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Assessing the efficiency of measures to enhance electric power quality in variable-frequency drive for scraper conveyors

V. L. Petrov, **A. V. Pichuev** ✉
University of Science and Technology MISIS, Moscow, Russian Federation
✉ *allexstone@mail.ru*

Abstract

The intensive implementation of variable-frequency drive machines and installations in underground mining processes necessitates addressing several issues, with a primary focus on ensuring the quality of electric power. Elevating the energy resource of mining machines and enhancing the energy efficiency of mining operations requires maintaining the rated indicators of electric power quality in mine power distribution systems. Achieving this involves assessing the level and composition of higher harmonic components in voltage and current within power circuits equipped with variable-frequency drives (VFD). Key objectives encompass the development of a simulation model based on the equivalent diagram of the power distribution system substitution with a scraper conveyor VFD to scrutinize the spectral composition of higher harmonic components in the power circuits of the mine power distribution system (MPDS). Additionally, the study involves analyzing the impact of harmonic filters (HFs), reactors, and sine filters on the quality of electric power in the VFD system of a scraper conveyor. Further analysis extends to the spectral composition of higher harmonic components in circuits related to insulation leakage and metering circuits of the residual-current device. Practical recommendations for improving electric power quality in the VFD system of a scraper conveyor are then developed based on the research findings. The established model of a variable-frequency drive system for scraper conveyors facilitates the assessment of the effectiveness of electric power quality improvement measures. The harmonic composition of voltage and current in the mine power distribution system is determined under maximum distortion conditions and in the presence of HFs, reactors, and sine filters. Research methods are chosen to unveil the spectral composition of voltage and current in symmetrical and single-phase modes of insulation leakage, as well as in metering circuits of residual-current devices (RCDs). It is noted that the harmonic composition of leakage voltage and current is primarily influenced by the parameters of the output voltage modulated by the autonomous frequency converter inverter. Considering the high level of harmonic components in voltage and current, adjustments to RCD settings, capacitive current compensator, and the protective shunting unit are recommended for electrical safety. The study emphasizes the importance of scientifically substantiating the rated indicators of higher harmonic components for leakage circuits and further exploring the physiological effects of higher current harmonics on the human body. The feasibility of installing a harmonic filter (HF) directly on the low-voltage supply section of a scraper conveyor should be technically justified. Interestingly, the presence of HFs, reactors, and sine filters does not significantly impact the harmonic composition or the magnitudes of coefficients of the harmonic components in the phase voltage of the system concerning ground and leakage currents through insulation. However, higher harmonic components induced in leakage current circuits may pose a potential hazard, leading to a violation of magnetic compatibility and posing risks in case of contact with live parts of electrical equipment.

Keywords

underground mining operations, mine power distribution system, electric power quality, electrical safety, scraper conveyor electric drive, filter-compensating device, sine filter, residual-current device, power distribution system insulation

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ЭНЕРГЕТИКА, АВТОМАТИЗАЦИЯ И ЭНЕРГОЭФФЕКТИВНОСТЬ

Научная статья

Оценка эффективности средств повышения качества электроэнергии в системе частотно-регулируемого электропривода скребковых конвейеров

В. Л. Петров, **А. В. Пичуев** ✉
Университет науки и технологий МИСИС, г. Москва, Российская Федерация
✉ *allexstone@mail.ru*

Аннотация

Интенсивное внедрение частотно-регулируемых электроприводов машин и установок в технологических процессах при подземной добыче полезных ископаемых предусматривает необходимость решения ряда проблем, одной из которых является обеспечение качества электроэнергии. Именно поэтому повышение энергоресурса горных машин и энергоэффективности ведения горных работ требует обеспечения нормативных показателей качества электроэнергии в подземных комбинированных электрических сетях (ПКЭС). Это возможно на основе оценки уровня и состава высших гармонических составляющих напряжения и тока в силовых цепях с частотно-регулируемым электроприводом (ЧРЭП). Основными задачами являются: разработка на основе эквивалентной схемы замещения электрической сети с ЧРЭП скребкового конвейера имитационной модели для исследования спектрального состава высших гармонических составляющих напряжения и тока в силовых цепях ПКЭС; исследование и анализ влияния фильтро-компенсирующих устройств (ФКУ), реакторов и синус-фильтров на качество электроэнергии в системе с ЧРЭП скребкового конвейера; анализ спектрального состава высших гармонических составляющих напряжения и тока в цепях утечки через изоляцию и цепи измерителя устройства защитного отключения; разработка практических рекомендаций в области повышения качества электроэнергии в системе с ЧРЭП скребкового конвейера. Разработанная модель системы частотно-регулируемого электропривода скребковых конвейеров позволила провести исследования эффективности средств повышения качества электроэнергии. Определен гармонический состав напряжения и тока в подземной комбинированной электрической сети в режиме максимального искажения и при наличии ФКУ, реакторов и синус-фильтров. Выбранные методы исследований позволили выявить спектральный состав напряжения и тока в симметричном и однофазном режимах утечки через изоляцию, а также в измерительных цепях устройств защитного отключения (УЗО). Установлено, что гармонический состав напряжения и тока утечки в основном определяется параметрами выходного напряжения, модулируемого автономным инвертором преобразователя частоты. Высокий уровень гармонических составляющих напряжения и тока необходимо учитывать при определении уставок УЗО, настройке компенсатора емкостного тока и блока защитного шунтирования. Для обеспечения электробезопасности необходимо научное обоснование нормативных показателей высших гармонических составляющих напряжения для цепей утечки и дальнейшее исследование физиологического воздействия высших гармоник тока на организм человека. Целесообразность установки ФКУ непосредственно на низковольтном участке питания скребкового конвейера должна быть технически обоснована. Наличие ФКУ, реакторов и синус-фильтров практически не оказывает влияния как на гармонический состав, так и на величину коэффициентов гармонических составляющих фазного напряжения сети относительно земли и токов утечки через изоляцию. Наличие наводимых в цепях утечки тока высших гармонических составляющих в симметричном режиме и режиме однофазной утечки тока может привести к нарушению магнитной совместимости при работе электронной измерительной схемы, блока питания и компенсатора емкостного тока утечки УЗО и представлять потенциальную опасность в случае прикосновения к токоведущим частям электрооборудования.

Ключевые слова

подземные горные работы, подземная электрическая сеть, качество электроэнергии, электробезопасность, электропривод скребкового конвейера, фильтро-компенсирующее устройство, синус-фильтр, устройство защитного отключения, изоляция электрической сети

Для цитирования

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Introduction

Currently, modern mines are actively adopting an advanced system of asynchronous variable-frequency drive (VFD) for heavy-duty stoping machines. This system enables the control of electric motor speed both during start-up and directly during mining operations. As a result, the structure of the mine power distribution system has been upgraded, giving rise to sections with direct current and variable-frequency current, collectively referred to as mine power distribution systems (MPDS).

These systems incorporate the use of asynchronous VFD for scraper conveyors based on frequency converters with an autonomous voltage inverter (FC with AVI) and pulse-length modulation (PLM).

Implementing a scraper conveyor VFD with frequency converters offers benefits such as smooth start-up, load limitation in a tow chain during jamming, equalization of loads between head and tail drives, and the ability to maintain a constant linear load of a scraper conveyor by regulating the speed of the scraper chain with varying coal inflow from a combine during its cyclic operation [1–3]. In MPDS, a frequency converter with a straight rectifier and autonomous voltage inverter is primarily employed to control the electric drive.

To enhance the energy efficiency of mining operations and the energy resource of mining machines, it is crucial to ensure the rated indicators of electric power quality in MPDS. This involves evaluating the level and composition of higher harmonic components (HHC) of voltage and current in power circuits with [4].

Scientific studies indicate that the level and composition of HHC depend significantly on factors such as the length of the supply line, the power of frequency converters (FC), the load of induction motors, and the presence of FCs at adjacent sections [5–8].

In the section-related power distribution system with a voltage of up to 1140 V, which powers the electric drive of a scraper conveyor, the total coefficients of harmonic components of voltage (K_U%) increase from 8.2% to 15.8% when the length of the 6 kV cable line supplying the section is increased from 3 to 6 km, and the total installed power of induction motors is increased from 1200 to 2000 kW, in the absence of harmonic filters (HF). This exceeds the rated values not only directly at the load node (K_{Urat} = 8%) but also at adjacent sections (K_{Urat} = 5%). The application of HFs in the first compensation stage helps reduce the level of voltage HHC to 5.14–7.6% [9].

A method to enhance electric power quality involves installing sine filters (SF) downstream from the frequency converter, enabling the filtration of voltage modulated by the frequency converter at the motor terminals[1] [10]. However, the current limitations in terms of design complexity and the challenges of parameter selection and adjustment for SF make it challenging to assess its efficiency in mine power distribution systems, rendering the analysis primarily theoretical.

An essential aspect is the examination of the harmonic composition of voltage and current leakage through insulation circuits in the power distribution system, as well as in metering circuits of residual-current devices (RCD). The prevailing trend in the advancement of leakage current protection involves the incorporation of microprocessor-based devices in electronic power supply units. This includes insulation control, automatic compensation control, and protective shunting to ensure self-check, fault diagnostics, and telemetry of data regarding the state of protection complexes. When operating in MPDS conditions, the issue of magnetic compatibility needs to be addressed [11]. Scientific studies in this domain reveal that HHC can significantly impact the efficiency of RCDs and the safety level of the power distribution system[2] [12, 13].

Hence, researching the impact of electric power quality on the effectiveness of variable-frequency drives for stoping machines in the mine power distribution systems of mining enterprises is a pertinent scientific problem.

The primary methodology employed in this study is mathematical simulation, providing a means to discern new scientific insights and the practical significance of these findings.

Purpose and objectives

The primary aim of this study is to assess the effectiveness of measures aimed at enhancing electric power quality in the control system of VFD for scraper conveyors within the MPDS of mining enterprises.

The primary objectives are as following.

1. Develop a simulation model based on the equivalent substitution diagram of the power distribution system, incorporating a VFD for a scraper conveyor.

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[1] EPCOS. Power Factor Correction. Power Quality Solutions. Product Profile 2009. URL: http://biakom.com/hfuhf/production/passive/EPCOS/PFC_Katalog2009.pdf

Danfoss. Output Filters Design Guide. URL: www.danfoss.com/NR/rdonlyres/27F81E1-3779-4406-8EA0-849044873F59/0/Output_Filters_Design_Guide.pdf

LC Sine Wave Filter for Motor Drives. Output Filters FN5040/FN5045. Schaffner. URL: http://www.schaffner.com/en/products/datasheet-low-res/product/fn-5040-fn-5045-lc-sine-wavefilter-for-motor-drives.html

[2] O'shea P. Counteracting high leakage currents. URL: https://www.powerelectronicsnews.com/counteracting-high-leakage-currents/

This model aims to investigate the spectral composition of the higher harmonic components of voltage and current in the power circuits of the mine power distribution systems (MPDS).

2. Conduct research and analysis on the impact of HFs, reactors, and sine filters on the electric power quality within the VFD system of a scraper conveyor.

3. Analyze the spectral composition of the voltage and current higher harmonic components in the insulation leakage current circuits and circuits of the residual-current device metering unit.

4. Formulate recommendations for improving electric power quality in the VFD system of a scraper conveyor.

Simulation model structure

The structure of the mine power distribution system for the electric motors of a scraper conveyor comprises various components. These include a site-specific substation's power transformer (TSVP) equipped with a built-in circuit breaker (AVDO) and a leakage current protection device (RCD) of the AZUR type. Additionally, there is a group of magnetic starters belonging to the PVIT series, and explosion-proof frequency converters situated in the power train. These converters are strategically placed at maximum proximity to the longwall face, maintaining a distance of not less than 50 meters from the face junction with an air drift. The length of the supply cable (CL) extending from the frequency converter to the conveyor's remote motors is determined by the longwall face length, which typically ranges from 400 to 600 meters.

Fig. 1 depicts the equivalent substitution diagram of the MPDS designed to power a scraper conveyor.

In the section with the industrial-frequency voltage, the active resistance of the system insulation relative to the ground is assumed to be $R_I \geq 300$ kΩ/phase, and the capacitance is $C_I \approx 0$. Considering the substantial length of the MPDS section with variable frequency, the active insulation resistance R_{IA}, R_{IB}, R_{IC} is accepted within the range from 31.5 to 300 kΩ/phase, and the capacitance C_{IA}, C_{IB}, C_{IC} is taken from 0.01 to 1 μF/phase. A single-phase leakage circuit was simulated with an active resistance R_y = 1 kΩ, equivalent to the resistance of a human body. The parameters of the RCD, including the connection to the power distribution system filter (R_{FI}, L_{FI}), the metering circuit (R_0, R_{PN}, L_{PN}) with the operational rectified current source $e_=$, and the parameters of the capacitive leakage current compensator (connection filter R_0, compensator R_g, L_g, shunting capacitance C_{sh}), were determined based on AZUR characteristics [14].

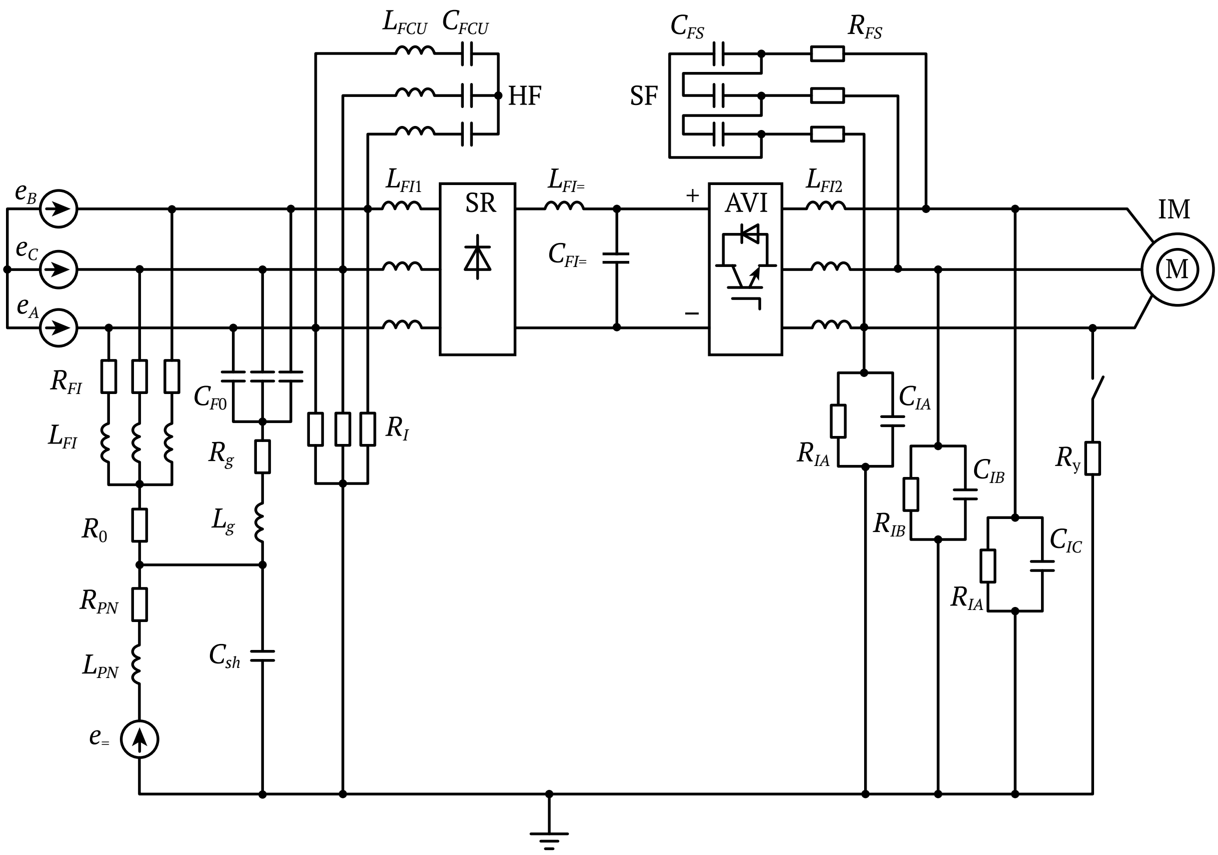

Fig. 1. Equivalent substitution diagram for the MPDS

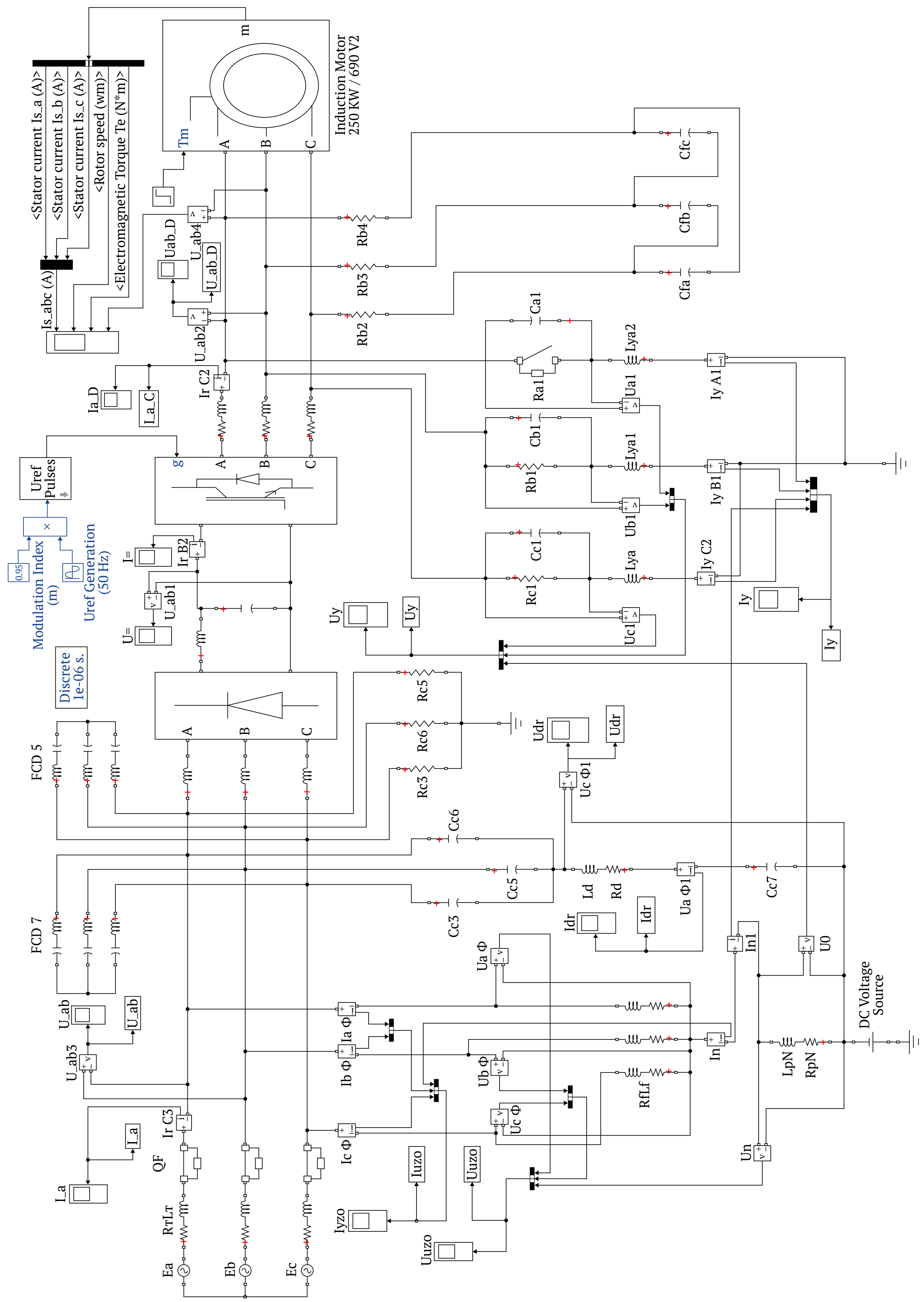

Fig. 2. Simulation model for the MPDS

The drive motors for the scraper conveyor consist of two to four induction motors of SG3-450L-8/4 type, ranging in power from 110 to 400 kW. In the equivalent diagram, an electric motor with a power of 250 kW is assumed in accordance with equivalence rules [15, 16], and its parameters have been calculated following practical recommendations [17]. A frequency converter from WANTAI is used as an equivalent power source for the drive motor. The parameters of throttles L_{FI1}, filter-compensating devices L_{FCU}, C_{FCU}, and sine filters L_{FI2}, L_{FS}, R_{FS} were determined based on Practical tips for selecting output filters[3]. The PD-SIN-0.5-300 sine filter was used as a prototype.

Fig. 2 illustrates the simulation model of the MPDS with a phase voltage U_F = 660 V. This model is equipped with an RCD featuring an R-L filter, a capacitive leakage current compensator, HFs, reactors, and a sine filter. Additionally, it incorporates insulation parameters at both the industrial and regulated frequency sections.

Table 1 provides a summary of the harmonic coefficients of voltage and current components in the power circuit of the MPDS at sections upstream and downstream of the FC.

The analysis of the spectral composition of the voltage and current higher harmonic components in the power circuit of the MPDS revealed the following.

The level of HHC, without considering the parameters of the external power distribution system (from the power source to the PUPP transformer), remains within permissible values according to GOST[4]. The 5th and 7th harmonic components of voltage emerge as the most significant.

Introducing reactors and HFs at the section upstream of the frequency converter, tuned to the 5th and 7th harmonics, proves effective in reducing the total coefficient of harmonic components of voltage K_U% from 2.81 to 0.51%. The most substantial impact is observed in a significant reduction of the total coefficient of current harmonic components K_I% from 80.45 to 5.63%. Simultaneously, the HHC indicators of current and voltage at the section downstream of the frequency converter remain practically unchanged ($K_U\% \approx 1{,}36\%$, $K_I\% \approx 0{,}3\%$).

Table 1

Total coefficients of harmonic components in voltage and current

MPDS structure	Upstream of FC with AVI		Downstream of FC with AVI	
	K_U%	K_I%	K_U%	K_I%
Without compensation means	2.81/2.77	80.45/80.89	2.81/1.35	0.29/0.28
Reactors	2.20/2.19	64.67/65.49	1.39/1.39	0.30/0.29
Reactors, SF	5.68/5.67	26.25/26.26	1.77/1.77	0.25/0.26
Reactors, HF-5	1.31/1.25	21.00/19.30	1.36/1.36	0.30/0.26
Reactors, HF-5, HF-7	0.51/0.31	5.63/3.46	1.35/1.35	0.29/0.28
Reactors, HF-5, HF-7, SF	0.40/0.37	1.89/1.08	1.69/1.69	0.25/0.26

Note. Mode of insulation leakage current (symmetrical, single-phase).

The inclusion of a sine filter downstream of the frequency converter (in the absence of a HF in the diagram) results to an increase of K_U% up to 5.68 %. This elevation could be attributed to potential factors such as inaccuracies in selecting the sine filter and adjusting reactor parameters or the introduction of HHC to the external power system through circuits of current leakage in insulation. Conversely, using only a sine filter as a compensator enables a fourfold reduction in the total coefficient of harmonic current components compared to the maximum distortion level (in the absence of a HF).

The combined application of reactors, HFs and SFs allows for achieving the maximum level of compensation for voltage and current HHC. However, the rationale for their use, considering the initially low values of the total coefficient of harmonic components, should be justified by the technical necessity to ensure the quality of electric energy at the section downstream of the frequency converter.

An additional noteworthy finding from the study is that the level of HHC and their harmonic composition is practically unaffected by the mode of current leakage through insulation (symmetrical/single-phase leakage). This is attributed to the substantial difference in magnitude (3–4 orders of magnitude) between the power distribution system parameters and the insulation parameters of the current leakage circuit (secondary circuits).

Fig. 3 presents characteristic oscillograms and spectrograms of current and voltage in the circuits of leakage through insulation at the FC-IM section. This is observed in the presence of reactors and HFs tuned to the 5th and 7th harmonics within the power distribution system.

[3] Practical tips for selecting output filters. URL: https://drives.ru/stati/prakticheskie-aspekty-po-vyboru-vyhodnyh-filtrov/

PROMPOWER throttles and sine filters. Technical catalog. URL: https://prompower.ru/docs/inverter-accessories/Chokes_Sinewave-Filters.pdf

[4] GOST 32144-2013. Quality standard of electric power in power supply systems of general purpose. Moscow: Standartinform, 2014. 39 p.

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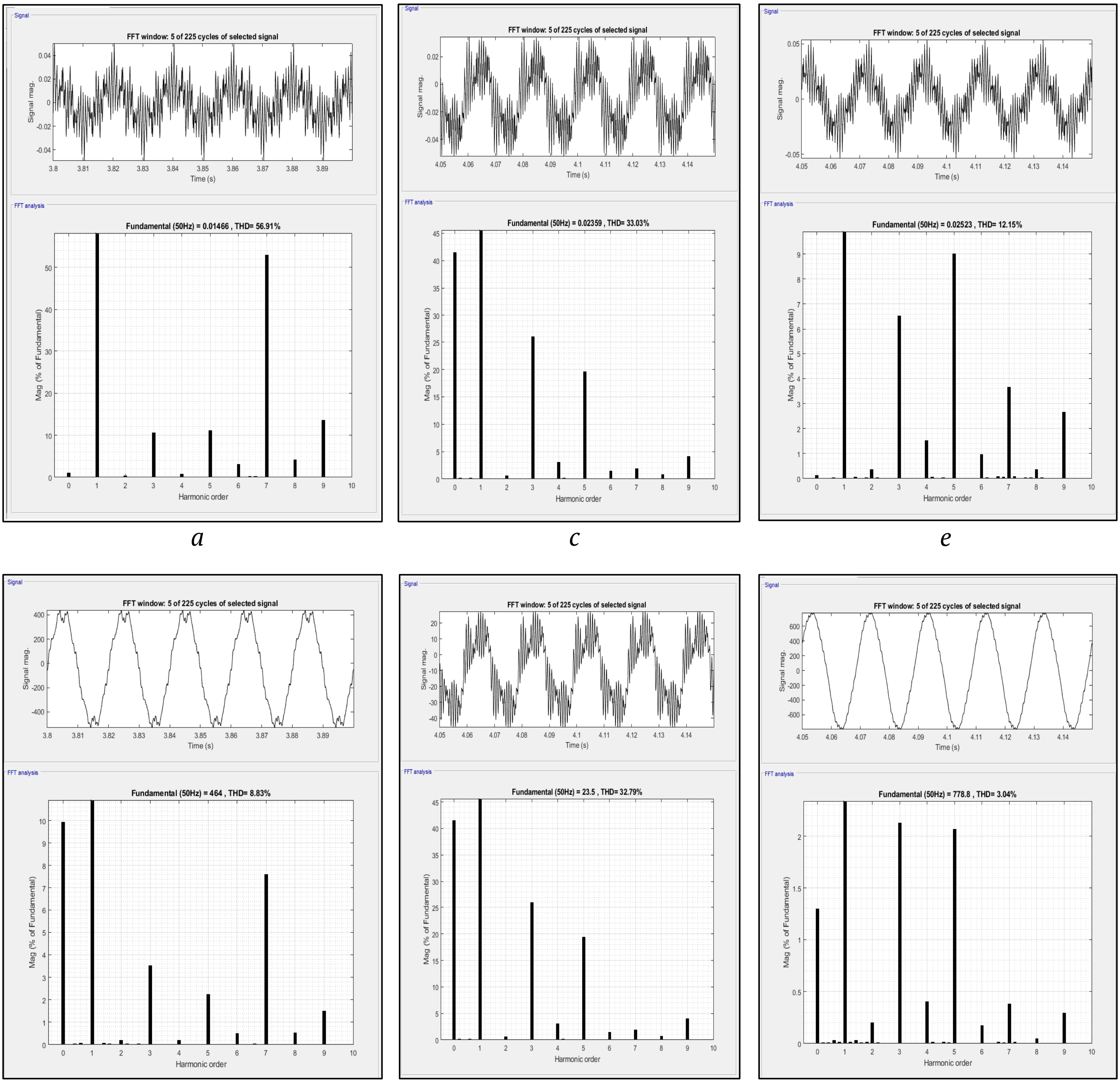
The harmonic composition of current and voltage in the phase insulation of the power distribution system at the FC-IM section, with reactors, HF-5, HF-7 activated at the TR-FC section, is presented in Table 2.

It is important to note that the coefficients of the n-th harmonic component of voltage $K_{U(n)}$ and the total coefficient of harmonic components of voltage K_U, induced in insulation leakage current circuits, in the RCD filter branches, and capacitive leakage current compensator, are not addressed by GOST[5]. This is because GOST refers to the quality standard indicators of electric energy in general-purpose power supply systems.

[5] GOST 32144–2013. Quality standard of electric power in power supply systems of general purpose. Moscow: Standartinform, 2014. 39 p.



a *c* *e* *b* *d* *f*

Fig. 3. Oscillograms and spectrograms of current and voltage in insulation leakage circuits with HFs at FC-IM section: symmetrical mode – leakage current (*a*), voltage (*b*); single-phase leakage mode – current in the damaged phase (*c*), voltage in the damaged phase (*d*), current in the undamaged phase (*e*), voltage in the undamaged phase (*f*)

Table 2

Harmonic composition of current and voltage in phase insulation

Harmonic number	Leakage mode $I^{(3)}_{y}$		Leakage mode $I^{(1)}_{y}$	
	$K_{I(n)}$%	$K_{U(n)}$%	$K_{I(n)}$%	$K_{U(n)}$%
0	1.05	9.92	41.43	41.45
2	0.4	0.2	0.57	0.57
3	10.5	3.52	25.95	25.85
4	0.75	0.19	3.07	3.05
5	11.1	2.23	19.6	19.4
6	3.02	0.51	1.45	1.43
7	52.58	7.59	1.95	1.87
8	4.16	0.52	0.76	0.74
9	13.49	1.51	4.12	3.96
Total	56.91	8.83	33.03	32.79

The analysis of the harmonic composition revealed that in the symmetrical mode, the 3rd, 5th, 7th, and 9th current harmonics, along with the 0th, 3rd, 5th, 7th, and 9th voltage harmonics, have the highest value. The 7th current harmonic and the 0th and 7th voltage harmonics exhibit the greatest distortion. In the single-phase current leakage mode with an active resistance R_y = 1 kΩ, the 0th, 3rd, and 5th current harmonics, as well as the 0th, 3rd, and 5th voltage harmonics, are most pronounced. The 0th and 7th current harmonics, along with the 0th and 3rd voltage harmonics, show the highest distortion.

The presence of the zero-harmonic component of voltage and current is explained by the existence of a rectified current source in the RCD metering device circuit, facilitating the control of insulation resistance in symmetrical leakage modes. Additionally, the flow of zero-sequence current in the single-phase leakage mode, with a spectral composition determined by the modulated voltage signal at the converter output, contributes to this phenomenon.

The study revealed that current leakage through a person induces a broad spectrum of harmonic components, impacting the individual. The 3rd, 5th, 6th, 7th, and 9th harmonics emerge as the most significant. Notably, the coefficient $K_{IH(3)}$ is considerably higher compared to its value with respect to the first harmonic. Such an extensive spectrum may have adverse effects on the human body. For instance, there is an increased likelihood of fibrillation if the peak of current harmonics coincides with the *P*- and *T*-periods of the cardiac cycle.

Fig. 4 presents characteristic oscillograms and spectrograms of zero-sequence current and voltage in RCD metering circuits in both symmetrical and single-phase leakage modes.

The analysis has revealed a prominent third harmonic in both voltage and current within the metering circuits, connection filter branches, and the RCD capacitive current compensator. Specifically, in the symmetrical leakage mode, the values of $K_{U(3)}$ and $K_{I(3)}$for the constant component of the third harmonic are significantly compared to those of the first harmonic.In the single-phase leakage mode, the presence of zero-sequence current in the RCD metering circuit results in an increase in $K_{U(0)}$ by up to 25%, $K_{U(3)}$ by up to 16%, and $K_{I(3)}$ by up to 8.5%. To mitigate the impact of the third harmonic component in the leakage current within the metering circuit diagram, a filter was chosen. Its application proved effective in enhancing the performance and efficiency of commercially available RCDs.

Conclusions and recommendations

1. The incorporation of HFs, reactors, and SFs has a positive impact on the quality of electric energy supplied to the electric motor through the frequency converter. This approach can be considered for practical implementation, provided that it adheres to the requirements for explosion-proof electrical equipment in mines. A crucial condition is ensuring temperature control within the HF and sine filter housings, maximizing heat dissipation from live parts and insulation.

2. The decision to install a HF directly on the low-voltage supply section of a scraper conveyor should be technically justified. This assessment should consider the need to achieve high electric power quality and economically justify the measure.

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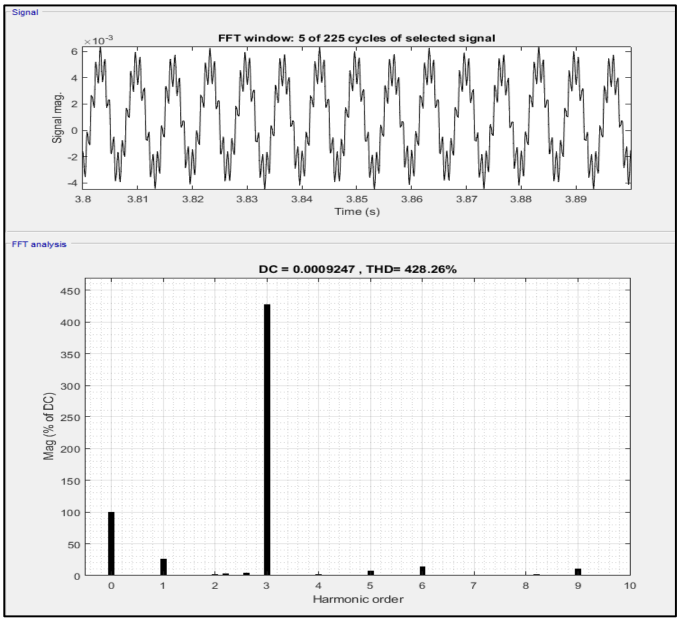
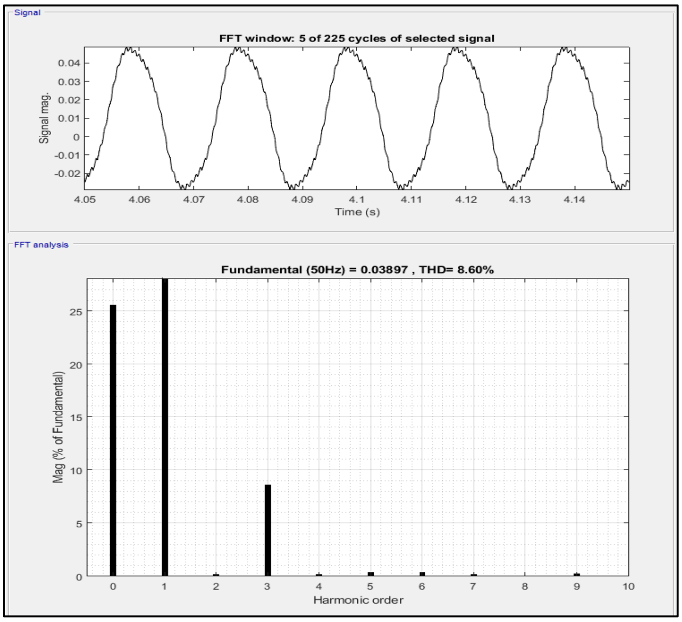
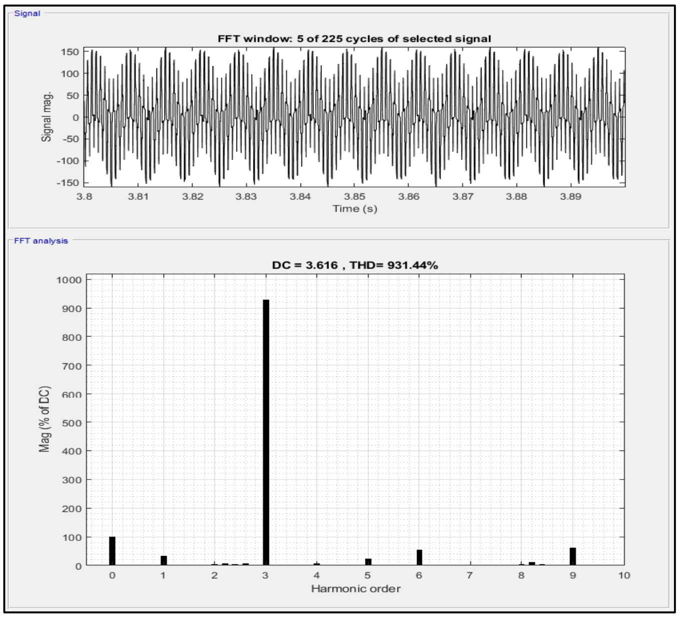


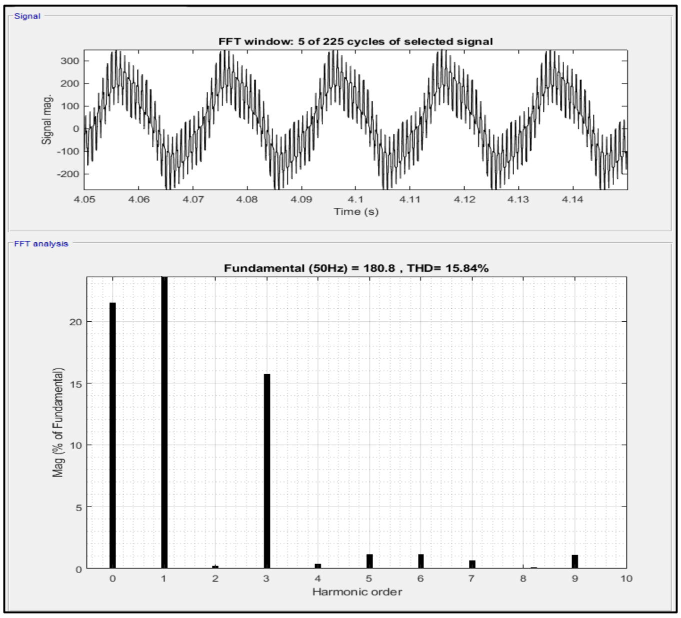
a



c



b



d

Fig. 4. Oscillograms and spectrograms of current in metering and zero-sequence voltage circuits: symmetrical mode – current (*a*), voltage (*b*); single-phase leakage mode – current (*c*), voltage (*d*)

It is essential to account for the fact that HFs and SFs in explosion-proof version for voltage class up to 1140 V are not manufactured. Additionally, there are limitations on mass and dimensional parameters, along with a requirement for forced ventilation of structural components.

3. The presence of a HF, reactors, and sine filters has minimal impact on either the harmonic composition or the magnitude of coefficients of the harmonic components in the phase voltage of the system relative to the ground and insulation leakage currents. However, additional filtering of higher harmonic components in the range of 1–1.5 kHz, utilized for forming the modulated AVI voltage, is necessary.

4. The existence of higher harmonic components induced in leakage current circuits in both symmetrical and single-phase leakage current modes can potentially disrupt magnetic compatibility during the operation of the electronic metering circuit, power supply unit, and the RCD capacitive leakage current compensator. This poses a potential hazard in case of contact with live parts of electrical equipment.

References

1. Shi J.G., Mao J., Wei X.H. Research on dynamic tension control theory for heavy scraper conveyor. *Applied Mechanics and Materials*. 2010;34–35:1956–1960. https://doi.org/10.4028/www.scientific.net/AMM.34-35.1956
2. Stecuła K., Brodny J., Tutak M. Informatics platform as a tool supporting research regarding the effectiveness of the mining machines' work. In: *CBU International Conference on Innovations in Science and Education*. 2017;5:1215–1219. https://doi.org/10.12955/cbup.v5.1099
3. Voronin V.A., Nepsha F.S., Ermakov A.N., Kantovich L.I. Analysis of electrical equipment operating modes of the excavation site of a modern coal mine. *Sustainable Development of Mountain Territories*. 2021;(4):599–607. (In Russ.) https://doi.org/10.21177/1998-4502-2021-13-4-599-607
4. Klyuev R.V., Bosikov I.I., Gavrina O.A., Lyashenko V.I. Assessment of operational reliability of power supply to developing ore mining areas at a high-altitude mine. *Mining Science and Technology* (*Russia*). 2021;6(3):211–220. (In Russ.) https://doi.org/10.17073/2500-0632-2021-3-211-220
5. Babokin G.I. Influence of process flow diagram and longwall length on specific energy consumption of shearers. *Mining Informational and Analytical Bulletin*. 2021;(2):139–149. (In Russ.) https://doi.org/10.25018/0236-1493-2021-2-0-139-149
6. Boykov I.L., Shestakov V.V., Zaklika M., Ulrich N. Experience in introducing frequency converters to drive face conveyors of the Vorgashorskaya mine. *Gluckauf*. 2010;(1):79–83. (In Russ.)
7. Shevyrev Y.V., Pichuev A.V., Shevyreva N.Y. Improving energy performance in networks with semiconductor converters. In: *2019 International Conference on Industrial Engineering, Applications and Manufacturing, ICIEAM 2019*. Sochi, March 25–29, 2019. Pp. 1–6. https://doi.org/10.1109/ICIEAM.2019.8743020
8. Feng D., Lu M., Lan J., Sun L. Research on switching operation transient electromagnetic environment of substations in a coal mine. *IET Generation, Transmission & Distribution*. 2016;10(13):3322–3329. https://doi.org/10.1049/iet-gtd.2016.0292
9. Babokin G.I., Shevyrev Yu.V., Shevyreva N.Yu. Power quality in coal longwalls. *Gornyi Zhurnal*. 2021;(7):80–85. (In Russ.) https://doi.org/10.17580/gzh.2021.07.14
10. Pustovetov M.Yu. Experience in developing sine-wave filter for power circuit of VVVF-drive with induction motor. *Bulletin of the Tomsk Polytechnic University*. 2014;324(4):84–94. (In Russ.) URL: http://earchive.tpu.ru/handle/11683/5238
11. Pichuev A.V., Petrov V.L. Equivalent circuit for mine power distribution systems for the analysis of insulation leakage current. *Mining Science and Technology* (*Russia*). 2023;8(1):78–86. https://doi.org/10.17073/2500-0632-2023-01-72
12. Babokin G.I., Kunitsky V.G., Shelenev P.I. Protective switching-off on a direct operating current for combined mine networks. *Mining Informational and Analytical Bulletin*. 2009;(S8):285–288. (In Russ.)
13. Shchutsky V.I., Babokin G.I., Lazarev A.I. Experimental study of the operating conditions of protective shutdown devices in a network with a frequency converter. *Elektrobezopasnost'*. 1996;(3–4):31–41. (In Russ.)
14. Pichuev A.V., Petrov V.L. Equivalent circuit for mine power distribution systems for the analysis of insulation leakage current. *Mining Science and Technology (Russia)*. 2023;8(1):78–86. https://doi.org/10.17073/2500-0632-2023-01-72
15. Syromyatnikov I.A. *Operating modes of asynchronous and synchronous motors*. Mamikonyants L.G. (Ed.) 4th ed., revised and additional. Moscow: Energoatomizdat; 1984. 240 p. (In Russ.)
16. Pichuev A.V. Information and analytical system for analyzing the reliability and safety of electrical installations at mining enterprises. *Mining Informational and Analytical Bulletin*. 2011;(3):355–359. (In Russ.)
17. Kopylov I.P. *Mathematical modeling of electrical machines*. Moscow: Vysshaya Shkola; 2001. 218 p. (In Russ.)

Information about the authors

Vadim L. Petrov – Dr. Sci. (Eng.), Vice-Rector, Professor of the Department of Energy and Energy Efficiency of Industrial Enterprises, University of Science and Technology MISIS, Moscow, Russian Federation; ORCID 0000-0002-6474-5349, Scopus ID 8919065900; e-mail petrovv@misis.ru

Alexandr V. Pichuev – Cand. Sci. (Eng.), Associate Professor of the Department of Energy and Energy Efficiency of Mining Industry, University of Science and Technology MISIS, Moscow, Russian Federation; ORCID 0000-0001-7457-5702, Scopus ID 57209798580; e-mail allexstone@mail.ru

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