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# Improvement of the electric energy quality in underground electric networks in highly productive coal mines

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**Abstract**

One of the main factors for the effective functioning of the power supply system in highly productive coal mines is the uninterrupted power supply of underground consumers for the entire process cycle at sufficient amount of electric energy at a high level of quality and performance. The analysis of electric energy consumption in highly productive coal mine has shown that about 57 % of electric energy consumers are located in underground workings. Consumers can be divided into the following areas of basic technological process of coal production: production areas (13 %); conveyor transport areas (13 %); preparation areas (8 %), and areas of auxiliary processes of coal production: mine drainage (23 %). The increase in the share of controlled-velocity electric drives in the total power balance of fully-mechanized longwalls leads to factors previously atypical of underground power networks. Such factors include changes to the harmonic composition of the network, arising higher current and voltage harmonics, affecting the supplying network and causing heating of electrical equipment, power and electric energy losses. Therefore, the most pressing issues are to improve electric energy quality in underground electric networks of highly productive coal mines. The study has developed a technique for experimental investigations of quality indicators of electric energy (presented in the form of algorithm) in respect to specific conditions of highly productive coal mines. These include dangerous facilities in terms of sudden gas/dust outbursts. This technique was tested at a number of coal mines of JSC SUEK-Kuzbass. The study also presents the results of experimental investigations to determine the actual level of total harmonic distortion (factor) in underground electric networks of fully-mechanized longwalls of coal mines. Of greater importance is justification of higher harmonic filter parameters. To this end a calculation algorithm based on the developed technique has been proposed. Research has shown that application of forward and inverse Clarke transformations for calculating the harmonic filter parameters is applicable for all voltage levels. The simulation model of power supply system of a coal mine fully-mechanized longwall allows conditions of higher harmonics damping to be studied by means of a device for improvement of electric energy quality. Applying the proposed technical solutions to improve the quality of electric energy based on the simulation modeling allowed the successful damping of higher harmonics to be achieved. For example, the total harmonic components voltage (THD (U)) was reduced from 9.07 to 1.77 %.

**Keywords**

coal mine, power supply system, electric energy quality, harmonic components, energy efficiency, underground electric networks; simulation model, resistivity bridge harmonic filter

**For citation**

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## ЭНЕРГЕТИКА, АВТОМАТИЗАЦИЯ И ЭНЕРГОЭФФЕКТИВНОСТЬ

Научная статья

# Повышение качества электрической энергии в подземных электрических сетях высокопроизводительных угольных шахт

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**Аннотация**

Одним из основных факторов эффективного функционирования системы электроснабжения высокопроизводительных угольных шахт является бесперебойное питание электроэнергией подземных потребителей всего технологического цикла при достаточном количестве электроэнергии с обязательным соблюдением показателей ее качества. Анализ электропотребления высокопроизводительной угольной шахты показал, что порядка 57 % потребителей электрической энергии расположены в подземных выработках. Потребители можно разделить на участки основного технологического процесса добычи угля: добычные участки (13 %); участки конвейерного транспорта (13 %); подготовительные участки (8 %), и участки вспомогательных процессов добычи угля: водоотлив (23 %). Увеличение доли регулируемых электроприводов в общем балансе мощностей выемочных участков приводит к появлению факторов, не характерных ранее для подземных электрических сетей. К таким факторам относятся изменение гармонического состава сети, появление высших гармоник тока и напряжения, оказывающих влияние на питающую сеть, нагрев электрооборудования, потери мощности и электроэнергии. Поэтому вопросы повышения качества электрической энергии в подземных электрических сетях высокопроизводительных угольных шахт являются актуальными. В результате проведенных исследований разработана методика проведения экспериментальных исследований показателей качества электрической энергии (представленная в виде алгоритма) применительно к специфическим условиям высокопроизводительных угольных шахт, в том числе опасных по внезапным выбросам газа и пыли. Данная методика была апробирована на ряде угольных шахт компании АО «СУЭК-Кузбасс». Также представлены результаты проведенных экспериментальных исследований по определению фактического уровня суммарного коэффициента гармонических составляющих в подземных электрических сетях выемочных участков угольных шахт. Важное значение имеет обоснование параметров фильтра высших гармоник, представленный алгоритм расчета которого основывается на разработанной методике. Исследования показали, что применение прямого и обратного преобразований Clarke для расчета параметров фильтра высших гармоник применимы для всех уровней напряжений. Имитационная модель системы электроснабжения выемочного участка угольной шахты позволяет исследовать условия демпфирования высших гармоник с помощью устройства повышения качества электрической энергии. Использование предложенных технических решений по повышению качества электрической энергии на основе имитационного моделирования позволило сделать заключение об успешном демпфировании высших гармоник, в частности, снижении суммарного значения напряжения гармонических составляющих (THD (U)) с 9,07 до 1,77 %.

**Ключевые слова**

угольная шахта, система электроснабжения, качество электрической энергии, гармонические составляющие, энергоэффективность, подземные электрические сети; имитационная модель, активный фильтр высших гармоник

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## Introduction

The stable operation of highly productive coal mines at a new technical and economic level forms the basis for the coal mining industry in Russia [1–3]. This is due to the current technological and geopolitical challenges that the Russian Federation is facing.

One of the main factors for the effective functioning of power supply system in highly productive coal mines is uninterrupted power supply for underground consumers of the entire process cycle at a sufficient amount of electric energy at a high level of quality and performance.

The technological processes in modern coal mines use power-intensive powerful stoping, tunneling, and transport complexes, digital telemetric control, protection, and blocking systems, as well as auxiliary devices. The high power intensity of the modern highly productive complexes is provided by various systems of electric drives, including controlled ones based on semiconductor devices, especially thyristor converters [4–6].

The use of these devices causes deviations in the electrical energy quality parameters from standard levels and leads to the inadmissible heating of electric motors, power transformers, cables, and other electrical equipment [7–9]. This poses a danger to the underground electric networks in highly productive coal mines with specific operating conditions and integrated technological process, on which the productivity of the whole enterprise depends. Therefore, it is of key important to monitor the quality of electrical energy in underground electric networks of high productivity coal mines.

## Basic Framework

Analysis of electric energy consumption in highly productive coal mine has shown that about 57 % of electric energy consumers are located in underground workings. Such consumers can be divided into the areas of basic technological process of coal production: production areas (13 %); conveyor transport areas (13 %); preparation areas (8 %), and areas of auxiliary processes of coal production: mine drainage (23 %), etc. Fully-mechanized longwalls (stoping areas) are among the most energy-intensive consumers and the initial step of the entire technological process of coal production. Therefore, this stage requires specialattention.

In the historical studies [10, 11] the findings of the harmonic composition analysis in the electric networks of step-down substations (SDS) of the highly productive Polysaevskaya coal mine (JSC SUEK-Kuzbass) were presented. In particular, Total Harmonic Distortion Voltage (THD(U)) for the corresponding substations SDS-12 (48 %), SDS-910 (37.7 %), SDS-948 (41.75 %) was determined. These results were corrected and upgraded in the course of the further research. The finished (upgraded) values of Total Harmonic Distortion Voltage (THD(U)) for the corresponding substations were as follows: SDS-12, 13.48 %; SDS-910, 10.77 %; SDS-948, 11.8 %.

A fully-mechanized longwall includes the following equipment: coal shearer; powered support; longwall conveyor; loader; crusher. Examination of fully-mechanized longwalls has enabled the share of controlled power of the process electrical equipment to be identified in the highly productive fully-mechanized longwall of the coal mine.

For the network which is the subject of this study, the share of controlled power through using converters is about 15 % for the Eickhoff SL-300r coal shea-rer, but much higher, about 33 % for the FFC-9 scraper conveyor. This is due to the use of a soft starter that works for a short time. However, during repair work the number of starts can be large. The controlled power percentage of the FSL-9 loader is 100 %, and its electric motor is powered by a frequency converter. The FBL-10G crusher is directly connected to the power supply network [4, 5].

It should be noted that about 35 % of electric drive systems are connected to a power supply network through converters which are the source of higher harmonics [5, 11]. The increase in the share of controlled-velocity electric drives in the total power balance of stoping faces leads to factors previously atypical of underground power networks. Such factors include changes to the harmonic composition of the network, as well as higher current and voltage harmonics which can affect the supply network. They can also lead to the heating of electrical equipment, power and electric energy losses.

The research was carried out in the highly productive fully-mechanized longwalls in the JSC "SUEK-Kuzbass" mines. Experimental investigations were conducted using the method presented in the form of algorithm (Fig. 1). An Algodue Elettronica UPM 3080 recorder of parameters was used to analyze harmonic composition in the underground electric networks of the coal mines. The analyzer, in addition to measuring the basic parameters of electric energy, allows individual and total harmonic distortion (factor) (THD) to be measured for voltage and current up to the 40th harmonic.

Analysis of the results of the experimental studies (Fig. 2) showed the significant exceeding of normative values of the voltage harmonic distortion (factor) $U_{ав}$, (for the harmonic components). The 5th and 7th harmonics are particularly prominent.

Total Harmonic Distortion Voltage (*THD*(*U*)) was determined as:

$$THD(U) = \sqrt{\sum_{n=2}^{40} \frac{U_n^2}{U_1}} 100\%, \quad (1)$$

where $U_n$ – voltage level of the $n$-th harmonic component; $n$ – harmonic number; $U_1$ – voltage level of the 1st harmonic.

GOST 32144-2013 “Electric energy. Electromagnetic compatibility of technical means” introduces limits for the parameter (THD (U)) which may not exceed 5 % (voltage level of 6 kV).

The study allowed the actual total harmonic component of voltage in the electric network of the fully-mechanized longwall to be determined. This amounted to 10.72 %, exceeding the normative value (not more than 5 % according to GOST 32144-2013) by 2.14 times.

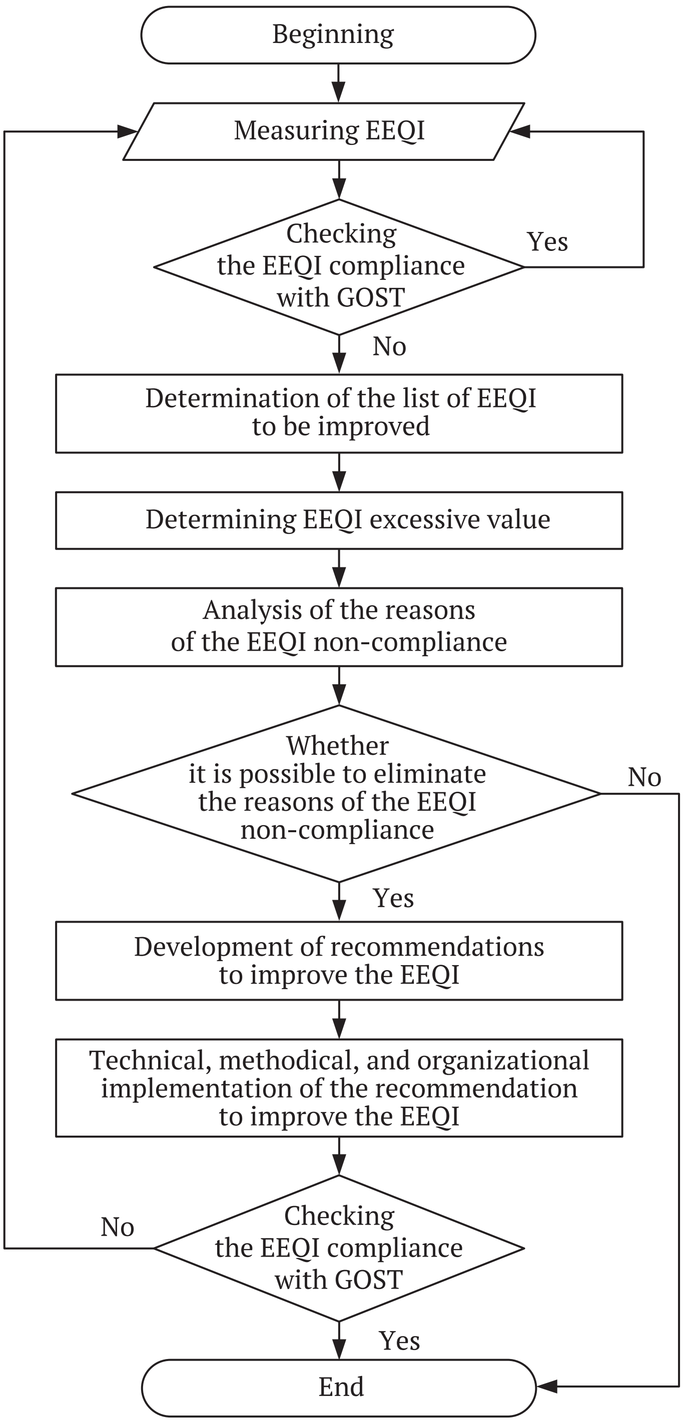


**Fig. 1.** Algorithm of experimental studies

The improvement of electric energy quality parameters in underground networks in highly productive coal mines may be achieved through the installation of resistivity bridge harmonic filters [12–14]. In order to select the optimal resistivity bridge harmonic filter, an algorithm was developed (Fig. 3). Selection of the resistivity bridge harmonic filter based on this algorithm was carried out through determining the power factor. If the power factor requires upward correction, then a resistivity bridge harmonic filter is proposed for installation. If no correction is required, then a number of passive narrow-band (higher) harmonic filters or a passive broad-band (higher) harmonic filter can be installed [15–17]. The experimental study showed a low power factor cos φ = 0.77 at the fully-mechanized longwall. Thus a resistivity bridge harmonic filter was adopted as a higher harmonic filter. Examination of the existing resistivity bridge harmonic filters shows that the most common connection diagram for resistivity bridge harmonic filter connection is the diagram with its parallel connection to the network with capacitive storage. This is due to the simplicity of the filter implementation [18, 19].

The general operation principle of a resistivity bridge harmonic filter consists of the following: active generation of compensating current ($I_{AHF}$) in antiphase with the load-affected current harmonic distortion ($I_{load}$), mutual compensation of these currents; and obtaining a sinusoidal current as a result ($I_{grid}$).

The theoretical basis for the creation of resistivity bridge harmonic filters is the instantaneous power theory (p-q Theory) presented in [19, 20]. According to this theory the instantaneous power is determined in the time domain through transformation of the voltage and currents from an *abc* reference frame to components in a stationary αβ0 reference frame. This is known as the Clarke transform.

In the case of underground electric networks of coal mines, where there is no zero protective conductor (insulated neutral mode), the matrices of Clarke transforms will be as follows:

– forward Clarke transformation for voltages in underground coal mine networks:

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}, \qquad (2)$$

where $u_\alpha$ – projection of voltage vector on α axis; $u_\beta$ – projection of voltage vector on β axis; $u_a$ – voltage of *A*-phase; $u_b$ – voltage of *B*-phase; $u_c$ – voltage of *C*-phase;

– inverse Clarke transform for voltages in underground coal mine networks:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix}; \qquad (3)$$

– forward Clarke transform for current in underground coal mine networks:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}, \qquad (4)$$

where $i_\alpha$ – projection of current vector on $\alpha$ axis; $i_\beta$ – projection of current vector on $\beta$ axis; $i_a$ – current of $A$-phase; $i_b$ – current of $B$-phase; $i_c$ – current of $C$-phase;

– inverse Clarke transform for current in underground coal mine networks:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}. \qquad (5)$$

Instantaneous total power in complex form:

$$\begin{aligned} s &= \bar{u}\bar{I}^* = (u_\alpha + ju_\beta)(i_\alpha - ji_\beta) = \\ &= (u_\alpha i_\alpha + u_\beta i_\beta) + j(u_\beta i_\alpha - u_\alpha i_\beta); \\ p &= u_\alpha i_\alpha + u_\beta i_\beta = \bar{p} + \tilde{p}; \\ q &= u_\beta i_\alpha - u_\alpha i_\beta = \bar{q} - \tilde{q}, \end{aligned} \qquad (6)$$

where $p$ – instantaneous actual (active) power; $q$ – instantaneous fictitious (reactive) power; $\bar{p}$ – average value of active power; $\tilde{p}$ – pulsed active power (average value is equal to 0); $\bar{q}$ – average value of reactive power; $\tilde{q}$ – pulsed (oscillating) part of reactive power.

The levels of currents in matrix form in coordinates $\alpha$ and $\beta$ are defined as:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{u_\alpha^2 + u_\beta^2} \begin{bmatrix} u_\alpha & u_\beta \\ u_\alpha & -u_\beta \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix}. \qquad (7)$$

The levels of currents in $\alpha$ and $\beta$ coordinates are defined as:

$$\begin{aligned} i_\alpha &= \frac{u_\alpha}{u_\alpha^2 + u_\beta^2}\bar{p} + \frac{u_\alpha}{u_\alpha^2 + u_\beta^2}\tilde{p} + \frac{u_\alpha}{u_\alpha^2 + u_\beta^2}\bar{q} + \frac{u_\alpha}{u_\alpha^2 + u_\beta^2}\tilde{q}; \\ i_\beta &= \frac{u_\beta}{u_\alpha^2 + u_\beta^2}\bar{p} + \frac{u_\beta}{u_\alpha^2 + u_\beta^2}\tilde{p} - \frac{u_\beta}{u_\alpha^2 + u_\beta^2}\bar{q} - \frac{u_\beta}{u_\alpha^2 + u_\beta^2}\tilde{q}. \end{aligned} \qquad (8)$$

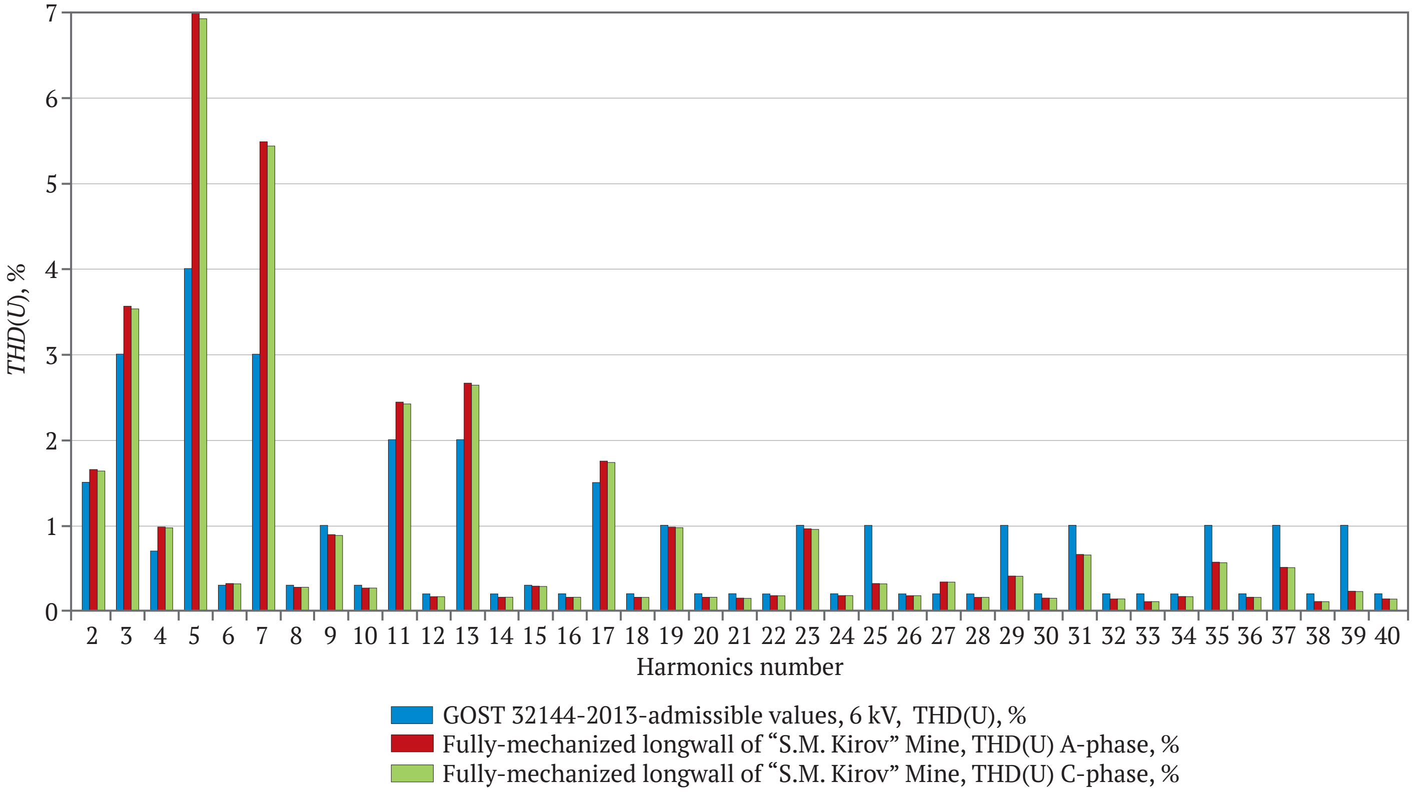


**Fig. 2.** Harmonic composition at the feeder cubicle of the fully-mechanized longwall of “S.M. Kirov” Mine (JSC “SUEK-Kuzbass”)

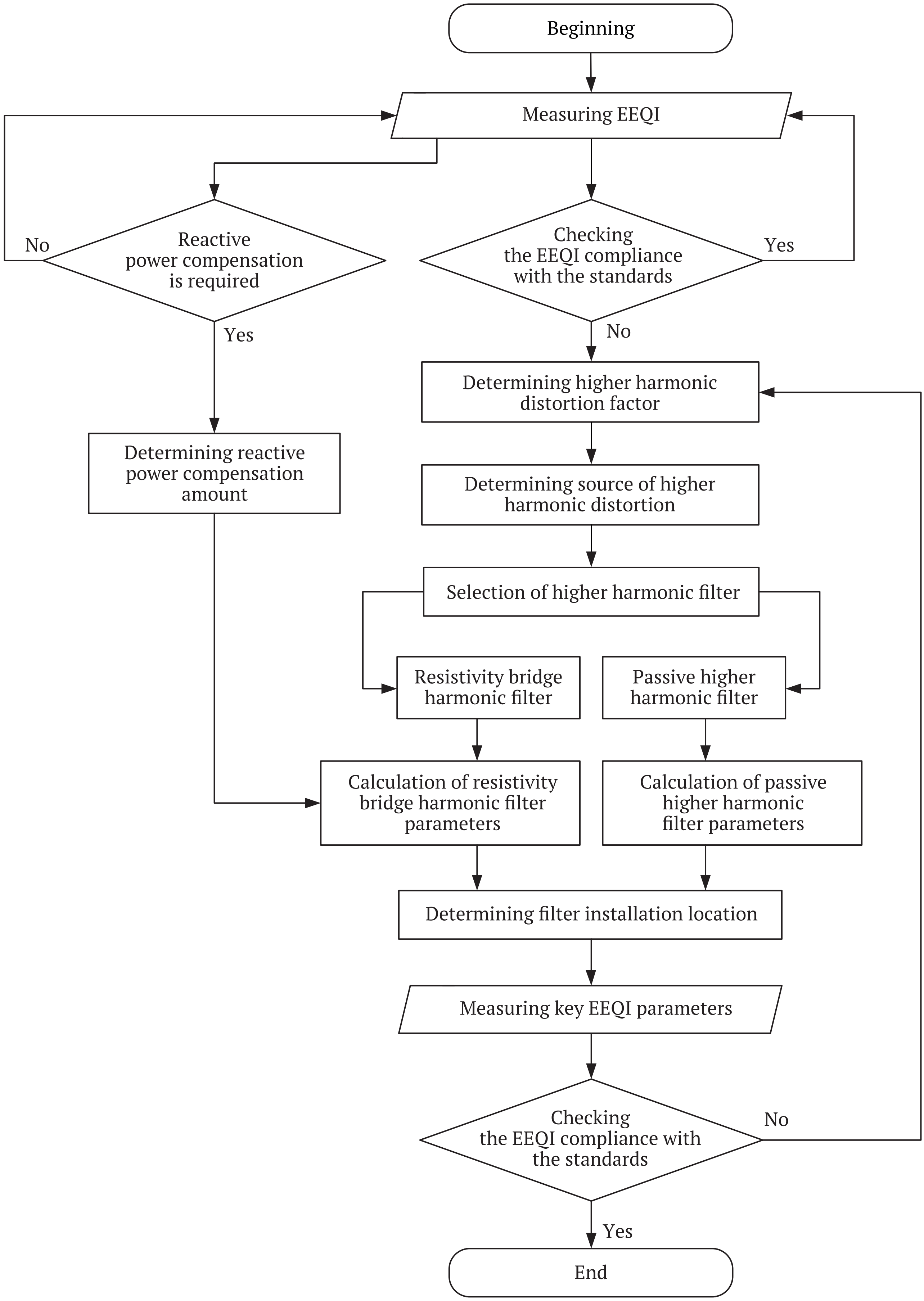


**Fig. 3.** Algorithm for selecting resistivity bridge harmonic filters for highly productive coal mines

The capacitance of the storage capacitor of the resistivity bridge harmonic filter according to [16] can be defined as:

$$C = 2\frac{\int_0^{T/12}(T_u + P_A)dt}{\Delta U_{dC}(\Delta U_{dC} + 2U_{dC})}, \quad (9)$$

where $C$ – capacitance of storage capacitor, μF; $T$ – supply-line voltage period; $T_u$ – capacitor distortion power (rectified voltage), VA; $P_A$ – IGBT losses power, VA; $\Delta U_{dC}$ – magnitude of rectified voltage variation, V; $U_{dC}$ – magnitude of rectified voltage, V.

In order to determine the capacitance of storage capacitor of a resistivity bridge harmonic filter we take the following assumptions:

$$T_u = \sqrt{3}U\sum_{n=2}^{40} I_n;$$

$$T_u = \sqrt{3}I\sum_{n=2}^{40} U_n; \quad (10)$$

$$P_A = P_{cond} + P_{sw} = i_c u_{ce} + \frac{1}{2}U_{CE_{\max}} I_{C_{\max}};$$

$$\Delta U_{dc} = 0,05U_{dc},$$

where $U$ – first harmonic rms voltage, V; $I_n$ – $n$th harmonic component current, A; $I$ – first harmonic rms current, A; $U_n$ – $n$th harmonic component voltage, V; $P_{cond}$ – IGBT static losses power, VA; $P_{sw}$ – IGBT dynamic losses power, VA; $i_c$ – instantaneous IGBT collector current, A; $u_{ce}$ – instantaneous IGBT emitter-collector voltage, V; $U_{CE_{\max}}$ – maximum IGBT emitter-collector voltage, V; $I_{C_{\max}}$ – maximum IGBT collector current, A. In this case, the resulting formula for calculating the storage capacity of a resistivity bridge harmonic filter for voltage levels of distribution networks of highly productive coal mines has the following form:

$$C = 2\frac{\int_0^{T/12}\left(\frac{S}{\sqrt{3}U_1}\sum_{n=2}^{40} U_n + \left(i_c u_{ce} + \frac{1}{2}U_{CE_{\max}} I_{C_{\max}}\right)\right)dt}{\Delta U_{dC}(\Delta U_{dC} + 2U_{dC})}. \quad (11)$$

Results of calculating storage capacity of resistivity bridge harmonic filter at different voltage levels of underground mine distribution networks are shown in Fig. 4.

The calculation of the input choke inductance of the resistivity bridge harmonic filter is as follows:

$$\Delta U = 2\pi f L I \text{ or } L = \frac{\Delta U}{2\pi f I}, \quad (12)$$

where $\Delta U$ – is choke voltage losses, V; $f$ – is power frequency, Hz; $I$ – current, A; $L$ – inductance, H.

The value of the input choke inductance of the resistivity bridge harmonic filter is calculated based on the total power of the circuit $S = \sqrt{3}UI$ and (12):

$$L = \frac{\sqrt{3}U\Delta U}{2\pi f S}. \quad (13)$$

The results of calculating the inductance of the input choke of resistivity bridge harmonic filter for voltage levels of underground mine distribution networks are shown in Fig. 5.

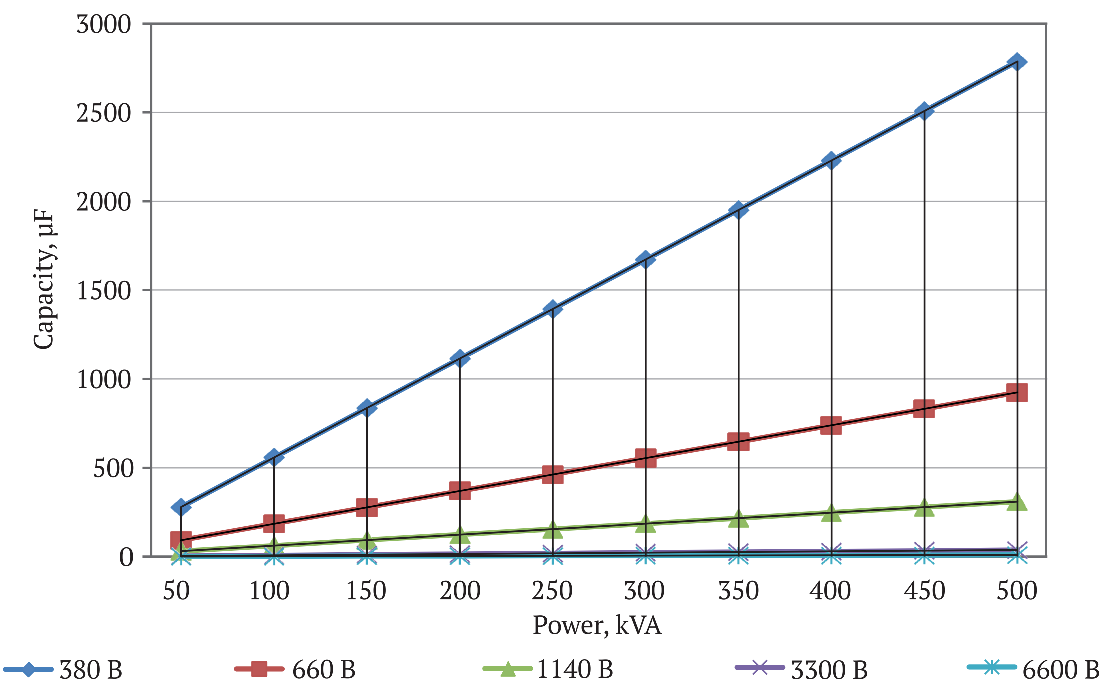


**Fig. 4.** Parameters of storage capacity of resistivity bridge harmonic filter

## Practical implementation of research findings

The study allowed for a device for automated monitoring of electric energy quality parameters to be developed.

The device is installed in the power train of fully-mechanized longwall of a mine. When current flows through the device, the analyzer determines the main parameters of electric energy quality (power factor, harmonic composition, etc.).

The research findings regarding the possibilities of higher harmonics dampening in underground networks of coal mines using the proposed device allowed a simulation model of the power supply system to be built (Fig. 6) This model establishes the possibility of reducing higher harmonics effect on the supply network. The model included a three-phase universal meter which allows the waveform at the voltage source to be estimated when the higher harmonic components compensation system is OFF and when it is ON. An oscillograph is used as the output device of the three-phase universal meter.

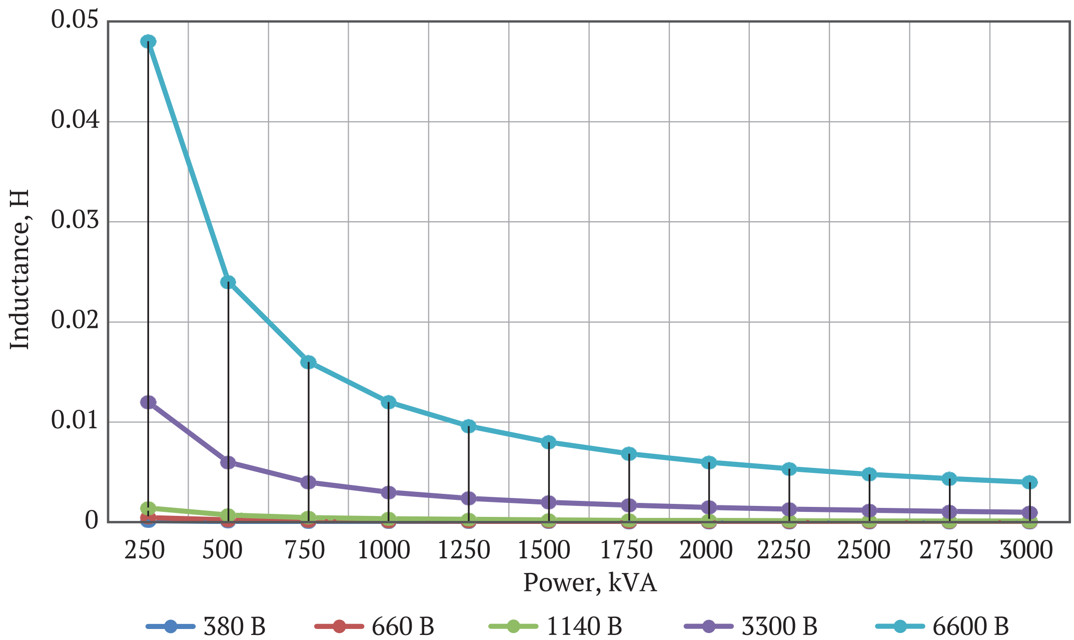


**Fig. 5.** Parameters of input (prefilter) choke of resistivity bridge harmonic filter

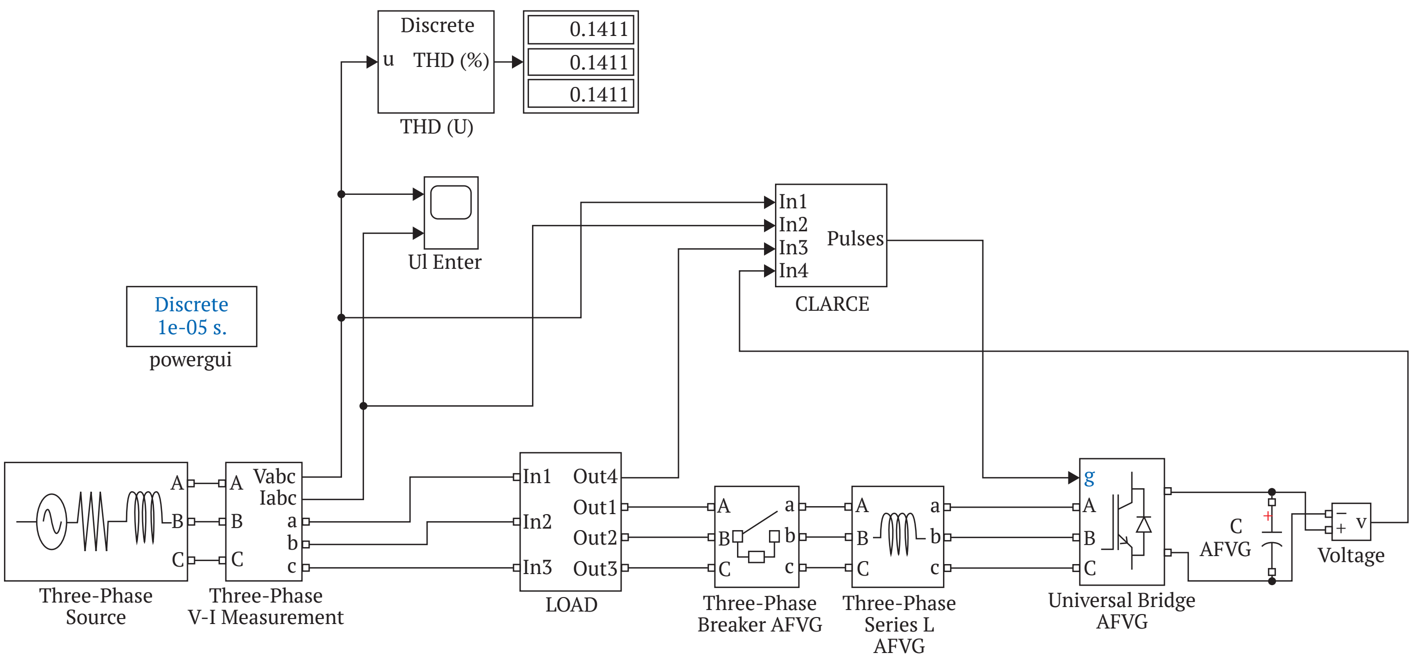


**Fig. 6.** Simulation model of power supply system for a coal mine fully-mechanized longwall with the basic process equipment and the resistivity bridge harmonic filter

The model also includes a resistivity bridge harmonic filter, connected to the power supply system of the fully-mechanized longwall. The resistivity bridge harmonic filter includes: an input reactor; a three-phase active bridge rectifier based on high-voltage IGBTs; a capacitive storage of the resistivity bridge harmonic filter C; and the filter control system. The simulation model includes several subsystems: LOAD (load (Fig. 7)); CLARKE resistivity bridge harmonic filter control system (Fig. 8).

The LOAD subsystem of the simulation model includes three step-down substations (TEC 1324, TEC 1534, TEC 1324) of the fully-mechanized longwall power train and a number of subsystems which simulate the load of the electric networks of the longwall: EickoffSL-300, FBL-10Glinik, FSL-9 Glinik, FFC-9 Glinik.

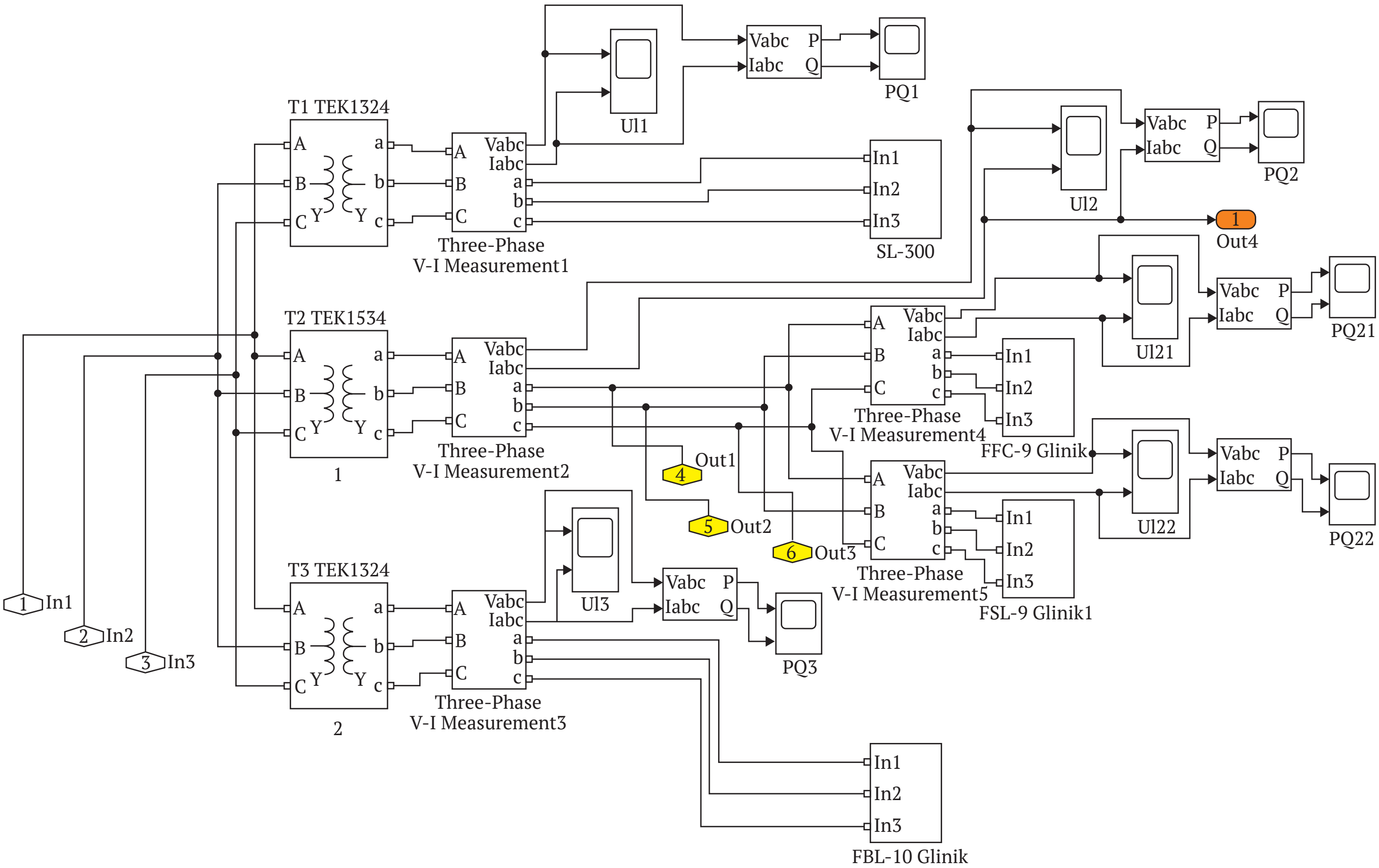


**Fig. 7.** LOAD (load) subsystem of the simulation model

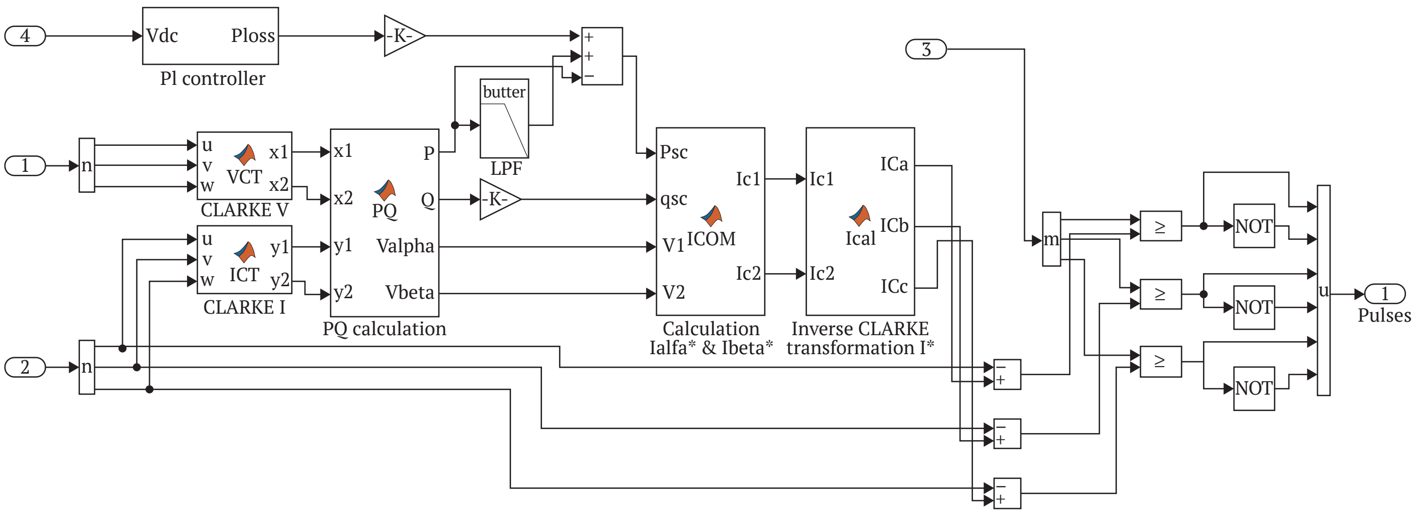


**Fig. 8.** CLARKE simulation model subsystem (resistivity bridge harmonic filter control system)

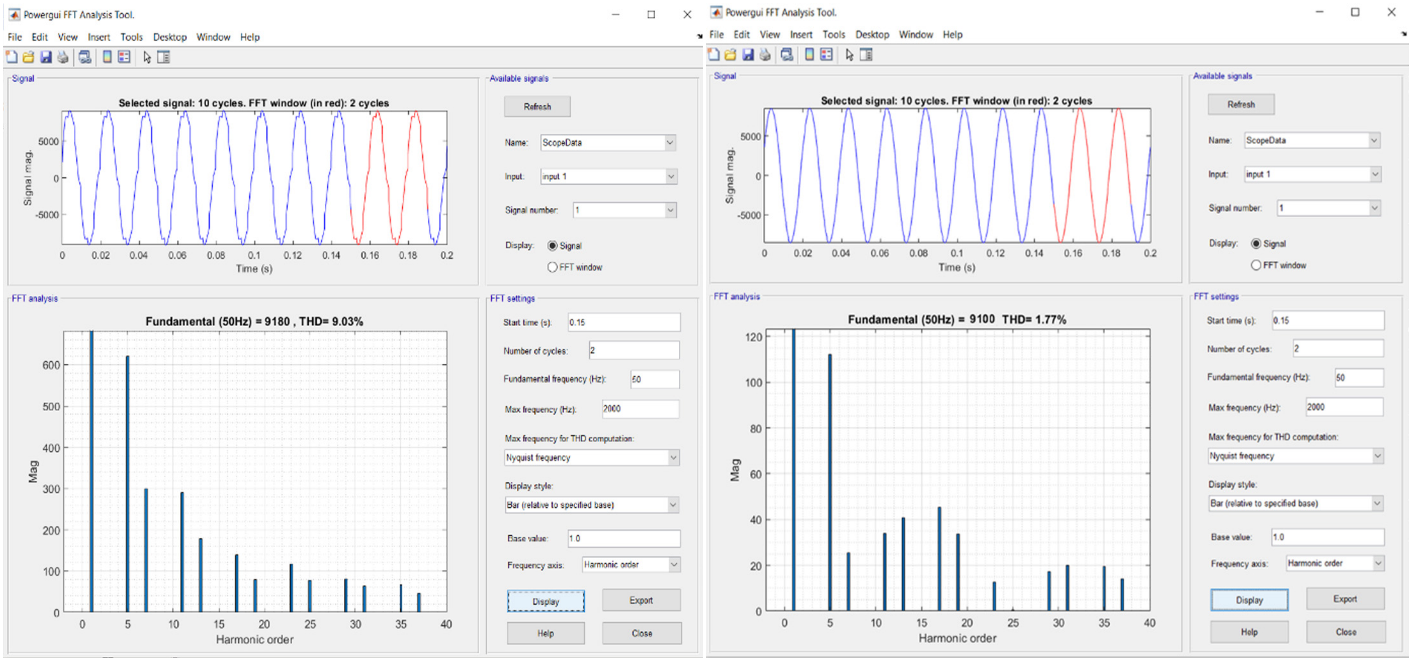


**Fig. 9.** Results of the simulation modeling of power supply system for a coal mine fully-mechanized longwall with basic process equipment and a resistivity bridge harmonic filter

The simulation modeling of power supply system for a coal mine fully-mechanized longwall with basic process equipment and a resistivity bridge harmonic filter (Fig. 9) showed significant reduction of the total voltage of harmonic components (THD (U)). This confirms the effectiveness of the resistivity bridge harmonic filter in underground electric networks of coal mines.

## Conclusion

The study presents the results of the first experimental investigations to determine a number of electrical energy quality indicators in specific conditions in coal mines with highly productive fully-mechanized longwalls using the technique herein developed. For example the results of determining the total harmonic components voltages (THD (U)) and power factor cos φ are given. Furthermore, the study also substantiated the effective application of devices aimed at improving the quality of electrical energy in underground electric networks of highly productive coal mines, the selection of which was carried out using the proposed technique. The parameters of the device were adjusted using the proposed technique. This allowed the analytical dependences to be obtained. It also allowed the parameters of the resistivity bridge harmonic filter for the specific conditions of the underground electric networks to be determined depending on the harmonic composition, voltage levels, and power of consumers of the fully-mechanized longwalls.

A simulation model of a power supply system of a fully-mechanized longwall aimed at investigating the conditions of higher harmonics dampening using the device for improvement of electric energy quality was constructed. Application of the proposed technical solutions, in order to improve the quality of electric energy based on the simulation modeling allowed successful damping of higher harmonics to be achieved, for example, a reduction of the total harmonic components voltage (THD (U)) from 9.07 to 1.77 %.

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