International Journal of Applied Engineering Research ISSN 0973-4562 Volume 11, Number 1 (2016) pp 233-238

Configuration of a standalone hybrid wind-diesel photoelectric unit for guaranteed power supply for mineral resource industry facilities

Aleksey Anatolevich Belsky

National Mineral Resources University (Mining University)
Russia, 199106, St. Petersburg, Vasilievsky Island, 21th line, 2

Aleksandr Nikolaevich Skamyin

National Mineral Resources University (Mining University)
Russia, 199106, St. Petersburg, Vasilievsky Island, 21th line, 2

Emiliia Vladimirovna Iakovleva

National Mineral Resources University (Mining University)
Russia, 199106, St. Petersburg, Vasilievsky Island, 21th line, 2

Abstract

The article addresses choosing optimal scheme of standalone power supply to consumers of mineral resource industry located far from a centralized power supply system using a hybrid wind-diesel photoelectric unit. Substantiation has been made for the configuration and type of generating units in the standalone hybrid electric complex. A structural diagram of a hybrid generating complex has been proposed that ensures flexibility to increase (decrease) the installed capacity of the complex depending on power needs. In addition, the article describes how to improve the electric power quality in electric circuits with independent power sources and semiconductor electrical energy converters that lead to an appearance of high harmonics in the voltage and current.

Keywords: standalone hybrid electrical complex, wind power station, photoelectric plant, permanent magnet synchronous generator, power quality.

Introduction

Currently in Siberia, the Far East, the Arctic Coast of Russia, geological exploration, production of new oil and gas fields, construction of long-distance pipelines for hydrocarbons transportation are underway. However, absence of a substantial remoteness of work locations from centralized power system slow down the process of mineral deposits development and make it more expensive. Nonetheless, about 70% of the country with population pressure people is not covered by the centralized power supply system.

Construction of decentralized power supply systems needs independent sources of electric power using fossil fuels, most common and versatile of which are diesel power plants (DG). Analysis of wind maps and solar opportunities in Russia shows that an alternative to the use of DG is the use of renewable electrical energy, by including own photoelectric and wind power station (PhG and WG) into the scheme of power supply for electric consumers scheme as primary or auxiliary power source. However, in order to increase DG fuel efficiency within complex, batteries and super-capacitors should be included [1,2].

This article deals with solving the actual problem of configuring standalone hybrid energy complex in order to ensure uninterrupted power supply to consumers in mineral resource industry.

Statement of the problem

Duration of autonomous operation of a power-generating complex on the basis of PhG and solar power stations (SPS) together with batteries in low wind and low light conditions is determined by the capacity of buffer batteries. However, the increase in batteries capacity leads to substantial increase in capital expenses, which reduces cost-efficiency of a complex based on renewable energy sources. Therefore, to ensure uninterrupted power supply to consumers, hybrid electric systems are used that include WG, PhG, buffer batteries and super-capacitors, and generator units running on hydrocarbon fuels, most common being Diesel power plants (DG). Use of WG and PhG in a hybrid complex with DG can reduce expenses for purchasing, delivery and storage of diesel fuel, with that, final choice of batteries capacity in the complex is made based on wind conditions (duration and frequency of calms, lighting conditions, average load curve, minimum time of batteries charging from WG, PhG, etc.). However, the scheme of a hybrid complex should ensure certain level of power supply reliability, minimum component structure, high imported fuel efficiency, and should be based on the principle of modularity. These principles make possible to increase (decrease) the total capacity of the complex depending on the needs of the facility in the mineral resource industry without prejudice to technical and economic parameters of the entire power supply system.

Existing schemes for construction of a standalone hybrid wind-diesel photoelectric complex with brief descriptions are shown in Table 1.

Table 1: Schemes of hybrid wind-and photoelectric diesel systems

Scheme number	Scheme number	Brief description
1.1	A system connected via a common AC bus of normal frequency (50 or 60 Hz)	Various energy sources (AC and DC) are integrated through their own AC/AC, DC/AC and AC/DC converters into industrial AC (50 or 60 Hz) frequency power grid from which the AC load is directly connected from the AC-bus, and the DC load is connected via a rectifier (AC/DC) [3]
1.2	A system connected via a common AC bus of high frequency (e.g., 400 Hz)	Various energy sources (AC and DC) are integrated through their own AC/AC, DC/AC and AC/DC converters into high-frequency AC grid (e.g., 400 Hz), and then via an intermediate converter with a DC link are connected to industrial frequency AC bus, which is connected to industrial load. DC load is connected to the intermediate DC-bus converter [4,5]
2.1	A system connected via a common DC voltage bus (DC-bus)	Various energy sources (AC and DC) are integrated through their own AC/AC, DC/AC and AC/DC converters into a DC circuit, from which the AC load is connected via a rectifier (DC/AC converter), and the DC load is directly connected from the DC-bus [6]

Scheme # 1.1 has the advantage of direct load connection and a common AC bus of the hybrid complex, thus ensuring high reliability of power supply from the generating complex. However, this scheme requires complex control systems for coordination of various energy sources and maintaining frequency of the output voltage at the level that corresponds to quality standards for electric power generation.

Scheme # 1.2 by means of the intermediate high frequency bus and the availability of a separate inverter of industrial frequency simplifies the task of maintaining output voltage frequency at the level of quality standards for electric power generation. However, presence of many converters reduces reliability of the system and increases complexity of its control. This scheme may be relevant where a significant portion of the load has non-standard input voltage frequency. There are no such loads in the mineral resources sector.

In Scheme # 2.1, a DC source (PhG, battery) can be connected directly to the DC bus or a DC/DC converter. However, in this scheme, output voltage variable frequency generators (e.g., generators with permanent magnets) connected via DC/DC converters with MPPT algorithms to the common DC bus may be used as AC sources. This scheme does not require synchronization of different energy sources, thus ensuring the principle of modularity of the hybrid complex, which makes it possible to increase (decrease) the installed capacity of the complex depending on power needs. Reliability of AC load power supply is achieved by installing multiple voltage inverters.

Thus, scheme # 2.1 hybrid complex is most suitable as a basis for power supply to mineral resource industry which is characterized by high degree of load non-uniformity during operation.

As a part of a hybrid complex it is advisable to use wind generators with multi-pole permanent magnets and DC/DC-converters with MPPT algorithms. These wind generators operate at variable wind wheel speeds, thus ensuring high efficiency of wind energy conversion [7].

According authors estimate, the most popular hybrid systems for mineral complex will be a power generating station with electrical power from 10 to 500 kW. For the convenience of construction and installation works the maximum unit capacity of WG is advisable to limit by level about 100 kW. The remaining items do not have such limitations. Their power is determined on the basis of economic efficiency. The unit cost of 1 kW installed capacity of the hybrid complex in the Russian market is estimated at 4-5 thousand euro. The cost depends on the operating conditions.

In such conditions, vital task is choosing optimal elements of the power generating unit, namely WGs and rechargeable batteries. This requires consideration of static and dynamic modes of WG operation for charging the batteries in order to determine the influence of WGs and batteries characteristics on system efficiency.

Method

In order to support these objectives, a computer simulation of a hybrid WG incorporated into uninterrupted power supply unit was made in MatLab SimPowerSystems environment. This computer model is shown in Figure 1. System operation was simulated for a WG with synchronous permanent magnet generator with 5 kW rated power at 12 m/s rated wind speed, with a wind wheel having a typical aerodynamic characteristic (nominal speed is Z_{nom}=4).

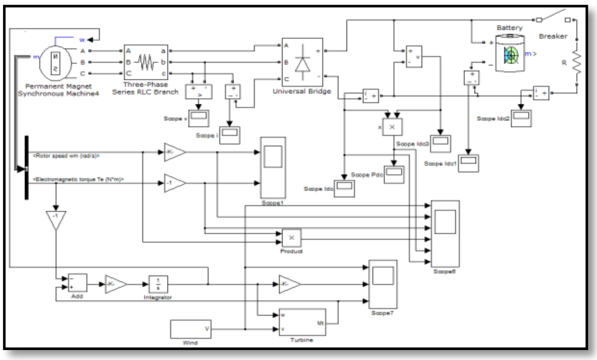

Figure 1: A computer simulation model of a hybrid WG

Computer simulation of wind wheel (windmill) operation in the form of torque to RPM rate at a given wind speed was made in the Simulink environment according to formulas (1) - (3) [8].

Between wind power efficiency *Cp* and relative windmill torque there is relationship defined by the expression:

$$C_p = \overline{M} \cdot Z, \quad (1)$$

whereas *Cp* is wind power efficiency; $\overline{M}$ is relative torque developed by the wind wheel; *Z* is wind wheel speed.

In doing so, for the ease of calculations, the abstract aerodynamic characteristics of wind wheel torque was approximated by a sixth degree polynomial [9]:

$$\overline{M} = a_6 Z^6 + a_5 Z^5 + a_4 Z^4 + a_3 Z^3 + a_2 Z^2 + a_1 Z + a_0 . \quad (2)$$

The coefficients in expression (2) that correspond to a typical aerodynamic characteristic of a three-bladed wind wheel are: a_6=13.6·10^{-6}; a_5=49.9·10^{-5}; a_4=69.1·10^{-4}; a_3=44.5·10^{-3}; a_2=0.125; a_1=0.093; a_0=0.025 [10].
Transition from the wind wheel relative aerodynamic torque to the torque developed by the wind turbine is made according to the formula:

$$M_w = \frac{1}{2}\overline{M}\pi R^3 \rho V^2 , \quad (3)$$

whereas M_w is the torque developed by the wind turbine, R is the radius of the wind wheel, m; [rho] is air density, kg/m^3 (under normal conditions of 1.225 kg/m^3); V - wind speed, m/s.
The remaining elements of the system, including a three-phase synchronous permanent magnet generator (parameters: stator phase resistance Rs (ohm) - 0.22; armature inductance (H) - 0.00165; voltage constant (V peak LL / krpm) - 550; pole pairs p - 20) and rechargeable batteries (lead-acid) with various voltage levels were simulated by means of SimPowerSystems [11].

A. Wind power station and storage element

During the research, waveforms of changes in rotation speed and electromagnetic torque of the generator, generator output power, load power and battery charging current were taken in the conditions of changing wind speed for batteries with various rated voltage. Waveforms were taken at voltages between 24 V (0.154 r.u.) and 120 V (0.769 r.u) at 12 V increments.
From the obtained data about dependence on WG power on wind speed for various rated battery voltages, characteristics of WG were derived relative units (r.u.) as shown in Figure 2. Battery voltage is measured in r.u. and is defined by expression $U^{*}=U_{nom.bat.} / U_{gen.}$ (relation of nominal battery voltage $U_{nom.bat.}$ to the amplitude of linear open-circuit voltage of WG generator $U_{gen.}$=156 V at rated speed).

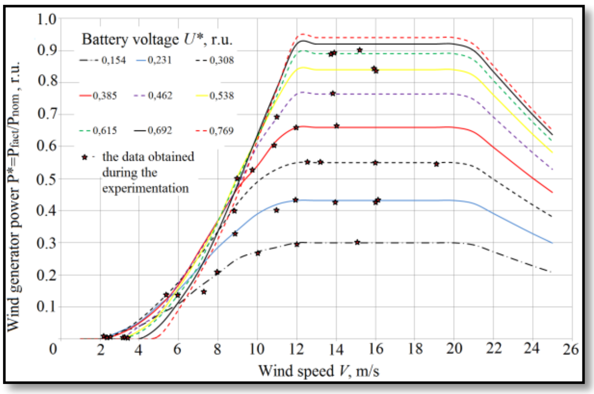

Figure 2: Power characteristics of WG with regard to the variation of nominal voltage of batteries obtained from simulation (lines) and experiments (stars)

The diagram shows that if a higher nominal battery voltage (U*) is selected, the maximum WG power to load (P*) increases, too, at rated (calculated) wind speed for this wind turbine, which is a positive fact. However, when a higher rated battery voltage (U*) is selected, the minimum operating speed of the WG increases, too, which has an adverse effect on efficiency of the wind power unit in areas with predominantly light winds. Thus, depending on wind conditions (taking into account average wind speed and wind speeds distribution by gradations (e.g., Weibull), one can determine the most effective basic (rated) voltage level of the battery, which will ensure maximum power generation of WG for the selected period at WG location.

B. Photoelectric power station

The main parameter when selecting photoelectric modules is the efficiency of converting solar energy into electricity (see Table 2), which determines the cost of a PhG. Currently, most widely used are photoelectric cells with efficiency about 14 ÷ 20% [12]. However, development of technologies for production of polycrystalline silicon makes us expect photoelectric cells with 35% efficiency on industrial scale [13].

Table 2: Basic parameters of photoelectric cells

Cell type	Efficiency, %	Degree of implementation
GaInP/GaAs/Ge	34.7	A laboratory sample has been obtained
Si-cell MCZ-crystalline	24.5	Transition to industrial production
Si-cell FZ-crystalline	21.5	Industrial production
SP e19/238 solar panel	19.1	Industrial production

The widespread under actual level of technology and production development conditions got mono- and polycrystalline silicon modules.
Photovoltaic module has three important parameters. The first is the open circuit voltage Uocv, the value of which depends on the junction potential. The second is the short-circuit current Isc, the parameter is in proportion with the number of electron-hole pairs formed in the *p-n* junction. The third is the full factor FF% of voltage-current plot, which indicates a range of wavelengths of solar radiation catches module.
Selecting power of photovoltaic module in the hybrid complex is determined by climatic and geographical characteristics of the areas on the basis of calculations of gross, technical and economic potential of solar energy, taking into account the internal parameters of solar cells.
Generally the wattage of the photoelectric modules based on the bottom value of solar radiation [14], which is characterized by a region where planned the use of the hybrid complex to produce electrical energy. Insolation reaches the lowest value at the month of December. The formula for calculating power output is:

$$P = I \cdot \cos(\mathrm{g}) \cdot \eta \cdot S \cdot F , \quad (4)$$

whereas I - the bottom value of the solar radiation flux density, g - the total canting angle between the direction of the Sun and the normal to the plane of the photoelectric module, η - efficiency of photoelectric module, F - total

factor takes into account the peculiarities of the photoelectric module and further degradation of its parameters, S - its area.
However under conditions of bare possibility of bottom value of solar radiation S, take into account the average value of solar radiation [15]. This option is valid for the calculation of certain regions of the Russian Federation - Yakutia, the Far East.

C. Diesel power plant
DG as a part of a standalone hybrid complex in conditions of varying load, wind speed and lighting is associated with high instability of the diesel unit load, which affects its efficiency, fuel component of cost of 1 kWh of electricity [16].
Diagram of DG specific fuel consumption with respect to nominal fuel consumption at recommended 80% DG load, depending on the degree of DG load, is shown in Figure 3. The diagram given for a typical diesel generator set with asynchronous generator, running at constant shaft speed, and for a diesel generator set with synchronous permanent magnet generator, working with varying shaft speed [17].

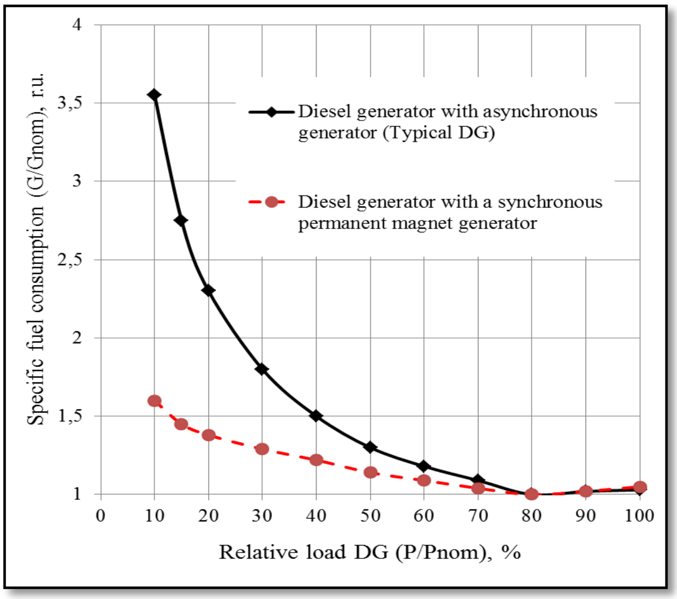

Figure 3: Specific DG fuel consumption

Figure 3 shows that efficient operation of a typical diesel generator with a synchronous generator running at a constant speed is ensured only at 70 to 100% loads, otherwise, if DG load factor is decreased, efficiency falls sharply. With that, DG load of 40 ÷ 70% can be considered conditionally acceptable with increased specific fuel consumption, but lower DG load is unacceptable because it is associated with sharp increase in fuel consumption.
Use of a diesel generator with synchronous permanent magnet generator working at varying shaft speed can increase DG efficiency under partial load up to 80% of the rated efficiency compared to a DG operating at constant engine speed. Thus, as a part of a standalone hybrid power generating complex it is most appropriate to use a DG operating at varying shaft speed, generator output being connected to DC bus of the whole complex via a rectifier and a harmonizing DC/DC-converter.

Results

In view of the above analysis shown, Figure 4, a block diagram, shows the proposed standalone hybrid wind-diesel photoelectric complex. The complex used to guarantee power supply to consumers in the mineral resource industry that comprises WG and DG with permanent magnet synchronous generators, rectifiers, PhG, united by the common DC bus with combined energy storage and general inverter output for connecting load. Hybrid complex topology may vary depending on use of power electronic devices (harmonizing DC/DC converters) in order to minimize dimensions and number of component units depending on the need to increase or decrease power generation.

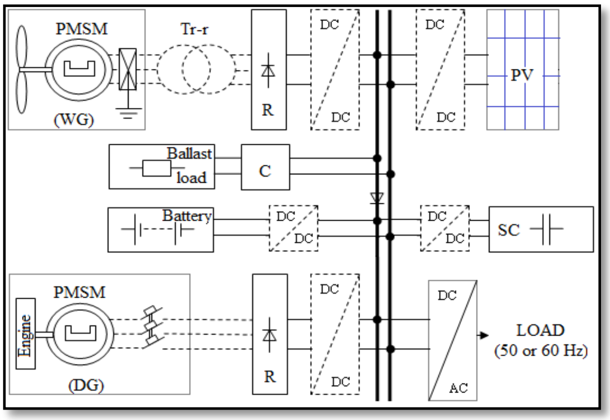

Figure 4: Structure of the standalone hybrid complex

Designations and abbreviations used in Figure 4: WG - wind generator; Tr-r - transformer; DG - diesel generator; PMSM - permanent magnet synchronous motor; R - rectifier; SC - super-capacitor; C - contactor; DC/DC - DC converter; DC/AC - inverter.
In the proposed layout of a standalone hybrid complex, the required amount of WGs, PhGs and DG is determined by required degree of power supply reliability with regard to individual rated power of power plants and stations.

Discussion

In the structure of the standalone hybrid complex presented semiconductor electric energy converters. The operation of such devices is based on the frequent transistor or thyristor switching. Therefore it is necessary to solve the problem of power quality improvement and reduction of high harmonics level in voltage and current. The most popular are the six and twelve-pulse configuration of frequency converters. The other configurations are based on parallel connection of six-pulse groups.
There are different kinds of facility which render possible minimizing generated high harmonics among which mention should be made of: the application of filter compensating devices and active filters [18], effective flowcharting of electric supply and the use of pilot-capacitive devices [19].
The filter compensating device is a simple enough device which is composed of a series-connected reactor and condensers. When there is a change of load configuration and, as a consequence, the change of harmonic configuration of voltage and current curves, it is impossible to secure neutralization of high harmonics in a

necessary volume with the help of filter compensating device.

Active filters are the most modern devices aimed not only at improving electric energy quality from the point of view of high harmonics, but at increasing capacity ratio of electric circuits as well. However, the absence of structures satisfying the conditions of their operation in networks, the high price and little information about electromagnetic compatibility with condenser batteries already existing at enterprises, oblige to search for a solution to the problem of reducing high harmonic level with simpler and less expensive devices and methods [20].

The design of frequency electric drives is made so that the distortions in the supply network are minimal and satisfy the requirements of the National Russian Standard [21] and European Standard [22]. In this case, the disadvantage consists in the high cost of this equipment. In addition, the lack of studies on the influence of high harmonics produced by frequency converters on the electric drive may have a negative impact on its performance.

Minimization of high harmonics is possible due to a decrease of the precircuit resistance (as a rule, it is a system resistance). It is known, that high harmonics in the bus sections appear as a consequence of the tension drop in the system resistance in the mains of industrial enterprises. It follows thence, that a decrease of the system resistance results automatically in a decrease of the influence of high harmonics on the electric equipment operation.

As we can see, each of mentioned means possesses its pros and cons. To choose the most rational of them is a complicated enough task, as besides the economic efficiency there is no other criterion, which could be put into grounds of such a choice. In addition, when we solve the problem of high harmonics reduction in electrical networks with the standalone hybrid complex and semiconductor electric energy converters, we need to have a clear picture of the connected load type and nature.

Conclusion

The article presents guidelines for choosing the conceptual block diagram of a standalone hybrid energy complex for guaranteed power supply to consumers in mining industry. Analysis of various types of diesel-electric generating units has been made, and recommendations have been given for use of DGs with variable shaft speed that ensured optimum specific fuel consumption under varying load. The article describes methods of high harmonics reduction and power quality improvement in electric networks with the presence of the standalone hybrid complex.

Further research will be directed towards the development and improvement of the hybrid complex management system for effective use of each energy source. Research will be focused on the development of a new concept, which is based on the application of AC voltage level on the DC bus for hybrid systems.

References

1. A.M. Tankari, M.B. Camara, B. Dakyo, C. Nichita, “Ultracapacitor integration for short-term energy management in a hybrid system”, *Compel-the International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, vol. 31 (1), pp. 294–312, 2012. DOI: 10.1108/03321641211184986.
2. F. Giraud, Z.M. Salameh, “Steady-state Performance of a Gridconnected Rooftop Hybrid Wind-Photovoltaic Power System with Battery Storage”, *IEEE Trans. Energy Convers.*, vol. 16 (1), pp. 1-7, 2001. DOI: 10.1109/ 60.911395.
3. K. Ch. Karasavvas, “Modular Simulation of a Hybrid Power System with Diesel, Photovoltaic Inverter and Wind Turbine Generation”, *Journal of Engineering Science and Technology Review*, vol. 01, pp. 38-40, 2008. URL: http://www.jestr.org/ downloads/volume1/fulltext8.
4. H.J. Cha, P.N. Enjeti, “A Three-Phase AC/AC High-Frequency Link Matrix Converter for VSCF Application”, *In the Proceedings of the IEEE 34th Annu. Power Electronics Specialist Conference 2003 (PESC’03)*, vol. 4 (15-19), pp. 1971–1976, 2003. DOI: 10.1109/TPEL.2008.2003256.
5. P.K. Sood, T.A. Lipo, I.G. Hansen, “A Versatile Power Converter for High-Frequency Link Systems”, *IEEE Trans. Power Electron*., vol. 3 (4), pp. 383-390, 1998. DOI: 10.1109/APEC.1987. 7067159.
6. C.K. Sao, P.W. Lehn, “A Transformerless Energy Storage System Based on a Cascade Multilevel PWM Converter with Star Configuration”, *IEEE Trans. Ind. Appl.*, vol. 44 (5), pp. 1621–1630, 2008. DOI: 10.1109/TIA.2008.2002180.
7. Ch. Freitag, “*Variable Speed Wind Turbines Equipped with a Synchronous Generator* (masterthesis)”. – Denmark: Aalborg University, 2011. URL: http://projekter.aau.dk/projekter/files /43280847/master.
8. T. Burton, D. Sharpe, N. Jenkins, E. Bossanyi, “*Wind Energy”, 2002*. DOI: http://dx.doi.org/ 10.1002/0470846062
9. H. Petersen, “Simplified Laws of Similarity for Wind Turbine Rotors. The Test Station for Small Windmills”, Riso National Laboratory, Roskilde, Denmark, 1984. URL: http://www.risoe.dk/rispubl/ reports/ris-m-2432.
10. A.A. Belsky, “*Electrotechnical Complex with a Hybrid Wind Power Unit for Guaranteed Power Supply* (master`s thesis)”, National university of mineral resources “Mining”, Saint-Petersburg, Russia, 2013. URL: http://spmi.ru/node/4088.
11. A.A. Belsky, D.I. Ivanchenko, “Simulation of Dynamic Operating Modes of a Hybrid Wind Power Plant”, *AENSI Journals. Advances in Environmental Biology*, vol. 8 (13), pp. 464–467, 2014. URL: http://aensiweb.com/old/aeb_August_ 2014.html.
12. E.V. Yakovleva, “Efficiency of Using a Power Complex with Solar Energy Direct Conversion Photoelectric Station in Republic of Tatarstan”, *Natural and Technical Sciences*, vol. 1, pp. 189-192, 2013.
13. T. Buonassisi, A.A. Istratov, M.D. Pickett, “Chemical natures and distributions of metal impurities in multicrystalline silicon materials”,

Progress in Photovoltaics: Research and Applications, vol. 14, pp. 513-531, 2006. DOI: 10.1002/pip.690.

14. G. Rauschenbach, "*Handbook on designing solar cells: lane. from English*". - Moscow: Energoatomizdat, 1983.
15. E.V. Iakovleva, "*Electrical power supply system for exploration work by using solar power* (master`s thesis)", National university of mineral resources "Mining", Saint-Petersburg, Russia, 2013. URL: http://spmi.ru/node/4088.
16. M.I. Tsyrkin, "DGP-UPS Systems", *Engine-Building*, vol. 4 (202), pp. 6-7, 2000.
17. M.A. Surkov, "*Improving Energy Efficiency of Autonomous Wind-Diesel Electrical Systems* (master`s thesis)". – Tomsk: Tomsk Polytechnic University, 2011. URL: http:// www.lib .tpu.ru/fulltext /a/2011/30.
18. Y.S. Zhelezko, "*Reactive power compensation and power quality improvement*". - Moscow: Energoatomizdat, 1985.
19. I.V. Zhezhelenko, Yu.L. Saenko, "*Power quality control in industrial plants*". - Moscow: Energoatomizdat, 2000.
20. A.N. Skamyin, "Efficiency increasing of condenser batteries operation in mining enterprise`s electric circuits", *Mining Institute Notes*, vol. 189, pp. 107-110, 2011. URL: http://pmi.spmi.ru/ru/zapiski-gornogo-instituta-no-189.
21. EN 50160, 2010. Voltage characteristics of electricity supplied by public distribution systems. British Standard Institute.
22. GOST 32144, 2013. Electric energy. Electromagnetic compatibility of technical equipment. Power quality limits in public electrical systems. Standardinform, Moscow, Russia.