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CHOICE OF ACCUMULATOR PARAMETERS AND TYPES OF TRACTION BATTERIES FOR THE MINE TROLLEY-BATTERY LOCOMOTIVES

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Abstract. The article sets out the research results of conditions and operation modes for the mine electric locomotives; defined the accumulator parameters and types of traction batteries for the trolley-battery locomotives. In the course were used the methods of system analysis of power consumption for these types of locomotives in the various technological operations, technical and economic performance of batteries of different electrochemical systems, as well as the results of instrumental measurements, mathematical calculations of the parameters of the traction batteries. It was established that the use of the battery-trolley locomotives in the ore haulageways will improve work safety in the load-hauldump underground operations by eliminating the contact wire at low altitudes of an underground working horizon. It was found that the application of lead-acid, nickel-iron and nickel-cadmium batteries for the mine locomotives does not provide necessary levels of reliability, efficiency and safety of operation. Scientific novelty of the work is the analysis of charge and discharge characteristics of various batteries during operation in mines, development of effective control system and traction control of the battery-trolley electric locomotives. To date, the use of lithium-ion and sodium nickelchloride battery types are considered to be a perspective direction. In this regard, development of lithium-iron-phosphate batteries is a useful step towards expelling the above batteries thanks to their lifetime, number of cyclic recharges, charging speed and voltage stability. Another promising type for the mine electric locomotives is the lithium-sulfur battery, which allows to obtain the maximum current density and characteristics similar to lead-acid batteries, and has no risk of fire, explosion, or other hazard. The practical value of given research results is concluded in developing the methods for motivated choice of nominal capacity traction battery, current/voltage values and the definition of the electrochemical systems types of the promising batteries for the mining electric locomotives. The following research results aim at further developing and improving the development of the energy saving and reliable battery for the mine battery-trolley electric locomotives, and implementation of control systems and operation control of the traction battery during exploitation of the mine electric locomotives.

Keywords: trolley-battery locomotives, lithium-ion battery, control system, underground workings (haulageways)

Introduction. At Ukrainian iron ore enterprises, electric locomotives are used to transport iron ore, to deliver materials and personnel in the underground mine workings [1, 2]. In the mine workings of the analyzed types are operated only the trolley-wire locomotives (overhead wire locomotives). They get their power supply from a trolley traction network (TTN) of DC with 250W voltage in the “trolley wire - rail” circuit. In the process of iron ore mining and delivery, the underground mine workings called haulageways are divided into main and loaddump [2]. Their geometry changes because of the technological structure of the mine workings, namely, the cross section of manufacturing and the height of the trolley wire (TW) suspension relative to the manufacturing floor. In the iron ore loading areas, the height of the TW suspension should be at least 1.8m according to safety regulations. In fact, this height can be lower, which is quite hazardous for miners if they accidently touch a trolley wire [3].

In view of this, in the course of electric locomotive operation, miners’ closeness to TWs results in accidental injuries by electric shock and, as a rule, 100% fatal outcome (Fig. 1) [4,5].

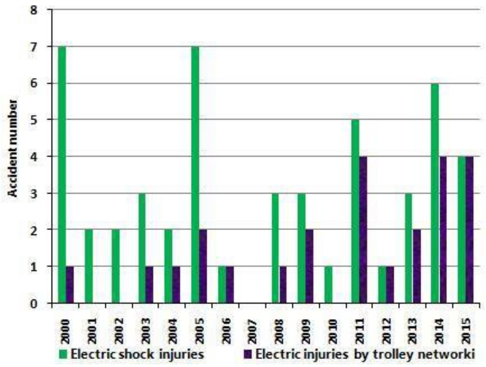


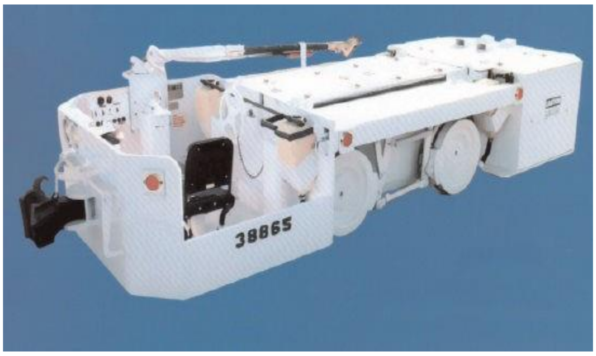
Figure 1. Accident number of electric shock injuries

One of the preventive measures is the introduction of combined electrical locomotives as to their power supply (trolleybattery locomotives). Such foreign producers as A.L.Lee Corporation (USA), ASEA (Sweden), Shandong China Coal Group (China) [6-8] (Fig.2) are developing this type of electric mine locomotives. In this case, at the main haulageways where a trolley wire is at the height safe enough for miners, a locomotive is supplied with power by the TTN. While operating at extremely hazardous places (loading haulageways), the locomotive has a self-contained power supply. Thus, a trolley wire being a major hazard for miners is eliminated [5-10].

Different types of storage devices, accumulators, ultracapacitors, etc. can be used as a self-contained power supply for traction electromechanical complexes (TEMC) in electric locomotives [5-8]. Our research aims at investigating battery traction power supplies.

At the same time, it is worth mentioning that there are two approaches in creating the trolley-battery locomotives. The first approach is realized when the traction battery (TB) voltage is equal to the electric traction network voltage, the second one – when the TB voltage is less than the trolley network voltage and it is sufficient only for a short locomotive transfer at a low speed in case of car transfer in the load and dump mining operations. The authors' preventive study on haulageway conditions in iron ore mining reveals that the TB position with 250 V voltage of traction engines (if powered by the trolley traction network) is impossible because of space limitations of the mine trolley locomotives as well as haulageway size limits [11]. Consequently, a dual purpose arises: the TB should be minimum both in battery capacity and in size.

a



b

c

Figure 2. Total view of the mine trolley-battery locomotives produced by A.L. Lee Corporation (USA) *a*, ASEA (Sweden) *b*, Shandong China Coal Group (China) *c*

The research aims at choosing optimum parameters and types of accumulators for a traction battery of the mine trolley-battery locomotives with adhesive weight of 14-16 t.

Materials and methods. Reasonable choice of the type and parameters TB defines the dynamic characteristics of the electric locomotive and efficiency of the electric locomotive traction system as a whole during operation under the loading points in standalone mode. The level of satisfaction of these requirements is largely determined by the battery as a source of electrical energy. In terms of iron ore mines, electric train is usually formed of 10 trolleys with a carrying capacity of 10 t, driven by an electric locomotive with adhesive weight of 14 t. The nominal value of the current for traction motors in one-hour mode is 200A. Relocation of the trolleys (car transfer) under the loading points is carried out by the electric locomotives according to the loading process technology. The trolleys are relocated twice under the loading points for their completely filling-half of the content for each car. Thus, at least 20 relocations are required to be done by the electric locomotive. Furthermore, due to the inaccurate rearrangements of the train, especially at the end of the loading cycle, the number of permutations increases by on average of 25% that makes up at least 25 movements in total. Referring to the measurements in the mines the duration of the trolley relocation under the loading points is approximately 10 s, and the total time of the reposition is 250 s. Considering, that the currents of two traction motors are 400 A, then the required TB capacity for performing a permutation of all trolleys can be determined as

$$Q_1 = I_p \frac{t_p}{T_h} = 400 \frac{250}{3600} = 27{,}8\,Ah$$

The operation time of the locomotive at a speed of 1 m/s along the 200-meter-length haulageway is about 200s. With an average amperage of 300A of the two motors while driving, the TB capacity consumption while driving of the train along the loading haulageway will be

$$Q_2 = I_d \frac{t_d}{T_h} = 300 \frac{200}{3600} = 16{,}7\,Ah$$

Approximate amperage of 35 A is required for supplying the motor-compressor of the mining electric locomotives with an engine power of 2.5 kW at a voltage of 80 V. Considering the average operation time of the motor-compressor in the loading haulageway of approximately 5 min, the TB capacity consumption will be

$$Q_3 = I_k \frac{t_k}{T_{h_{hh}}} = 35 \frac{5 \cdot 60}{3600} = 3Ah$$

Power lighting circuits of about 500 W at a voltage of 80 V requires a current of approximately 6 A. The TB capacity consumption with the operation time of 15 minutes in the loading haulageway can be

$$Q_4 = I_l \frac{t_l}{T_h} = 6 \frac{15 \cdot 60}{3600} = 1{,}5Ah$$

Taking into account the battery efficiency and extra capacity consumption during the locomotive haul cycle, the total battery capacity will be about 70 Ah.

The given calculations can be approximate and should be specified during further research considering the actual values of the locomotive haul cycle. So, the capacity can be decreased up to 60 A*h by prolonging the battery charging duration due to the intervals between shifts. Taking into account the TB capacity in operation, its rated capacity for 6-7 haul cycles per one shift can make 400 A*h.

TB parameter choice is determined by locomotive haulage requirements: mine car transfer under the loading points (chutes), movement along haulageways, power supply of a motor compressor engine and lighting.

The total TB capacity consumption is $Q_\Sigma = Q_1 + Q_2 + Q_3 + Q_4$ where Q_1 is the TB capacity consumed to transfer mine cars under the chutes; Q_2 is the TB capacity consumed to move the rolling stock along the loading haulageways; Q_3 is the TB capacity consumed to supply power to a locomotive compressor engine; Q_4 is the TB capacity consumed to provide lighting for a locomotive.

While a locomotive is in operation the TB can be boosted taking on average 0,8 hour per a haul cycle. In this case, the boost charge current rate can be determined

$$I_c = \frac{Q_\Sigma}{t_c} = \frac{75}{0{,}8} = 94A$$

The boost charge voltage of an iron nickel battery with U_e=1,6 V per one element and their number n=60 will make

$$U_c = n \cdot U_e = 60 \cdot 1{,}6 = 96V$$

This method of calculation may be the basis for the choice of parameters and modes of operation of the mine trolleybattery locomotive with an absolute view of the TB mass-dimensional values.

The market as a chemical power source for electric produced several types of batteries: lead-acid, lithium ion, sodium nickel chloride and nickel-cadmium. The most accessible and popular lead-acid batteries do not have a high self-discharge, cope with strong loads, are relatively inexpensive, but have a relatively large weight compared to other batteries, require monitoring of electrolyte level and have a high probability of failure. Advanced lithium-ion batteries have such advantages as - large energy density, fast charge batteries (30-40 minutes), low self-discharge, high environmental friendliness, resource - more than 1000 discharge / charge cycles. The disadvantages of these batteries: they may explode if charging or the battery is damaged, limited lifetime - 5 years, the high cost. For sodium-nickel chloride batteries as advantages are: low price and availability at the level of lead-acid batteries, high capacity at the level of the lithium-ion battery, life of more than

1000 discharge/charge cycles, environmental friendliness and safety. The disadvantages of these batteries are: the need to maintain a high operating temperature, cold batteries heating requirement, sensitivity to temperature changes.

On the issue of the performance of different batteries can be noted as follows:

1. Lead-acid battery: Efficiency - 80-90%, operating temperature can range from -40 to +40°C, voltage of the discharged battery -1,8 V, EMF of the charged battery -2,18 V, voltage -2 V, energy intensity - 30-60 *W·h*/kg, life cycle of the battery is 1000-1500 cyclic recharges.

2. Li-ion battery: voltage of the charged element -4,2 V, voltage of the discharged one- 2,75 V, temperature from -20 to +60 °C, charging time - 2-4 hours, life cycle - more than 1,000 battery charge cycles.

3. Sodium-nickel-chloride battery: operating temperature - +300 °C, power consumption - 730 *W·h*/kg, EMF - 2,6 V, life cycle - 1000 cyclic recharges.

4. Nickel-cadmium batteries: operating temperature from -50 to +40 °C, operating voltage – 1,3 V, EMF - 1,37 V, power - 150-500 W/kg, power consumption - 65 W·h/kg. The cycle of life - up to 1000 battery charge cycles A crucial factor in TB application accompanied by traction electric equipment in the mine locomotives is the choice of an accumulator type. Iron nickel accumulators (Ni-Fe) are cheaper than nickel-cadmium ones (Ni-Cd) (Table 1).

Table 1. Options of iron nickel accumulators

Accumulator type	FL350V5	FL500V5
Rated capacity, A*h	350	500
Total dimensions, mm	165×167×538	165×167×538
Mass with electrolyte, kg	20,6	24,0
Mass without electrolyte, kg	16,8	20,2
Battery charging current, A	70	100
Charging time, hour	8,0	8,0
Final voltage, V	1,6	1,6

They do not contain toxic cadmium, have a longer lifetime and a higher mechanical robustness. However, they are characterized by high self-discharge, low energy throughput and almost zero efficiency at a temperature lower -10 °C.

There are three basic types of nickelcadmium accumulators: open-type accumulators with lamella electrodes (pocket-plate cells), accumulators with sintered electrodes (tubular-plate cells) and hermetically sealed accumulators.

Figure 3 shows discharge characteristics of batteries of different electrochemical systems at a constant discharge current, and a temperature of 20 °C for the operating conditions in the mine. As seen in Figure 3, the battery gives the largest amount of its energy on the linear portion of the discharge characteristics.

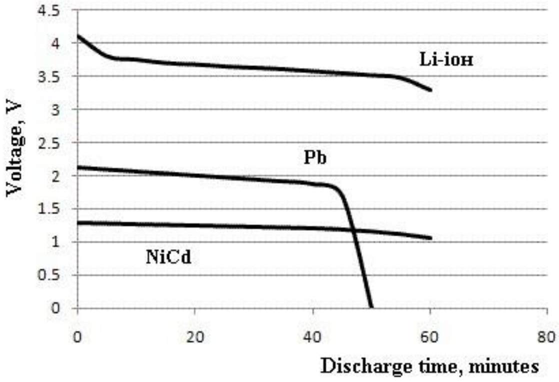


Figure 3. The discharge characteristics of batteries of different electrochemical system

The average value of the energy given by the battery during discharge on the linear portion of the characteristic is defined:

$$W_a=U_a \cdot I_d \cdot t$$

where Ua is average discharge voltage; Id is discharge current; t is discharge time.

The cheapest lamella nickel-cadmium accumulators are characterized by a flat discharging curve, good lifetime and durability, but high specific energy. Specific energy and discharge rate of nickelcadmium accumulators with sintered electrodes are higher, they are efficient at low temperatures. Yet, they are more expensive, characterized by a memory effect and thermal runaway. Sealed Ni-Cd accumulators are characterized by a horizontal discharging curve, high discharge rates and efficiency at low temperatures, but they are more expensive than sealed leadacid batteries and have a memory effect. Toxic cadmium is a disadvantage of Ni-Cd accumulators.

Lead-acid batteries have good performance, and the development of sealed designs raises the question about their use in the mine electric locomotives. The specific weight and volume characteristics of lead-acid accumulators are achieved at the level of 20-50 W·h/kg and 50-100

W·h/l. Unfortunately, the use of active mass coefficient of the lead-acid batteries is low, due to the uneven distribution of the process through the thickness of the electrodes and delivery difficulties of sulfuric acid to the reaction zone. Therefore, the process proceeds mainly on the surface of the plates. At low and intermediate electrode discharge currents is discharged more uniformly and active mass utilization factor is increased, but not more than 65 - 80%. As discharge, internal resistance of a lead-acid battery increases due to increased activity of the masses and the electrolyte resistance. At temperatures below 0 °C increases internal resistance of the battery considerably due to the cooling of the electrolyte. Discharge characteristics of lead-acid batteries are shown in Figure 4.

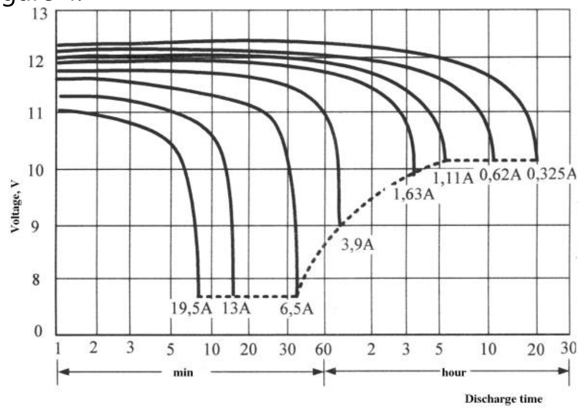


Figure 4. Discharge characteristics of sealed lead-acid batteries

As seen from these characteristics, the final discharge voltage of a lead-acid battery depends on the magnitude of discharge current.

The discharge capacity of a battery depends on the mode of its charge. The best ratio is achieved using the current when the current decreases at the end of the charge which will provide minimal outgassing. The battery charge is carried out either by stepwise reduction of charging current or charging mode transition to a falling current (at a constant voltage). Fig.5 shows charging characteristics of a sealed lead-acid battery to 100% of discharged current of 0,05 C for 20 hours.

The charge is conducted at a DC of 0.1 C at the first stage, and a constant voltage at the second stage. Most manufacturers recommend to charge a battery at a constant voltage of 2,4-2,45 V per cell. From Figure 5 it is clear that up to 90% of capacity, the battery gets charged at constant current.

Required recharge (110% C) may be provided in the charge voltage stabilization mode while reducing the charging current until 0,02 C. Acceleration charging process is achieved by increasing the charging current to the value at least 0,3 C.

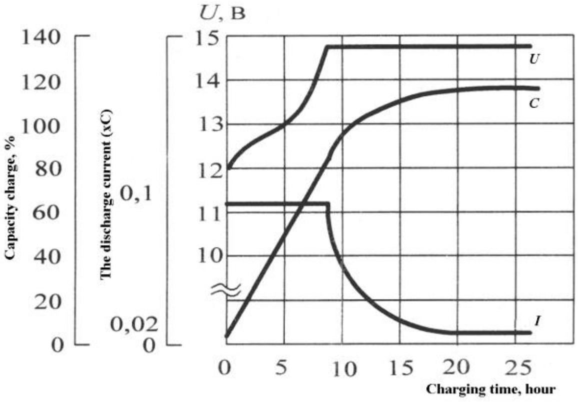


Figure 5. Charging characteristics of the sealed lead-acid batteries

Significant influence on the discharge characteristics of a sealed lead-acid battery has a discharge depth and the amount of charge/discharge cycles. Figure 6 shows the dependence of a battery capacity on the depth of discharge at different amounts of charge/discharge cycles.

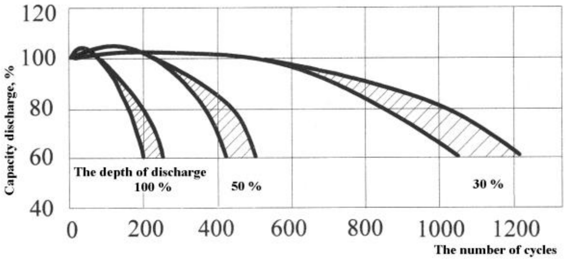


Figure 6. Dependence of battery capacity on discharge depth at different amounts of charge/discharge cycles

Summarizing the analysis and the possibility of using lead-acid batteries for the mine trolley battery electric locomotives,it can be noted that the using of lead-acid batteries has its own advantages and disadvantages. Average discharge voltage in lead-acid batteries is - 2,1V per one cell, while in alkaline accumulators it is 1,1V. In the acid accumulators, discharge energy can be 1,42,1 times higher than that of alkaline accumulators. Yet, it should be noted that in the course of charging the lead-acid batteries in the trolley-battery locomotives (deceleration with electric regeneration, onthe-run boost charge of a locomotive), the occurring chemical reactions can be hazardous, especially in case of high charging intensity. Lead-acid batteries are characterized by oxygen and hydrogen evolution as a result of water hydrolysis, thus increasing the risk of explosions in mine workings. In this case, the charging system should effectively control the battery charging and prevent from hydrogen and oxygen evolution.

In the lithium-ion accumulators for a negative electrode is used carbon material with incorporated lithium ions. Active material of a positive electrode is cobalt oxide also with incorporated lithium ions. Electrolyte is a solution of lithium salt in nonaqueous solvent.

The specific weight and volume characteristics of modern lithium-ion batteries are reached at 100-260 W·h/kg and 250-800 *W·h*/l. Operating voltage of the battery is 3,53,7 V and remains in operation while reducing capacity to a level of 20% C.

Figure 7 shows the discharge characteristics of a lithium-ion battery at a temperature of 20 °C and different discharge currents.

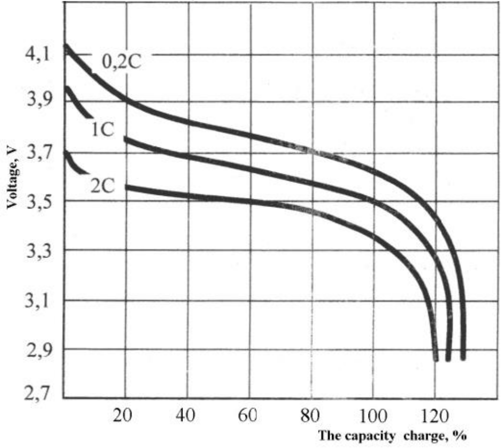


Figure 7. Discharge characteristics of a lithium-ion battery at different discharge currents

As the following graphs show, the degree of reduction in battery capacity has no significant effect on its discharge characteristics.

Also, discharge characteristics with temperature decrease to 0 °C change insignificantly. Figure 8 illustrates discharge characteristics of a lithium-ion battery at different temperatures.

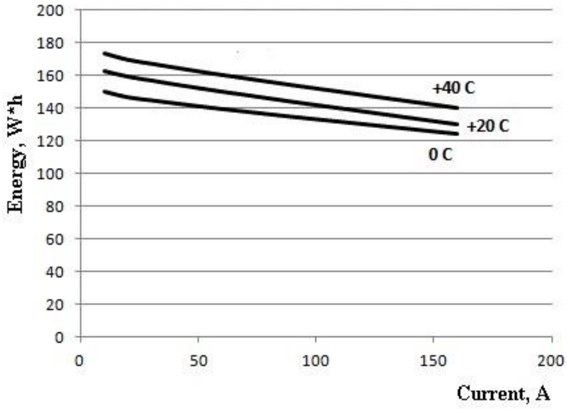


Figure 8. The discharge characteristics of a lithiumion battery at different temperatures

As the following graphs show, dependencies of discharge energy on discharge current at different temperatures represent line graphs. When charging an empty battery to a voltage limit is usually reported up to 80% of rated capacity (Figure 9).

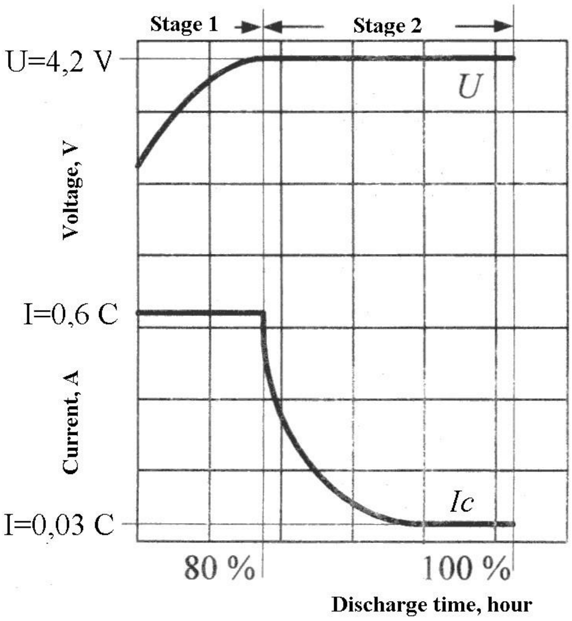


Figure 9. Charge mode of a Lithium-ion battery

A full battery charge cycle is achieved at a constant voltage in a falling current mode to a level of 0,03 C.

Lithium-ion accumulators have high specific energy, good lifetime and efficiency at low temperatures. Their high specific energy has resulted in their production increase in recent years. Lithium-ion accumulators have only two essential drawbacks: a high price and the need in a special (usually incorporated) charging/discharging system preventing lithium accumulators from spontaneous ignition and even explosions when operation conditions are violated.

Sodium-nickel-chloride accumulators are the second best after lithium-ion ones on the basis of their specific energy, as they are more efficient under hard operation conditions. This accumulator type also has its advantages and disadvantages. The advantages of this accumulator type include high specific capacity compared to lithiumion accumulators, low price and wide availability of the accumulator basic materials, a higher lifetime (over 1000 full charging/discharging cycles and over 7 years of active operation), resistance to separate elements failure because of low strength of the elements, which are out of order (up to 5% of losses), high environmental safety (basic components of sodium-nickel-chloride accumulators are safe).

Externally, the element is a steel cuboid, which is filled with metallic sodium (negative electrode material), a ceramic tube inserted from beta alumina, which is both an insulator between positive and negative electrodes and the solid electrolyte, permeable to sodium ions A ceramic separator is filled with the material of the positive electrode: nickel chloride and iron chloride, sodium allyumohlorida powder, and inserted into the contact plate, the output of which is located at the end of the battery cell. Since all of the electrode materials are solids under normal conditions, it should be kept in a heated to 300 ° state.

Current batteries are not purely sodium nickel chloride, but nickel-iron-sodiumchloride. The introduction of iron chloride in the positive electrode will result in lower internal resistance of the battery. Also during discharge pure sodium nickel-chloride system at the end of the discharge output falls sharply (almost 2 times). Adding iron chloride enables to avoid this effect. Battery recycling is very simple - they can be sent to the smelter without unmounting. As a result of melting is formed iron-nickel alloy, which can be used in the steel industry. Even during the thermal runaway battery is particularly kind to the environment (the main components and steel body are low-toxic or non-toxic at all for the environment). The external battery case is a double-walled steel body, between the walls of which is a vacuum. This thermos allows to avoid large dissipation by the battery (in normal conditions dissipates about 100W of heat), which is important not only for the functioning of batteries, but for safety use. There is a heater and air cooling system to maintain a constant internal temperature in the battery case. Heating the batteries to the operating temperature takes a heater about 24 hours. The heater maintains the temperature at the set level (above 270°C) from battery power. During the discharge is released about 10% of energy, which requires cooling of the batteries to a temperature below the maximum operating (350°C).

For proper function of a battery is installed smart control system making possible to maintain an internal status of a battery at the optimum level and automatically turn off power at no load in emergency situations (built-in crash sensor). The system can be operated via a serial port on a PC with Windows. Not only is available a function of monitoring the battery status in real time, but also the possibility of tuning the parameters of the battery for a specific application area.

The drawbacks of sodium-nickelchloride accumulators include the need in an intellectual battery control system, the necessity in high operational temperature support inside the battery (level 300°C and about 100W to support this temperature). It takes at least twenty-four hours to heat-up a cold battery to be ready for operation.

Long service life and high performance cycler put the sodium nickel-chloride batteries on one of the first places among the existing battery. At the moment, the only major obstacle is the inflated cost of this type of battery. As soon as the price reduction takes place per kilowatt-hour of battery capacity to 300USD level that can actually be achieved (the cost of production is less than 150USD per 1 kWh), then their use to electric transport, including in electric locomotives, will become a reality.

As outlined in the text previously, when designing the contact and battery electric locomotives is of great importance the choice of the type of battery based on massdimensional values and energy resource. The analysis in this direction showed that in the short term the most appropriate is the use of lithium-ion and sodium nickel-chloride types of batteries in which the specific weight energy will be greater than 200 W·h/kg at the resource 3000 cycles (compared to 1 000 cycles to date), and the cost of $ 0,12 / W·h.

In 1996 was invented a lithium iron phosphate battery, and the mass production of such batteries was launched in 2008. Lithium-iron-phosphate battery is actually a variation of lithium ion, wherein in the cathode instead of lithium cobaltat is used the material LiFeP04. Such a replacement of a cathode material resulted in essential change of the settings that lithium-ironphosphate batteries are often considered as a separate category of power supplies. Compared to lithium ion, and other batteries, lithium-iron-phosphate have almost a recordbreaking durability. Known batteries of this system allow for 7000 charge and discharge cycles at lower capacity until 80% of the initial value. Also, unlike lithium ion, these batteries degrade slowly during storage, allowing them to be stored for 15 years. Charging time of a Lithium iron phosphate battery is about 15 minutes. An interesting feature is the fact that a large part of a battery runtime supports on the findings of a stable voltage of 3.2 V. In some cases, this eliminates the need for additional voltage regulators, which complicate the design and reduce the efficiency of the device.

A promising type of lithium-sulfur batteries was established in 2004 through the use of a different design of the cathode. In lithium-sulfur batteries, it is a liquid that contains sulfur, which increased the maximum current density. When charging, lithium and sulfur becoming lithium sulfide, in turn, during discharge is the reverse process of decomposition of sulfate in sulfur and lithium. The lithium sulfur batteries provide a voltage of about 2,1 V, the same as the lead-acid batteries. Existing examples of lithium-sulfur batteries have the specific capacity of up to 400 W•h/kg, theoretically specific capacity of the battery can be up to 2600 *W•h*/kg. The battery is fully safe, the probability of explosion or the risk of fire during operation is minimal. In this regard, this battery can be made simpler and easier in design due to the lack of protection systems.

In 2013 was made an experimental prototype lithium-sulfur battery with a cathode of composite material comprising graphene and sulfur. It resulted in increase the number of charge-discharge cycles up to 1500. Currently the technology is not sufficiently developed for mass-production of such batteries

Besides the analyzed types, there are other future developments of batteries made by scientists of such countries as USA, Japan, Sweden etc. [6,7]. The new types are being developed for reducing the charging time TB using nanotechnology.

An appropriate monitoring and control systems should be implemented for the reliable and stable operation of the TB in the mine contact-battery electric locomotives. Such a system should have a modular structure, the general view of which is shown in Fig.10.

Monitoring and control system of the TB should ensure the following functions:

1. Battery protection against harmful overcurrent and overvoltage.
2. Control of pre-emergency battery condition and emitting of the alarms.
3. Automatic mode control charge/recharge of a battery.

The analysis of the real operation conditions of the mine trolley-battery electric locomotives allowed to formulate the charge system requirements for the TB in the electric locomotive, the main ones are:

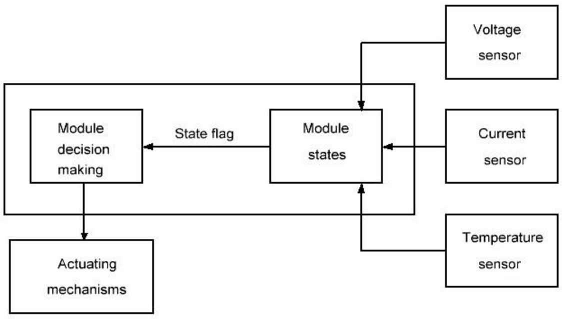


Figure 10. General view of the control system structure

1. 1. Ensuring charge/recharge mode of a battery in the electric locomotive under specified current or voltage;
2. 2. Ensuring the stabilization of a given current charge/recharge of a battery within a preset range with the necessary deviations.
3. Ensuring the charging voltage regulation within the preset range.
4. Ensuring the stabilization of the preset charge voltage with temperature compensation within the required range and permissible deviations.
5. Providing the automatic three-stage battery charging mode depending on the ambient temperature by the following algorithm:

1st stage - a charge current I1=100-125 A until the battery voltage U1, the value of which depends on the ambient temperature.

2nd stage - a charge equal to the DC voltage U1 achieved at the first stage under the control of the charging current to the level of decrease I2=1-2 A.

3rd stage - a constant recharging current of a battery I2= 1-2 A with increasing battery voltage to the U2 level.

The timing diagram of a battery is shown in Fig. 11.

After every disconnection of the contact network, the charging algorithm of a battery should start with the first stage.

For battery charging and uninterruptable power supply of the auxiliary loads of the locomotive (compressor, lighting) from the contact network can be recommended the functional diagram of the device, shown in Fig.12.

The device comprises a transistor chopper UA based on TA transistor IGBT driver with EA, the zero diode VD2. Chopper UA by pulse-width modulation (PWM) voltage contact system converts the voltage of the auxiliary load. This chopper UA performs the following functions:

Overcurrent control;

Control of the emergency overcurrent;

Control of the chopper temperature structure and protection against overheating;

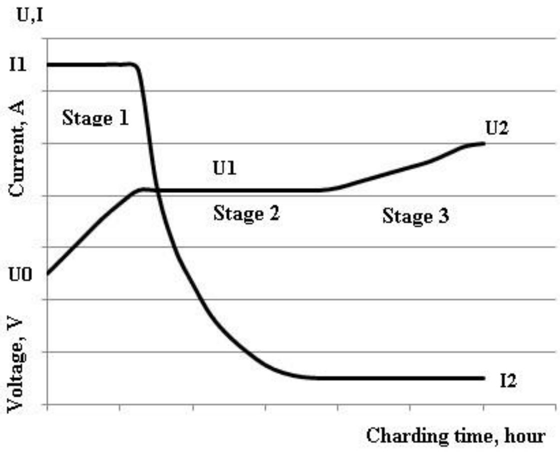


Figure 11. Timing diagram of the charging status of a battery for the electric locomotive

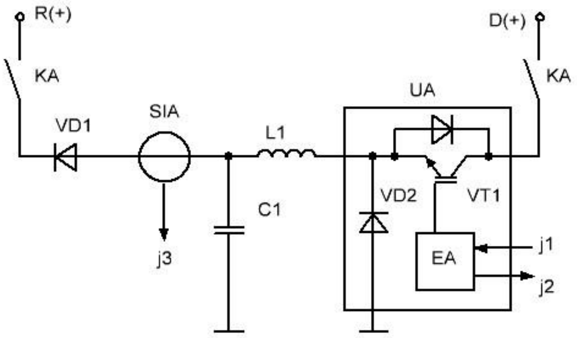


Figure 12. Functional diagram of the device for charging TB and power auxiliary loads

- A minimum supply voltage level control driver on the condition of reliable switching transistor IGBT.

The device has an LC- filter based on capacitance C1 and inductance L1.

Chopper UA performs pulse width modulation of the contact voltage Un of the clip D (+) and supplies the converted voltage in the auxiliary load circuit through the clip R (+). The auxiliary load is powered from the voltage and the battery is charged. Thus, the device carries out charging of the battery and power the auxiliary loads of the locomotive.

Safety rules prohibit to charge the battery during electric motion. But the standard was developed at a time when the charge operation was controlled by the staff, with the imperfect tools, without automation systems. Today, the problem is solved with the use of automatic control equipped with appropriate sensors for monitoring and protection (temperature of the electrolyte, gassing, etc.). Therefore, the device with the battery charging control process function can improve reliability and safe operation of the battery.

Fig. 13 shows a diagram of an uninterruptible power supply of the auxiliary loads with electric voltage control UR (SUB sensor, jUR sensor signal). Protection VB diode eliminates battery power from the contact network. In the separation of the current collector from the contact network, the locomotive loses power, the VB diode starts to conduct current from the battery to the circuit auxiliary loads, which provides their uninterrupted supply.

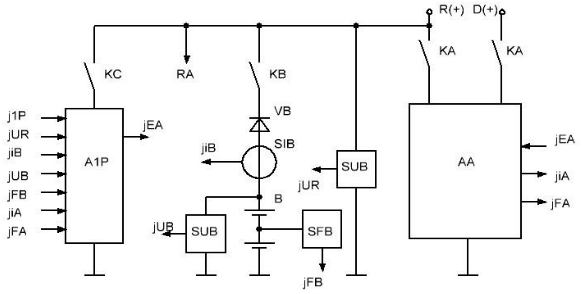


Figure 13. Functional diagram of an uninterruptible power auxiliary loads from the TB

Research and development aimed at reducing the cost of the relatively expensive TB groups definitely will be continued in the future. The decrease in prices for Li-ion, sodium Nickel-chloride batteries in conjunction with solutions on providing secure and high-capacity TB on the basis of these battery electrochemical systems will create more favorable conditions for the expansion of their application as batteries for industrial use.

Meanwhile, it is not necessary to reject the development directed to the establishment of independent power supply for traction electromechanical complexes on the basis of, for example, supercapacitors and other electric energy storage elements.

Conclusions

1. Presented the methodology and calculations of the parameters of batteries designed for traction batteries of mine battery-trolley electric locomotives for the conditions of the iron ore mines Kryvbas. The calculations of voltage and battery capacity are approximate and should be refined in the course of further studies based on the actual parameter values of the voyage operations of the electric locomotives.

2. The analysis of parameters and characteristics of different types of batteries for forming batteries that can be used for the mine battery-trolley electric locomotives. It was found that a promising direction is the use of lithium-ion and sodium nickel-chloride batteries, but the cost of these batteries is quite high, which limits a wide variety of applications for the mine electric locomotives.

3. The introduction of lithium-ion and sodium-nickel chloride batteries needs additional research and development of technological processes control system charge/discharge of the batteries. Also it is expected to reduce the cost of these battery types and their availability of subsequent use in the mine trolley-battery locomotives. It is also necessary to consider the prospects of using self-contained power supply on the basis of, for example, other types of supercapacitors and electric energy storage elements.

4. Created and developed a system charge for the traction battery and uninterrupted power supply of the auxiliary loads for the trolley-battery locomotive.

References

1. Volotkovsky, S.A. (1981). Rudnichnaya elektrovoznaya tyaga [Mine locomotive traction]. Moscow: Nedra [In Russian]

2. Sinchuk, I.O. & Huzov, E.S. & Debelyi, V.L. & Debelyi, L.L. (2015). Shahtnyi elektrovoznyi transport. Teoriya, konstruktzyi, elektrooborudovaniye: uchebnik [Mine locomotive transport. Theory, design, electrical equipment: course book]. Krivoy Rog-Donetsk: ChP Sherbatyh A.B. [In Russian]

3. NPAOP 10.0-1.01-10. Pravyla bezpeky u vugolnyh shahtah (2005) [Safety Rules in Coal Mines]. Lugansk:Kopitzentr

4. Sichuk, O.N. & Huzov, E.S. & Likarenko, A.G. & Zhivotovsky, A.G. (2008) Elektrobezopasnost rudnichnoy otkatki [Electrical safety of ore haulage] Kyiv: Tehnika [In Russian]

5. Sinchuk, O.M. Shahtnyi kontaktnoakkumulyatornyi elektrovoz [Mine trolley-battery locomotive]. *Gornyi zhurnal – Mining journal*, 6, pp. 55-57 [In Russian]

6. Stepankov, V.P. (1988) Osobennosti organizatzii lokomotivnoy otkatki s ispolzovaniyem kombinirovannyh elektrovozov. [Specific features of locomotive haulage using combined electric locomotives]. *Gornaya mehanika, rudnichnyi transport, tehnicheskoye obsluzhivaniye i remont gornogo oborudovaniya - Mining Mechanics, mine transport, maintenance and repair of mining equipment*. Moscow, pp. 130-138 [In Russian]

7. Karagayev, V.I. & Khaimin, A.D. & Bystrov, S.A. (1982) Primeneniye kabelnogo barabana dlya elektropitaniya elektrovoza v ortah [Trolley drum for locomotive power supply in orts]. *Bezopasnost i nadezhnost elektrosnabzheniya gornorudnyh predpriyatiy - Safety and reliability of power supply of mining enterprises*. Dnepropetrovsk:pp. 104-105 [In Russian]

8. Akkumulyatorno-kontaktnyi elektrovoz A. L. Lee Corporation [Trolley-battery locomotive A. L. Lee Corporation] *alleecorp.com.* Retrieved from http://alleecorp.com/equipment/locomotive/batterytrolley-locomotives/ (Accessed 2016-12-20) [In Russian]

9. Asea akkumulyatornyye lokomotivy i drugiye shvedskiye NG lokomotivy [Asea Battery locomotives and other Swedish NG locomotives] *gn15.info*. Retrieved from http://gn15.info/forum/viewtopic.php?t=7043/ (Accessed 2016-12-20) [In Russian]

10. Proizvoditeli lokomotivov [Locomotive producers] *chinacoalintl.com* Retrieved from https://chinacoalintl.com/ (Accessed 2016-12-20) [In Russian].

11. Sinchuk, O.N. & Shokarev, D.A. & Skapa, E.I. & Huzov, E.S. & Karamanits, F.I. (2011) Sinergeticheskyi tyagovoy asinhronnyi elktrotehnicheskyi privod dlya kontaktno-akkumulyatornogo dvuhosnogo elektrovoza [Synergetic asynchronous traction drive for trolley-battery two-axle

locomotive]. *Elektromehanichni ta energozberigayuchi sistemy - Electromechanical and energy systems.* 4 (16), pp. 65-68 [In Russian]

12. Sinchuk, O.N. & Sinchuk, I.O. & Huzov, E.S. & Shokarev, D.A. (2014) Tyagovyye elektromehanicheskiye kompleksy shahtnyh kontaktnyh elektrovozov [Traction electromechanical complexes of mine contact electric locomotive]. *Elektricheskiye i kompyuternyye sistemy - Electrical and computer systems*. 15, pp. 286-291 [In Russian]

13. Sinchuk, O.N. & Huzov, E.S. & Sinchuk, I.O. & Chorna, V.O. (2015) Kontrol teplovyh rezymov tyagovyh dvigateley i skorosty shahtnyh elektrovozov [Control of thermal modes of traction motors and speeds of mine electric locomotives]. *Informatika, informatzionnyye tehnologii, avtomatizatsiya - Computer science, information technology, automation*. 1, pp. 27-32 [In Russian]

14. Miller, A. R. & Hess, K.S. & Barnes, D.L. & Erickson, T.L. (2007) System Design of a Large Fuel Cell Hybrid Locomotive. *Journal of Power Sources* [In English]

15. Masek, Zdenek & Lenoch, Vaclav & Lelek, Tomas. (2016) Simulation Model of Hybrid Shunting Locomotive. *Transactions on Electrical Engineering* No. 3,
pp. 75-90 [In Englis]