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THE USE OF FREQUENCY CONVERTER AND ACTIVE RECTIFIER OF VOLTAGE FOR THE POWER QUALITY IMPROVEMENT IN COAL LONGWALLS

Improvement of productivity and performance in coal longwall mining is achievable via transition to longwalls to 250–400 m long and by increasing installed capacity of longwall equipment systems up to 4200–5600 kW. The up-to-date longwall mining uses energy- and resource-saving machines equipped with variable frequency motors. In this case, inclusion of the frequency converters in the machinery electrics results in essential distortion of voltage from the nominal sine waveform and leads to the power quality degradation in longwalls. With a view to enhancing power quality in longwall networks, the authors propose to use variable frequency motors with frequency converters with active rectifiers of voltage.

When selecting a frequency converter with the active rectifier for voltage in underground power network, it is recommended to take into account the longwall power supply specifics, the cross-effect of the frequency converters operating in neighbor lines, the variable nature of power system loads and the change in the number of the frequency converters in simultaneous operation. To that end, the power supply model is developed to study consumed power quality with regard to the power network topology, parallel-operating frequency converters and actual loads of electric motors. The modeling has determined the mechanisms of effect exerted by the frequency converters on the power quality in operation with active rectifiers of voltage. The carrier frequency and inductance of the buffer reactor of the three-level active rectifier, which ensure the standard quality power supply in longwall, are substantiated.

Keywords: *Longwall, longwall mining system, variable frequency motor, total voltage harmonics factor, voltage distortion, active rectifier of voltage, modeling*
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Introduction

Enhancement of productivity and performance in coal longwalls is achievable via transition to longwalls up to 250–400 m long and by increasing installed capacity of longwall machine system [1, 2]. For example, it is succeeded to raise the rated capacity of SL shearer–loaders to 1200–2200 kW and of scrape conveyors Anzhera 38 and PF 4/1032 up to 1600–2500 kW. Capacities of scraper loaders, crushers and pumping stations are also being increased.

Longwalls are powered by central underground substations via 6 kW cable lines to 5–8 km long. The operating experience of scraper conveyors with head and tail power units composed of 3–4 hauling blocks having capacity of 400–630 kW, with induction motor–hydraulic coupling or with two-speed induction motor shows that

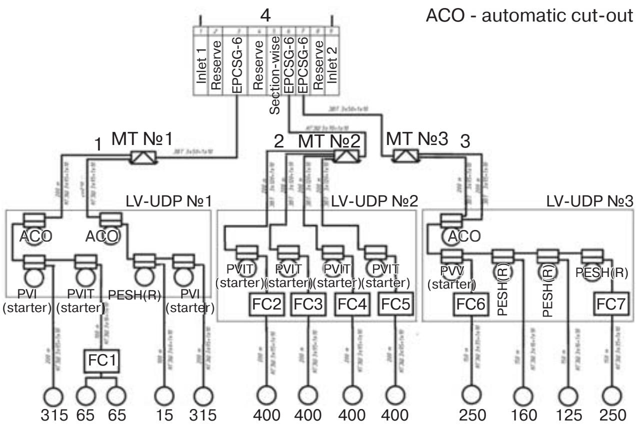

Fig. 1. Longwall power supply diagram

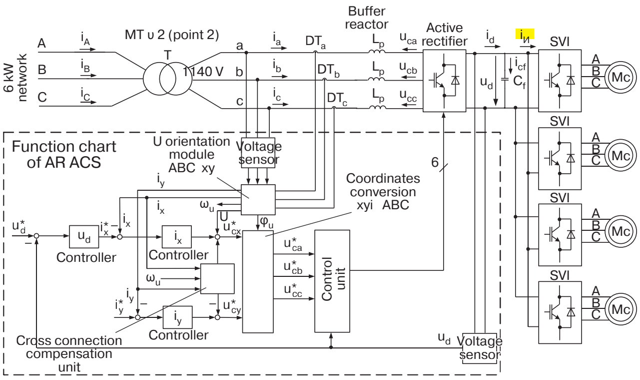

Fig. 2. Scraper conveyor electrics circuit with power supply from MT 2 2

actuation of a loaded conveyor goes with high-ampere starter currents in power network, which leads to voltage falls, frequent protection operations and shutdowns of the conveyor [3, 4]. The electric motors of the above-listed types are incapable to ensure rapid force limitation in the pulling chain in case of its seizure, or to level the loads applied to the head and tail power units in the steady-state and transitional regimes of the conveyor operation [5]. A variable-frequency induction motor (VFIM) of a scraper conveyor, with individual frequency converter for each drive, ensures smooth actuation of the motor, limitation of loads in the pulling chain in case of its seizure, and levelling of loads of the head and tail power units, and enables maintenance of continuous unit load on the scraper conveyor by means of the scraper chain velocity adjustment in case of a varied-size coal flow from the conveyor during its cycle operation [6, 7]. The system of maintenance of constant unit load on the scarper conveyor, scraper loader and main belt conveyors improves energy efficiency of the whole longwall mining equipment system [7]. Variable frequency drives also operate at pumping stations in longwalls to ensure saving of power in operation of the longwall mining equipment [8, 9].

On the other hand, frequency converters distort voltage from its sine waveform in power networks [10–12]. The cause of that is generation of higher harmonics by the frequency converters. The voltage since waveform distortion in the power network leads to increased power loss and reduces service life of electric equipment because of extra aging of insulation, worse instrument accuracy and deficient automation and communication operation [13].

For another thing, the increase in capacity of electric drives leads to higher distortions and fluctuations of voltage in network. Voltage distortion worsens performance of process equipment, induction motors, illumination sources and other electric systems [13]. Heavy voltage distortions initiate protection relay actuation and disengagement of electric equipment. As a consequence, the production process is broken, the action time is lost and the coal production output drops [14].

The estimate of the variable frequency motor influence on the power quality in the underground network in compliance with the Russian State Standard GOST 32144-2013 Electric Power. Power Quality Standards in General-Purpose Power Supply System uses such power quality factors (PQF) as the total voltage harmonics factor and the voltage distortion [15]. GOST 32144-2013 sets the allowable total factor of voltage harmonics as 8% on the side of 1140 V and 5% on the side of 6 kV, and the allowable voltage distortion in power supply is 10%.

Power quality analysis

The power quality estimate in underground power networks with VFIM is to account for: specifics of the power supply of underground users; cross-effect of frequency converters in neighbor lines; variability and mutual influence of loads on equipment; change in the number of frequency converters in simultaneous operation.

In this regard, it is required to model power supply system including the power network topology, concurrent frequency converters and actual loads of motors. Such model can assist the analysis to find out how the frequency converters affect the power quality and if the actual values agree with the standard, and, based on the findings, to make a decision on suppression of higher harmonics. The model uses the standard power supply diagram in use in longwall 19 in Kostromovskaya mine of MMM-Coal LLC (**Fig. 1**) [3, 16].

6 V power supplied from a central power station is distributed between substations by high-voltage explosion-proof cellular type switch gear (EPCSG-6). Equipment in the longwall is fed by three mobile transformers (MT).

MT 1 supplies JOY 4LS20 shearer with induction motors: two cutting motors with capacity of 2×315 kW, two advance motors with capacity of 2×65 kW and one pump motor with capacity of 15 kW. The advance motors are supplied by one frequency converter FC1 mounted on the shearer, nearby the motors.

MT 2 feeds Anzhera-34 scraper conveyor having the head and tail power units each including two hauling blocks with induction motors having capacity of 400 kW. Each motor of the conveyor is supplied using FC2…FC5 arranged at low-voltage underground distribution point LV-UDP 2.

MT 3 powers a loader, a crusher, a sprinkling pump and an oil pump with induction motors having capacities of 250 kW, 160 kW, 125 kW and 250 kW, respectively. The drives of the loader and oil pump are supplied from FC6 and FC7, respectively, arranged at LV-UDP 3.

In all cases, the frequency converter uses a six pulse rectifier.

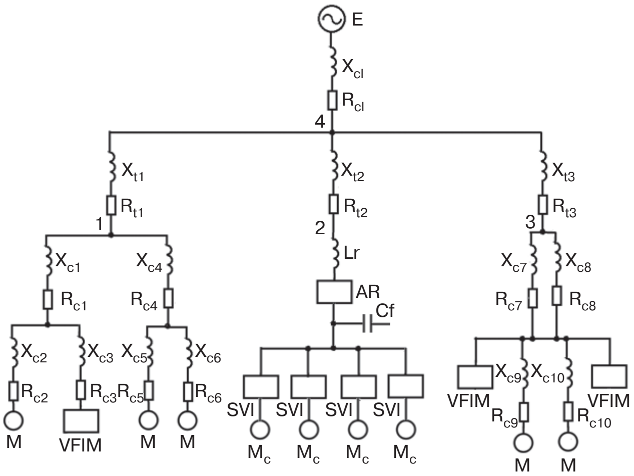

Fig. 3. Equivalent power network with AR for longwall supply

Using the model, the power quality is quantitatively analyzed at MT 1, 2 and 3 1140 V outlets (points 1, 2 and 3) and at EPCSG 6 V inlet (point 4) [16]. It is found that with higher capacity of variable frequency motors of scraper conveyor and with longer 6 kV power line, higher voltage distortions are observed at the listed points. The highest distortions take place at MT 2 1140 V outlets (point 2) which supply the scraper conveyor. With increasing capacity of the variable frequency motors of the scraper conveyor, the distortions increase in neighbor lines 1 and 3. In all analyzed cases, with the increasing load and length of 6 kV power line, the total factors of voltage harmonics increase and overrun standard values. At EPCSG 6V inlet at point 4, the voltage distortion δU_4 was determined. With the increasing load of the scraper conveyor and with the longer 6 kV line, the voltage distortion grows and may exceed the standard of 10%.

One of the recently promising way of improving power quality (PQ) in operation of AC VFIM is including an active rectifier (AR) in a frequency converter (FC) [17–20]. AR-assisted FC is an effective tool of the power quality improvement and power saving for mechanisms and machines with VFIM. Active rectifiers enable two-way power exchange with the power network, which improves the motor performance, ensures almost sine-wave current and allows smooth adjustment of power factor. For this reason, AR find increasingly wide application in various size and class mining equipment, for example, excavators and mine hoists.

Let us determine how the frequency converters influence the power quality in coal longwall with AR in use.

The highest distortion of voltage in the network appear at point 2 at MT 2 1140 V outlet (see Fig. 1) which supplies the scarper conveyor [16]. Thus, to improve power quality in coal longwall, it is suggested to add the scraper conveyor VFIM with a three-level active rectifier with the pulse width modulation (PWM).

Figure 2 shows the scraper conveyor power supply circuit with VFIM supplied by MT 2 (point 2 in Fig. 1). The DC link in FC is AR.

The scraper conveyor electrics circuit includes an active rectifier fed by a reducing transformer (T) at MT 2 via buffer reactor Lr, a capacitor (Cf) and self-excited voltage inverters

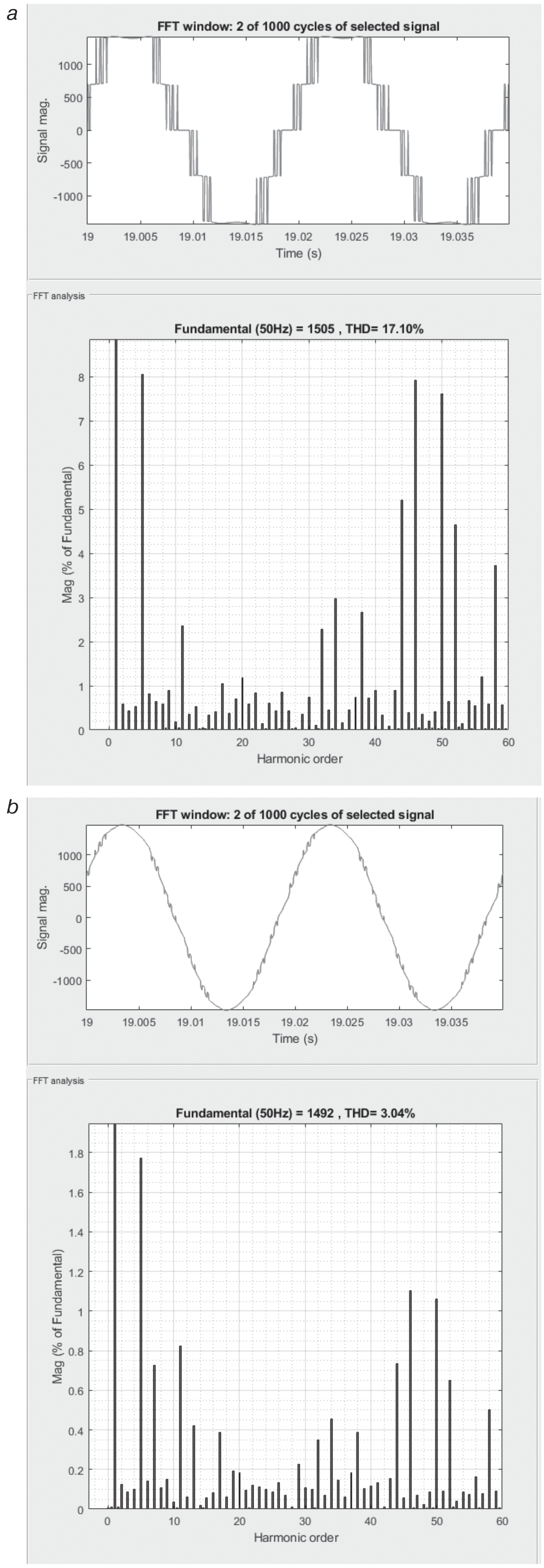

Fig. 4. Voltage and its harmonics at *a* — inlet of AR and *b* — 6 kV inlet of MT 2

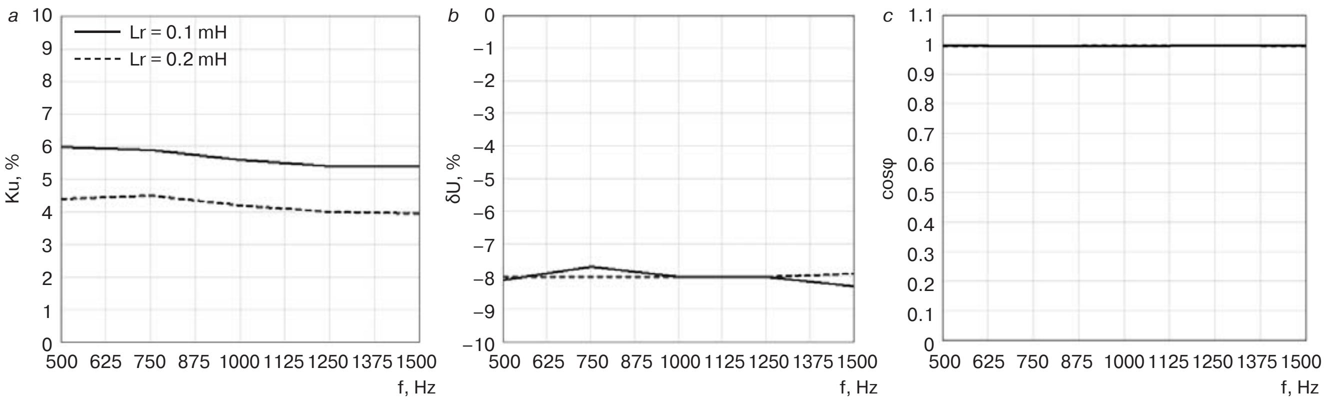

Fig. 5. Total factor of voltage harmonics (*a*), voltage distortion δU (*b*) and power factor cosφ at 6 kV inlet of MT 2 (*c*) as function of carrier frequency of PWM

(SVI) supplied from common DC buses and transferring energy to the scraper conveyor induction motors.

Figure 2 also shows the function chart of the automatic control system (ACS) of AR [21]. It is based on vector ACS proposed in [22, 23].

ACS is implemented in the synchronous orthogonal coordinates (x, y) oriented in line of the voltage vector $\overline{U}$ of the power network, which enables independent control over the active i_x and reactive i_y constituents of the rectifier input current vector $\overline{I}$ [22].

The vector ACS contains a one-loop ACS of the reactive current i_y and a two-loop ACS of the rectified voltage U_d with the internal loop represented by the control loop of the active current constituent i_x.

The discriminants of the preset (i_x^*, i_y^*) and actual (i_x, i_y) values of converted currents come to the inlets of current controllers. The outlet current controller signals, being compensated, come to the inlets of the control voltage vector coordinate converter xy→ABC. After conversion of coordinates, the control inputs u_{ca}^*, u_{cb}^* and u_{cc}^* are generated and fed to the AR control block.

The converter power factor is controlled via setting the reactive constituent i_y^* of input current.

The control inputs are u_{cx}^* and u_{cy}^*, and the disturbance inputs are the load current i_l and the supply voltage vector components u_x and u_y. The controllable values are the voltage u_d at the active rectifier outlet and the mains current components i_x and i_y [23]. The structure of AR includes cross connections and the internal feed-back via the rectified voltage u_d [22, 23].

The synthesis of the vector AR ACS includes compensation of the effects of cross connections, internal feed-back via the rectified voltage u_d and the perturbation effect via the mains voltage U. This enables the vector AR ACS synthesis based on the subordinate control of coordinates [22, 23].

The transfer functions of the current controllers i_y and i_x and the rectified voltage controller u_d are the proportional integral controls (PI controls) [22].

Let us find out how the frequency converters influence the power quality in coal longwall supply with AR.

The equivalent power network of longwall, which is used as the basis of the model of power quality given AR is shown in **Fig. 3**.

All elements in the equivalent network are reduced to the voltage of 1040 V. The adopted legend includes: X_{cl6}, R_{cl6}—the induced and active resistances of 6 kV cable lines, respectively; X_{t1}... X_{t3} , R_{t1}... R_{t3}—the induced and active resistances of the transformers at MT 1... MT 3; X_{c1}... X_{c10} , R_{c1}... R_{c10}—the induced and active resistances of 1040 V cable lines.

Nodes 1, 2, 3 and 4 (see Fig. 3) stand for 1140 V outlets at MT 1, MT 3 and MT 3, and 6 kV inlet at EPCSG-6 (see Fig. 2).

The variable frequency induction motors without AR are modeled as VFIM blocks. The invariable velocity motors are modeled as blocks M.

The scraper conveyor motor model includes the buffer reactor Lr and the three-level AR block which bus-feeds the blocks of inverters I which transfer energy to the conveyor induction motors Mc. Between AR and I, in accordance with the scraper conveyor electrics circuit (see Fig. 2), the capacitor Cf is included.

The developed model makes it possible to calculate the total voltage harmonics factor K_U and voltage distortion δU in the nodes of longwall power network. We have chosen such node to be 6 kV inlet at EPCSG-6. This is point 4 in Figs. 1 and 2.

For evaluating the total voltage harmonics factor K_U and voltage distortion δU at point 4 in the model, the tests were carried out in the heaviest operating regime in terms of the power quality. Such regime fits the scraper conveyor operation capacity P_{sc} = 2000 kW (5 variable frequency motors each having capacity of 400 kW, the longwall length is 400 m) when the 6 kV cable line length L_6 to connect EPCSG-6 and the central power station is 8 km, which is the maximum length.

In the studies of influence of the frequency converters on the power quality with the use of AR included variation of commutation frequency of semiconductor switches and variation of the buffer reactor inductance in AR.

The results are depicted in **Figs. 4** and **5**.

Figure 4a presents the voltage waveform and its spectrum at the inlet of AR. Figure 4b shows the voltage waveform and spectrum at 6 kV inlet of MT 2 (see point 2 in Fig. 1). The comparison of Figs. 4a and 4b shows that the buffer reactor and transformer reduce essentially the higher harmonics in the voltage spectrum at 6 kV inlet, which allows obtaining the sine-similar waveform of the voltage signal.

Figure 5 offers the graphs of the total factor of voltage harmonics, voltage distortion δU and the first harmonic power factor cosφ at 6 kV inlet of MT 2 as function of the carrier frequency of PWM at the buffer reactor inductances Lr = 0.1 mH and Lr = 0.2 mH.

The analysis of the obtained relationships allows drawing some conclusions below:

1. With the increasing carrier frequency of PWM from 500 to 1500 Hz, the total factor of voltage harmonics at 6 kV inlet of MT 2 decreases.

2. With the increasing buffer reactor inductance Lr from 0.1 to 0.2 mH, the total factor of voltage harmonics at 6 kV inlet of MT 2 decreases, and at 0.2 mH it is not higher than the standard value of 5%.

3. When both the carrier frequency of PWM increases from 500 to 1500 Hz and the buffer reactor inductance Lr grows from 0.1 to 0.2 mH, the voltage deviation remains unaltered and is not higher than the standard value of 10%.

4. At the carrier frequency of PWM within the range from 500 to 1500 Hz and the buffer reactor inductance Lr in the range from 0.1 to 0.2 mH, the voltage rectifier ensures maintenance of the network power factor at the level of 1.

Finally, the use of three-level AR of voltage with sinusoidal PWM in the variable frequency motor of scraper conveyors is an effective tool of improvement of power quality in coal longwalls.

Conclusions

1. The computer model of a standard power supply network for longwall, with regard to the mine mains topology, parallel-operating frequency converters and real-time loads of electric motors, has been developed. The mathematical model enables power quality analysis, power supply diagram substantiation and selection of a voltage rectifier for the longwall power network at the stage of design.

2. The modeling has quantitatively shown that the use of the three-level active rectifier of voltage with sinusoidal PWM in the variable frequency motor of scraper conveyors is an effective tool of improvement of power quality in coal longwalls. For example, with AR, the total voltage harmonics factor K_{U4} and the voltage distortion δU_4 are not higher than the standard values. The power factor at 6 kV inlet of MT 2 equals 1.

3. Based on the accomplished research, it is recommended to select the carrier frequency of sinusoidal PWM of three-level AR in the range from 500 to 1500 Hz and the inductance of the buffer reactor of AR in the range from 0.1 to 0.2 H.

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