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UNINTERRUPTIBLE POWER SUPPLY SYSTEM FOR MINING INDUSTRY ENTERPRISES

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Immediate problem of compensating falls and deviations of voltage in the power supply systems of mining enterprises in order to ensure the proper level of power supply reliability for the most important technological consumers is substantiated in the article. The main causes of the voltage falls and deviations occurrence in the power supply systems of mining enterprises have been identified. The degree of different nature voltage falls and deviations influence on the dynamic and static stability of power supply systems is established. The necessity of ensuring an uninterrupted and guaranteed power supply mode for continuous technological processes of mining production is shown. The analysis of the existing regulatory documentation in the field of guaranteed and uninterrupted power supply is carried out. Based on the results of experimental studies and mathematical modeling, a relationship has been revealed between formally independent sources of electricity supply from the viewpoint of existing regulatory documentation. The expression allowing determination of cohesion coefficient of two power supply sources is given. The necessity of taking into account the degree of sources interconnection in the synthesis of uninterruptible power supply systems for mining enterprises is justified. The analysis of existing technical means and solutions for reserving power supply for mining enterprises, including modern uninterruptible online power supply systems, own needs power plants, as well as dynamic voltage distortion compensators, is done. The classification of the consumers categories related to possibility of their complete or partial shutdown in emergency modes in case of voltage falls and interruptions is given. System of uninterruptible power supply for mining enterprises based on the combined use of alternative and renewable energy sources, uninterruptible power supply sources and a multi-step automatic reserve transition system, which allows ensuring uninterrupted mode of energy supply for the most responsible consumers of mining enterprises, was developed.

***Key words*:** Mining, uninterruptible, power supply, reserving, generator, alternative, renewable, reliability

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Introduction. The problem of ensuring a continuous mode of electricity supply to the enterprises of Russian Federation raw minerals complex is caused by the remoteness of the main potential deposits from centralized energy systems, the territorial dispersion of production facilities and the continuity of key technological processes [1].

Transmission of electrical energy from a centralized power system is associated with the possibility of short-term disruptions in the electricity supply of consumers in the form of falls and the disappearance of voltage, the source of which is different [1]. The provision of industrial facilities with electric power from the power stations of the power system via power lines (PL) is associated with short-term power supply disruptions (SPSD) of consumers (in the majority of cases in the form of voltage disappearance and falls) that result from short-circuits (SC) and lightning damage. In the absence of own power plants, SPSD are directly transformed into power supply systems (PSS) of enterprises, which can lead to emergency stops of electrical equipment of different voltage classes, affecting the course of the technological process of mining production.

According to the regulations of the Russian Federation Energy Strategy for the period up to 2030, the task is set to increase the debt-neutral indices of the centralized energy systems operation of from 0.996 to 0.9997, which corresponds to the interruption in power supply of 36 hours per year and the approximation of this indicator to international standards of reliability [1]. However, according to the conducted studies and calculations, it was revealed that the level of centralized networks reliability in the Russian Federation is in the range of 0.95-0.97, which is below the regulated index (0.996) and corresponds to an interruption in power supply of 72 hours per year [14]. At the same time, the transition to the regulated level of reliability stated by the Russian Federation Energy

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Strategy, even in the distant future, will require large expenditures to develop and increase the reliability of all elements in the centralized power system. Even in the conditions of such metropolises as Saint-Petersburg, the duration of a power supply interruption can reach 72 hours per year.

The most promising and effective alternative to existing centralized electric grids are distributed generation systems with combined use of alternative and renewable energy sources [2, 3]. For the conditions of mining enterprises, in order to improve the reliability of energy supply for the most important consumers in accordance with the Russian Federation Energy Strategy, parallel operation of centralized electric grids with distributed generation system, based on the combined operation of wind power plants, solar power plants and generator units operating on organic fuel, is necessary, also equipped with fast-functioning devices of multi-stage automatic reserve transition [4-6].

Statement of the problem. According to mentioned above, the falls may be the result of short-circuits not only in external or internal PSS of the enterprise, but directly at the place of power consumption due to the start-up of powerful asynchronous electric motors, starting currents of which are 7-8 times higher than rated ones. The case of electric motors group self-starting requires separate consideration. In this case, it is necessary to divide the behavior of the industrial objects' energy system at different types of changes and disturbances, which will be determined by the type of its stability [7, 11].

Electric power supply of first category electric receivers with a particularly complex, continuous technological process that requires a long time to restore to the normal mode of operation, is recommended, if feasible, to be carried out from two independent mutually reserving power sources, which are subject to additional requirements determined by the features of the technological process.

Methodology. While conducting research, it is necessary to take into account the differences between the terms guaranteed and uninterrupted power supply of the object. Guaranteed is the power supply mode from the main and one or several backup power sources, which limits the duration of possible short-term interruptions in the electric supply of the enterprise's consumers. Thus, short-term power failures in this case are allowed. The mode of power supply from the main and one or several reserve sources is called uninterrupted, when energy supply of the enterprise consumers is carried out in a continuous mode. In addition, the power supply sources for critical facilities should be mutually redundant [9, 20].

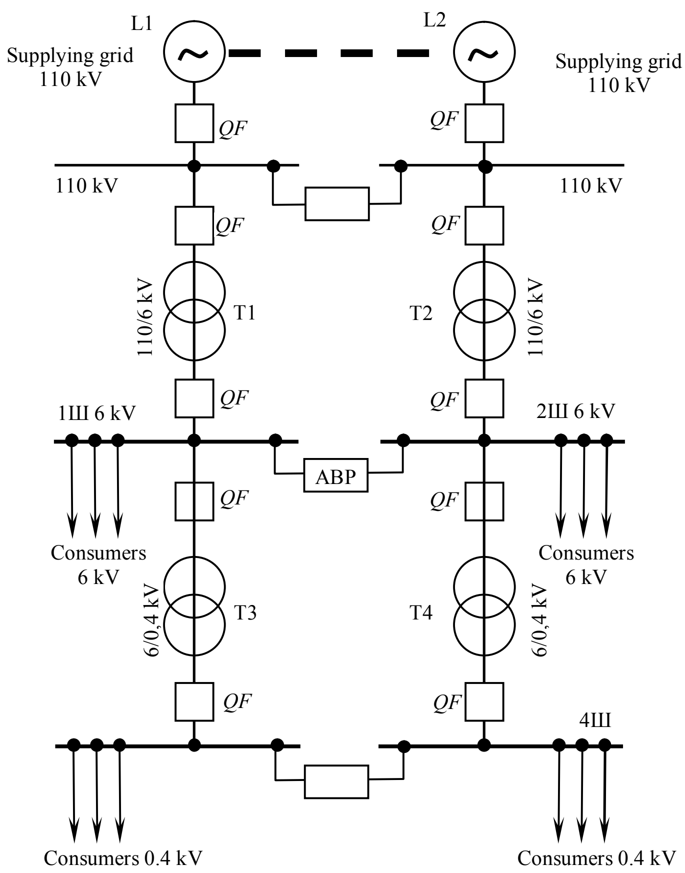

Fig.1. Generalized scheme of mining enterprises PS

The general structure of the mining enterprise PSS with power supply from a single power system is shown on Fig.1. This scheme is characterized by the presence of an electromagnetic link between the lines L1 and L2 [12, 13], i.e. the power sources of the 6 (10) kV buses are not independent. Reliability of electricity supply to consumers for the conditions of LLC

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«Kirishinefteorgsintez», PJSC «Tatneft» and «Gazprom transgaz Saint-Petersburg» can be estimated, taking into account the risk of accidents by the criterion of the technological processes stability.

Evaluation of the consumers' power supplies independence was carried out using the cohesion coefficient of power sources:

$$k_{ch(j,i)} = \frac{\Delta U_j^{SCi} U_{iR}}{\Delta U_i^{SC} U_{jR}},$$

где $k_{ch(j,\,i)}$ – cohesion coefficient of j power source relative to i; ΔU_i^{SC} – voltage deviation of i source at short-circuit (SC); ΔU_j^{SCi} – voltage deviation of j source at SC of i; U_{iR} – rated voltage of i source; U_{jR} – rated voltage of j source.

At short-circuit on 1B in the conditions of LLC «Kirishinefteorgsintez», the voltage at B2 decreased to $0.6U_r$ with the voltage drop on the damaged section to $0.24U_r$ (where U_r is the rated voltage on the buses), i.e. cohesion coefficient of dependent sources k_{ch} = 0,4. The duration of the short-circuit processes was 0.184 sec and resulted in the disconnection of 40 technological units receiving power from the 1B buses. After cutting off the SC, part of the technological units connected to the 2B buses restored normal operation by self-starting the drive motors. Phase currents and process voltages during the considered emergency mode are shown on Fig.2.

In the conditions of PJSC Tatneft, studies of power supply stability in case of damages in the 6(10)/0.4 kV field power lines of the Ashalchinskoye field with difficultly recoverable hydrocarbon

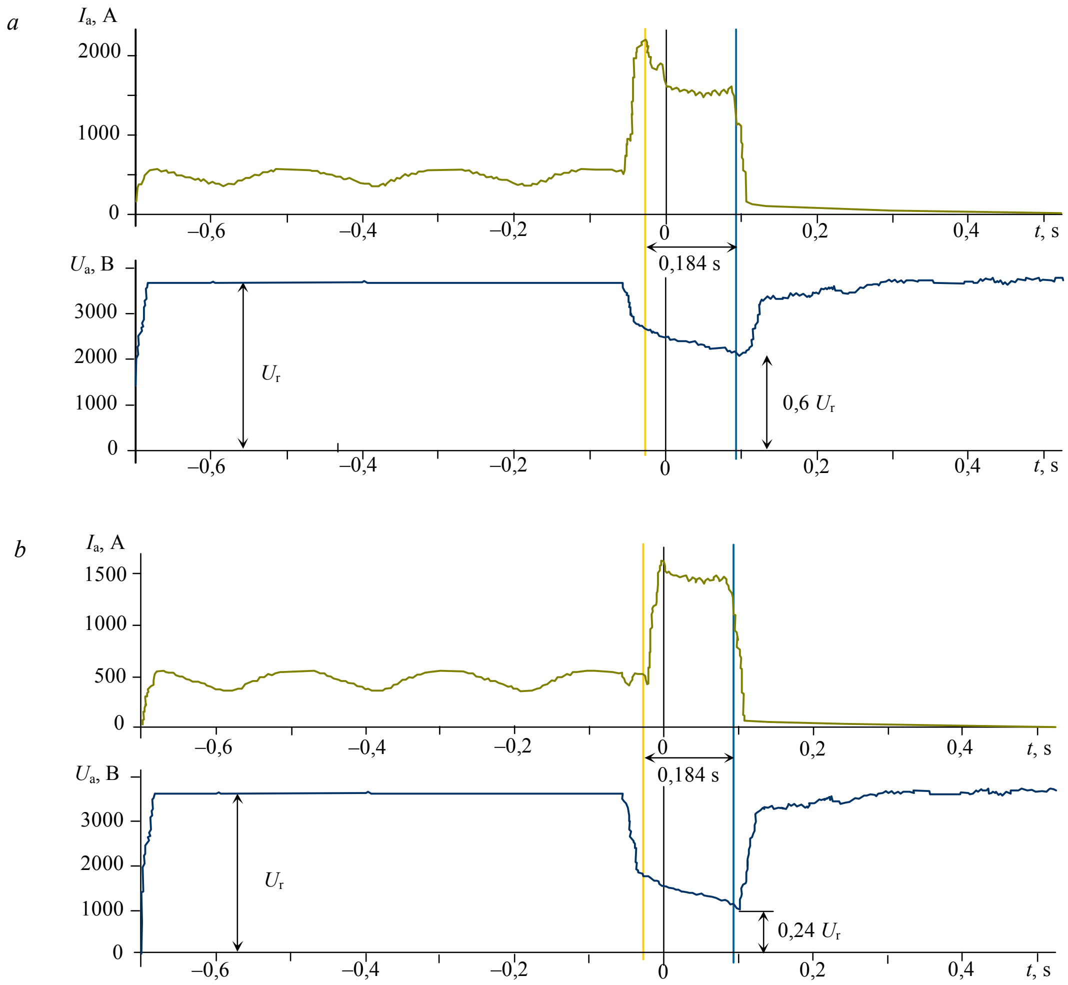

Fig.2. Current and voltage of phase A bus terminals 1B (*a*) и 2B (*b*)

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recources were carried out. To support the technological production process on this field, a boiler plant consisting of six units with a total capacity of 150 MW that generates steam for injection into the wells was introduced. The power of the fans and breathers was supplied from two sections 1B and 2B of busbars with a voltage of 0.4 kV, not directly connected to each other. In addition to significant energy costs, there were problems with ensuring stability of the steam generation process due to faults and failures caused by damage in the systems of external and internal power supply.

Over half a year, more than 40 emergency shutdowns of the steam generation process were registered, which resulted in a disruption of the production process continuity. To determine the cause of emergency stops caused by the SPSD in the UEG and the external PSS of the field, as well as the cohesion of the supply lines on the higher voltage side, the quality control of electrical energy was performed with the help of «Resurs-UF» devices [8, 17, 18].

The table shows several results of electrical energy quality measurements in these networks using the «Resource-UF» devices. Voltage falls on the section 1B with a duration of up to 0.24 s reached 70 % and led to the shutdown of the boiler house fans and breathers. The voltage failures on the 2B section reached the same values and led to the disconnection of the corresponding technological devices.

Depth and duration of voltage falls at phases A, B and C of 0.4 kV busbars, not connected electrically

Time	Section 1B. Resurs UF N 1677						Section 2B. Resurs UF № 861					
	Phase A		Phase B		Phase C		Phase A		Phase B		Phase C	
	δU, %	Δt_{br}, s	δU, %	Δt_{br}, s	δU, %	Δt_{br}, s	δU, %	Δt_{br}, s	δU, %	Δt_{br}, s	δU, %	Δt_{br}, s
9:09:52	65.900	0.170	71.800	0.240	70.600	0.160	69.6	0.23	64.3	0.23	70.7	0.24
9:17:06	51.400	0.080	50.800	0.090	51.800	0.100	47.8	0.08	48.3	0.09	48.8	0.08
9:41:15	37.200	0.110	37.000	0.120	37.100	0.110	34.1	0.09	34.2	0.09	33.5	0.09

For a generalized assessment of the power supplies cohesion, simulation of the two- and three-phase short-circuits processes on the buses of substations for external and internal power supply was performed.

Assesment of the cohesion degree of power lines from the unified energy grid was performed using simulation in the MatLab Simulink software. Based on the simulation results of the two- and three-phase short-circuits processes on the substation buses of external and internal power supply, a generalized assessment of the variation in the power lines cohesion is given.

It is established that when the interaction degree and the parameters of the power lines are varying, the change in the cohesion coefficient is in the range from 0 to 0.7, which does not allow the use of quick-acting and thyristor systems (QART and TART), dynamic voltage distortion compensators [10, 16] due to deep voltage falls in adjacent sections of intact substations and power lines.

To increase the technological processes sustainability at enterprises of gas transmission systems, along with power supply from the grid, supply from autonomous diesel generators (ADG) of limited capacity was provided, in particular, at the gas treatment unit for injection (GTUI) of the compressor station «Portovaya». The ratio of the capacities between transformer substation, connected to the power grid, and the diesel generators is 0.05 kV or less. In these conditions, the problem of assessing the allowable quality of electricity generated by reserve generators. Measurements results of the quality indicators of electric energy generated by the reserve sources of the GTUI meet the requirements of state standard 32144-2013. The harmonic distortion coefficient does not exceed 2.38 %. The cost of electricity generated by ADG is comparable to the cost of electricity consumed from the grid. The use of ADG together with the power system allows to increase the sustainability and prevent the disruption of gas transport technological process, as well as to significantly reduce the probability of accidents at GTUI.

Analysis of perspective technical means and solutions. The efficiency of reserve transition is estimated by the time of an interruption in the power supply from the moment when the electric consumer is disconnected from the main power source before switching to the reserve one.

Quick activation of the reserve element is possible only by means of automation. Devices that implement such activation are called automatic reserve transition devices (ART).

As measures of reserving responsible electrical consumers, the following types of electrical devices can be taken:

– various type power stations of own needs (PSON);
– power sources of uninterruptible power supply (static and dynamic);
– voltage distortion dynamic compensators.

The dependence of power sources is greatly influenced by the resistance of the system: the greater the resistance, the higher the cohesion coefficient. For example, with cohesion resistance of 0.1 p.u., and a system resistance of 0.05 p.u. the cohesion coefficient is 0.1, whereas for a system resistance of 0.3 p.u. the cohesion coefficient will increase and become equal to 0.39. The value of the cohesion coefficient is also affected by the cohesion resistance. Obviously, the lower the cohesion resistance, the higher the dependence of power sources. For example, with a system resistance of 0.5 p.u. and cohesion of 0.5 p.u. the cohesion coefficient is 0.28, whereas with cohesion resistance of 0.1 p.u. the cohesion coefficient will increase and become equal to 0.492.

The disadvantage of existing guaranteed power supply systems is the inability to recharge the batteries from the reserve generator - there may be a need for a reverse switching from the reserve power source to the main power supply source, and the battery level may be not sufficient to support the work of uninterruptable consumers during the switching and synchronization of the generators' output voltage phases, and in case of failure of both generators, for accident-free completion of the technological process.

Therefore, the key distinguishing feature of the developed uninterruptible power supply system is the provision of a multi-stage automatic reserve transition (in considered case two stages of reserve transition are considered) while maintaining the required level of batteries' power, and thereby ensuring uninterrupted power supply to responsible consumers.

Proposed technical solution. The developed uninterruptible power supply system, connected to the main power source, contains a reserve power source, and also includes a charger, integrated in the power grid structure, connected to the alternating current buses of the reserve generator by a rectifier and a switch, thereby providing the required level of batteries' charge for power supply of uninterruptable consumers during the subsequent switching between generators. The structure of this system is shown on Fig.3 [15].

For this purpose, a multi-stage automatic reserve transition system has been developed, which ensures uninterrupted power supply for the responsible consumers of the mineral-raw complex facilities.

The categorizing of load disconnection is the division of the entire supplied load into categories, which implies the order of load disconnection in the case of a complete load disconnection (CLD), the disconnection of the partially disconnectable load (PDL) or the reduction of its energy consumption, and the importance of the uninterruptable load (UL) in the technological process. In this case, the power supply of the complex is provided for accident-free completion of the technological process, when it is required to support the work of a certain group of electric consumers.

The proposed system functions as follows. In the normal mode, the electric power supply of all consumers is carried out by an autonomous power station 1. When an emergency situation occurs in the operation of an autonomous power station 1, during start-up and reaching the rated operation mode of the reserve generator 2, the power supply of the responsible uninterruptable consumers is provided by the energy supplied by the battery. Liquidation of the reserve generator's 2 power deficit is carried out by sequential disconnection of the consumers in accordance with the unloading stages. The switching algorithm between the three power supply sources and the coordination of their joint operation is incorporated in the control system 19. When starting the reserve generator 2 and then connecting it, the responsible consumers receive power from the battery 7.

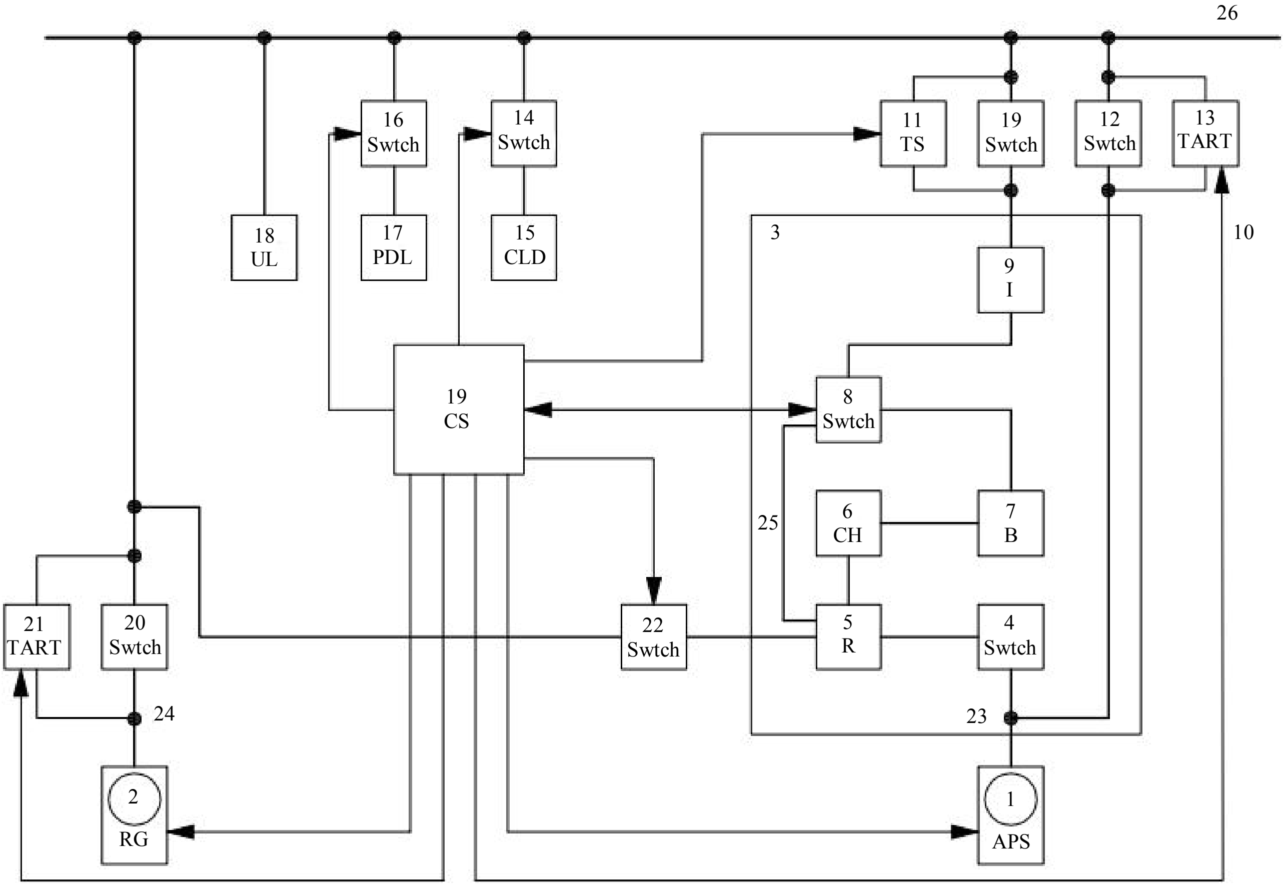

Fig.3. Structural scheme of uninterruptable power supply

1 – autonomous power station; 2 – reserve generator; 3 – power grid connection block; 4 – switch for connecting the rectifier to the bus of an autonomous power station; 5 – rectifier; 6 – charger; 7 – battery; 8 – switch for connecting the battery to the inverter, and also providing power from the batteries and the rectifier; 9 – inverter; 10 – switch for connecting the inverter to the main AC bus; 11 – thyristor switch; 12 – switch for connecting an autonomous power station to the main AC bus; 13 – thyristor device of automatic reserve transition; 14 – means of automatic shutdown of completely disconnectable consumers; 15 – completely disconnectable consumers; 16 – means of automatic shutdown of partially disconnectable consumers; 17 – partially disconnectable consumers; 18 – uninterruptable consumers; 19 – control system; 20 – switch for reserve generator connection; 21 – thyristor device of automatic reserve transition; 22 – switch connecting the alternating current output of the reserve generator to the rectifier; 23, 24 – AC buses powered from an autonomous power station and a reserve generator, respectively; 25 – DC buses connecting the rectifier with a switch for connecting the battery to the inverter; 26 – main AC buses

Synchronization of the voltages U_I at the output of the inverter 9 and U_{RG} reserve generator 2 is provided with help of the thyristor switch 11 and the thyristor automatic reserve transition 21 blocks. Connection of the reserve generator 2 to the main bus of the alternating current 26, excepting current overloads, is possible when phase angle mismatch between the corresponding voltages is within 30 electrical degrees. Otherwise, the current rises up to twofold if the reserve generator 2 is connected to the main bus of alternating current 26 when the phases are in opposition. This leads to the activation of relay protection devices and electric grid automation with the occurrence of a break in the power supply, leading to a violation of the technological process.

To connect the reserve generator 2 without a phase mismatch between its output voltage and the output voltage of the inverter 9, a thyristor device of automatic reserve transition 21 is connected parallel to the switch 20. The thyristor automatic device of reserve transition is intended to ensure operation of uninterruptable consumers in the event of an emergency situation related to the loss of supply voltage at one of the working inputs, with the help of the fastest switching to the remaining input without the occurrence of current overloads.

Optimization of transient processes by the criterion of phase mismatch minimization of the source voltages is ensured by synchronization of the thyristor device of automatic reserve transition 21 switching moment with the angle of voltage phases mismatch on the generator terminals with the voltage at the output of the inverter in the range from 0 to 30 electric degrees, and also occurs control of the voltage recovery process in PSS with automatic switching to the regular power supply scheme after the restoration of the voltage at the input where the failure occurred.

When the normal mode of power supply from the autonomous power station 1 is restored , there is also a risk of increasing the angle of phase mismatch between the voltage U_{APS} at the output of the autonomous power station 1 and the U_{RG} of the reserve generator 2. To prevent this, a thyristor device of automatic reserve transition 13 is connected in parallel to switch 12. After the emergency mode has been eliminated, a thyristor switch 11, connected in parallel to the switch 10, is activated to prevent the power flow from the inverter 9 to the grid. The control system 19 monitors the joint operation of the thyristor device of automatic reserve transition 13 and 21 and the thyristor switch 11 to ensure synchronization of the various power supply sources operation start.

In the case of emergency mode, the energy of the batteries 7 supplied to the most responsible uninterruptable consumers 18 when switching from the autonomous power station 1 to the reserve generator generator 2 must be restored to the rated level, which is achieved with the help of a switch 22 connecting the alternating current bus 24 of the reserve generator 2 to the rectifier 5. The charger 6 provides and maintains the required level of charge on the batteries 7, and the switch 8 does not allow a power flow in the inverter 9, and also provides a constant power supply to the control system 19. In the event of the batteries 7 malfunction, a control system is supplied via the DC bus 25 connecting the switch 8 and the rectifier 5.

Commands for disconnecting disconnectable consumers, supplying critical loads, as well as starting reserve generators, should be executed synchronously [21]. In addition, the grid connection unit can be replaced by an uninterruptible power supply source of dual conversion operating on-line [22].

The power of the batteries (B) should be selected taking into account the constant power supply of the control system while maintaining the rated operating mode of the most responsible uninterruptable consumers for the time of switching between the autonomous power station and the reserve generator, and in the event whereas the reserve can not be started, the capacity of the battery must ensure accident-free completion of uninterruptable consumers' technological processes, which will minimize economic losses.

The choice of capacity and type of power sources largely determine the reliability of electricity supply and quality of electrical energy, as well as the economics of the designed electrical grids.

For selection of uninterruptible power supply source (UPSS) capable of providing continuous power supply to the critical load during SPSD, as well as the start-up of the reserve generator, it is necessary to determine its parameters: source power, time of autonomous operation, type and capacity of used power storage devices.

The choice of uninterruptible power supply source power S_{UPSS} should be based on the analysis of the electric load graphs taking into account their static characteristics and considering the limitations caused by the duration of the reserve power supply start-up as part of the multistage reserve transition system and the allowable depth of the voltage fall and the need for dynamic stability of the first and special group consumers.

Rated power of UPSS can be found by the formula:

$$S_{r.\text{UPSS}} \geq \frac{k_r(1U_D)S_L K_{\text{L.E}}}{K_{\text{UPSS}}},$$

where k_r = 1,1-1,2 – coefficient of reserve according to UPSS recommendations; U_D – allowable reduction of supplied voltage допустимое снижение питающего напряжения by the condition of ensuring the dynamic stability of electric consumers; $K_{\text{L.E}}$ и K_{UPSS} – respectively, the equivalent input power coefficient of the load and the output power coefficient of UPSS.

The amount of energy, stored in the UPSS should be sufficient to ensure the normal operation of the consumers for the time of ART t_{ART} operation and the start and receiving of the load by an independent source (generator), i.e. the operating time from the batteries must satisfy the condition:

$$t_{\text{B}} \ge \frac{t_{\text{ART}}}{t_{\text{gen.res.}} + t_{\text{rec.}}}.$$

Battery capacity:

$$C_{\text{B}} \ge \frac{I_{\text{B}} t_{\text{B}}}{K_g K_D},$$

где C_{B} – required capacity, A·h; I_{B} – current, consumed from B at time of ART, A; t_{B} – time of B operation at time of ART, h; K_g – coefficient of allowable capacity, p.u.; K_D = 0,5-0,7 – coefficient of battery discharge depth, taken according to battery type.

The current consumed from the battery in the period of the ART is determined by the formula:

$$I_{\text{B}} = \frac{P_{\text{load}}}{\eta_{\text{I}} U_{\text{B}}},$$

где P_{load} – average power of the load, W; η_{I} = 0,9-0,95 – efficiency of DC/AC conversion by the inverter; U_{B} – rated voltage of the battery, V.

To improve the reliability of the uninterruptible power supply system, it is necessary to provide timely revision of reserve generators, current and general repairs without reducing the rated load of the power plant, and also consider the effect on the reliability level of the emergency (unplanned) repairs and units reserving.

Discussion. A distinctive feature of the developed system of mining enterprises uninterrupted power supply is the combined operation of autonomous sources with various parameters within the framework of a unified electrotechnical complex. In the event of emergency conditions in the centralized power system, uninterruptible power sources ensure continuity of power supply for the time of start-up and transfer to the rated mode of generators or accident-free completion of the technological process. Switching of power supply between sources is carried out by fast-acting thyristor commutators in a time not exceeding the permissible duration of power supply interruption for the most important consumers. With reference to industrial conditions, the developed system does not have exact analogs, abroad such devices are realized only for power supply of domestic consumers.

Results

1. The immediate problem of falls and voltage deviations compensation in the power supply systems of mining enterprises in order to ensure the proper level of reliability of power supply for the most important technological consumers is substantiated.

2. The main reasons for the occurrence of voltage falls and deviations in power supply systems for mining enterprises have been identified.

3. The degree of various nature voltage falls and deviations influence on the dynamic and static stability of power supply systems is established.

4. Based on the results of experimental research and mathematical modeling, the correlation between formally independent sources of electricity supply from the point of view of existing regulative documentation is found.

5. The analysis of existing technical means and solutions for reserving power supply for mining enterprises, including modern uninterruptible power sources operating online, power stations for own needs, as well as dynamic voltage distortion compensators, is done.

6. A system of uninterrupted power supply to mining enterprises was developed based on combined use of alternative and renewable energy sources, uninterruptible power sources and a multistage automatic reserve transition system, which ensures a continuous mode of power supply for the most responsible consumers of mining enterprises.

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