Computing, Telecommunication and Control, 2023, Vol. 16, No. 4, Pp. 37–48.
Информатика, телекоммуникации и управление. 2023. Том 16, № 4. С. 37–48.

Research article
DOI: https://doi.org/10.18721/JCSTCS.16404
UDC 004.04

OPTIMIZATION AND CONTROL SYSTEM OF POWER CONSUMPTION BASED ON VIRTUAL POWER PLANT TECHNOLOGY

Yu.N. Kozhubaev[1] ✉, *D.S. Kazanin*[2]

[1] Saint-Petersburg Mining University, St. Petersburg, Russian Federation;
[2] Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation

✉ y.n.kozhubaev@gmail.com

Abstract. In modern society, the problem of electricity is becoming more and more acute. Until now, most of the electricity has been produced from non-renewable sources: oil, gas, coal and the like. Moreover, the use of such resources leads to environmental pollution and depletion of the Earth's interior. Despite the lack and finiteness of non-renewable energy resources, we can still face excessive energy production. This problem arises due to the fact that it is impossible to accurately predict in advance the amount of electricity that the consumer will need. This, in turn, entails obtaining a significant amount of unused electricity. The use of virtual power plant technology will help to solve this problem. Nowadays, mobile technologies that allow you to solve important issues and problems from anywhere in the world are becoming increasingly popular. These portable technologies, along with the technology of a virtual power plant, will simplify the control of electricity production and costs.

Keywords: Virtual power plant, Industry 4.0, Internet of Things, energy consumption, renewable energy

Citation: Kozhubaev Yu.N., Kazanin D.S. Optimization and control system of power consumption based on virtual power plant technology. Computing, Telecommunications and Control, 2023, Vol. 16, No. 4, Pp. 37–48. DOI: 10.18721/JCSTCS.16404

Научная статья
DOI: https://doi.org/10.18721/JCSTCS.16404
УДК 004.04

СИСТЕМЫ УПРАВЛЕНИЯ И ОПТИМИЗАЦИИ ЭНЕРГОПОТРЕБЛЕНИЕМ НА БАЗЕ ТЕХНОЛОГИЙ ВИРТУАЛЬНОЙ ЭЛЕКТРОСТАНЦИИ

Ю.Н. Кожубаев[1] ✉ , *Д.С. Казанин*[2]

[1] Санкт-Петербургский горный университет,
Санкт-Петербург, Российская Федерация;

[2] Санкт-Петербургский политехнический университет Петра Великого,
Санкт-Петербург, Российская Федерация

✉ y.n.kozhubaev@gmail.com

Аннотация. В современном обществе всё более остро встаёт проблема электроэнергии. До сих пор большая часть электроэнергии производится за счёт невозобновляемых источников: нефть, газ, уголь и подобных. Более того, использование некоторых подобных ресурсов влечёт за собой загрязнение окружающей среды и истощение недр земли. Несмотря на недостаток и конечность невозобновляемых энергоресурсов, мы до сих пор можем столкнуться с избыточным энергопроизводством. Данная проблема возникает вследствие того, что заранее нельзя точно предсказать объем электроэнергии, который потребуется потребителю. Это, в свою очередь, влечёт за собой получение довольно значительного объема неиспользуемой электроэнергии. Использование технологии виртуальной электростанции позволит помочь с решением данной проблемы. В наше время всё большую популярность получают мобильные технологии, которые позволяют решать важные вопросы и проблемы из любой точки планеты. Данные портативные технологии в сочетании с технологией виртуальной электростанции позволят упростить контроль производства и затрат электроэнергии.

Ключевые слова: Виртуальная электростанция, Индустрия 4.0, Интернет вещей, энергопотребление, возобновляемая энергия

Для цитирования: Kozhubaev Yu.N., Kazanin D.S. Optimization and control system of power consumption based on virtual power plant technology // Computing, Telecommunications and Control. 2023. Т. 16, № 4. С. 37–48. DOI: 10.18721/JCSTCS.16404

Introduction

The Fourth Industrial Revolution, also known as the Digital Revolution or Industry 4.0, aims at improving the quality of life for all segments of society by integrating accessible digital technologies into everyone's daily life [1–3].

The digital revolution includes various aspects based on various systems: physical systems (CPS), Internet systems (iOS) and the Internet of Things (IOT) familiar to many [4–6].

This industrial revolution can be characterized by the introduction of more flexible technologies for mass-demand goods, which entailed a transition to a new, qualitatively different level of production automation. In turn, more competent and economical energy consumption and the transition to renewable sources of electricity are also important.

Industry 4.0 covers many areas of scientific, industrial and information activities, such as additive manufacturing, the Internet of Things, cloud computing, modeling and much more.

In general, the mathematical formulation of the optimization problem consists in determining the largest or smallest value of the objective function $f(x1, ..., xn)$ under the conditions $gi\ (x1, ..., xn) \le bi\ (i = 1, ..., m)$,where f and gi are set functions, bi are some real numbers. If all f and gi are linear, then the corre-

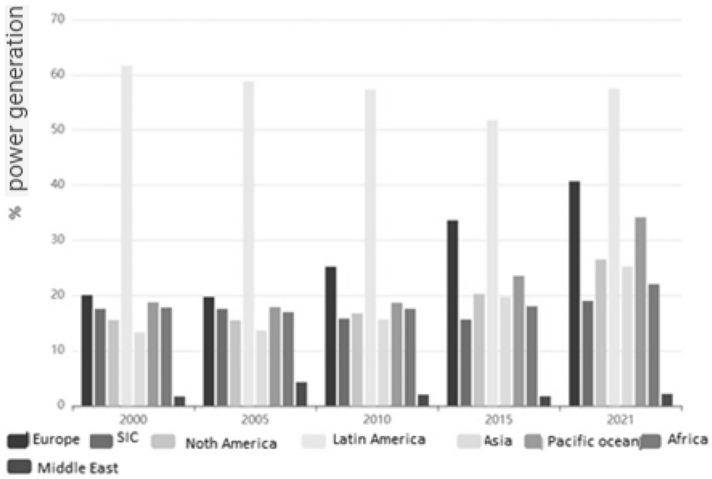

Fig. 1. The trend of renewable energy generation [10]

sponding problem is a linear programming problem. If at least one of these functions is nonlinear, then the corresponding problem is a nonlinear programming problem. Let $z = f(x1, x2, ..., xn)$. Then we can write: z*max (min) and gi $(x1, ..., xn)$ £ bi, $i = 1, ..., m$.

This model can be interpreted as follows to the problems of choosing the best options for economic behavior: z is the optimization goal of the economic system; $f(x1, ..., xn)$ is the corresponding objective function; $x1, x2, ..., xn$ are indicators of the degree of using the means to achieve the goal, which can characterize the output of different types of products, equipment utilization, resource use, etc.

gi $(x1, ..., xn)$ is a function of the total cost of funds of the i-th group used to achieve goals;

bi are the marginal limits of the total cost of funds of the i-th group, are fixed by a restriction on gi (x) above.

The best results are shown by a model using various concepts of the Industry 4.0.

Alternative energy

The main aspect of the Fourth Industrial Revolution is the receipt and proper use of electricity and the transition from non-renewable sources of its production to renewable ones.

Renewable energy or, as it is also called, alternative energy is obtained from natural sources that do not deplete the environment (solar, wind, water, etc.). This type of energy is becoming increasingly popular, because within the framework of Industry 4.0, environmental protection plays an important role if it is necessary to obtain a fairly large amount of electricity [7–9].

In the future, it is assumed that over the next two to three decades, more than two-thirds of the electricity received will be produced from renewable sources.

However, it is worth noting that one of the most important problems is not only obtaining the vast majority of energy resources from renewable sources, but also their competent distribution. This problem arises because of the distance between clean energy sources and the distribution and storage centers of energy resources.

As a solution to this problem, it is possible to introduce a digitized energy network in which all routes of energy resources, places of their shortage and excess will be most transparent. Of course, for a more flexible and accurate management of this network, it would be necessary to involve the consumer in it, but already in the intermediary role in the transfer of energy resources.

Gradually, consumers will be able not only to use and transmit electricity, but also to store, produce, purchase, sale, and manage the course of stored electricity. New scientific developments are already heading in the direction of the most effective ways for users to carry out all these operations [10–12].

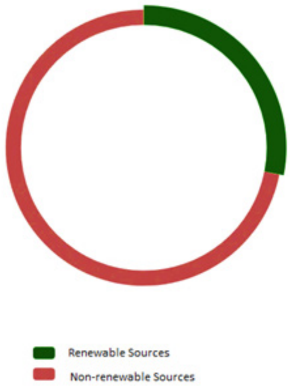

Fig. 2. Share of renewable energy for 2021 [10]

As part of all this, new virtual environment markets and various intelligent platforms will gain even more weight. They will facilitate and accompany the emergence of new business models that allow individuals or different communities to control energy consumption and utilization.

Based on all this, according to forecasts, the formation of an energy system in which the consumer will be able to sell his excess energy will begin by 2030. Within the framework of Industry 4.0, everyone will be able to contribute to the development and change of the entire society and economy.

Using the Internet of Things in the energy sector

The reduction of economic problems to optimization models of solutions, which are a concretization of the general problem of mathematical programming, is based on a number of initial assumptions about the nature of the analyzed economic processes and the choice of the best solutions.

One of these optimization models may be a model for the exchange of excess electricity using the Internet of Things.

The Internet of Things (IoT) is a sector of progressive information technologies, which includes many different aspects.

Various consumer solutions can be attributed to IoT, such as "smart home", intelligent and interactive personal gadgets and various types of intelligent technology. Also, various business and industrial solutions can be attributed to the Internet of Things.

Various devices with their own built-in module or IoT chip are best suited for creating a common network in which various operations will be transmitted in real time. If we add data exchange and two-way communication, we can get a solution for data monitoring and processing, as well as the ability to remotely monitor various operations [13–15].

Smart meters based on IoT can be perceived as intelligent systems for the consumer segment that will help in creating a common network. After all, IoT is a network of physical carriers that have the ability to exchange data. If we apply this concept to utility meters, we will be able to integrate various utility and energy companies into the smart grid that contribute to the distribution, storage and control of energy resources.

Smart meters, which will form the basis of the power grid, will allow utilities to receive and provide complete information about electricity flows. This, in turn, will allow end-users to have better control over their investments in the energy network.

However, this approach requires some solutions from telecommunications and electrical networks. After all, reliable and convenient data transmission technology is necessary for the correct operation of the entire IoT meter infrastructure. For example, it would be quite difficult to use power lines in an intelligent network for communication, even though it is used in Europe. The use of wired telephone networks for

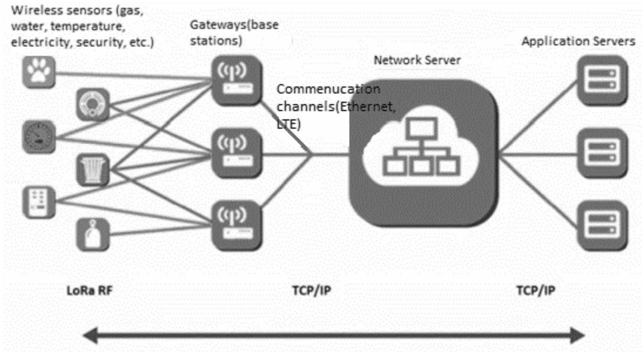

Fig. 3. LoRaWAN

the purpose of transmitting meter data is also often difficult. In this regard, for the counter to work on the IoT platform, a reliable connection is necessary, which cannot always be provided [16–18].

A broadband Wide Area Network (LoRaWAN) can be used as one of the possible solutions to this problem. It was specially designed to support devices on the IoT platform. This modern network solution uses several ISM band frequencies, which depend on the region of application.

Although this technology can only support some specific bandwidth for each device, but this approach is much more deterministic and systematic. For example, meters for the disposal of gas emissions can be mounted independently of the main source of energy supply.

In addition, the service life can reach up to 15 years, thanks to the low power consumption functionality of the LoRaWAN network. The range of such a network can vary from 4 to 20 km, which is a significant advantage for creating a complete infrastructure of meters on this basis.

As an example, one of these networks, which is currently considered the largest LoRaWAN network, is being built by Tata Communications in India. Such a large network on the open IoT platform can be used not only for smart meters, but also as one of the most important components of smart cities [19–21].

The following points can serve as criteria for choosing the Internet of Things for optimization and management:

Cost reduction. The Internet of Things allows you to reduce financial costs when managing energy consumption. Enterprises and individuals reduce energy consumption by controlling and optimizing it using Industry 4.0 concepts. Energy storage technologies and the use of renewable energy sources can help reduce energy consumption.

Improving efficiency. The Internet of Things and cloud solutions can improve energy efficiency by automating energy-intensive processes and optimizing energy consumption. This can help businesses and individuals reduce energy consumption and increase productivity.

Processing large amounts of data. By collecting and analyzing energy consumption data, IoT and cloud solutions enable businesses and individuals to make data-driven energy use decisions. This can help them identify areas where energy is being wasted and make informed decisions about energy use, resulting in cost savings and increased sustainability.

Smart buildings. IoT and cloud-based energy management solutions are also evident in smart buildings. With automation and sensors, smart buildings can optimize energy consumption and reduce costs. Smart building solutions include smart thermostats, lighting, and energy-efficient HVAC systems.

Virtual Power Plant Technologies

Due to the high demand for electricity, there is also a need for clear control over the activities of each power plant. The virtual power plant technology copes with this very well. Virtual power plants are software and hardware complexes that allow managing numerous power generation plants, as if they were a single power plant.

Special software distributes electricity between end users, as well as allows you to store "surpluses" that can be used in the future to compensate for deficiencies during daily production declines. An important and responsible part is precisely the dynamic (and real-time) distribution of power supplies between consumers. This is a rather complex process in which many different factors have to be taken into account: the number of consumers, their relative location (their coordinates), the location of adjacent and responsible energy sources, the parameter of terrain variability and the scale factor. Depending on all this, load centers will be calculated. They are calculated using the method of potential functions and the formula:

$$\prod(x, y) = \sum_{(i=1)}^{n} \left[P_i * e^{-a*\left[(x-x_i)^2+(y-y_i)^2\right]} \right], \tag{1}$$

where n is the number of consumers; x and y are the coordinates of these consumers; P is the power of the consumer; and a is the parameter of terrain variability.

The extremes of this function will be the optimal locations of power sources. In turn, consumers are divided into groups corresponding to the coordinates of power sources. The distribution is made according to the formulas:

$$x_i = \frac{X * P_i}{\sum_k (P_i)_k}, \tag{2}$$

$$y_i = \frac{Y * P_i}{\sum_k (P_i)_k}, \tag{3}$$

where X and Y are the coordinate vectors of consumers of the i-th group; P_i is the power vector of consumers of the i-th groupv; and k is the group number.

Another important aspect of such software is the presence of self-learning artificial intelligence, which allows you to predict production declines and excessive peaks in advance. By optimizing traffic within a single power grid, such software allows you to smooth out unnecessary deviations, which, in turn, has a positive effect on the performance of the entire power grid. As the power grid can include such units as various energy producers (solar power plants, thermal power plants, hydroelectric power plants), virtual power plants, therefore, figuratively speaking, there can be an exchange between sellers and buyers of electricity [22–24].

One of the goals of the virtual power plant is the possibility of joint energy trading and the flexibility to manipulate the production of this very energy. In turn, any decentralized unit for the production, consumption or exchange of electricity can be integrated into the public network of a Virtual Power Plant.

This system structure includes:

1. Energy producer
2. The consumer
3. Accumulators for energy storage
4. VoIP gateways
5. Software for managing the overall operation of the network

Since virtual power plants consist of network assets that produce energy from alternative (renewable) sources, the total capacity of such a station can constantly change. In order to reduce fluctuations in the production capacity, assets of a different nature of energy generation should be used as part of such a station. For example, if there was a sunless season, wind generators or hydroelectric power plants could compensate for this shortage. Rapid adaptability to environmental conditions and consumption volume is one of the main distinguishing features of a virtual power plant relative to conventional power plants.

A large amount of different data and commands is transmitted inside the virtual power plant. For this purpose, a highly secure bidirectional connection is used. Such a connection between each individual asset and the power plant allows for a constant data exchange in real time, which in turn allows for timely monitoring of the free capacity of the assets, and hence the entire virtual power plant. This kind of data also allows you to forecast electricity costs in a timely manner and control pricing in the electricity market [25–27].

Within the framework of Industry 4.0, of which Virtual Power Plants are a part, the digitization of electricity is an irreversible process. In modern realities, electricity production is increasingly moving from large power plants powered by fossil fuels to smaller decentralized power plants using alternative energy sources, which are already combined into a common Virtual power plant.

Like various intermediary platforms, such as hotel booking platforms that do not own a single hotel or various car rental services that do not have their own fleet of vehicles, virtual power plants will be a kind of a management tool for interconnected energy assets.

Such an approach to the distribution of electricity can be much more profitable than the one we are used to, because the number of electricity consumers is increasing every day. The number of electric motors and electric vehicles is growing, the number of network hubs and distributed computing centers is increasing. In order to meet all the growing needs for electricity, the decentralization of energy supply and a hybrid approach to obtaining electricity can become key tools in providing the electricity market with all the necessary assets.

Prepayment system

For full-fledged decentralization and the formation of a full-fledged electricity market, reliable and convenient ways to pay for this energy and some currencies that will embody a certain amount of energy being bought or sold are needed.

If we take a living example from European countries, the UK has taken a big step forward in this matter and introduced prepaid meters.

But in this particular example there are some disadvantages:

1. The operation of their counters is based on smart cards, the balance of which can be replenished and from which funds are debited for a certain amount of energy spent. This approach implies some physical medium, the use of which is not always convenient and cost-effective.
2. Such smart cards are not convenient because in order to replenish them, you need to contact special replenishment points, which, in turn, entails time and sometimes financial costs.
3. One of the main problems is the renewal of meter tariffs. On older samples, this happens manually, which can take quite a long time. This entails situations when the new tariff becomes less profitable, but the consumers lack this information and fail to calculate the costs properly, with inadequate funds debited from the smart cards at the end of the month.
4. There is no bidirectional energy exchange channel in this system. This does not allow end users to act as an energy supplier.
5. Finally, the problem lies in the fact that the tariff payment is monthly. This eliminates the opportunity to save on energy and build a correct plan for its consumption.

Some of these problems can be solved by implementing a token-based prepayment system. For example, we can introduce some equivalent transfer from rubles to a unit of energy exchange and call it Watt (Wt). These will be conditional virtual units of payment for physical energy. For example, you can open a personal account in your name and store a certain amount of Wt on it. Since this currency is not physical, then the costs of its production, maintenance and storage are minimal [28–30].

This approach can be compared to the work of the banking system, in which a separate virtual power plant can act as a bank. The introduction of various mobile applications allowed banks to reduce their financial costs for maintaining the system and at the same time allowed users to manage their financial

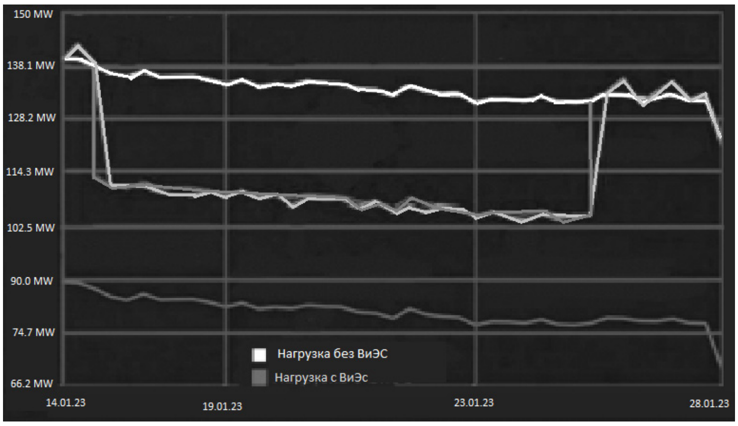

Fig. 4. Modeling of a system with and without VPP

affairs from anywhere in the world, at any time and transparently monitor all transactions with their accounts [31–33].

In the concept of Virtual Power Plants, it is possible to create a system similar to a banking system, where Wt will be the single currency. The storage of this currency on the account allows the consumer to secure the right to receive the appropriate amount of electricity. End users will be able to buy, sell and replenish the amount of Wt that they have on their accounts, and it will also be possible to exchange this virtual currency in a ratio of 1 to 1 for real electricity [34–35]. As an example, the beGateway organization uses this system and provides it to various organizations. In addition, some of the cryptocurrencies (Bitcoin, Ethereum etc.) can also be taken as tokens.

Results

To demonstrate the advantages of the virtual power plant operation, a simulation was carried out based on the indicators of the Dutch power plant with and without the use of virtual power plant technology. The simulation results can be seen on the graph (Fig. 4).

As can be seen from the graph, using the technology of a Virtual Power Plant (VPP), it is possible to obtain the released power within 20 MW. Of course, these indicators may vary depending on the terrain and related technologies. The released capacity can be transferred to other areas where there is a shortage.

For greater convenience and universal use of these systems, convenient mobile applications are being developed. It is necessary that this application is available for any type of installation: both through the APK file and through the built-in applications of Play Market, Apple Store and others. We have developed a blank mobile application that will provide the most understandable user interaction with the virtual power plant service.

Authorization can be done by phone number using the method of double authentication (Fig. 5).

The main page should be as clear as possible for the user and should not overload them with a large amount of information (Fig. 6).

The Kotlin language was used to develop the mobile application. Development was carried out according to the MVP pattern and the CRUD paradigm. Since the application is under development, at the moment its functionality is limited to several functions:

1) User authorization
2) Balance monitoring
3) Linking bank cards to your account
4) Security Settings
5) Display usage statistics

At the moment, there are no applications aimed at solving this problem on the market.

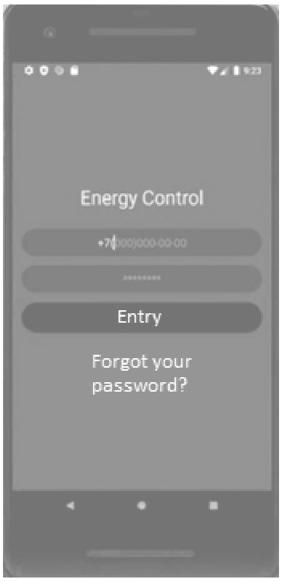

Fig. 5. Authentication screen

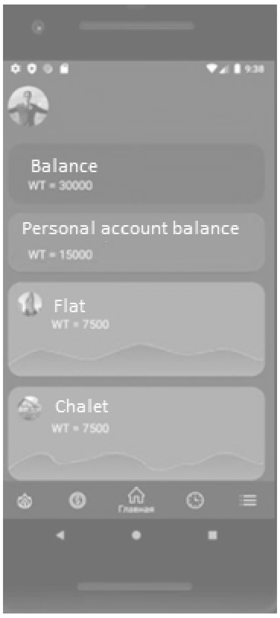

Fig. 6. The main application screen

Conclusion

The approach to obtaining and distributing electricity using virtual power plant technology is advanced and promising. It has many advantages:

1. Reduction of electricity tariffs. This solution allows each individual to regulate the required amount of electricity received, which allows optimizing the consumption of excess capacity.

2. Improved forecasting of electricity generation. Thanks to information from users' electronic accounts, it is possible to predict the consumption and the required amount of energy produced.

3. Consumer convenience. Mobile applications and a convenient format of interaction with the system of virtual power plants will allow us to form the most convenient way to exchange the existing data.

REFERENCES

1. **Guan T., Lin H., Sun Q., et al.** Optimal configuration and operation of multi-energy complementary distributed energy systems, Energy Procedia, 2018, Vol. 152. Pp. 77–82. DOI: 10.1016/j.egypro.2018.09.062

2. **Shklyarskiy Y.E., Batueva D.E.** Operation mode selection algorithm development of a wind-diesel power plant supply complex. Journal of Mining Institute, 2022, Vol. 253. DOI: https://doi: 10.31897/PMI.2022.7

3. AutoGrid Virtual Power Plant. Available: https://www.auto-grid.com/products/ virtual-power-plant/ (accessed 16.03.2020).

4. **Safiullin R.N., Afanasyev A.S., Reznichenko V.V.** The Concept of Development of Monitoring Systems and Management of Intelligent Technical Complexes, Journal of Mining Institute, 2019, Vol. 237. DOI: https:// doi: 10.31897/pmi.2019.3.322

5. **Kakran S., Chanana S.** Smart operations of smart grids integrated with distributed generation, A review: Renewable and Sustainable Energy Reviews, 2018, Vol. 81, Part 1. Pp. 524–535. DOI: 10.1016/j.rser.2017.07.045

6. **Yakovleva T.A., Romashev A.O., Mashevsky G.N.** Digital technologies for optimizing the dosing of flotation reagents during flotation of non-ferrous metal ores. Mining Informational and Analytical Bulletin, 2022, Vol. 6 (2). Pp. 175–188. DOI: https://doi:10.25018/0236_1493_2022_62_0_175

7. **Aman M.A., Abbasi M.Z., Ali M., et al.** To Negate the influences of Un-deterministic Dispersed Generation on Interconnection to the Distributed System considering Power Losses of the system, Journal of Mechanics of Continua and Mathematical Sciences, 2018, Vol. 13 (3), Pp. 117–132.

8. **Abramovich B.N., Bogdanov I.A.** Improving the efficiency of autonomous electrical complexes of oil and gas enterprises, Journal of Mining Institute, 2021, Vol. 249. DOI: https:// doi: 10.31897/PMI.2021.3.10

9. **Fishov A., Shiller M., Dekhterev A., et al.** Stability Monitoring and Control of Generation Based on the Synchronized Measurements in Nodes of Its Connection, Journal of Energy and Power Engineering, 2015, Vol. 9. Pp. 59–67. DOI: 10.17265/1934-8975/2015.01.007

10. **Beloglazov I., Krylov K.** An Interval-Simplex Approach to Determine Technological Parameters from Experimental Data. Mathematics, 2022, Vol. 10. DOI: https://doi: 10.3390/math101

11. **Ivanin O.A., Director L.B.** The Use of Artificial Neural Networks for Forecasting the Electric Demand of Stand-Alone Consumers, Thermal Engineering, 2018, Vol. 65, no. 5. Pp. 258–265. DOI: 10.1134/S004060151805004X

12. **Ushakov E., Aleksandrova T., Romashev A.** Neural network modeling methods in the analysis of the processing plant's indicators, 2021. DOI: https://doi:10.1007/978-3-030-57453-6_4

13. **Howell S., Rezgui Y., Hippolyte J.-L.** Towards the next generation of smart grids: Semantic and holonic multi-agent management of distributed energy resources, Renewable and Sustainable Energy Reviews, 2017, Vol. 77. Pp. 193–214. DOI: 10.1016/j.rser.2017.03.107

14. **Sychev Y.A., Zimin R.Y.** Improving the quality of electricity in the power supply systems of the mineral resource complex with hybrid filter-compensating devices. Journal of Mining Institute, 2021, Vol. 247. DOI: https://doi: 10.31897/PMI.2021.1.14

15. **Sha A., Aiello M.** Topological Considerations on Decentralised Energy Exchange in the Smart Grid, Procedia Computer Science, 2018, Vol. 130. Pp. 720–727.

16. **Zakharov L.A., Martyushev D.A., Ponomareva I.N.** Predicting dynamic formation pressure using artificial intelligence methods. Journal of Mining Institute, 2022, Vol. 253, Pp. 23–32. DOI: https://doi.org/10.31897/PMI.2022.11

17. **Marah R., Hibaoui A.E.** Algorithms for Smart Grid management, Sustainable Cities and Society, 2018, Vol. 38. Pp. 627–635. DOI: 10.1016/j.scs.2018.01.041

18. **Yakovleva T.A., Romashev A.O., Mashevsky G.N.** Digital technologies for optimizing the dosing of flotation reagents during flotation of non-ferrous metal ores. Mining Informational and Analytical Bulletin, 2022, Vol. 6 (2), Pp. 175–188. DOI:10.25018/0236_1493_2022_62_0_175

19. **Novykh A.V., Mendez Perez J.A., Gonzalez-Diaz B., Sviridenko I.I., Gogolev G.V., Timofeev V.A.** Increasing the Efficiency of Hybrid Power Plants Using Accumulating Devices. Energeticheskie ustanovki i tekhnologii [Power Plants and Technologies], 2018, Vol. 4, no. 3, Pp. 58–66. (in Russ.)

20. **Nurgalieva K.S., Abdullah K.A., Seyed M.A., Slavko N., John William G.G.** Application of Neural Network and Time-Domain Feature Extraction Techniques for Determining Volumetric Percentages and the Type of Two Phase Flow Regimes Independent of Scale Layer Thickness Applied Sciences, 2022, Vol. 12. Pp. 1–13.

21. **Ushakov E., Aleksandrova T., Romashev A.** Neural network modeling methods in the analysis of the processing plant's indicators, 2021. DOI: 10.1007/978-3-030-57453-6_4

22. **Filippov Ye.V., Zakharov L.A., Martyushev D.A., Ponomareva I.N.** Reproduction of reservoir pressure by machine learning methods and study of its influence on the cracks formation process in hydraulic fracturing. Journal of Mining Institute, 2022, Vol. 258, Pp. 924–932. DOI: https://doi.org/10.31897/PMI.2022.103

23. **Shamil I.R., Grigoriev A., Beloglazov I.I., Savchenkov S.A., Gudmestad O.T.** Research risk factors in monitoring well drilling – A case study using machine learning methods, Symmerty, 2021, Vol. 13, no. 7, Pp. 1–19. DOI: https://www.mdpi.com/2073-8994/13/7/1293

24. **Sultanbekov R.R., Beloglazov I.I., Islamov S.R., Ong M.C.** Exploring of the Incompatibility of Marine Residual Fuel: A Case Study Using Machine Learning Methods, Energies, 2021, Vol. 14, no. 8422, Pp. 1–16.

25. **Brilliant L.S., Zavialov A.S., Danko M.U., Andronov K.A., Shpurov I.V., Bratkova V.G., Davydov A.V.** Integration of machine learning methods and geological and hydrodynamic modeling in field development design.Neftyanoe Khozyaystvo – Oil Industry, 2022, Vol. 3, Pp. 48–53. DOI: 10.24887/0028-2448-2022-3-48-53

26. **Romashev A.O., Nikolaeva N.V., Gatiatullin B.L.** Adaptive approach formation using machine vision technology to determine the parameters of enrichment products deposition. Journal of Mining Institute, 2022, Vol. 256, Pp. 677–685. DOI: https://doi.org/10.31897/PMI.2022.771

27. **Lutonin A., Shklyarskiy J.** Topology and control algorithms for a permanent magnet synchronous motor as a part of a vehicle with in-wheel motors. In P roceedings of the E3S Web of Conferences. EDP Sciences, 2021, Vol. 266, Pp. 04001.

28. **Holkar K., Waghmare L.M.** An overview of model predictive control. International Journal of control and automation, 2010, Vol. 3, Pp. 47–63.

29. **Brigadnov I., Lutonin A., Bogdanova K.** Error State Extended Kalman Filter Localization for Underground Mining Environments.Symmetry, 2023, Vol. 15. DOI: https://doi.org/10.3390/sym15020344

30. **Yu S., Fang F., Liu Y., Liu J.** Uncertainties of virtual power plant: Problems and Countermeasures. Applied Energy, 2019, Vol. 239, Pp. 454–470.

31. **Yavuz Levent, et al.** Transformation of microgrid to the virtual power plant – a comprehensive review. IET generation, transmission & distribution, 2019, Vol. 13, no. 11, Pp. 1994–2005.

32. **Yan Q., Zhang M., Lin H., Li W.** Two-stage adjustable robust optimal dispatching model for multi-energy virtual power plant considering multiple uncertainties and carbon trading. Journal of Cleaner Production, 2022, Vol. 336, Pp. 130400.

33. **Pasetti M., Rinaldi S., Manerba D.** A virtual power plant architecture for the demand-side management of smart prosumers. Applied Sciences, 2018, Vol. 8, No. 3, Pp. 432.

34. **Baringo A., Baringo L.** A stochastic adaptive robust optimization approach for the offering strategy of a virtual power plant. IEEE Transactions on Power Systems, 2016, Vol. 32, no. 5, Pp. 3492–3504.

35. **Kasaei Mohammad Javad, Majid Gandomkar, Javad Nikoukar.** Optimal management of renewable energy sources by the virtual power plant. Renewable Energy, 2017, Vol. 114, Pp. 1180–1188.

INFORMATION ABOUT AUTHORS / СВЕДЕНИЯ ОБ АВТОРАХ

Kozhubaev Yuriy N.
Кожубаев Юрий Нургалиевич
E-mail: y.n.kozhubaev@gmail.com
ORCID: https://orcid.org/0009-0006-1822-7117

Kazanin Dmitriy S.
Казанин Дмитрий Сергеевич
E-mail: um-urii@rambler.ru
ORCID: https://orcid.org/0000-0003-0218-9604

Submitted: 15.06.2023; Approved: 13.12.2023; Accepted: 15.12.2023.
Поступила: 15.06.2023; Одобрена: 13.12.2023; Принята: 15.12.2023.