Simulation of asynchronous electric drives with energy recuperation for lifting mechanisms of non-ferrous metallurgy enterprises

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The paper analyzes two promising variants of an energy-saving electric drives for lifting mechanisms of non-ferrous metallurgy enterprises. As the first variant, a variable-frequency asynchronous electric drive with active rectifier according to a modified main circuit is proposed. The second one is an asynchronous electric drive with pulse control in a rotary circuit and a network-driven inverter. There is shown an expediency of applying the suggested options for electric drives of lifting mechanisms, the load of which is an active moment, and the lowering and lifting modes in a work cycle are equal in time. Computer simulation models for the considered variants have been developed in MatLab software package; transients in electric drives for typical cycle execution of lifting mechanisms have been analyzed and compared for each variant. A qualitative and quantitative comparison of dynamic processes in electric drives, their power modes and the resulting energy efficiency has been carried out.

Key words: asynchronous electric drives of lifting mechanisms, general-purpose electric cranes, metallurgical cranes, active rectifier, pulse control, recuperation, active filtering, invert conversion, energy efficiency, computer simulation.

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Introduction

Solving the problems of electrical energy rational use and energy efficiency of energy department in industry is directly related to the improvement of technical solutions in the electric drive, which is the main consumer of electricity generated in the world. The share of such consumption is very high and, according to various estimates, amounts to 60–70% of the world's total generation as a whole [1]. For example, in Russia alone, the total electricity consumption of all loads in 2019 amounted to just over 1 trillion kW·h [2]. Thus, the electricity consumption by electric drive systems in general (in industry, electric transport, everyday life) is 600–700 billion kW·h.

Energy saving in metallurgy is of particular significance. In the Russian Federation, there acts the "Development strategy for ferrous and non-ferrous metallurgy in Russia for 2014–2020 and for the period until 2030", one of the sections of which is devoted to energy saving by various means. The process chain at concentrating mills is provided, among other factors, by a large fleet of electric drives of processing machines — both powerful overhead cranes and general-purpose catheads, and specialized metallurgical cranes: of foundries and rolling plants; forging, turnaround charging, dogging cranes and so on. Due to the significant power, uniqueness, and a number of historical and economic reasons, such mechanisms of cyclic action are mainly equipped with outdated types of electric drives, in which the energy saving issues were not given the principal attention. In addition, it is widely believed that the energy consumption of drives at concentrating mills is not too high against a background of power intensity of the main technological process — ore dressing. Nevertheless, even a slightly understated estimate of the share of energy consumption of electric drives at 20% of the total energy consumption at a concentrating mill, gives an idea of the energy-saving opportunities in this segment.

In the last decade of the XX century and the first two decades of the XXI century, there was a significant breakthrough in the quality of control and all-round automation of various manufacturing technologies, mainly due to the improvement of the systems of the electric drive power part and digital microprocessor controlling means for them. Another evident trend is connected with an increase in the energy efficiency of electric drives. Its practical implementation can be exemplified by replacement of unregulated electric drives by adjustable ones for continuously working mechanisms, where previously it was not economically sound. For example, for different types of superchargers, crushers, mills, and classifiers that have a pronounced long-term shift or daily cycle of operation. A number of such continuous mechanisms are also used as the main and auxiliary ones at enterprises of non-ferrous metallurgy.

In modern conditions, the researchers and manufacturing companies are faced with a common complex task of ensuring the high-quality control in static and dynamic operating modes of electric drives as well adapting the energy-saving solutions so as to be able at the operation stage to compensate complication and, as a result, rise in price of electric drive systems. This can be combined organically for modern continuously working mechanisms. It is more difficult to achieve a significant effect in areas where previously controlled-velocity electric drives have been widely used.

In industry-wide mechanisms such as those mentioned above of cyclical action at concentrating mills of non-ferrous metallurgy, only controlled-velocity electric drives have been traditionally used, which is obviously determined by the technology of their functioning. One of the most typical kinds of such mechanisms is lifting ones; lifting mechanisms of different cranes, elevators and some other equipment may be used as relevant examples.

Not taking into account in this paper the oldest electric drive system of a "G-D" type ("generator – DC motor", "magnetic amplifier – DC motor" and the like), created even in 1950–1980, the standard electric drives for such mechanisms until the early 1990s of the last century were:

– the electric drives based on induction motor with a phase-wound rotor (IMPR) and a relay-contactor control system with an external bracket;

– DC electric drives according to a "TC-D" system — "thyristor converter – DC motor" with various control systems.

Obsolescence and inability to meet constantly increasing requirements for work technique of lifting mechanisms combined with general requirements for energy efficiency are gradually displacing these electric drives in many areas, including non-ferrous metallurgy enterprises. As a modern alternative at the market of electric drives for industry-wide mechanisms there are most commonly offered and applied in practice the system of variable-frequency electric drive (VFED) with the main circuit including:

– an uncontrollable three-phase diode rectifier bridge (UR);

– DC link (DCL) with capacitive (inductive-capacitive) filter, braking circuit with an external resistor, devices of the capacitor filter smooth charge (by low current);

– an autonomous three-phase bridge voltage source inverter (VSI) on transistor IGBT-keys with their switching on the principle of pulse-width modulation (PWM) of the output voltage of VSI;

– an induction motor with a short-circuited rotor (IMSCR) as a control object.

The VFED management features with the ability to control the speed of rotation of the stator magnetic field and to stabilize the interlinkage amplitude of IMSCR rotor or stator circuit have been significantly developed. These methods, including up-to-the-minute digital vector ones, allow us to obtain high-precision, deep-regulated electric drive systems with a rate control range *D* up to several tens thousands to one.

Despite the numerous advantages, the most widespread VFED power circuit for lifting mechanisms is not efficient, since UR presence in the power circuit does not permits to guarantee all the required energy modes. Braking in it is carried out with the energy losses on external impedance or applied is dynamic braking by a special VSI control with energy losses in the machine windings and on the converter elements. To provide more advanced energy modes, UR is replaced by an active rectifier (AR) — a three-phase bridge device similar to VSI. When using AR with appropriate control instead of UR, it is possible to ensure energy exchange between the current network and the motor in both directions. In braking modes of the electric drive, for example, when lowering the cargo, switching from the main speed to the underspeed, AR then performs the function of a recuperator. This solution with a recuperator for lifting mechanisms is more acceptable with relation to power-saving criteria, but this type of electric drives is often inadequate for the shop mains supply, frequently noisy with various interferences.

It seems advisable to consider options for upgrading converter circuits for lifting mechanisms of concentrating mills and to compare their dynamic and energy behaviour by means of computer simulation, what exactly is the purpose of this paper.

Suggested options for power parts of electric drives

In the Smolensk branch of the National Research University "Moscow Power Engineering Institute" (NRU MPEI), there were put forward an improved power circuit with AR (see **Fig. 1**) as well as control technology for it [3–4], both for high-voltage versions with a nominal linear voltage of 6.3 kV and (somewhat later) for low-voltage ones of 380 V. The proposed modifications of the power part allow one to apply this scheme with the greatest efficiency precisely for electric drives of lifting mechanisms.

The scheme in Fig. 1 contains a three-phase UR – UD, a DCL with an LC-filter, a Br braking circuit with a VTbr

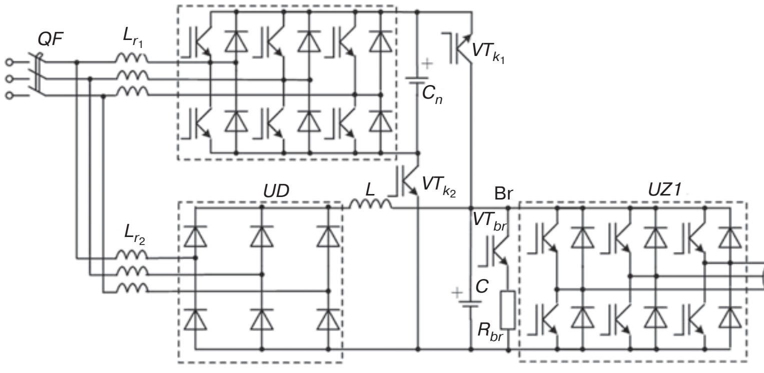


Fig. 1. Modified multifunctional scheme of VFED with AR

chopper transistor and a Rbr external brake resistance, a three-phase VSI – UZ1, a three-phase AR – UZ2 with its own C_n capacitive storage, additional transistor keys VTk1 and VTk2, IMSCR – M. It is a modification of the existing VFED schemes, but unlike the existing ones, it permits to use more features of AR – UZ2.

The proposed power circuit topology (Fig. 1) with appropriate control, described in detail in [3–4], is able to provide a four-quadrant electric drive with both motor and energy-efficient braking modes — with energy recuperation into the mains supply. As a means of redundancy, the Br braking circuit is also left in the scheme as an auxiliary option for organizing electric braking. In addition, the scheme allows the AR use in the reactive power compensator (RPC) mode, as well as the active harmonic filter (AHF) of the mains voltage, similar to [5], which is especially effective for workshop electrical networks. At that, the circuit also acquires the properties of good electromagnetic compatibility with the mains supply in addition to the properties of energy efficiency in braking modes. There appears an opportunity to fully implement the international recommendations on the mains voltage quality [6]. The vector controlling means of VSI UZ1, as well as in some cases even scalar ones in a closed loop system, make it possible to provide the necessary process requirements in this system with a good safety margin, both in statics and in dynamics of electric drives.

Another option for constructing a power circuit, proposed in the NRU MPEI Smolensk branch and for many years investigated there is a scheme with pulse regulation in the asynchronous motor phase rotor circuit, supplemented with a network-driven inverter (NDI) (see Fig. 2). This scheme is designed for another control object — an induction motor with a phase-wound rotor (IMPR) [7–9].

It should be noted here that most mining mechanisms do not require a significant range of speed control — usually this indicator is no more than $D = (40–50){:}1$, and most often does not exceed $D = 10{:}1$. Therefore, along with the use of VFED systems, it is also expedient to apply simpler systems for the electric drive parametric control (EDPC) without the possibility of regulating the stator magnetic field speed of rotation. One of these systems is the induction motor with a pulse regulator in a rectified current circuit, which has been known for several decades.

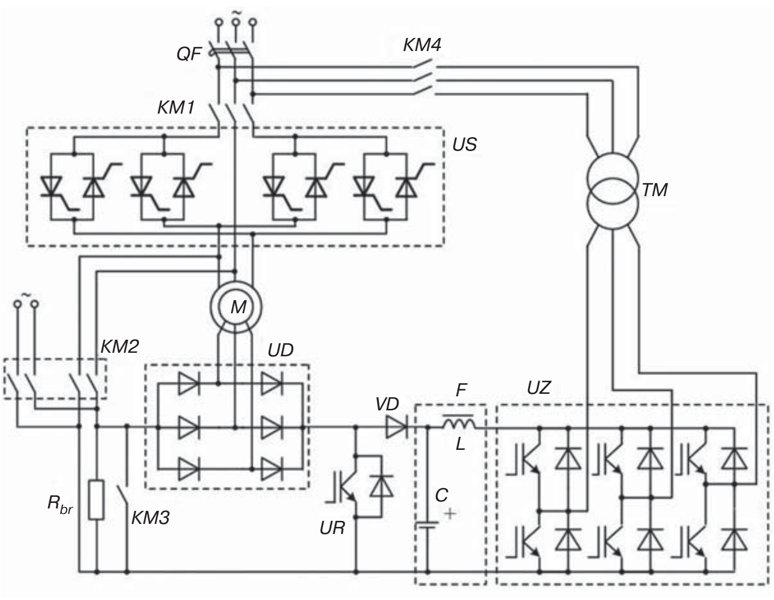


Fig. 2. Scheme of EDPC with NDI

It is easier to operate compared to the scheme in Fig. 1 and develops the ideas of building electric drives with pulse control in combination with the capabilities of asynchronous-valve stage (AVS). The scheme in Fig. 2 includes the following components: a three-phase UR – UD included into IMPR phase-wound rotor circuit, pulse key — UR regulator, LC-filter with switched capacity *C*, a network-driven inverter UZ, power matching transformer TM, thyristor reverser US, a number of contacts of contactors KM1-KM4 that schematically support various energy modes. So, specific braking modes in this scheme, for example, dynamic braking modes with independent, self- and compound excitation, can be provided by breaking KM3 and closing KM2. The contactor KM1 is used to connect the main part of the circuit to the mains supply, and KM4 is used to organize a channel for the slip energy recuperation into the mains supply.

The main weakness of the previously used schemes with AVS was quite significant (up to 40–70%) slip losses during regulation [9]. In the proposed version of the scheme, this disadvantage is minimized due to the presence of a transistor UZ, the control of which makes it possible to recuperate part of the energy into the mains supply with a rational combination of available opportunities for the formation of braking modes in the scheme.

The drive energy efficiency according to the power scheme of Fig. 2 increases due to the reduction or complete absence of energy losses at external resistances and the possible recovery of slip energy into the mains supply. The implementation of recuperation in this scheme is carried out in the dynamic braking mode of the motor. On dynamic braking, the kinetic energy of cargo movement during lowering is converted into electrical energy and is returned to the mains supply with the deduction of losses on active resistances of the circuit. In the dynamic braking mode, the contacts of contactors KM1 and KM3 are open, and that of KM2 and KM4 are closed. At the same time, the motor M is disconnected from the supply network. Power is supplied to the stator circuit of the motor from a DC source through the contacts of contactor KM4. In parallel to the stator winding, when KM2 is closed and KM3 is opened, switched on is Rbr brake resistor, designed to reduce the part of the rotor's rectified current coming from the rotor winding to stator one.

The variant of EDPC scheme with NDI is most interesting for the purposes of a "soft" modernization of considerable fleet of existing electric drives of lifting mechanisms with IMPR being kept, which is already often available in the system in practice. In general, the application of EDPC scheme with NDI allows, as for the scheme in Fig. 1, to obtain a four-quadrant fully controlled induction motor with a wide range of the control band of its coordinates and the ability of slip energy recuperation into the mains.

On the whole, many publications are devoted to the feature analysis of modern converters for various types of electric drives and the construction of adequate models of energy consumption [10–27], but simulation of special solutions for lifting mechanism drives has received there insufficient attention.

Models of electric drives according to the suggested power schemes

Let us consider an electric drive system designed for lifting mechanism of an overhead crane as an example of simulation of the two considered variants of power circuits (Fig. 1 and Fig. 2). Previously, the same input data for these variants were determined according to the mechanical and process parameters. The cargo winch design, weights of the cargo and hook assembly, lifting height of the cargo, and so forth, have been taken as these data for the load simulation.

For the systems under study, the following devices have been taken as an example of driving motors of the same rated power P_r = 55 kW for rated maximum sinusoidal (rms) value of line voltage $U_{l\,rms}$ = 380 V with an equal number of pole pairs p_p =3:

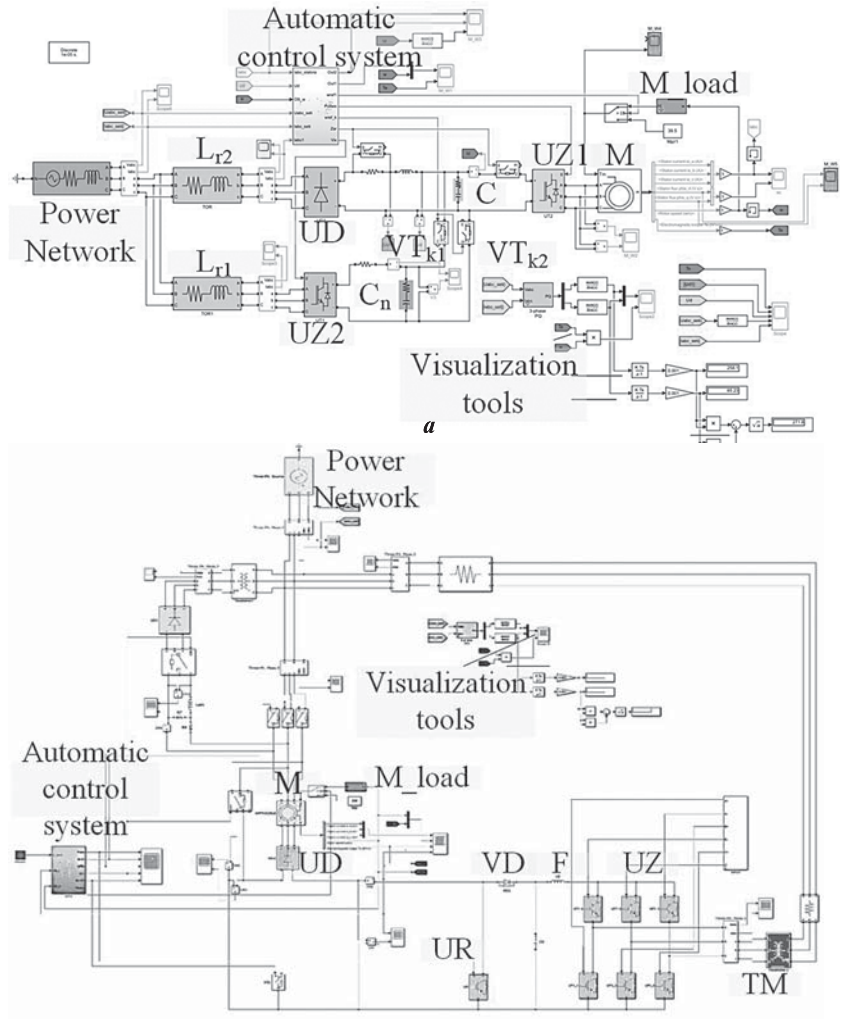
– for VFED with AR according to the scheme of Fig. 1 — a general-industrial IMSCR of AIR250M6 (АИР250М6) type;

– for EDPC with NDI according to the scheme of Fig. 2 — a crane IMPR of 4MTH225L6 type.

The study of dynamic and energy properties of the systems has been carried out with the help of structural simulation tools in MatLab.

The model corresponding to the scheme in Fig. 1 is shown in Fig. 3, *a*, and the scheme in Fig. 2 is shown in Fig. 3, *b*.

In addition to the elements of the systems in Fig. 1 and Fig. 2 with their similar designations, the models in **Fig. 3** contain the motor shaft load block (M_load), submodels of the corresponding automatic control systems and submodels of diverse process visualization tools.



a

b

Fig. 3. The model of VFED with AR (*a*) and the model EDPC with NDI (*b*)

Series of computer experiments have been carried out on the above-described models, simulating the typical operation modes of lifting mechanisms. Standard process cycle of the work includes the following elements when lifting the cargo:

– smooth (with a given rate) motor start at underspeed within a given range of its regulation (*D* = 8:1 is taken in the example);

– smooth change and work at the primary rate;

– smooth braking up to underspeed;

– smooth braking up to zero speed (stop));

– short process pauses are made between some elements of the cycle.

In the lowering mode, similar elements of the cycle are formed with the opposite direction of motor rotation and lowering with a cargo, or lowering of an empty hook assembly.

Oscillography of mechanical parameters of the motors, such as speed of rotation, electromagnetic moment, is fulfilled. In parallel, the electrical and magnetic parameters (currents, interlinkages) are recorded. In the model, active and reactive power are registered, as well as the total capacity is calculated. Besides, the power at the motor shaft is calculated, which is the product of electromagnetic moment and the motor speed of rotation $P_t = M \cdot \omega$.

The Automatic control system block for the scheme in Fig. 3, *a* contains the control subsystems UZ1 with vector control and direct orientation along the vector of the rotor field, as well as two control algorithms UZ2 — in AHF mode (in the motor mode of the system) and in the recuperator mode (in generator one).

The block with the same name for the scheme in Fig. 3, *b* includes the system with a pulse key — UR controller with subordinate coordinate control, an external speed loop, feedback on the rotor EMF (slip) and an internal loop of the rotor rectified current. The network-driven inverter UZ in the scheme in Fig. 3, *b* is controlled at a fixed control angle (without PWM) from a separate unit. External speed loops for managing VSI UZ1 of the scheme in Fig. 3, *a* and UR pulse regulator of the scheme in Fig. 3, *b* have the same settings.

The electric drive simulation results by the example of the production cycle execution

Simulation for the presented systems is implemented according to the above-mentioned script of the process cycle execution with the same settings of the speed controllers presented in both the first and second systems. A series of computer experiments was performed to evaluate the dynamic and energy behaviour of the suggested systems. When evaluating the dynamic behaviour, it was found that both systems execute the reference-input signals with good quality in dynamics. The control systems provide process modes of operation with speed stabilization to an accuracy of at least 5% at the lower characteristic, the required limitation of the dynamic torque at a level below the critical one and the stator current limitation in dynamics at a level of 2–3 times of the nominal one. The performance of the systems, which is provided by various solutions in control systems, is also equivalent.

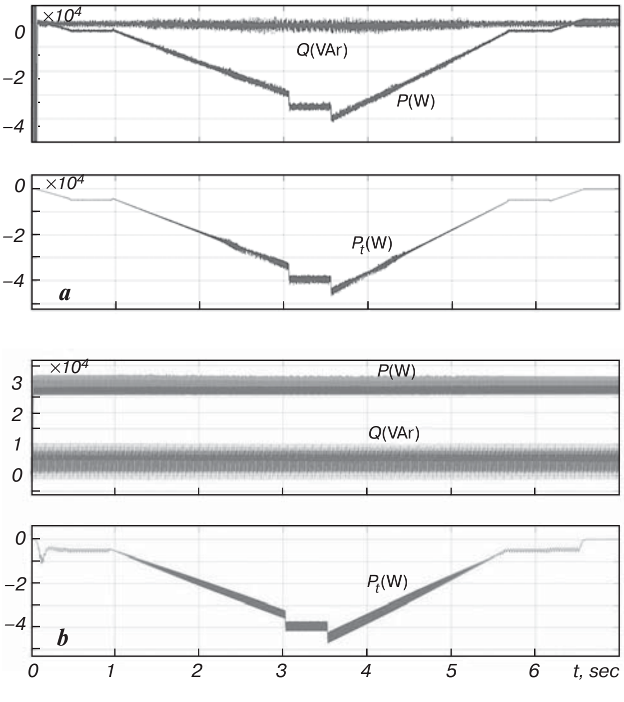


Fig. 4. Oscillogram of energy characteristics when working on the cargo lowering stage in systems of VFED with AR (*a*) and EDPC with NDI (*b*) (P — active power, W; Q — reactive power, Var; P_t – motor shaft power, W)

The most distinctive for assessing the energy parameters of electric drives of lifting mechanisms with relation to energy-saving properties is the functioning area when lowering the cargo at underspeed and primary speed and during switching from one to another speed.

Fig. 4, *a* and Fig. 4, *b* depict oscillograms of the computer experiment when electric drives operate in this area according to the schemes of Fig. 1 and Fig. 2, respectively.

In contrast to the system dynamic properties, its energy characteristics differ significantly.

By comparing the oscillograms shown in Fig. 4, *a* and Fig. 4, *b*, it can be seen that VFED system with AR according to the scheme of Fig. 1 provides high-quality energy recovery to the mains supply during the cargo lowering (see Fig. 4, *a*). It is evident that both mechanical and active power have the same negative sign when lowering the cargo. In this mode, active power is recuperated into the mains supply. It can also be seen that up to 85–90% of mechanical power on the motor shaft is returned to the mains supply.

Energy properties of EDPC system with NDI in comparison with the properties of VFED with AR differ essentially. It is clear that, despite the operation of the network-driven inverter, which compensates the losses of slip energy during parametric control, the active power sign when executing the cycle part during the cargo lowering remains positive. Thus, even in the generator operating modes of the motor, the electric drive system continues to consume active power. One can also see that there is also a quite essential consumption of reactive power by EDPC scheme with NDI — about 1.5 times more than that in VFED scheme with AR.

The results of the energy consumed evaluation separately on stages – when lifting and lowering the cargo, as well as a whole for the simulated typical cycle, taking into account the stops and process pauses during functioning, are summarized in the **Table 1.**

Similar studies have been conducted for high-voltage electric drives with a nominal line voltage of 6.3 kV, where the results on energy efficiency of VFED system with AR are even more pronounced.

Economic performances

An assessment of economic results of applying the suggested variants for the modernization of electric

Table 1
Energy values at the stages and for a whole operating cycle

Scheme	Energy, kJ					
	on lifting		on lowering		for a cycle as a whole having regard to stops and process pauses	
	P	Q	P	Q	P_Σ	Q_Σ
VFED with AR (by Fig. 1)	214.6	68.3	–96.5	18.8	113.0	86.3
EDPC with NDI (by Fig. 2)	315.2	231.9	281.2	350.1	625.2	580.2

drives of lifting mechanisms at non-ferrous metallurgy enterprises can be made having the initial data on the functioning of the Russian energy industry [2], as well as knowing the structure of energy consumption by branches of production and industries. More than half of the electricity generated falls at the aggregate share of the entire industry — about 600 billion kW·h. The share of this volume for non-ferrous metallurgy in different years doesn't essentially varies and is some 10%, or around 60 billion kW·h. Setting that electric drives consume 20% of this volume according to the most conservative estimates, then this consumption is about 12 billion kW·h per year.

The energy consumption values for the experiment according to the scheme of Fig. 2 (EDPC with NDI) are close to that for the scheme of Fig. 1 (VFED with AR) without using an active front end and upgrading the circuit. Energy savings per hour for VFED with AR in relation to EDPC with NDI (the energy consumption of which is close to that of the currently used schemes) for lifting mechanisms is approximately 80%.

Thus, the energy savings per year, when using schemes like Fig. 1, is approximately 9.5 billion kW·h. Having accepted the minimum electricity rate for industry in the regions of operation of concentrating mills as 2 rubles (2.67 cents) per 1 kW·h, we get that the use of the suggested solutions in a comprehensive program for replacing about 1 thousand electric drives of high and medium power with energy-efficient ones within the industry will save 19 billion rubles ($253 million) per year.

Capital investments to upgrade approximately 1,000 of the same electric drives will amount to about 3 billion rubles ($40 million) per year. Thus, the annual economic benefit will be approximately 16 billion rubles ($213 million).

Conclusions

As a result, the analysis carried out by means of computer simulation has showed the following:

– it is advisable to use at concentrating mills of non-ferrous metallurgy enterprises both electric drives based on a multifunctional circuit of a variable-frequency drive with an active front end according to Fig. 1, and an upgraded circuit of parametric control with pulse regulation and a network-driven inverter according to Fig. 2 in order to ensure the necessary process requirements of lifting mechanisms;

– static and dynamic behaviour of the variants under consideration (accuracy, operating speed, nature of transients) are comparable and meet the necessary process requirements for lifting mechanisms at concentrating mills of non-ferrous metallurgy enterprises both in statics and dynamics;

– in terms of energy efficiency, the scheme of a variable-frequency drive with an active front end is essentially (approximately 5.5 times — see the Table 1) superior to the scheme of parametric control, the advantage of which, in its turn, is the preservation in the course of possible modernization of a rather expensive control object — an asynchronous motor with a phase-wound rotor. At the same time, the total capital investments for modernization may be lower as compared with a deeper modernization with complete replacement of the currently used electric drive systems with a multifunctional circuit of a variable-frequency drive with an active rectifier.

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References

1. Ilyinsky N. F., Moskalenko V. V. Electric Drive: Energy and Resource Saving. Moscow : Akademiya, 2008. 201 p.

2. Report on the Functioning of the UES of Russia in 2019. URL: https://www.so-ups.ru/fileadmin/files/company/reports/disclosure/2020/ups_rep2019.pdf (Access data: 29.12.2020).

3. Rozhkov V. V., Fedotov V. V. Improving the Properties and Characteristics of Avariable-Frequency Drive with an Active Rectifier. *2020 International Russian Automation Conference (RusAutoCon)*. pp. 903–907. DOI: 10.1109/RusAutoCon49822.2020.9208030.

4. Krutikov K. K., Rozhkov V. V. Application of Multifunctional Power Active Filters as Part of a Powerful Variable-Frequency Electric Drive. *Elektrichestvo*. 2011. No. 2. pp. 32–38.

5. Maklakov A. S. Analysis of PWM Boost Rectifier in Modes of Reactive Power Compensation. *Russian Internet Journal of Industrial Engineering*. 2013. No. 1. pp. 43–50.

6. IEEE Standard 519-2014. IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems. Published Date: 2014-06-11.

7. Danilov P. E., Baryshnikov V. A., Rozhkov V. V. Theory of Electric Drive : a Textbook. Moscow; Berlin : Direct-Media, 2018. 416 p.

8. Abrosov Ya. A., Danilov P. E., Baryshnikov V. A. On the Prospects for the Development of Modern Crane Electric Drives. *Problems and Prospects for the Development of Energy, Electrical Engineering and Energy Efficiency: Materials of the III International Scientific and Technical Conference*. Cheboksary: Izdatelstvo Chuvashskogo Universiteta, 2019. pp. 322–328.

9. Meshcheryakov V. N. Electric Drive Systems with an Induction Motor with a Phase-Wound Rotor : a Textbook. Lipetsk : LGTU, 1999. 80 p.

10. Fomin I. N. The Frame Approach for Systematization Computational Models of Power Supply. *Journal of Applied Informatics*. 2016. Vol. 11, No. 2. pp. 99–106.

11. Gnatyuk V. I., Sheynin A. A. Determinig the Optimal Rates of Electrical Power Consumption. *Journal of Applied Informatics*. 2014. No. 3. pp. 68–78.

12. Plakhtii O., Nerubatskyi V. Analyses of Energy Efficiency of Interleaving in Active Voltage-Source Rectifier. *2018 IEEE 3rd International Conference on Intelligent Energy and Power Systems (IEPS)*. pp. 253–258. DOI: 10.1109/IEPS.2018.8559514

13. Straka M., Blahnik V., Pittermann M. Verification of Control Behaviour of Three-Phase Voltage-Source Active Rectifier with Vector Control. *2020 International Conference on Applied Electronics (AE)*. pp. 1–4. DOI: 10.23919/AE49394.2020.9232705

14. Blahnik V., Peroutka Z., Molnar J., Michalik J. Control of Primary Voltage Source Active Rectifiers for Traction Converter with Medium-Frequency Transformer. *13th International Power Electronics and Motion Control Conference, 2008*. pp. 1535–1541. DOI: 10.1109/EPEPEMC.2008.4635485.

15. Cornic D. Efficient Recovery of Braking Energy through a Reversible DC Substation. *Electrical Systems for Aircraft, Railway and Ship Propulsion*. 2010. 11700008. DOI: 10.1109/ESARS.2010.5665264

16. Dujic D., Zhao C., Mester A., Steinke J., Weiss M., Lewdeni-Schmid S., Chaudhuri T., Stefanutti P. Power Electronic Traction Transformer-Low Voltage Prototype. *IEEE Transactions on Power Electronics*. 2013. Vol. 28, Iss. 12. pp. 5522–5534.

17. Filote C., Ciufudean C., Alaei S., Cozgarea A. M. Harmonic Elimination and Power Factor Improvement of Three-Phase Rectifier Using RNSIC Variant. *2011 International Conference on Clean Electrical Power (ICCEP)*. 12304548. DOI: 10.1109/iccep.2011.6036326

18. Grinberg R., Canales F., Paakkinen M. Comparison Study of Full-Bridge and Reduced Switch Count Three-Phase Voltage Source Inverters. *7th International Conference-Workshop Compatibility and Power Electronics (CPE), 2011*. pp. 270–275.

19. Heldwein M. L., Mussa S. A., Barbi I. Three-Phase Multilevel PWM Rectifiers Based on Conventional Bidirectional Converters. *IEEE Transactions on Power Electronics*. 2010. Vol. 25, Iss. 3. pp. 545–549.

20. Kwak S., Toliyat H. A. Design and Rating Comparisons of PWM Voltage Source Rectifiers and Active Power Filters for AC Drives With Unity Power Factor. *IEEE Transactions on Power Electronics*. 2005. Vol. 20, Iss. 5. pp. 1133–1142.

21. Luo X., Wang J., Dooner M., Clarke J. Overview of Current Development in Electrical Energy Storage Technologies and the Application Potential in Power System Operation. *Applied Energy*. 2015. Vol. 137. pp. 511–536.

22. Pena-Alzola R., Liserre M., Blaabjerg F., Sebastián R., Dannehl J., Fuchs F. W. Analysis of the Passive Damping Losses in LCL-Filter-Based Grid Converters. *IEEE Transactions on Power Electronics*. 2013. Vol. 28, Iss. 6. p. 2642–2646.

23. Santarius P., Tlusty J., Valouch V. Harmonic Voltage Mitigation Power Systems by Using Cooperative Control of Active Power Filters Without Mutual Communication. *2008 IEEE International Conference on Industrial Technology*. 10179543. DOI: 10.1109/icit.2008.4608429

24. Takahashi H., Aoki K., Maoka A., Kim Y. I. Current and Future Applications for Regenerative Energy Storage System. *Hitachi Review*. 2012. Vol. 61, No. 7. pp. 336–340.

25. Zhai H., Zhuo F., Zhu C., Yi H., Wang Z., Tao R., Wei T. An Optimal Compensation Method of Shunt Active Power Filters for System-Wide Voltage Quality Improvement. *IEEE Transactions on Industrial Electronics*. 2020. Vol. 67, Iss. 2. pp. 1270–1281.

26. Zhang Y., Xie W., Zhang Y. Deadbeat Direct Power Control of Three-Phase Pulse-Width Modulation Rectifiers. *IET Power Electronics*. 2014. Vol. 7, Iss. 6. pp. 1340–1346.

27. Zhang Y., Qu C. Direct Power Control of a Pulse Width Modulation Rectifier Using Space Vector Modulation Under Unbalanced Grid Voltages. *IEEE Transactions on Power Electronics*. 2015. Vol. 30, Iss. 10. pp. 5892–5901. NFM