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ZZB battery supply unit for the self-propelled SWS-1700ENB blast truck

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Abstract:

The article presents the latest solution of the ZZB battery power unit for the working system of SWS-1700ENB self-propelled blast truck, developed at the KOMAG Institute of Mining Technology in Gliwice. Use of an internal electric charger allows charging the ZZB batteries assembly from the power grid with a rated voltage of 500V and 1000 V without the need for the blast truck to travel to the charging place with the possibility of charging the batteries from the electric generator while the vehicle is driving. SWS-1700ENB self-propelled blast truck, manufactured by Lena Wilków Sp. z o. o. with the ZZB assembly is intended for use in underground, non-methane mining plants extracting metal ores and underground, non-methane mining plants extracting minerals other than hard coal and metal ores.

Keywords: mining industry, electric machines, battery supply, battery supply assembly, blast truck.

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1. Introduction

In mining plants extracting the minerals from hard or very hard rocks with high uniaxial compressive strength (over 150 MPa), drilling and blasting processes are used [1]. After drilling the blast holes in the face, they are filled with explosives. After blasting, the mined material is transported with wheel loaders and transportation cars, and the roof is secured by bolting machines [2]. The diagram of the copper ore extraction process is shown in Fig. 1.

Fig. 1. Copper ore extraction process

Face machines (i.e. drilling jumbos, blast trucks cars, bolting machines) have two power sources: a diesel engine is used for run, while in the face machines (due to ventilation conditions and the emission of toxic exhaust gases into the surrounding mine atmosphere) electricity is used. This requires to unwind the electric cable each time when the machine arrives at the work place and roll it up after the technological operations are completed.

2. Current solution

Self-propelled blast trucks use a diesel engine to drive the system. However, an electric motor is used to drive the technological devices installed in these trucks, which drive a hydraulic pump, which in turn drives a modular pumping device used to produce and load explosives [3, 4]. The vehicle is staffed by three people: an operator and two blast miners. In the existing solutions, the electric motor is supplied by 500 V from the mine network via a retractable electric cable. Each time unwinding and rewinding the cable is burdensome, it takes about 2/3 of the time required for placing explosives in blast holes and poses a high risk of rockfall for the working crew of the truck in the face area F. Experience gained in development of battery suspended drive trains for coal mining industry, KOMAG Institute specialists used in development of power supplying of machines with batteries (32 kWh) composed of lithium-iron-phosphate cells (instead of the previously used wire power supply) for the electric motor driving the pump of the MUP-4 module, which prepares and loads explosive emulsion into the blast holes. KGHM-ZANAM implemented this solution in the WS-172, WS-153 (WS1.5L), (WS1.7) and WS-173/S (WS1.7B) blast trucks - 42 machines (Fig. 2). The battery of the first machine (WS-172) is charged from an external, free-standing, dedicated charging module. For the next machines, the electric charger was installed inside the battery unit, as a result of the modernization of the ZB-1 power supply unit, what enabled charging the batteries directly from the mine's power grid with a rated voltage of 500 V, without the need to run the blast truck to the dedicated charging module. The above solutions use an electric motor with a power of 15 kW and a rated voltage of 150 VAC [3, 4].

Fig. 2. WS-173 blast truck [5]

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All previous solutions of blast trucks are powered by an electric cable or a diesel engine. Unwinding an electric cable at a mine face is difficult and time-consuming, and poses a risk of rockfalls, so operators sometimes prefer power supply from a diesel engine despite the nuisance associated with exhaust gases and the deterioration of the microclimate and work comfort.

Using the sodium-nickel batteries in the SWS-1700ENB self-propelled blast trucks, manufactured by Lena Wilków Sp. z o. o., Poland is another stage of the battery drive development.

As part of the project co-financed by NCBR from the European Regional Development Fund: "A new generation of modular drilling and bolting machines with battery drives, intended for operation in underground mines of copper ore and mineral raw materials", implemented by Mine Master in cooperation with AGH University of Science and Technology, Wrocław University of Science and Technology and the Łukasiewicz Research Network - EMAG Institute of Innovative Technologies, the prototypes of Roof Master RM 1.8KE self-propelled bolting machine and the Face Master FM 1.7KE drilling jumbo were developed and manufactured for testing (Fig. 3).

Fig. 3. Face Master 1.7KE (BEV) [6]

These are the first machines in Poland designed for conditions in the mines belonging to KGHM SA, in which a battery drive consisting of five sodium-nickel batteries with a capacity of 190 Ah and an energy of 123.5 kWh is used (instead of a diesel engine), with nominal voltage of 650 V driving a permanent magnet motor with a power of 133 kW. However, bolting/drilling uses power supply from the mine network and (in an emergency) from the traction battery. Both machines have built-in chargers that allow charging the batteries from the mine power grid (in the voltage range of 500 - 1000 V), as well as during braking and descending on slopes [7]. After surface tests, the machines were subjected to underground tests at KGHM, ZG Lubin Branch [8, 9]. A comparison of selected battery-powered heavy machinery used in underground workings of mineral extraction plants is presented in Table 1.

Table 1. Comparison of Selected Battery-Powered Heavy Machinery Solutions

Manufacturer	**KGHM ZANAM**		**MINEMaster**	
Model	WS-173	WS-153	FM 1.7KE	FM 1.8KE
Type of machine	Blast truck	Blast truck	Drilling vehicle	Bolting vehicle
Length	9 950 mm	8 900 mm	14 400 mm	13 600 mm
Width	2 750 mm	3 150 mm	2 400 mm	2 450 mm
Height	1 700 mm	1 500 mm	2 200 mm	1 800 mm
Total weight	21 000 kg	19 200 kg	18 500 kg	20 500 kg

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Engine power	115 kW	115 kW	133 kW	133 KW
Drive engine type	Diesel	Diesel	Electric	Electric
Battery module	ZB2 (LiFePO4)		Sodium-nickel battery	
Nominal battery voltage	264 V; DC		650V DC	
Battery energy	32 kWh		123,5 kWh	
Nominal charging voltage	500 V; 50 Hz		500-1000 V; 50 Hz	
Communication interface	CAN bus		CAN bus	
Enclosure protection rating	IP 67		IP67	
Weight	850 kg		1080 kg	

3. SWS-1700ENB self-propelled blast truck

The SWS-1700ENB self-propelled blast truck (Fig. 4) is an articulated machine on a tire chassis consisting of two main units: driving one and working one. Both are connected to each other by a joint with a vertical axis of rotation on roller bearings. One hydraulic cylinder is installed between the parts to turn the machine. The hydraulic cylinder is controlled by a steering wheel (controller) from the operator's cabin through a hydraulic turn distributor. The drive unit makes a frame with the driving system. Additionally, the drive unit is equipped with operator's cabin, electrical installation, hydraulic installation, fire extinguishing installation, and hydraulic unit of the working system. The working part is a platform with a self-supporting structure welded from steel sheets with a built-in operating system - a modular pumping unit.

Fig. 4. SWS-1700ENB self-propelled blast truck

Characteristics of the SWS-1700 ENB self-propelled blast truck:

- the machine is equipped with a raised work platform with an opened shield which can be used as additional platform, dismantled in the areas with low seam height,
- battery power supply of the working system drive with a possibility of charging the battery from the 500 V or 1000 V mine network,
- sodium-nickel batteries of increased fire safety, adapted to work in a high-temperature environment,

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- high battery power guaranteeing the operation of the battery system in optimal parameters with enough energy for reliable blasting operation with a double-filled emulsion tank (750 liters),
- charging the battery while driving from an electric generator installed on a diesel engine,
- possibility of operating the pump device module also using a diesel engine,
- air-conditioned, closed operator's cabin,
- air-conditioned, open service compartment,
- supporting structure resistant to the conditions prevailing in KGHM mines (i.e. bumpy and water-logged transport roads, temperature, dust, high humidity, aggressiveness of mine water),
- the machine is equipped with the required auxiliary systems, such as:
  - permanent, automatic fire extinguishing installation,
  - central lubrication system,
  - operator system prevention against collision,
  - optional DOTRA radio communication system.

The basic mechanical and electrical parameters of the SWS-1700ENB vehicle are presented in Table 2.

Table 2. Basic parameters of the SWS-1700ENB truck

Parameter	SWS-1700ENB
Weight	19,500 kg
Length	9,250 mm
Width	2,610 mm
Height	1,700 mm
Payload	1,400 kg
Wheelbase	3,700 mm
Track width	2,340 mm
Ground clearance	325 mm
Turning radius	±41°
Engine type	CUMMINS QSB4.5C160
Max engine output	119 kW at 2,200 RPM
Payload material weight	100 kg
Fire suppression system	Lena IP-4M
Electrical installation	24V DC (2x12 V)
Battery capacity (24V)	180 Ah or 185 Ah
Battery pack type	ZZB

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4. ZZB battery power supply unit

The ZZB battery power supply unit developed at the KOMAG Institute of Mining Technology in Gliwice was installed in the SWS-1700ENB blast truck (Fig. 5) manufactured by Lena Wilków Sp. z o. o.

Fig. 5. ZZB battery power supply unit installed in the SWS-1700ENB blast truck

Using the ZZB unit is very simple. After turning on the main switch on the ZZB unit, it is controlled from the control panel installed in the truck operator's cabin. All information about the battery, charge status, voltage, current, temperatures and more is available on the panel. There are also diagnostic connectors in the operator's cabin for servicing.

The ZZB battery power supply unit enables powering an electric motor with a power of 22 kW and voltage of 400 V, as well as an auxiliary 24V DC circuit of the truck.

Charging takes place from the 500V or 1000 V mine network. Selecting the charging voltage does not require any electrical switching. Two electrical cables are used, one for 500 V and 1000 V, and by coding the cables, the control system detects which network the device is connected to.

While the blast car is moving, it is possible to recharge the battery from a 6 kW electric generator.

A graphic control panel (Fig. 6 and Fig. 7) is installed in the truck operator's cabin, which provides text and graphic alarm signalling and the ability to monitor the process (operation of the electric motor, charging from the network and charging from the generator) in the form of a synoptic screen and parameter lists. A program managing the unit’s operation is implemented in the control panel. In turn, the ZZB unit has an installed programmable controller, dedicated to use in mobile applications. This controller is an input/output module and enables control of the ZZB unit devices. The panel communicates with the controller, the MBS system supervising the battery pack, the inverter and the charger via the CAN bus. Information is also sent via the CAN bus to a display screen installed in the ZZB unit. Functionality of the display screen is similar to the functionality of the operator panel and its location in the ZZB unit facilitates servicing.

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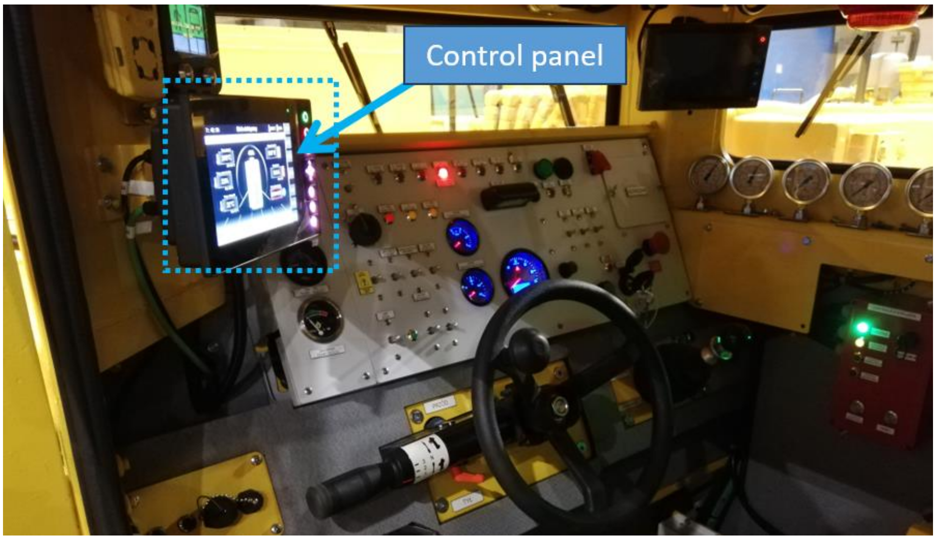

Fig. 6. Operator's cabin with a panel controlling the ZZB unit

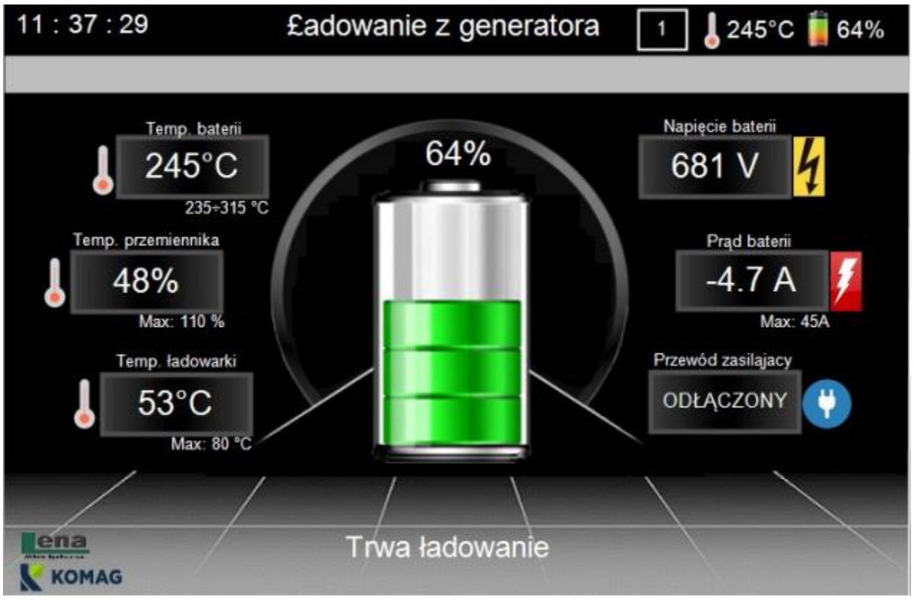

Fig. 7. Screenshot of the control panel of the ZZB-1 module

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Structure of the control system is presented in Fig. 8.

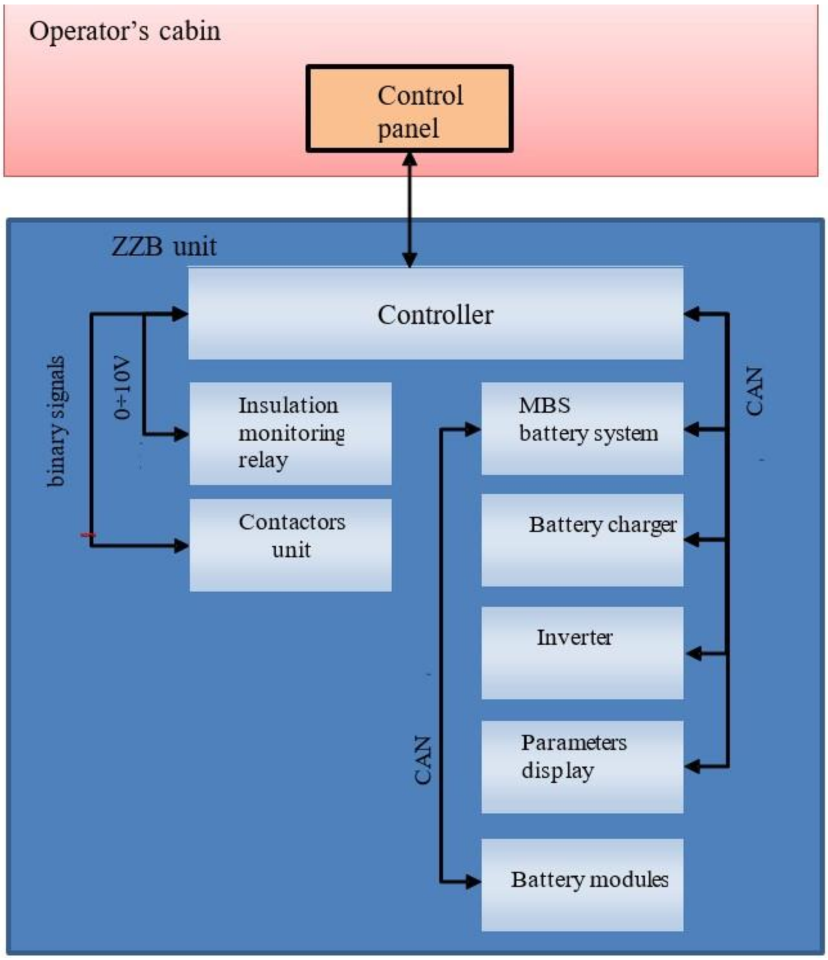

Fig. 8. Structure of the control system

Main technical parameters of the ZZB battery power supply unit is presented in Table 3.

Table 3. Technical parameters of the ZZB battery power supply unit

Type of battery cells	Sodium-nickel
Rated battery voltage	650 V; DC
Battery energy	2 x 24.7 kWh
Rated output voltage	3 x 400 V; 50 Hz
Maximum output power	22 kW
Battery charging	3 x 500 V or 3 x 1000 V
Charging the battery from a diesel engine	generator 3 x 500 V, 6 kW
Cooling	water
Communication interface	CAN bus
Degree of enclosure protection	IP 67
Dimensions	1126 x 885 x 1270 mm
Mass	1250 kg

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5. Functionality of sodium-nickel battery

The main innovative feature of the SWS-1700ENB blast truck is the powering of the hydraulic power unit motor from the ZZB unit with sodium-nickel batteries.

Compared to batteries constructed from lithium-iron-phosphate cells, the use of sodium-nickel cells is characterized by [9, 10]:

- increased resistance to high ambient temperatures,
- a higher degree of safety in production and use, the battery composition is free of harmful substances, eliminating potential health hazards for users,
- can be fully recycled, supporting sustainable environmental practices,
- the lack of use of lithium,
- the use of cheap and readily available materials - such as sodium, iron, nickel and aluminium,
- the need to keep the internal operating temperature high, which reduces overall energy efficiency.

Z60 series batteries with a voltage of 650 V and a capacity of 38 Ah (Z60-650-38) were used in the ZZB unit solution used These are high temperature batteries. The enclosure contains cells, thermally insulated from the enclosure with an internal negative pressure. Outside each battery there is a BMI electronic module, which plays a control role.

This series of batteries is intended for mobile applications, therefore tight and shock-resistant connectors are used, the battery electronics communicates using the CAN bus, insulation resistance (electrical) is measured, and in the case of a threat, the battery terminals are disconnected (after a power supply failure of EMERGENCY line). The battery is equipped with an optional air cooling system, which allows excess heat to be removed from the interior of the battery after intensive use. The cooling system was neglected in the case of ZZB modules due to the low load compared to the battery capacity and the intermittent nature of operation. functionality of the BMI module includes control of built-in contactors, control of battery warm-up circuits, measurement of insulation resistance, communication and measurement functions (including voltage, current, battery temperature, SOC calculation). Additionally, BMI has a built-in soft start system ("precharge") that limits the battery's starting current and numerous self-diagnostic functions. If necessary, it reports information (errors) at four levels of significance and impact on the operation of the battery - from the information level to the level of immediate disconnection of the battery from the firing vehicle installation.

The battery has two installed heaters. The first one (power approx. 750 W) is supplied by 230 V AC, 50/60 Hz and also used to keep the battery temperature while charging. Warming up the battery from a cold state to a state allowing charging/operation takes up to 24 hours, usually slightly less. The second heater, with lower power (approx. 200 W), is supplied by DC voltage from the battery and is used to independently maintain the battery temperature. An example of the temperature curve of the sensors and the average battery temperature during warm-up is shown in Fig. 9a - in this case, the operating temperature (235°C) was reached after less than 20 hours of warm-up. 9b shows an example of the process of maintaining the temperature of the internal battery heaters - the average battery temperature is maintained at 245°C±3°C. In the utilized batteries, the temperature sensors are located near the front panel [12].

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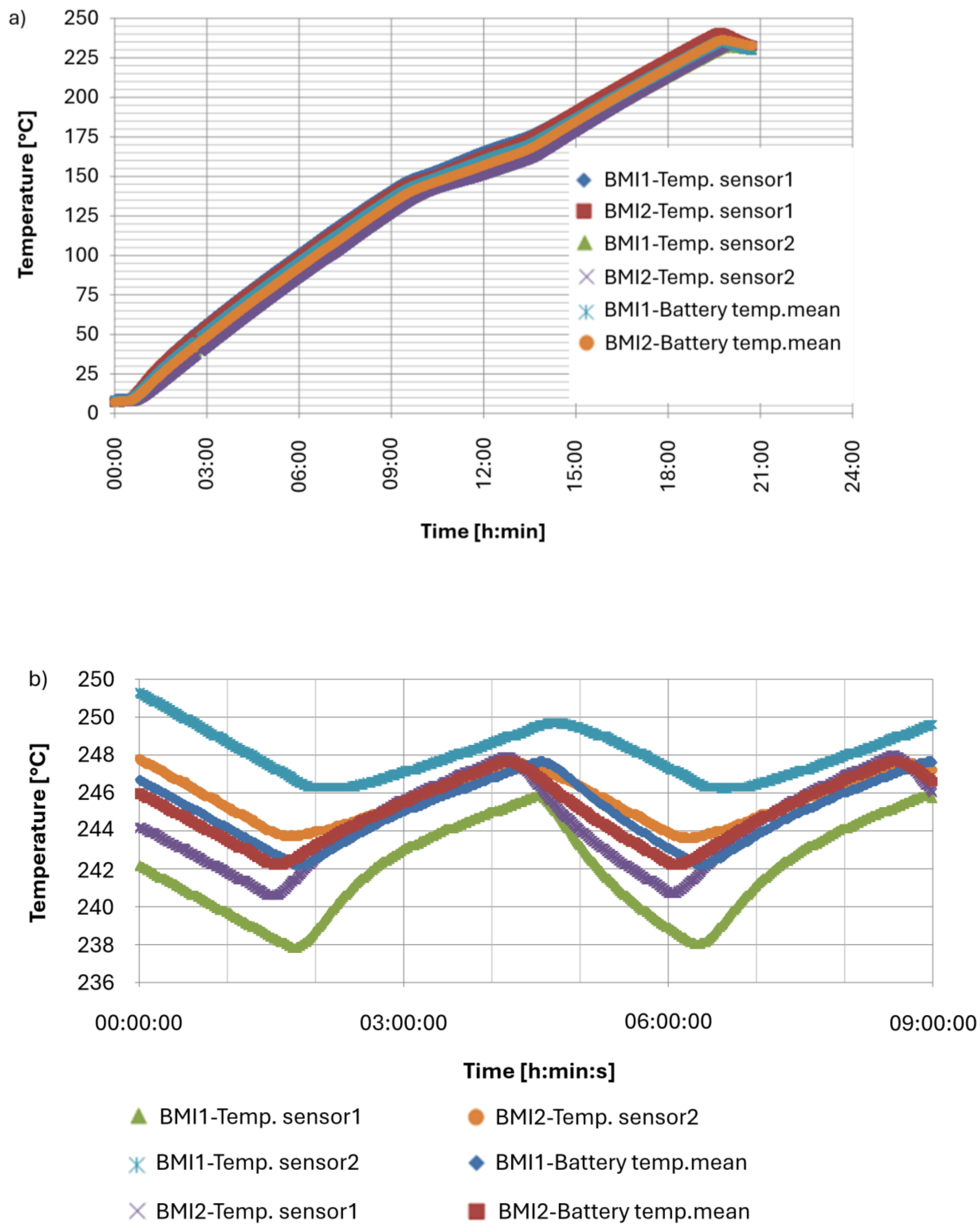

Fig. 9. Examples of sensor temperature and average battery temperatures recorded during: a) warming up the battery, b) while maintaining the battery temperature

In the case of the trucks operating in mines underground, this requires installing a transformer on the truck supplying 230 V voltage (when powered from 500 V or 1000 V). This, in turn, requires additional space for the transformer and its accessories (contactor, fuse, etc.). Not every charging place has a 230 V power supply that can be used. In addition, it would require connecting the additional cable, presence of an additional socket, etc.

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Charging the battery is a long process. It consists of a charging phase with a constant current of 10 A (CC phase), which then turns into a charging phase with a constant voltage of 672.8 V + 1 V (CV phase). The charger should regulate the voltage with an accuracy of 0.1%. Charging is completed when the charging current drops below 0.5 A for a set time. The charging process time is up to 12 hours (first charging from SOC=0%), typically less than 8-9 hours (charging from SOC>20%). An example of the charging current and state of battery charge (SOC) during the first and subsequent charging is shown in Fig.10.

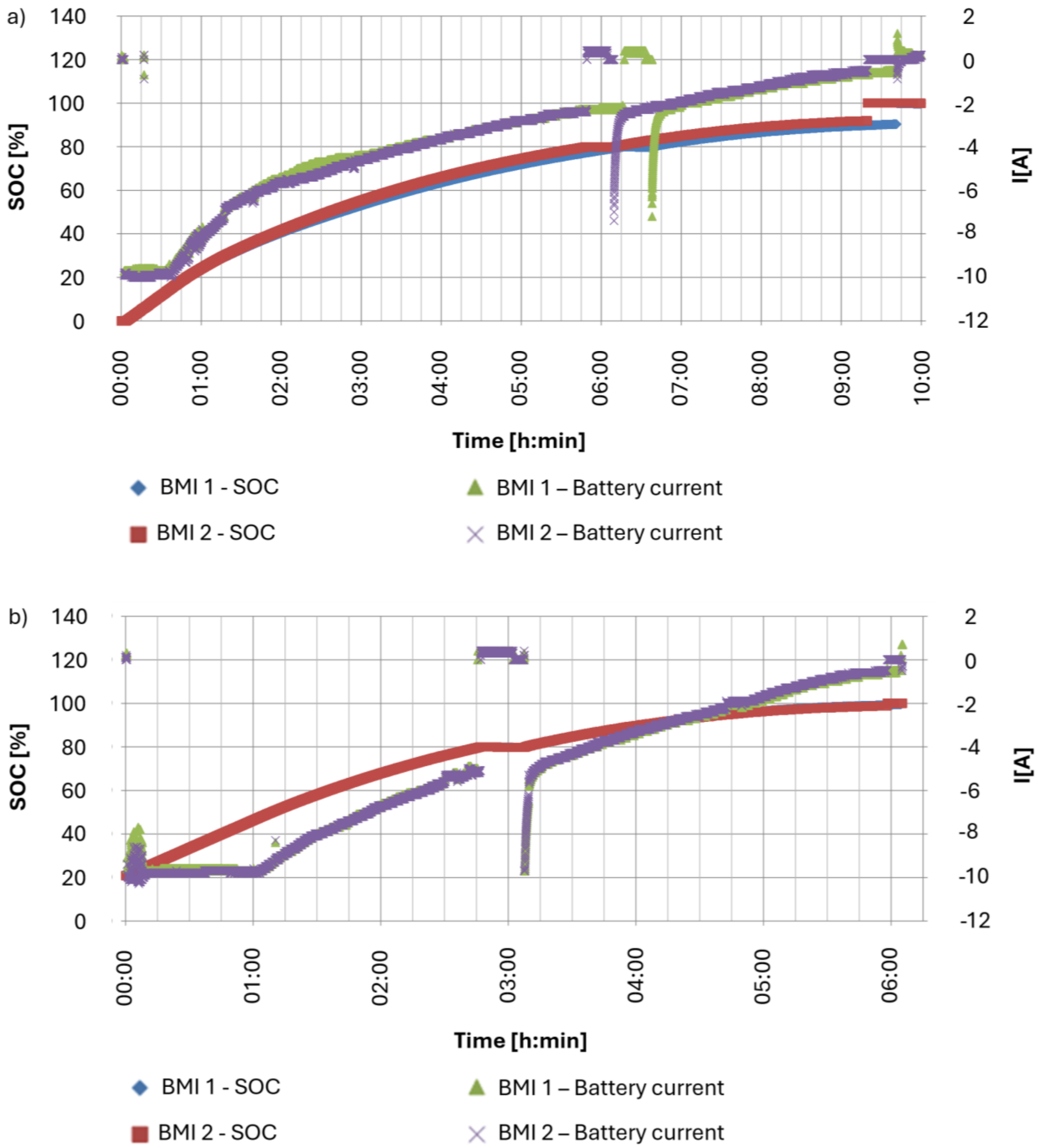

Fig. 10. Examples of curves of states of charge (SOC) and battery charging currents, recorded during: a) the first charging, b) subsequent charging of one of the ZZB sets being started

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During charging, there is a break managed by the BMI module (typically at SOC = 80%), approx. 25-30 minutes, needed for the battery internal OCV test. During this time, voltage of the battery open circuit is determined, as well as the heating efficiency of the internal DC heater.

In addition, it is necessary to fully charge (reach the EOC state), preferably in each charging cycle or every 24 hours of using the battery. Using the battery for 36 hours after reaching the last EOC will generate a warning, and after another 24 hours warning to complete the charging process. Then, discharge current is limited, up to the discharge lock, which is removed when full charging is completed (up to the EOC state).

Recommended battery discharge time is minimum 2 hours. Temporary discharges with higher power are allowed, so that the total discharge time is a minimum of 2 hours. In these cases, increase in internal temperature and the possible use of a cooling system should be taken into account. In the case of a single 38 Ah battery, the permissible instantaneous current is 85 A. That is, the permissible momentary power is over 50 kW, and the continuous power, guaranteeing discharge within 2 hours, is approximately 12 kW (depending on the battery voltage).

The BMI battery module can communicate at a speed of 250 kbps using the CAN bus. This bus is connected to an additional controller called MBS (Multiple Battery Server). It acts as an intermediary between batteries connected to its B-CAN (Battery CAN) line and the V-CAN (Vehicle-CAN) bus with the PLC controller in the blast truck. It is also possible to connect a diagnostic computer with ZEBRA Monitor software to the B-CAN bus, which is used to monitor the battery, read current diagnostic information, read historical battery data and reset errors. It also allows data to be recorded over time, which is useful for analysing the anomalies. The program supports up to 16 batteries (limitation in the MBS module). The data exchange protocol on the B-CAN bus is secret and is not available to the user.

6. Implementation and initial operation

After the positive certification tests, the SWS-1700ENB self-propelled blast truck with a ZZB battery power unit was approved for operation in mine undergrounds by the decision of the President of the State Mining Authority. At the beginning of 2023, it was implemented in the underground mines of KGHM Polska Miedź S.A. “Rudna” Mining Plant, 11 items. The next two items are planned for implementation in 2025.

The truck operates in very difficult environmental conditions, where the ambient temperature reaches +45°C, air humidity up to 98% and dust content in the surrounding environment up to 20 mg/m^3. The electrical system of the ZZB battery power unit is exposed to shocks, impacts and mechanical impacts while the blast truck is moving.

The vehicle's initial operation allowed for drawing the following conclusions:

- the charged battery is enough for the truck operation for up to 3 work shifts, i.e. to pump out over 2 tons of explosives,
- using the internal battery charger enables charging the batteries directly from the mine network with a rated voltage of 500 V or 1000 V without the need for the operator to make additional switches in the electrical system,
- full battery charging cycle is up to 10 hours,
- using the electric generator enables recharge the battery while the truck is moving,
- shortening the time spent by the crew at the face by eliminating the need to unwind and rewind the power cable, thus protecting the crew against rockfalls,
- reducing the emission of exhaust gases and noise at the mine face,
- using the high-temperature sodium-nickel batteries requires the battery to be maintained at the proper operating temperature and to be regularly fully charged.

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7. Conclusions

The main innovation of the SWS-1700ENB blast truck is the power supply of the hydraulic motor from the ZZB with sodium-nickel batteries.

Compared to batteries made of lithium-iron-phosphate cells, the sodium-nickel cells have the following features:

- increased resistance to high ambient temperatures,
- a greater degree of safety in manufacture and use, in composition of the batteries there are no harmful substances, eliminating a potential threat to users' health,
- operation at ambient temperatures from -40°C to +50°C, enabling using them in various climatic conditions,
- possibility of their recycling, supporting sustainable ecological practices,
- competitive price,
- no need to use a BMS system,
- no need to use lithium (a rare earth element).

Table 4 summarizes the key differences between LFP (LiFePO4) and nickel-sodium cells.

Table 4. The comparison of the parameters of LFP and nickel-sodium cell technologies

Parameter	**LFP (LiFePO4)**	**Nickel-Sodium (NaNiCl2)**
Nominal Voltage (per cell) [13]	3.2V	2.58V
Charge/Discharge Efficiency [14]	90-98%	85-90%
Self-Discharge (per month) [13]	<3%	Very low (<0.1%) with high temperature maintenance
Energy Density (volumetric)	Medium (220-350 Wh/l)	Low (100-150 Wh/l)
Energy Density	90-160 Wh/kg	10-120 Wh/kg
Cathode Active Material [15]	Lithium iron phosphate	Nickel chloride (NiCl)
Anode Active Material [15]	Graphite	Metallic sodium
Electrolyte Conductivity [15]	Liquid electrolyte based on lithium salt	Molten salt (depends on high temperature)
Resistance to Deep Discharge	High	Very high (no degradation)
Capacity Degradation over Time [13]	Low (10-20% loss after approx. 2000 cycles)	Minimal degradation under stable operating conditions
Cycle Life [14]	2000-7000 cycles	3000-4500 cycles
Charging Time	Fast	Medium
Cold Start	Problem-free even at low temperatures	Requires pre-heating to operating temperature
Heat Dissipation	Minimal	Significant, requires thermal insulation
Production Cost ($/kWh) [14]	100-150	200-400
Operating Temperature Range [13]	-20°C to 60°C	250°C to 350°C

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Typical Applications	- Electric vehicles, - Portable devices, - Home energy storage	- Stationary energy storage, - Emergency power systems, - Grid energy storage
Advantages [16]	- High stability, - Low cost, - No toxic materials	- Resistance to extreme conditions, - Low capacity degradation
Disadvantages [16]	- Medium energy density, - Sensitive to temperatures below -20°C	- High production cost, - Requires maintenance of high temperature

The solutions presented in the article give pro-ecological effects as well as improving safety i.e.:

- increased efficiency of the truck operation compared to the existing solutions with cable power supply by shortening the time of loading the explosive material into the blast holes,
- ensuring the continuous operation of the truck for up to 3 work shifts on one battery charge, (applying over 2 tons of explosives into blast holes),
- increased mobility of the truck in loading the explosives into blast holes - in the case of a sudden threat, the truck can be immediately withdrawn from the face,
- increased work safety by eliminating the operation of the operator outside the cabin related to unwinding and rewinding the power cable,
- reduced emissions of exhaust gases and noise at mine faces,
- possibility of charging batteries from the mine's electrical network with a rated voltage of 500 V or 1000 V (at different places of the mine),
- functional interface for the truck operator with full monitoring of battery operating parameters in every state of its operation.

The following two inventions submitted to the Polish Patent Office were used in developing the described solution:

- P.443134 - Three-source system for charging mining machine batteries with electricity (authorized KOMAG).
- W.131551 - Self-propelled blast truck (authorized Lena Wilków Sp. z o.o.).

The SWS-1700ENB self-propelled blast truck with the ZZB battery power unit was awarded a platinum medal during the 17th International Fair of Inventions and Innovations INTARG 2024, which took place on May 21-23, 2024 at the International Congress Centre in Katowice.

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