	Without PFCD	PFCD (a)	PFCD (b)	PFCD (c)	PFCD (d)
K_I	31.1	9.55	6.52	9.92	9.84
K_I (5)	22.1	0.24	0.28	3.4	3.14
K_I (7)	9.62	1.62	0.05	1.84	1.82
K_U	6.69	2.97	2.43	2.59	2.55
K_U (5)	3.74	0.07	0.08	1.04	0.96
K_U (7)	2.3	0.67	0.02	0.79	0.78

PFCD: Passive filter compensating device

Table 2: Results of hybrid FCD simulation

Indicators (%)	Without PFCD	PFCD	Hybrid PFCD
K_I	31.1	3.55	0.15
K_U	6.69	5	0.02

PFCD: Passive filter compensating device, FCD: Filter compensating device

calculating the reference signals. It is this advantage that a system that uses for neural inference a neural network. Among the set of neural-fuzzy algorithms, the Adaptive-Network-Based Fuzzy Inference System (ANFIS) system has become most widespread in real-time systems (Zhukov, 2016). ANFIS implements the fuzzy Takagi-Sugeno system and is a five-layer neural network of direct signal propagation (Andrievskaya et al., 2014). Within the framework of this work, an imitation model of the AHF was developed. In this case, the task signal generation subsystem is represented by a neural-fuzzy system designed in the Matlab Neuro-Fuzzy Designer editor and implemented as a simulation model in the Simulink environment using the Fuzzy Logic Controller block from the Fuzzy Logic Toolbox. This allowed us to investigate the use of an active filter with an intelligent control system in the simulation model of the power supply system of the plant.

The analysis of the total coefficient of harmonic current and voltage components on the low side of the step-down transformer in simulation of the investigated CEC using hybrid FCD is presented in Table 2.

Spectral compositions of currents and voltages on the low side of the step-down transformer, obtained as a result of simulation of the investigated power supply system using PFCD and hybrid FCD are shown in Figures 5 and 6.

3. CONCLUSION

On the basis of the conducted research, we would like to make the following conclusions:

1. The built simulation model in Matlab/Simulink based on the real SPS showed good convergence of the results of experimental research and modeling in the assessment of the main indicators of EMC, which served as the basis for applying FCD to reduce the level of HH current and voltage;
2. As a result of simulation of non-sinusoidal operating modes of electric receivers of an industrial enterprise using the example of CJSC "Belshpala" and the PFCD of Schneider Electric, Varset, it was possible to reduce the amount of active losses in the elements of the shop SPS and the supply line of 6 kV by 37.9 MWh/year or up to 3.96% (instead of 12.8%);
3. The use of an AHF with an intelligent reference signal generation system as part of a hybrid filter compensating device in the simulation model of the power supply system significantly reduced the level of higher harmonic components, which is a more efficient method of compensating HH of current and voltage than using a local PFCD.
4. As a result of using the hybrid FCD, the total active losses from the harmonic components of the SPS are <1%.

In sum, the proposed model is effective in reducing energy losses in electricity systems at an industrial enterprise and can be applied in other countries for increasing energy saving and, as a result, energy efficiency.

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