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ENHANCING PERFORMANCE EFFICIENCY OF ELECTRIC CONSUMERS WITHIN SURFACE INFRASTRUCTURE OF COAL MINES

This study analyzes influence exerted by coordinate adjustment of electromechanical systems (EMS) in the structure of electric consumers within the surface infrastructure of coal mines, namely, mine hoists, on high-order harmonic generation. The authors propose a test procedure and a functional chain of the mine hoist EMS for the analysis of high-order harmonic generation at different-type coordinate adjustment. The article describes the simulation models of EMS of mine hoists with different-type coordinate adjustment. The results of the simulation modeling of the mine hoist EMS with standard setting, open-loop control, as well as with parallel and mixed-type coordinate adjustment are analyzed. The conclusion on the influence exerted by the coordinate adjustment on the high-order harmonic generation by the electric consumers of surface infrastructure of coal mines is drawn.

Keywords: *coal mine, mine hoist, electromechanical system, coordinate adjustment, high-order harmonic generation, harmonic content, simulation modeling*
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Introduction

Intensification of underground coal mining in Russia facilitates reduction of coal cost owing to modernization of the main process equipment of coal mines [1–4]. At the present time, major coal production using the underground method is carried out in the Kemerovo Region of Russia, and the key coal producer is the Siberian Coal Energy Company.

Mine hoists are one of the main transport elements of coal mines, and it appears to be impossible to abandon their use in the short term. The hoists transport people, equipment and consumables downward to mine roadways and upward to ground surface. What is more, skip hosts lift produced minerals to ground surface. Optimization of mine hoists in terms of resource saving of cables (one of the basic element of a hoist) and efficient control through starter current limitation in electric motor drive can use a number of methods available to adjust coordinates of electromechanical systems (EMS). In particular, parallel adjustment and mixed-type adjustment of coordinates are suitable as a replacement for the ‘standard setting’ of a technical optimum.

A hoist located on ground surface is a powerful nonlinear power consumer, and it generates high-order harmonics which govern electromagnetic compatibility of both surface and underground electric installations.

Problem formulation

In view of the aforesaid, the relevant scientific problem is the analysis and estimation of influence exerted by coordinate adjustment of EMS of power consumers within the surface infrastructure of coal mines (mine hoists) on generation of high-order harmonics, in particular, on the content of harmonics and on the overall current and voltage harmonic distortion factor.

Methodology

A special procedure was developed for the analysis of influence exerted by different methods of coordinate adjustment with a view to enhancing energy- and resource-saving on the level of generation of high-order harmonics. The procedure included simulation modeling in Matlab. Some simulation models of EMS of mine hoists, namely: non-continuous EMS of mine hoist; EMS of mine hoist with technical optimum settings (the most common system of electric motor drive of a mine hoist); EMS of mine hoist with parallel adjustment of coordinates; EMS of mine hoist with mixed-type adjustment of coordinates were built for the assessment of the level of harmonic generation in the power supply system as well as the harmonic spectrum.

The issues of electromagnetic compatibility in power supply systems are addressed in a number of studies though not for the specific conditions of coal mines [5–17]. The main source of harmonics in the power supply system of a coal mine is the electromechanical system (EMS) of a hoist with an electric drive representing the three-phase rectifier—dc motor configuration and a control. An EMS includes feedback coupling and regulator group which optimize operation of hoists through application of a number of constraints toward longer life of a hoist owing to extended endurance of hoisting cables. All existing feedbacks in electromechanical systems can be either direct or flexible. A direct feedback wires signal continuously, i.e. in any period of time of EMS operation, and a flexible feedback wires signal only at the run time of EMS. The standard ‘optimum setting’ of EMS of a hoist uses two direct feedback kinds: current and speed.

Advance of the electric drive systems, including mine hoists, displaced expediency of using an elastic feedback which greatly improves quality of control and resource saving in terms of one of the main elements of hoists—cables. However, for the efficient use of elastic feedback, it is necessary to review the new systems of control over mine hoists by means of coordinate adjustment: parallel adjustment and mixed-type adjustment of coordinates. Synthesis and analysis of using such EMS in mine hoists is described in the studies [18, 19].

Test program, procedure and facilities

The aim of the study is to analyze how adjustment of coordinates of electromechanical systems within electrical consumers of surface infrastructure of coal mines influence generation of high-order harmonics.

Test program:

Stage I—Analysis of electromechanical system of mine hoist;

Stage II—Development of simulation model for electromechanical system of mine hoist;

Stage III—Simulation modeling of electromechanical system of mine hoist in terms of generation of high-order harmonics;

Stage IV—Assessment of adequacy of simulation model;

Stage V—Analysis of simulation modeling results;

Stage VI—Summary on influence exerted by adjustment of coordinates of electromechanical systems within electrical consumers of surface infrastructure of coal mines on generation of high-order harmonics.

The list of criteria selected to assess the influence exerted by adjustment of coordinates of electromechanical systems within electrical consumers of surface infrastructure of coal mines includes:

- The total harmonic distortion of voltage;
- The total harmonic distortion of current;
- Spectrum plot of THD(U) (Nyquist stability criterion);
- Spectrum plot of THD(I) (Nyquist stability criterion).

The test procedure of the analysis of influence exerted by adjustment of coordinates of electromechanical systems within electrical consumers of surface infrastructure of coal mines embraces all stages of the Test Program above, namely: building of simulation models of EMS of mine hoists in Matlab; simulation modeling of different operating regimes; estimation of modeling results by the goodness of fit between a simulation model and a real hoist; analysis of the results using the above listed criteria. After the analysis of the simulation modeling results, a summary and the main conclusion are prepared on applicability of the results and on possible areas of further research in this sphere of scientific interests.

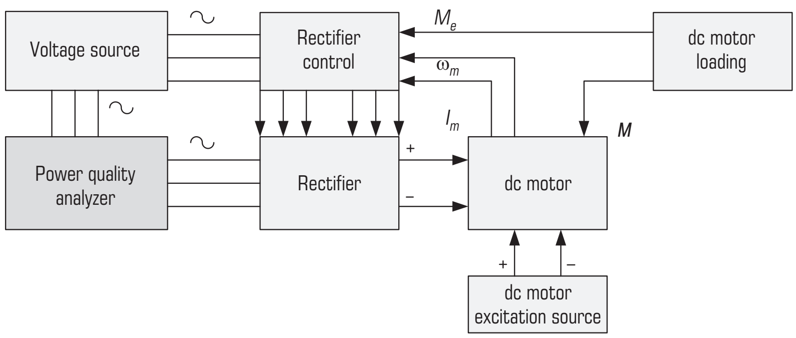

Fig. 1. Functional chain of EMS of mine hoist to analyze generation of harmonics at different adjustment of coordinates:
M_e – elastic moment of EMS; ω_m – motor armature velocity of rotation; I_m – motor current; M – motor moment

Implementation

Aimed at assessing generation of high-order harmonics in the power supply system of a coal mine, the simulation models of EMS of mine hoist were developed with different techniques of coordinate adjustment using the functional chain in **Fig. 1** as a basis. According to this chain, feed voltage goes to a power quality analyzer for recording of high harmonics of EMS and, then, to a controlled rectifier. Concurrently, feed voltage enters the rectifier control for the hard locking of the phase–pulse control system with the power line. The load is a dc motor with independent excitation, and the dc motor load is a three-phase system of a mine hoist with the variable rigidity cables. The control signals in the functional chain are implemented as the velocity, current and elastic moment feedbacks.

The structural circuit of the electromechanical system with parallel coordinate adjustment is shown in **Fig. 2*a*.** According to Fig. 2*a*, the signals from the ramp-function generator, as well as the signals from the current, velocity and elastic moment feedbacks come to a combiner. The control signal goes to a transfer member of the controlled rectifier (transducer) and, then, to the dc motor in the form of three links with electromotance feedback. The signal from the motor goes to the second and third phases of the mine hoist (loaded and empty hoist vessels). From the second and third phases of the mine hoist, the elastic moment signal is

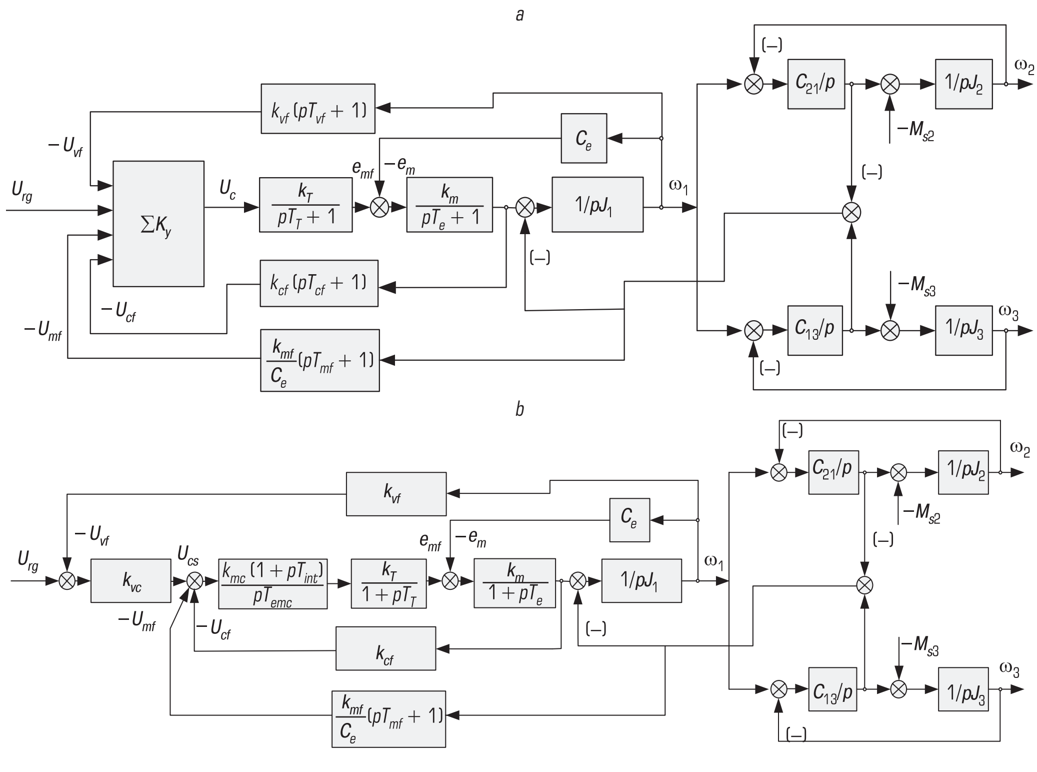

Fig. 2. Structural circuit of EMS: with parallel coordinate adjustment (*a*) and with mixed-type coordinate adjustment (*b*)
U_{rg}–voltage signal from ramp generator; U_{mf}, U_{vf}, U_{cf} – signals of elastic moment, velocity and current feedbacks, respectively; U_{cs} – current selector signal; U_c, U_{rc} – signals of control voltage and rectifier (transducer) control; e_{mf} – electromotance; e_m – motor feedback; k_m – moment gain of motor armature; T_e – electromagnetic time constant; T_T, T_{emc} – time constants of transducer and elastic moment control, respectively; k_T, k_{ca} – gains of transducer and combiner amplification; k_{cf}, k_{vf}, k_{mf} – gains of current, velocity and elastic moment feedbacks, respectively; T_{cf}, T_{vf}, T_{mf} – time constants of current, velocity and elastic moment feedbacks, respectively; J_1 – reduced inertia moment of the first phase, including inertia moments of motor, reducer, coiler and hoist pulleys; J_2 – reduced inertia moment of the second phase (loaded hoisting vessel); J_3 – reduced inertia moment of the third phase (empty hoisting vessel); ω_1 – motor spin rate; ω_2 – loaded hoisting vessel velocity reduced to motor spin rate; ω_3 – empty hoisting vessel velocity reduced to motor spin rate; M_{s2} – reduced static moment of loaded hoisting vessel; M_{s3} – reduced static moment of empty hoisting vessel; C_{21} – reduced stiffness of cable wires between coiler and loaded hoisting vessel; C_{13} – reduced stiffness of cable wires between coiler and empty hoisting vessel; e_{mf} feedback of motor; p – operator; $\sum K_y$ – control signal combiner; T_{int} – integrated time constant of elastic moment control; k_{mc}, k_{vc} – gains of elastic moment control and velocity control, respectively

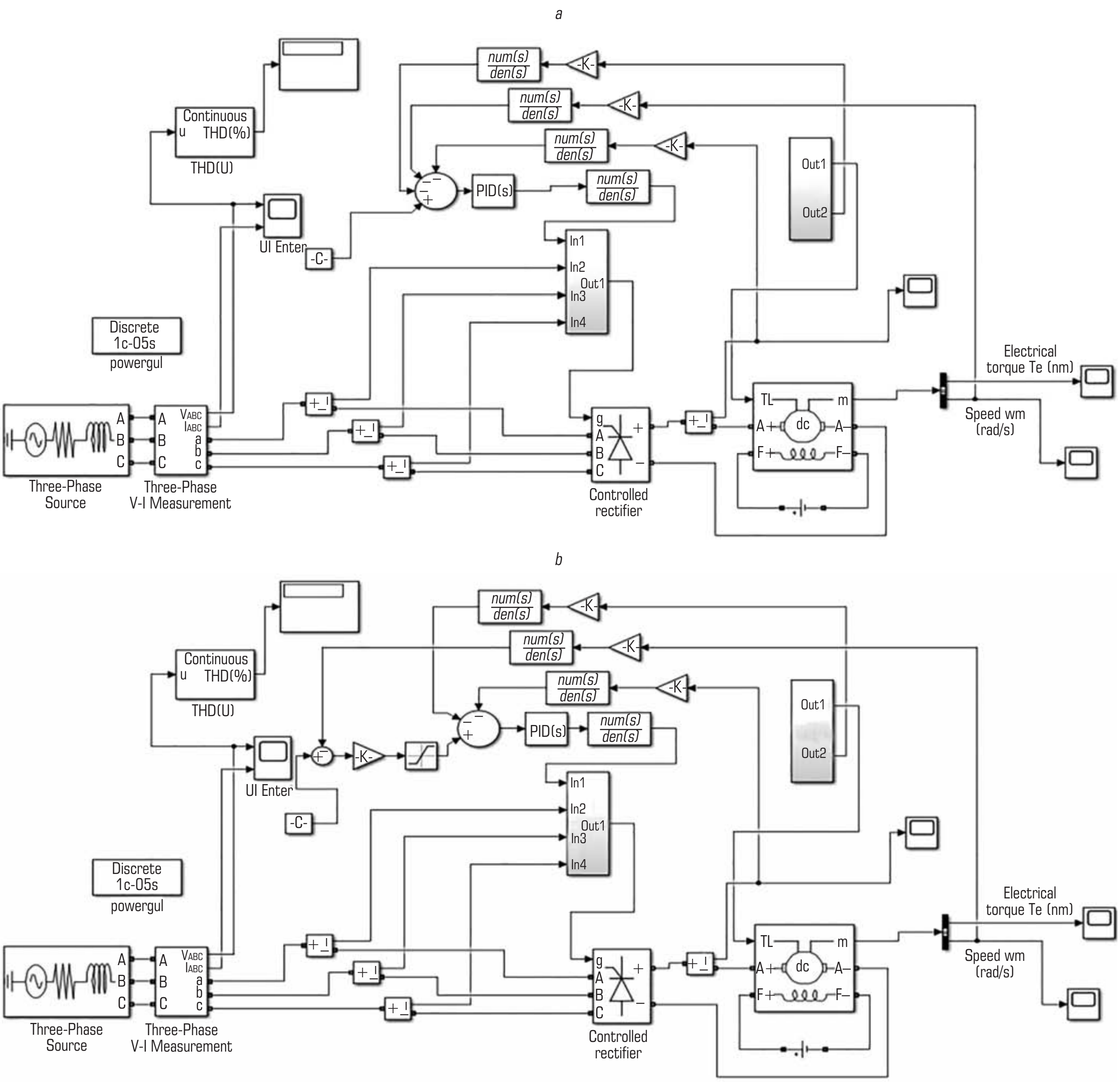

Fig. 3. Simulation model of mine hoist EMS: with parallel coordinate adjustment (*a*); with mixed-type coordinate adjustment (*b*)

picked up and sent to the phase–pulse control and, also, as the load, to the dc motor.

The structural circuit of EMS with mixed-type coordinate adjustment is shown in **Fig. 2*b***. The structural circuit includes a number of feedbacks: direct velocity feedback; this signal goes to a first combiner together with the signal from the ramp-function generator; direct current feedback, and direct and flexible elastic moment feedbacks; these signals go to a second combiner together with the signal from the velocity control. This circuit, as the previous circuit, is a three-phase circuit which enables more comprehensive evaluation of operation of an electromechanical system in the structure of a mine hoist.

According to the structural circuit of EMS of a mine hoist with the mixed-type coordinate adjustment, the signal from the ramp-function generator goes to the first combiner together with the velocity feedback signal, and the obtained velocity control signal goes to the second combiner together with the current and elastic moment feedbacks. Then, the signal goes to PID control, through the transfer member of the control rectifier (transducer) to the dc motor in the form of three links with the emf feedback. The signal from the motor goes to the second and third phases of the mine hoist (loaded and empty hoisting vessels, respectively). Using the described structural circuit, a simulation model of the mine hoist EMS with the parallel coordinate adjustment was built in Matlab (**Fig. 3*a***). The simulation model involves two subsystems: phase–pulse control of rectifier and three-phase mechanism of the mine hoist, designed and implemented earlier [20, 21].

The simulation model of the mine hoist EMS with the mixed-type coordinate adjustment in **Fig. 3*b*** also involves two subsystems: phase–pulse control of rectifier and three-phase mechanism of the mine hoist. It should be mentioned that in the simulation modeling, parameters of the motor, power source and the mine hoist mechanism remained the same in the test kinds of the coordinate adjustment in EMS.

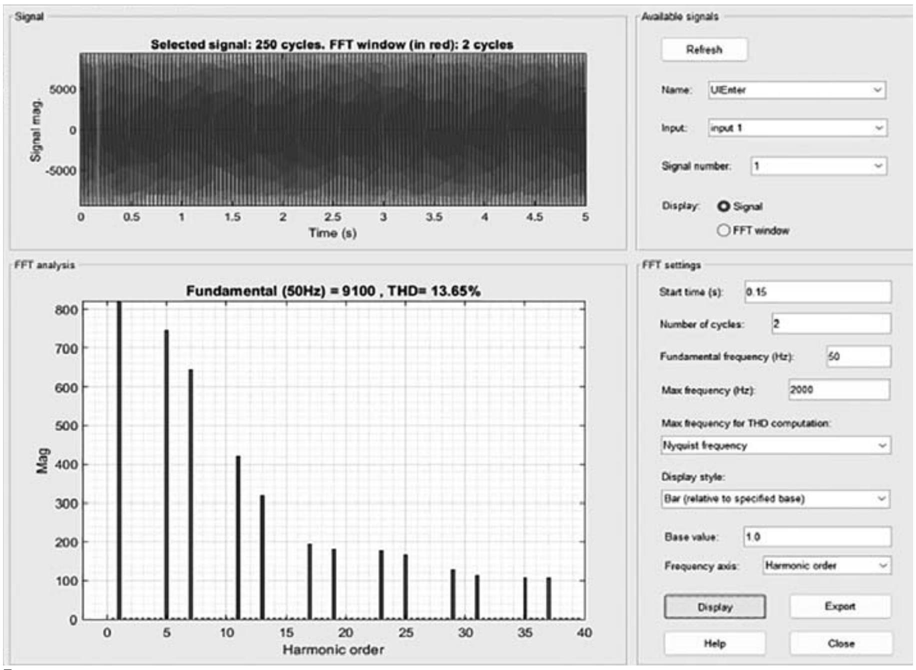

Fig. 4. THD (U) on mine hoist with mixed-type coordinate adjustment of EMS

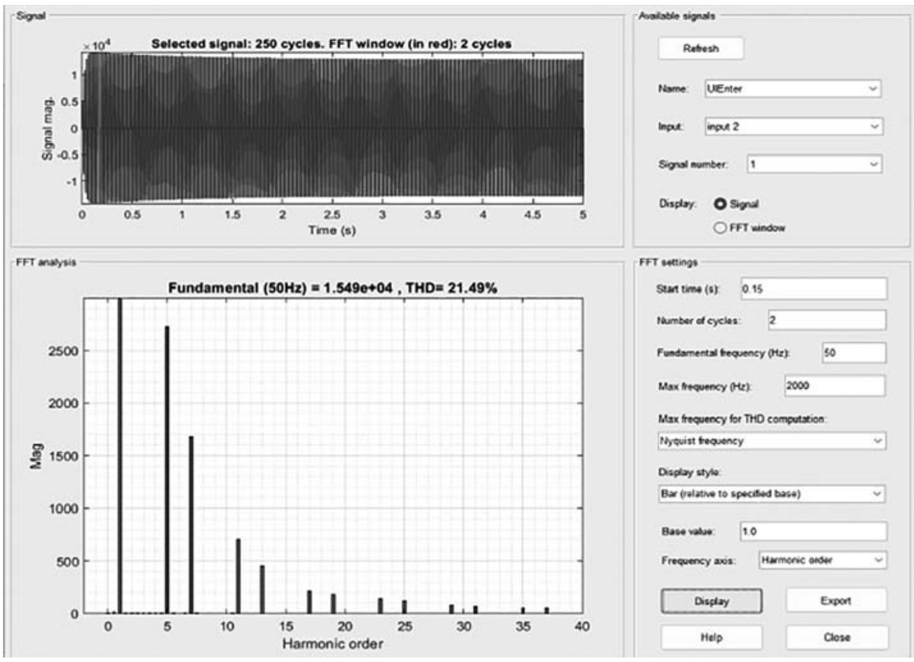

Fig. 5. THD (I) on mine hoist with mixed-type coordinate adjustment of EMS

Figures 4 and **5** depict the simulation modeling data for the three-phase EMS of the mine hoist, with the mixed-type coordinate adjustment, with a view to generation of high-order harmonics, in particular, THD(U) and THD(I). The study confirmed generation of dominant harmonics 5 and 7, as well as 11 and 13 by the control rectifier [22, 23].

Testing data processing and analysis

The analysis of the simulation modeling data determined the rates of THD(U) and THD(I) in case of the mixed-type coordinate adjustment—13.65 and 21.49%, respectively. The peak and the net values of voltage and current of the mine hoist, and the waveforms of their signals are found.

The study of the three-phase EMS of mine hoists with different coordinate adjustment and without adjustment (open-loop three-phase EMS) provided a harmonic generation pattern in **Fig. 6**.

Figure 6*a* shows the simulation modeling results for EMS of a mine hoist in case of different-type coordinate adjustment with respect to THD(U). It follows from the implemented analysis that though the guideline value of THD(U) is not more than 5% for the voltage up to 6 kV (State Standard GOST 32144-2013), the actual average THD(U) is 13.66% and remains almost unchanged (the variation range 0.22%), both at different-type coordinate adjustment and without adjustment (open-loop system).

Figure 6*b* shows the simulation modeling results for EMS of a mine hoist in case of different-type coordinate adjustment with respect to THD(I). It follows from the analysis that the actual value of THD((I) is 21.49% and remains almost unchanged (the variation range 0.09%), both at different-type coordinate adjustment and without adjustment (open-loop system).

The study of the actual values of THD(U) and THD(I) on real-life mine hoists proved high adequacy of the simulation models, not less than 0.9, which is an allowable value for engineering systems.

Conclusions

It is found that types of coordinate adjustment of EMS in the structure of a mine hoist have no influence on the level and magnitude of harmonic generation, neither in terms of THD(U) nor THD(I).

It is proved to be necessary to install harmonic filters in power supplies to damp the harmonics since the actual values of THD(U) greatly (by a factor of 2.73) exceed the guideline values. The harmonic filters can improve the power quality in specific conditions of coal mines.

The simulation models presented in the article are suitable for modeling coal mine power supply with a view to improving power quality by means of optimization of harmonic filtering parameters depending on power capacity of nonlinear electrical consumers located on mine surface (mine hoists).

The implemented research results are listed below:

1. The test procedure is developed for studying the influence exerted by the coordinate adjustment approach to EMS of coal mine hoist on harmonic generation;

2. The simulation models of EMS of mine hoists with different-type coordinate adjustment are constructed for the assessment of the level and content of harmonic generation;

3. It is proved to be necessary to include the harmonic filters in the system of power supply of coal mines for enhancing the power quality in the specific conditions of such industrial plants.

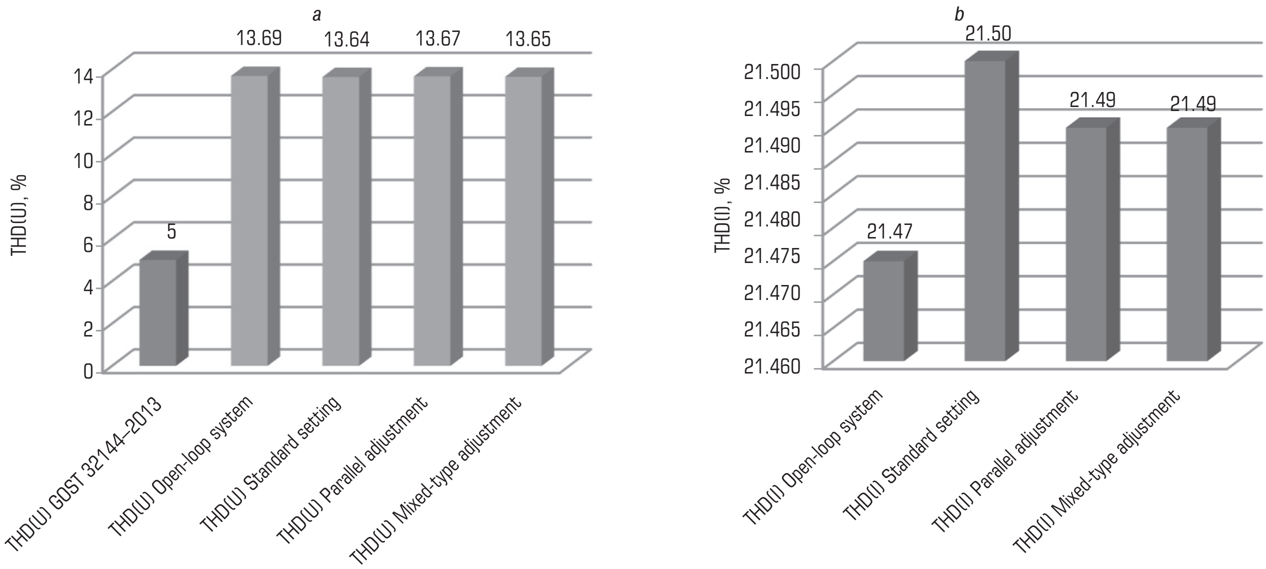

Fig. 6. Simulation modeling results for EMS of mine hoist in case of different types of coordinate adjustment: THD(U) (*a*), THD(I) (*b*)

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