

Article

Design and Research on Power Systems and Algorithms for Controlling Electric Underground Mining Machines Powered by Batteries

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Abstract: This article discusses the work that resulted in the development of two battery-powered self-propelled electric mining machines intended for operation in the conditions of a Polish copper ore mine. Currently, the global mining industry is seeing a growing interest in battery-powered electric machines, which are replacing solutions powered by internal combustion engines. The cooperation of Mine Master, Łukasiewicz Research Network—Institute of Innovative Technologies EMAG and AGH University of Science and Technology allowed carrying out a number of works that resulted in the production of two completely new machines. In order to develop the requirements and assumptions for the designed battery-powered propulsion systems, underground tests of the existing combustion machines were carried out. Based on the results of these tests, power supply systems and control algorithms were developed and verified in a virtual environment. Next, a laboratory test stand for validating power supply systems and control algorithms was developed and constructed. The tests were aimed at checking all possible situations in which the battery gets discharged as a result of the machine's ride or operation and when it is charged from the mine's mains or with energy recovered during braking. Simulations of undesirable situations, such as fluctuations in the supply voltage or charging power limitation, were also carried out at the test stand. Positive test results were obtained. Finally, the power supply systems along with control algorithms were implemented and tested in the produced battery-powered machines during operational trials. The power systems and control algorithms are universal enough to be implemented in two different types of machines. Both machines were specially designed to substitute diesel machines in the conditions of a Polish ore mine. They are the lowest underground battery-powered drilling and bolting rigs with onboard chargers. The machines can also be charged by external fast battery chargers.

Keywords: battery drive; battery power; supply self-propelled mining machines; electric mining machines; control algorithms



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1. Introduction

The concept of working machine drive based on an electric motor or internal combustion engine, i.e., the obtaining of mechanical energy that can be used to drive the carriage system of the machine and its working systems, refers to complete drive units. Both internal combustion engines and electric motors have been known and successfully used for many years in stationary and mobile machines. However, electric motors do not consume oxygen and do not emit exhaust fumes, which has a positive effect on the environment and human health [1]. They do not generate as much noise, and their efficiency reaches the level of more than 90% or even 98%, so they generate much less heat. In addition, the electric drive unit is less complicated [2]. Therefore, wherever mains power can be used, the electric drive wins. In the case of vehicles, mobile machines, or machines working far from the

source of power supply, the internal combustion engine is commonly applied. However, if we want to use battery power, which is also referred to as battery drive, additional serious problems arise. The major drawback of battery power supply is the limited range or limited operating time of the machine, especially when we take into account the long charging time. The use of additional electrically powered systems, such as lighting, air conditioning, or a mechatronic system, further shortens the working time. The key issue in the case of such machines is, therefore, to manage and control the battery condition as well as to optimize battery supervision systems [3]. In the case of underground mining, the operating time reduction due to low temperatures is not the only problem. Apart from the technical aspects, economic considerations related to the cost of purchase and battery operation are also extremely important [4,5].

Very important factors related to the underground mining of metal ores are the costs involved in the ventilation of workings and the negative impact of substances produced during combustion of liquid fuels by the machines on the health of the working staff. In order to reduce costs and improve the working conditions of the workers, it is advisable to replace diesel engines with electric motors powered by the mains and battery. Such a tendency is observed in many countries around the world, with Canada being the precursor [2,6]. This applies in particular to self-propelled mining machines, such as drilling and bolting rigs, LHD loaders, and haul trucks. It should be emphasized, however, that the user expects electrically driven machines to have the same parameters and functional properties as the ones powered by internal combustion engines. This is a serious challenge because battery power still remains a new issue despite the fact that the electric drive is known and widely used also in mining machines. In addition, it should be noted that the difficulty results mainly from the specific conditions of underground mining and related requirements.

The electric drive of mains-powered vehicles and working machines have been used in industry for many years. It is applied not only in trams, trains, stationary machines, cranes or gantries, but also in those working machines that move in a limited area or at a low speed, or in machines that are transported to various workplaces and can be powered by electrical energy supplied by a cable or pantograph, so the output or time of operation are practically irrelevant. Selected examples include the Metso Nordberg NW 80 semi-mobile crushing set, the John Deere autonomous farm tractor with a cable reel, the CAT 7495 cable excavator, the Hitachi ZE85 excavator, or the Hitachi EH4000AC3 dump truck, which is powered by a pantograph. These are, of course, only selected examples of electric working machines. In addition, in underground mining, electric machines powered from the mine's mains are used wherever it is possible.

Of course, mobile machines pose a challenge, as opposed to stationary machines, such as belt conveyors, fans, or even transfer points, i.e., grids. Typical electric and mains-powered underground mining machines are also longwall shearers and roadheaders as well as narrow-gauge loaders, which operate in a limited area. Typical mobile electric machines include haul trucks and loaders, which are powered by mains and are therefore equipped with a cable reel. Examples include the Aramine L150E mini loader for narrow excavations, the Sandvik LH514E loader, the Epiroc Scooptram EST1030 loader, and the Philips HC12BE dump truck. Battery-powered electric working machines are widely used in a variety of industries. The best known are passenger cars, trucks, or increasingly used electric buses, but in the case of these machines, we have practically only a chassis without demanding working systems, and the working conditions are completely different. However, among heavy working machines that perform various processes, there are also battery-operated versions, especially excavators or agricultural machines, including tractors.

In underground mining, due to very difficult working conditions and high requirements, battery-powered machines began to be designed and used relatively late, mostly in the last three years. Currently, several manufacturers have selected solutions of battery-powered machines that are designed to work in various conditions:

- Aramine—L140B miniloader [7]

- Artisan vehicles (since 2019, it has belonged to Sandvik) A4 and A10 loaders, Z50 haul truck [8]
- Epiroc (until 2018 Atlas Copco)—Boomer M2 and E2 drilling rigs, Boltec M and E bolting rigs, Scooptram ST14 loader, Minetruck MT42 haul truck, Easer L, Simba M4, M6, and E7 raiseboring rigs [9]
- Komatsu (do 2017 Joy Global)—several models of haul trucks [10]
- MacLean Engineering—more than 20 models of auxiliary machines [11]
- Normet—a few auxiliary machines [12]
- Phillips Machine—haul trucks [13]
- Sandvik—LH518B loader, DD422iE drill rig, LZ101LE bulldozer [14]

Global companies Komatsu and CAT have announced that in the nearest time, they are going to roll out battery-powered machines, such as drilling and bolting rigs [15], as well as the LHD loader [16].

In the case of drilling, bolting, and auxiliary rigs, the working process is for some time carried out in one place; therefore, the most common solutions are usually applied to charge the battery at the workstation. On the other hand, LHD haul trucks and loaders are in motion most of the time, hence the use of quick battery replacement systems combined with quick charging or quick charging without replacing the battery. Additionally, braking energy, which recharges the batteries, is quite often recovered for all types of battery-operated machines [2]. Braking energy recovery is applied not only in self-propelled mining machines on a wheel-tire chassis but also in cog-wheel railways used in coal mining [17].

The results of simulation tests, however, show the advantage of fast charging, especially in long-term operation. In one of the studies [18], the authors have demonstrated that in the case of five-year operation, fast charging is more advantageous from the point of view of the efficiency and operating costs of machines. It is therefore advisable to use an onboard charger, with the possibility of charging from the mains at the workplace and the function of braking energy recovery. In addition, the machine can be charged with external high-power chargers.

Designing machines for underground mining necessitates the use of modern methods that make it possible to meet the requirements of users, taking into account extremely difficult working conditions [19,20]. The battery power supply of machines is an additional design and economic challenge [21]. Other challenges in the design of modern machines intended for underground operation include aspects related to occupational health and safety, among others the problem of excessive noise, which is increasingly often discussed [22], but also the rapidly developing robotization and automation [23] as well as digitization [24,25].

The works carried out in cooperation with Mine Master, Łukasiewicz Research Network—Institute of Innovative Technologies EMAG and AGH University of Science were used in the design of two self-propelled mining machines, namely a drilling rig and a bolting rig. Self-propelled drilling and bolting rigs perform drilling and bolting, which belong to basic cutting processes applied in the room and pillar mining system. In the case of these machines, the above-mentioned processes determine the working system's power demand. The bolting process is necessary and allows controlling the excavation stability [26,27]. Drilling is performed in the case of both drilling and bolting rigs. The energy consumption and efficiency of the drilling process depend on many factors, especially on the drilling method, hole diameter, type and condition of the tool, as well as the physical and mechanical properties of the mined rock [28,29].

Both machines were manufactured and tested. Bench and operational tests were carried out. The tests, which were mainly focused on the functional properties of battery power supply, confirmed the correctness of the developed power systems and operation algorithms. Technical data and additional information can be found in the catalog on the website of the manufacturer (Mine Master Spółka z o.o., Poland, Wilków) [30]. It should be clearly emphasized that these are the first machines in the world designed for low headings.

The Roof Master RM 1.8KE bolting rig is 1.8 m high, whereas the Face Master FM 1.7LE drilling rig has a height of 1.65 m (Figure 1). They can be maneuvered in workings having a width of 4.5 m in the room and pillar mining system. It should be emphasized that both machines have been equipped with onboard battery chargers, which enable direct charging from the mine's mains. The aforementioned solutions of the competing companies require excavations with dimensions considerably exceeding 2 or even 3 m.

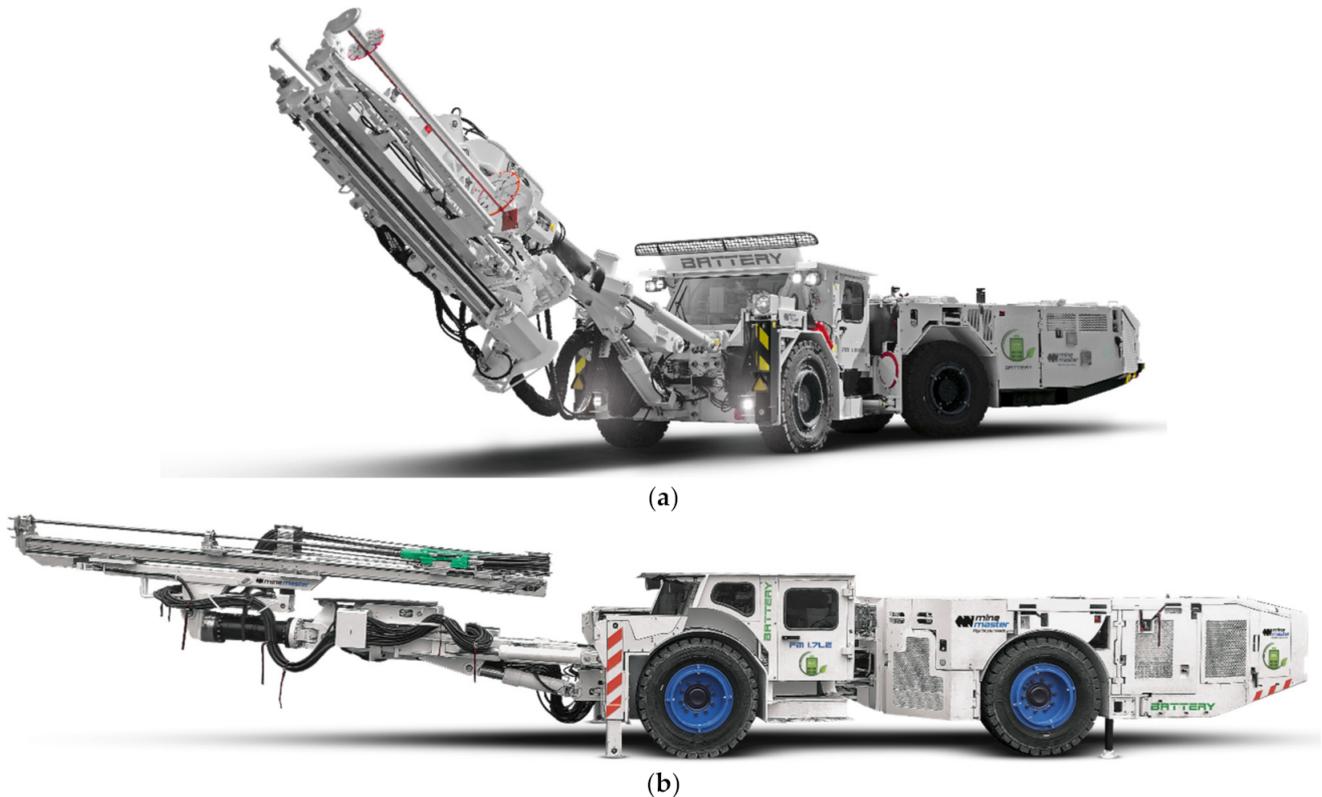


Figure 1. Mine Master battery-powered electric self-propelled mining machines: (a) Roof Master RM 1.8KE bolting rig, (b) Face Master FM 1.7LE drilling rig.

The subject of mining battery machines has been widely discussed in recent years at various conferences and in scientific journals. Manufacturers are offering more and more new solutions to battery-powered mining machines that are designed for specific operating conditions [31]. Due to the necessity of charging, these machines must be adapted to the power grid of the future user. Detailed information on the settings and parameters of power systems and control algorithms still remains the “know-how” of their manufacturers. General control algorithms for a typical cycle of discharging and charging a battery can be found in various variants in numerous studies. [32,33]. Especially in recent years, research has been conducted on modern regulators and artificial intelligence [34,35]. There are also algorithms that take into account other systems, for example, hybrid, charging with solar panels or wind turbines [36,37].

The main problem was to design machines specially for a Polish ore mine that could substitute currently operated diesel machines. However, battery-powered machines are different, and it was necessary to carry out underground tests in the mine to specify detailed requirements concerning power systems and control algorithms. One of the biggest challenges was to design very low machines equipped with onboard chargers and the possibility of using external fast chargers. As stated before, both machines are considerably lower than 2 m, which is a significant achievement compared to competitor products.

The above-quoted selected items relate to machines working overground, especially vehicles. Studies on underground battery-powered low machines, in particular those regarding power systems and control algorithms, are unavailable. The existing research and experiences concern battery-powered solutions applied only in overground machines, so they are not useful in the discussed case. Due to various reasons, only some types of batteries, power systems, and components can be used in underground mine conditions. Batteries pose the biggest problem. It is possible to use many different batteries, such as lead acid (VRLA), nickel cadmium (NiCd), lithium iron phosphate (LFP), lithium nickel manganese cobalt (NMC), lithium nickel cobalt aluminum (NCA), and sodium nickel chloride (Na-NiCl₂). Sodium nickel chloride (Na-NiCl₂) batteries are the best solution for many reasons, including in particular the risk of explosion and fire, operating temperature, ventilation, and durability. In the case of other components, the manufacturers' recommendations regarding operating conditions are applied [2]. This is an important issue in underground mining machines, which needs to be further explored.

2. Materials and Methods

For each newly designed underground mining machine, it is necessary to define requirements based on the working conditions and the user's expectations. This is particularly important in the case of a completely new solution, such as battery-powered self-propelled electric mining machines. The working conditions and user's requirements are different for each mine. Therefore, the first stage of works involved carrying out underground research, which consisted of recording selected parameters of machines. The recorded and analyzed data, as well as the collected comments and requirements of the future machine user, were used to develop assumptions and guidelines for the designed power system along with control algorithms. Next, power systems and control algorithms were developed and checked in simulation tests in a PLC environment. During the research, the properties of various types of batteries, as well as the structure and parameters of the systems managing their operation, were considered. The control algorithms developed as part of the described tests take into account the requirements resulting from the machine operation schedule with the distinction of basic cycles such as standby, ride, operation, and the adopted concept of the drive system. In order to carry out further investigations, it was necessary to design and construct a laboratory stand allowing for the simulation of the machine load and battery discharge, mains battery charging, and braking energy recovery. Tests were performed for all possible combinations of parameters.

The analysis was carried out for typical cases and situations where the braking energy was recovered for a fully charged battery or the battery was charged during the work of the machine operational systems. The performed validation confirmed the correctness of the developed power systems and control algorithms that were used in the self-propelled drilling rig and self-propelled bolting rig. The operational tests of the manufactured machines also proved the correctness of the power systems and control algorithms.

3. Underground Tests of Machines with a Combustion Engine

Underground tests were carried out for two internal combustion machines, the operational parameters of which were similar to the planned battery-powered machines. The Roof Master RM 1.8 bolting rig (Figure 2a) and the Face Master FM 1.7 drilling rig were used for tests. The tests were conducted in the KGHM Polska Miedź S.A. mine O/ZG Polkowice-Sieroszowice. The parameters of the drive system were recorded during the machine ride, while the parameters of the working process and pressure in the hydraulic system of the working parts were recorded during operation (Figure 2b). The data were recorded during the drilling and bolting process as well as during rides to other workstations and to the repair chamber.

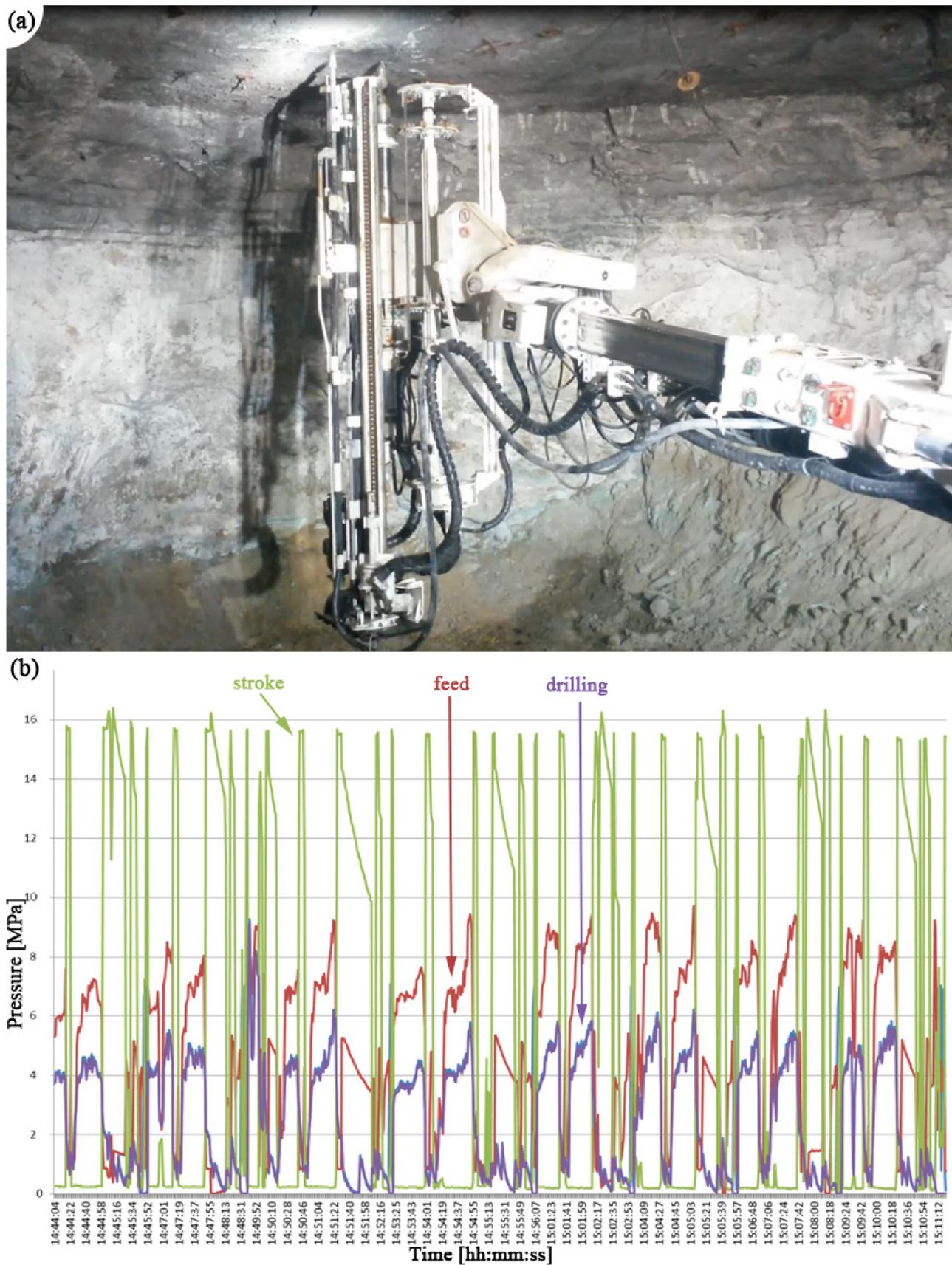


Figure 2. Underground tests in the KGHM mine: (a) Roof Master RM 1.8 diesel bolting rig, (b) recorded pressure courses in the turret hydraulic system.

Figure 2 presents a selected photo from the tests and an example of a graph of pressure courses versus time.

Based on the analysis of the test results and the user's requirements, the following was determined:

- Typical schedules of machines operation;
- Actual parameters of the supply network;
- Speed of movement of machines, taking into account the slope and quality of the ground;
- Profile of the route covered by the machines;
- Resistance to movement for various routes and floor conditions;
- Power demand for individual phases and operating conditions.

The performed analyses allowed developing a detailed concept of a self-propelled vehicle with an equivalent electric drive powered by batteries.

4. Power System of the Drilling and Bolting Rig

One of the most important systems in the designed machine is the electric power system. It is the electric power supply system that the mobility of the machine, and, in consequence, its working parameters and performance characteristics, depend on. The main electric circuit (high-current) has been designed to have the same configuration for the drilling and bolting rig. The only difference is in the size of the main engine, battery, or hydraulic systems. Based on the assumptions resulting from the functionality of the machines in the combustion version, a power system was designed, the schematic diagram of which is presented in Figure 3.

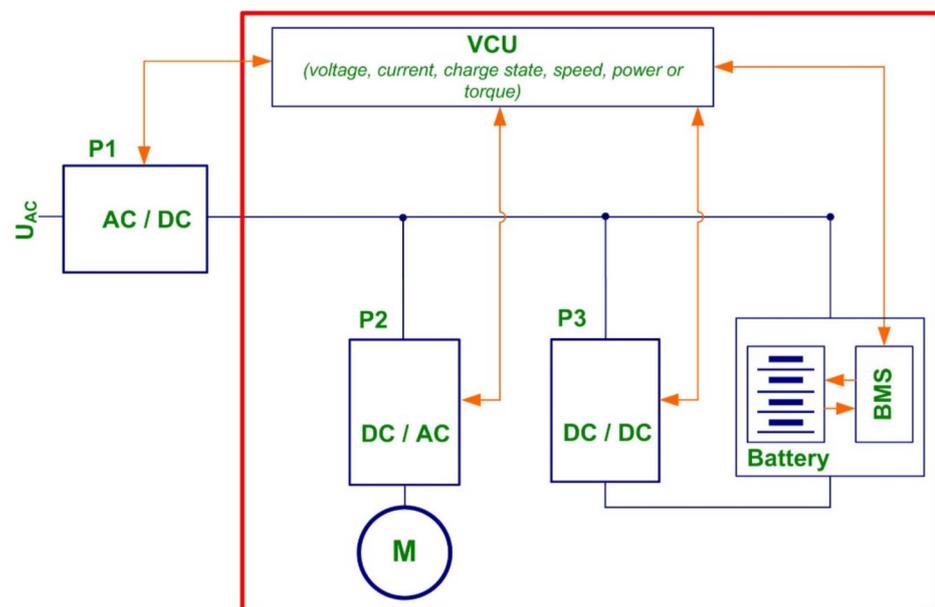


Figure 3. Schematic diagram of the machine power system.

The system is composed of three converters P1, P2, and P3. The P1 converter is used to connect the AC (alternative current) network to the DC (direct current) bus on the machine. For standard network parameters, the rectifier will work in the passive mode, which consists of rectifying the voltage. Improvement in the active mode is achieved by installing an LC (inductor-capacitor) filter on the inverter input. The P3 converter is used to charge the battery, while the P2 inverter is used to supply and regulate the main drive motor M (controller). The control is effected by the VCU (vehicle control unit), which contains a PLC (programmable logic controller) with a program for controlling the machine.

The P2 converter is used during the ride. The P3 converter connected to the battery uses the DC/DC application and operates in the VCM (voltage control mode) with the option of maintaining the voltage on the DC bus side. The P2 converter supplying the drive motor operates in the DC/AC mode at that time. The diagram of the system during the machine's ride has been shown in Figure 3 (red frame). During the machine's ride, the engine draws power only from the battery. A significant advantage is the energy return to the battery during the downhill ride.

Battery charging and operation take place in accordance with the system shown in Figure 3. Owing to the battery charger incorporated in the machine, it is charged directly from the mine's mains. The work of both machines in the excavation, i.e., drilling and bolting, is always carried out when the machine is connected to the mine's mains. In practice, however, voltage drops may occur in the power supply station, which results in a break in the machine's operation. To prevent these interruptions, the possibility of supplying the hydraulic system with a battery has been provided in the system. In the case of very difficult conditions occurring in the process of hard rock drilling, it is possible to use battery power with increased power on the main motor.

According to the assumptions, the ride is battery-powered. The power consumed by the motor is the power from the battery, decreased by losses in the converters. The power flow during the machine ride is shown in Figure 4 (red line).

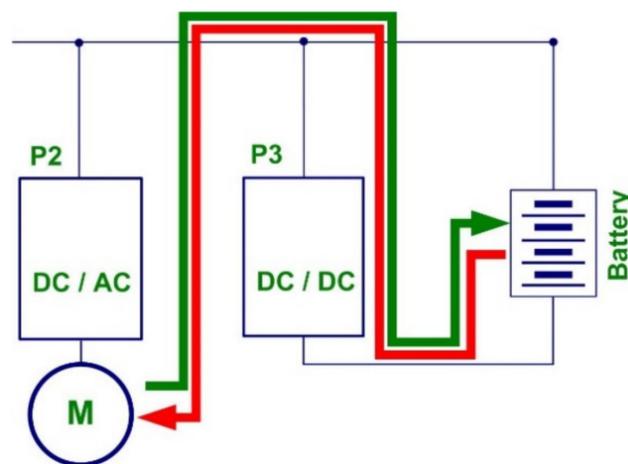


Figure 4. Diagram of power flow during the machine ride (red) and braking (green).

During the ride, energy will always flow from the battery to the main motor. In the analyzed cases, the losses from the converters were not taken into consideration when developing the power flow diagrams. The losses are converted into heat and carried away by the cooling system.

Braking is an important element of the machine's ride, which affects its safety. The main role in this process is played by dynamic braking with the option of main motor braking with energy return to the battery. Battery charging must always finish with a certain reserve so that the battery has some capacity to receive the braking energy. The power flow during braking is shown in Figure 4 (green line). Power flows from the motor to the battery.

The battery is charged near the power supply station or in the repair chamber. Charging takes place via the P1 and P3 converters. Charging energy from the mains is stored in the battery. Figure 5 (green line) shows power flow during charging.

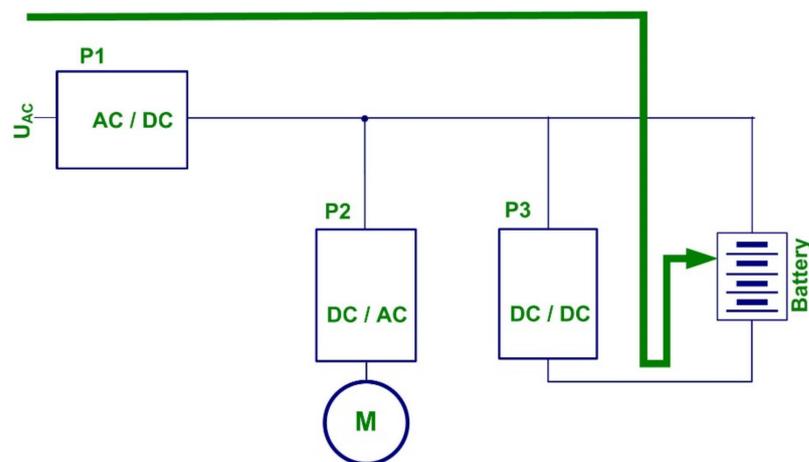


Figure 5. Diagram of power flow during charging of the machine.

After the machine has arrived at the workstation, it is possible to recharge the battery in the time between the drilling of subsequent holes or between the installation of subsequent bolts, or during the auxiliary processes. This allows using the machine's working time more efficiently. The master control system controls the total current drawn from the mains. The power flow has been shown in Figure 5 (green line).

5. Control Algorithms

The next stage involved developing algorithms for controlling the electric power system during the ride and operation of the machine, taking into consideration various combinations. Due to the similar structure of the power electric circuits of the drilling and bolting rigs, common algorithms were developed for both types of machines.

The P1, P2, and P3 converters were configured depending on the selected operating mode. The appropriate configuration ensures the correct operation of the machine and allows applying appropriate limitations, which guarantees the safe operation of the powered equipment. Particular attention was paid to the configuration of converters cooperating with the bank of batteries. The supervision system was configured to prevent deep discharge of the battery and to ensure optimal charging conditions set by the battery management system (BMS). Depending on the mode (ride or operation), the relevant converters are blocked or configured. After the appropriate machine operating mode has been selected, the configuration of the equipment is performed automatically by the PLC controller, which communicates by means of CAN (controller area network) transmission bus.

5.1. Algorithms for Switching on the Supply Voltage

The supply voltage is switched on according to two algorithms, depending on the mode (operation or ride). The main supply voltage is the DC bus voltage for battery operation and the AC voltage when the machine is in the operating mode (drilling or bolting). Before the main voltages are switched on, the auxiliary voltage supplying the circuits of PLC controllers and protection systems is switched on. The converters are configured before switching on the main power.

The algorithm controlling the process of switching on the voltage during the machine ride is shown in Figure 6. During the machine ride, a bank of batteries is used as a power source. The unit checks all the systems one by one and prepares them for operation according to the control algorithm. In this mode, the machine must not be connected to an AC power source via cable, the power cord must not be unwound, and the power supply system must function properly. Before the ride, the battery power system must be prepared.

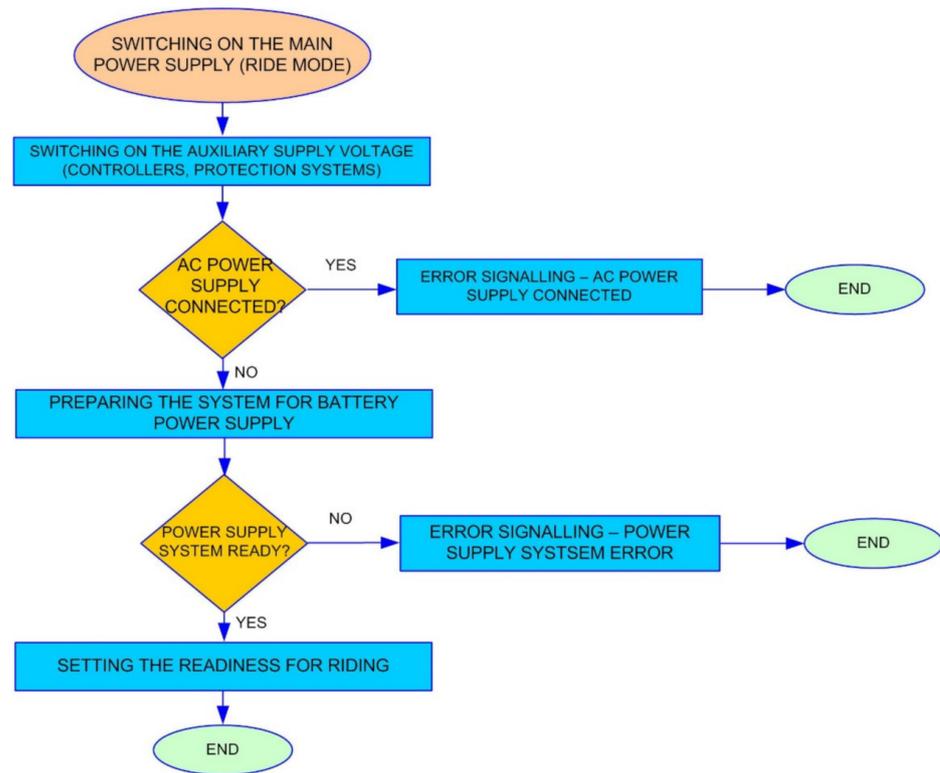


Figure 6. Algorithm for the procedure of switching on the supply voltage in the ride mode.

The algorithm controlling the process of switching on the voltage in the operating mode has been shown in Figure 7. In the operating mode, after switching on the auxiliary voltage, the converters (P1, P2, and P3) are configured for work. While the machine is in operation (drilling, bolting), the mine's AC network is used as a power source. As in the case of machine rides, the power system is first prepared, and its correct operation is checked. In the next step, the battery is connected, and the P1 and P3 converters are connected to the circuit. The electrical system is now ready for operation.

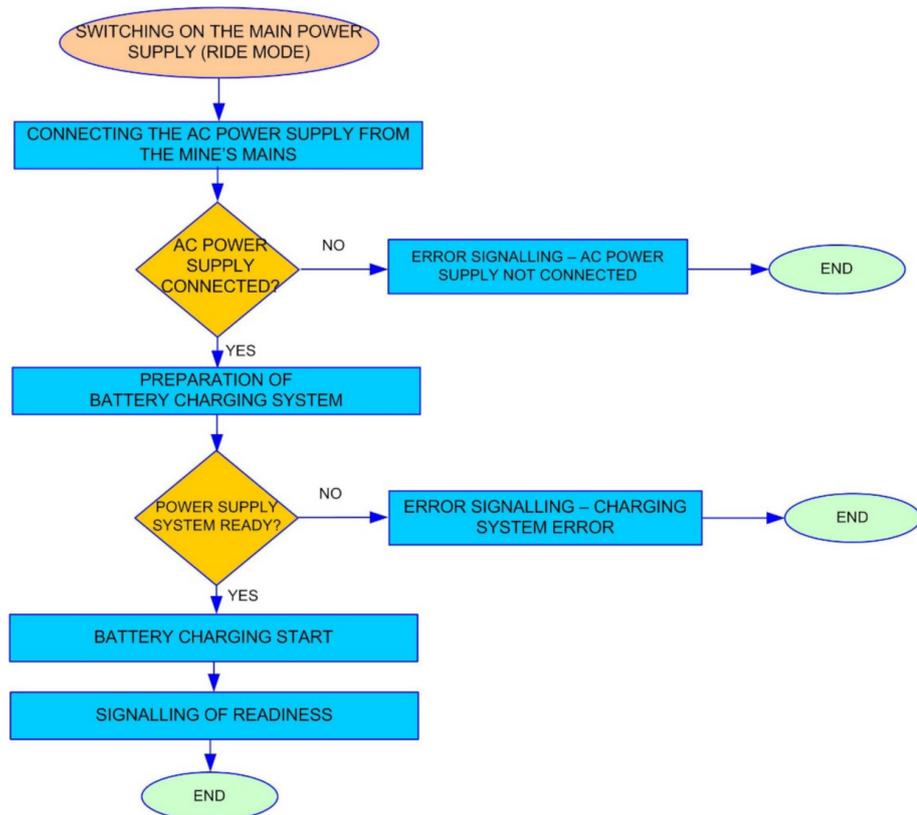


Figure 7. Algorithm for the procedure of switching on the supply voltage in the operating mode.

5.2. Algorithms for Controlling the Electric Power System of the Machine

The algorithm controlling the electric power system is also selected depending on the operation or ride mode. The algorithm during the machine's ride has been shown in Figure 8. In the ride mode, after switching on the voltage, the electric system is ready for riding. The converters (P2, P3) are configured for the ride mode. Before starting a ride, the machine control system checks the state of charge of the batteries. Riding is not possible when the battery is completely discharged. After receiving the command to ride, the control system starts the electric motor of the ride drive. During the ride, the master control system in the PLC continuously monitors the depth of battery discharge. The system informs the operator about the battery discharge status on an ongoing basis. If the critical discharge is reached, the machine must be stopped; otherwise, the battery management system (BMS) will disconnect the battery. Riding cannot be continued unless the battery has been recharged to the minimum value. In most cases, braking of the machine is accompanied by energy return to the battery. In an emergency, when the bank of batteries has been disconnected or the motor is stopped due to a failure of the inverter, the master control system initiates emergency braking using mechanical brakes. The ride (switching on the main motor) is continued when the system is ready for riding, i.e., after the cause of the emergency stop has ceased and the errors are deleted.

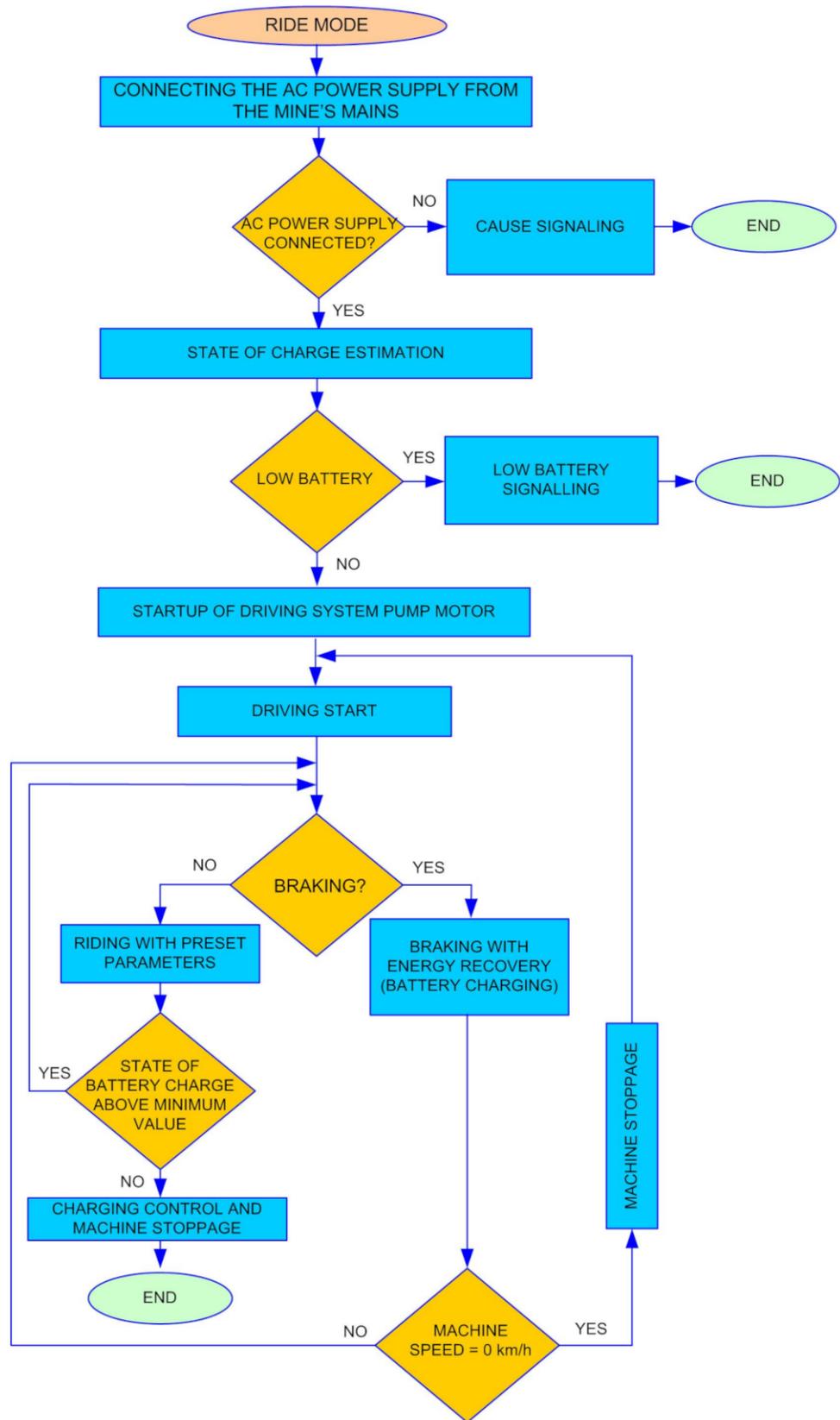


Figure 8. Algorithm controlling the electric power system during the ride.

The algorithm for controlling the electric power system during operation is shown in Figure 9. After switching on the voltage in accordance with the procedure described

above, the electrical system is ready for operation. The converters (P1, P2, and P3) are configured for operation. In the operating mode, the state of charge of the battery is constantly monitored by the controller of the master control system. After the work request has been received by the master control system, the motor of the operating system pump is turned on. After the supply voltage has been switched on, the condition of the insulation resistance is constantly monitored. If a decrease in resistance is detected, the supply voltage of the machine must be switched off.

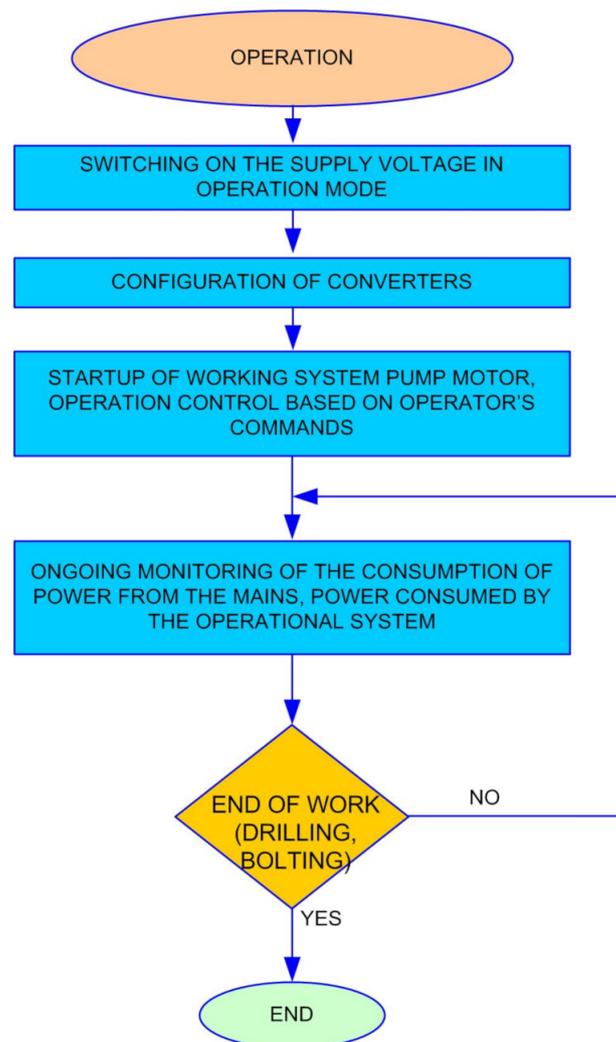


Figure 9. Algorithm controlling the electric power system during operation.

6. Validation Tests

Laboratory validation tests were carried out for the developed power systems and control algorithms. The tests of the electric drive system of the self-propelled drilling rig and the self-propelled bolting rig in the riding and operation mode were conducted at a special stand in the measuring system shown in Figure 10. The system uses a test platform for PMSM (permanent-magnet synchronous motor), equipped with two synchronous motors coupled with each other, an AC/AC frequency converter with an active rectifier, enabling energy return to the supply network, a PLC logic controller, a switching and measuring apparatus and an operator's panel with a display. The stand with the motors and the operator's desk is shown in Figure 11.

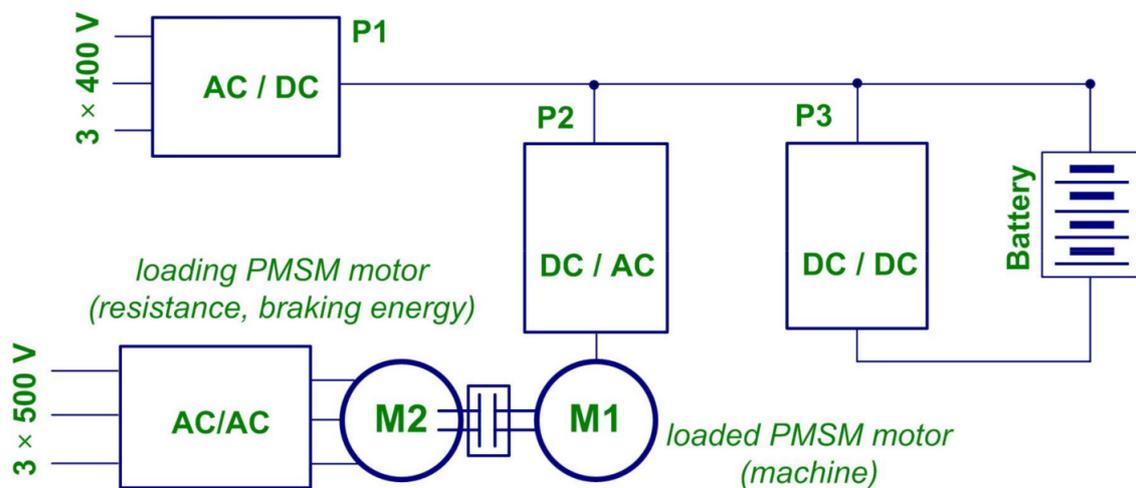


Figure 10. Measuring system for validation tests of the electric drive in the riding and operation mode.



Figure 11. Stand for testing the drive system.

The basic element of the system subjected to validation was the DC busbar. The AC/DC converter (P1 diode rectifier), supplied with the voltage of 3×500 V from an inductive regulator, is connected to the bus. The P3 DC/DC converter connects the bus with the bank of batteries. The P2 DC/AC converter controls the main drive motor, i.e., the M1 motor.

In order to check the behavior of the system during mains voltage fluctuations, the AC/DC converter (diode rectifier) was supplied with the voltage of 3×500 V from an inductive regulator, allowing for changes of this voltage within a range wider than the expected tolerance range of $0.85 \div 1.2 U_N$. The DC bus can be powered during standby/operation and, depending on the connection to the mains, from the AC/DC converter or via the DC/DC converter from the main bank of batteries.

Due to the need to check the behavior of the system at different battery voltage values and during mains voltage fluctuations, the stand was equipped with the M2 motor coupled with the M1 machine motor, which was the loading machine (Figure 10). The main motor load generated by the M2 motor can be regulated by the AC/AC converter controlling the motor, and the value and direction of the torque for any value and direction of rotational speed can be fully adjusted, from positive to negative values. This means that the M2 motor can both load and drive the M1 motor, which allows representing (simulating) the downhill ride and, therefore, motor braking. When driving in a flat area or on a slope, the M1 machine works as a drive motor, drawing energy via the DC/AC converter and the DC bus from the bank of batteries. During drilling or bolting, the vehicle is connected to a 3×500 V power supply network, and the M1 machine also functions as a drive motor but draws energy via the DC/AC converter and the DC bus, in this case, from this power

supply network. The electric energy generated in the load motor is returned to the supply network via the AC/AC converter. This is the most typical type of operation of the vehicle drive system.

The test of discharging the battery corresponded to long riding with a constant load in the real system. Additionally, it was checked how the voltage at the battery terminals changed as the depth of discharge, and the load increased. The tests were conducted using a battery consisting of six modules connected in series with the following parameters:

- Rated voltage: 499 V;
- Rated capacity: 58.8 Ah;
- Rated energy: 30 kWh;
Max. voltage: 562 V;
- Nominal voltage: 390 V;
- Max. dynamic discharge current: 120 A;
- Max. dynamic charge current: 60 A;
- Continuous discharge power: 60 kW;
- Continuous charge power: 30 kW.

The battery was discharged by the loading drive in the following system: battery > P3 converter > P2 converter > M1 machine drive motor M1 > M2 loading motor > energy return to the mains 3×500 V.

The battery was discharged at approximately 30 kW (half the discharge power) to 35% available energy. Further discharge was blocked by the battery management system (BMS). The conducted tests allowed obtaining battery discharge characteristics (Figures 12–14), which enable determining the battery discharge rate, the voltage drop in the state of charge and time function, as well as the amount of load in the state of charge function. A non-linear fitting was performed for voltage changes and a linear fitting for load change so as to find formulas describing these characteristics. An almost perfect match of the functions was achieved. In all the cases, the R-square (COD—coefficient of determination) value is significantly above 0.99. The formulas and matching factors are given in the charts. During the tests, the voltage changed from 504 to 486 V. Reducing the state of charge to 35% decreased the voltage by more than 3%. During battery discharging from 100% to 35%, a load of 37 Ah was consumed. The state of 35% charge was reached after nearly a 42 min operation. The function formula allows calculating that the battery will be completely discharged after 135 min.

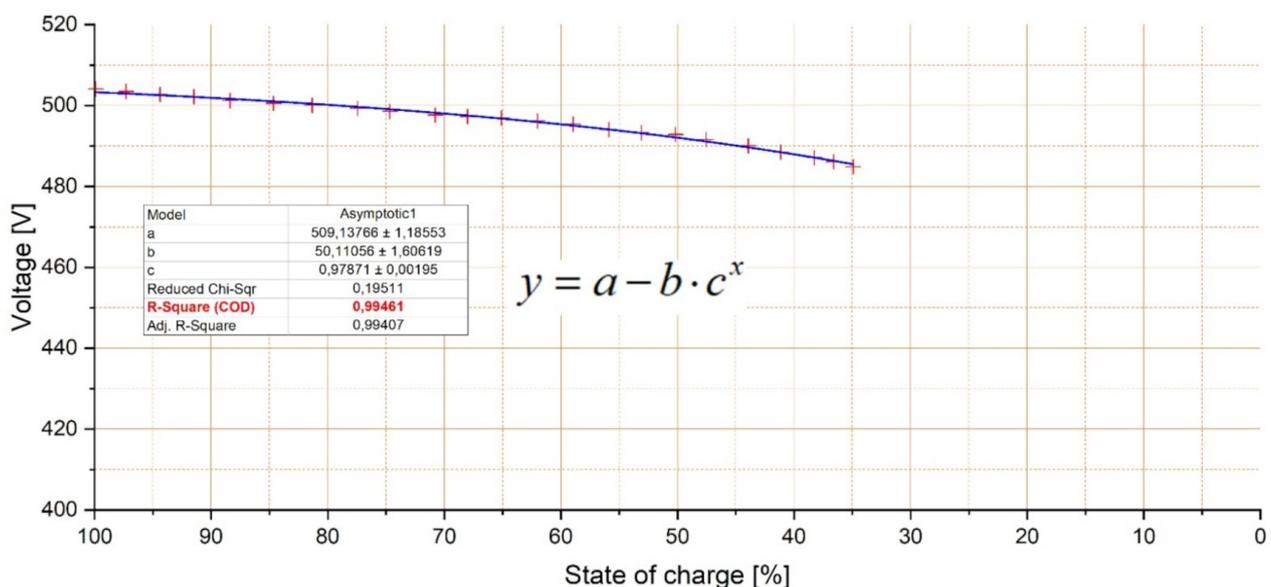


Figure 12. Battery discharge—battery voltage as a function of the state of charge.

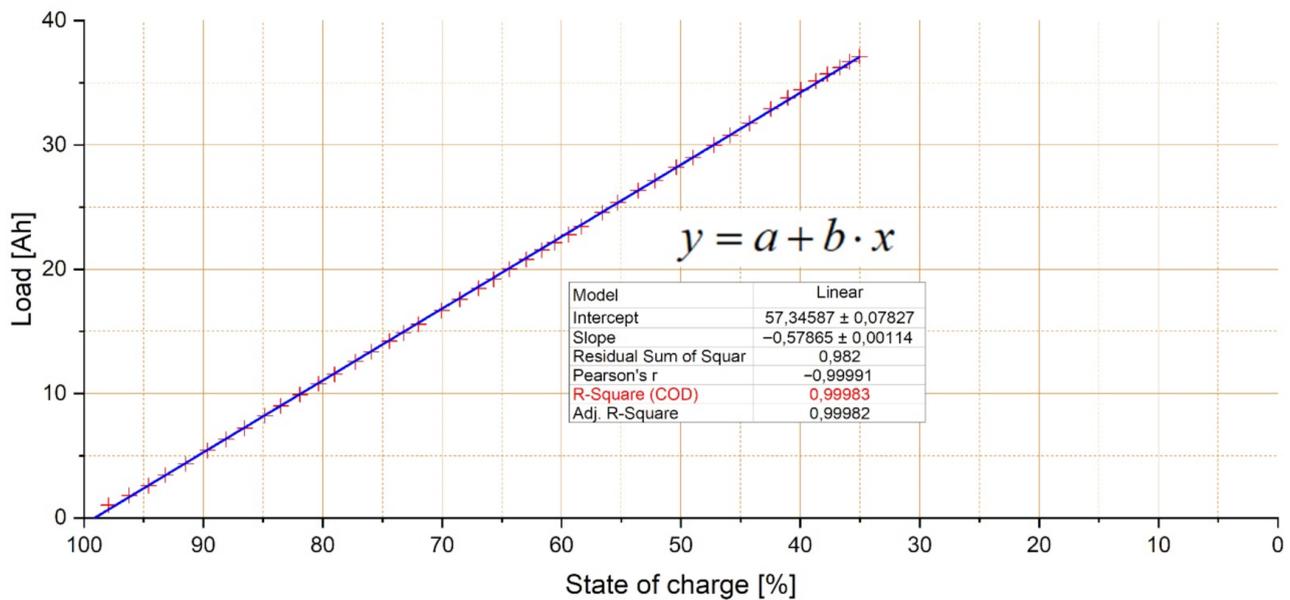


Figure 13. Battery discharge—load as a function of the state of charge.

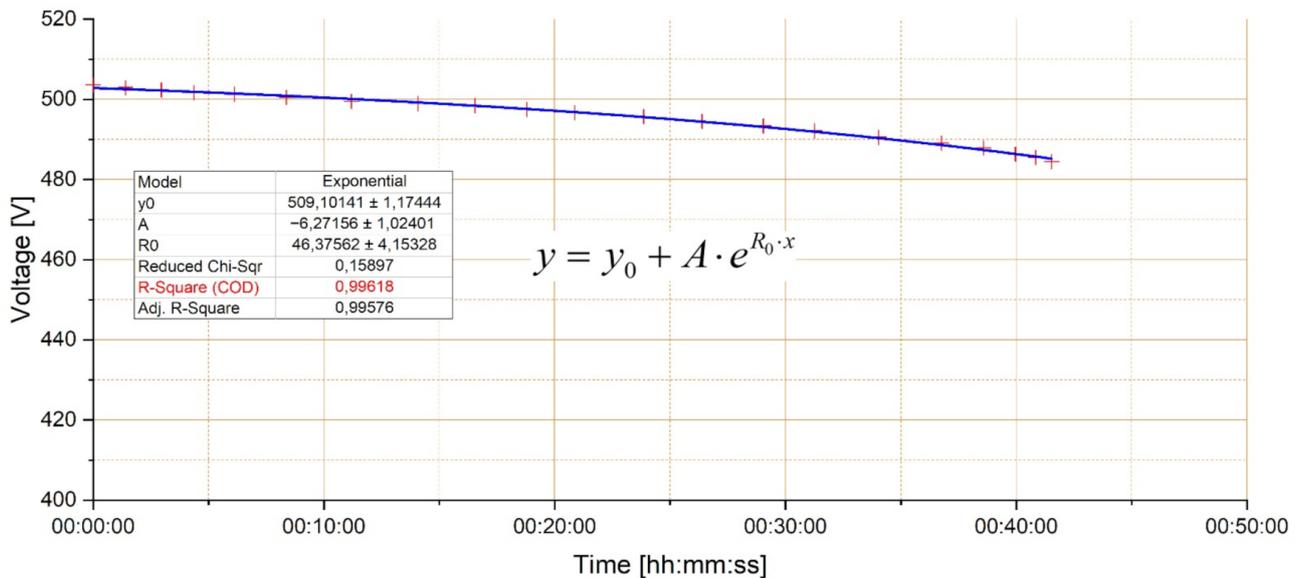


Figure 14. Battery discharge—battery voltage versus discharge time.

Next, tests of charging the bank of batteries were carried out. The *P3* charging converter enables full control over the charging current and voltage. However, the basic condition for obtaining the full required charging dynamics is that the voltage of the *DC* bus must be greater than the voltage of the battery.

Charging tests were carried out in two modes, in accordance with the presented configuration:

- Battery voltage setting mode (energy storage) with the setting of maximum charging current limitation;
- Charging current setting mode with the setting of maximum voltage limitation on the battery.

For the battery voltage setting mode, the preset voltage was the voltage of the fully charged battery: $U_{zad} = U_{bat.max} = 540$ V, and the maximum charging current $I_{max.tad} = 60$ A was set as the charging current limitation. In this mode, charging with the current set by

the battery management system (BMS) was continued until the battery was fully charged (100%). The state of charge is indicated by the BMS of the battery used for battery tests.

For the charging current setting mode, the preset current was maximum charging current $I_{zad} = I_{max.load} = 60$ A, and the maximum battery voltage $U_{bat.max} = 540$ V was set as voltage limitation. The charging current in this mode was also set by the BMS battery management system up to a level of 100%.

Based on the research, it was found that both modes were identical in this case. This is due to the fact that charging parameters are set by the battery management system (BMS), which is the master unit for the charging converter. Therefore, the values of the charging parameters set in the converter are treated each time as acceptable parameters, i.e., limit parameters, which the BMS does not exceed.

Figure 15 shows the course of the battery charging current. To reduce the current fluctuations around the mean value, it is recommended that a choke with a larger inductance should be used. The inductance of the choke used in the tests was 0.3 mH.

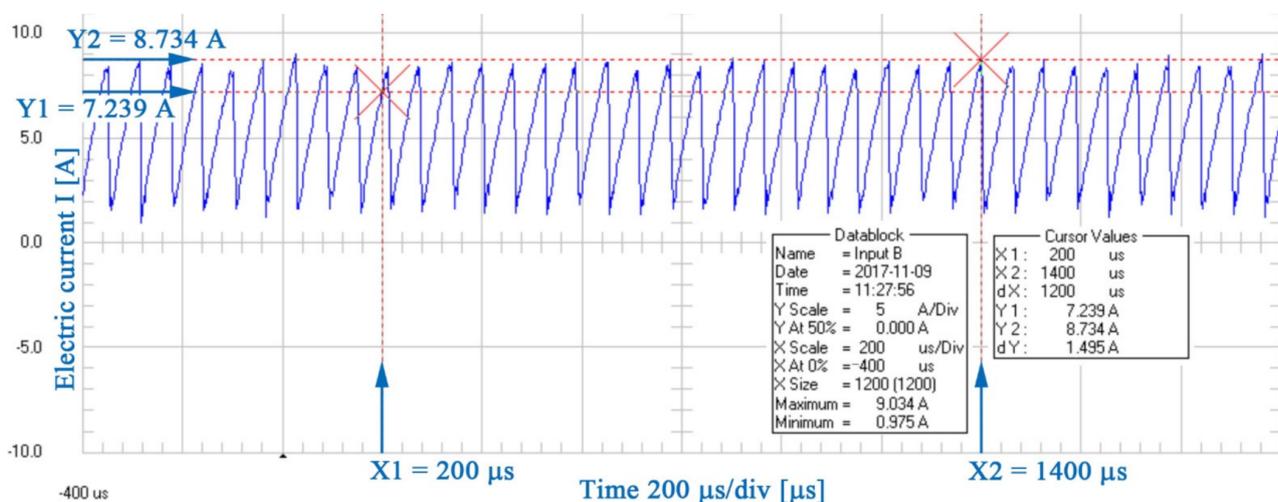


Figure 15. Battery charging current waveform—average battery charging current 5A.

Next, dynamic tests were conducted with battery power and motor load in accordance with the developed system. The dynamic tests involved wide-range changes of the drive motor's loading torque, from the positive to negative nominal value. Therefore, the M2 motor can both load and drive the M1 motor, which simulates riding with recovery due to motor braking. During the simulation of a ride in a flat area or on a hill, the M1 motor works as a drive that draws energy through the DC/AC converter and the DC bus from the bank of batteries. During the battery discharge, there is no possibility of limiting the current drawn from the battery by the P3 converter. However, the current can be limited by the inverter supplying the motor. The tests of the work of the inverter powering the drive motor were conducted in the following modes:

- Speed control;
- Torque control;
- Power control.

Speed control—increasing or decreasing the load (torque) during the drive's operation in the speed control mode causes an increase or decrease in the current and power consumed by the drive system while maintaining a constant rotational speed (to the value set in the converter of maximum current/power, beyond which the speed begins to decrease).

Torque control—increasing or decreasing the load (torque) during the drive operation in the torque control mode causes a reduction or increase in the rotational speed until the driving torque and load torque balance is achieved. The current and power consumed by the drive system also change.

Power control—increasing or decreasing the load (torque) during the drive operation in the power control mode causes a reduction or increase in the rotational speed. The current and power consumed by the drive system also change.

The motor braking tests with energy recovery for the battery involved changing the sign of the torque of the machine loading the drive motor, as a result of which it changed its function from loading to driving, and the tested *M1* motor became a generator. The electric power generated in this motor was transmitted through the *P2* converter to the DC busbars and, next, through the *P3* converter to the *BA* bank of batteries. The smooth transition of the *M2* machine torque from the load torque to the driving torque resulted in a smooth change of the sign of the power drawn from the bank of batteries to power supplied to this battery in the full range of load torque changes. At this point, it should be noted that the above tests were aimed at verifying the functionality of the proposed electric drive system of the analyzed mining machines and not checking the quantitative relationships, all the more so because the tested system was a model one and did not fully reflect the real target system.

The attempt to limit the power consumed by the drive system was aimed at verifying the possibility of limiting the power consumed by the drive system during drilling or bolting supplied from the mains when the power available from the mains is limited to 65 kW. The test was carried out with mains power supplied through the *P1* converter. As the *P1* converter cannot limit the power consumed, this limitation was effected through the *P2* converter supplying the motor. After the drive motor reached the permissible power (limit value), the drive torque was increased while the rotational speed was reduced. This is an advantageous feature of this type of drive as it prevents the tool from jamming in the rock mass. This is one of the standard limitations in converters working as inverters and can be set in a wide range. The test was conducted for the limitation set at 50% motor rated power with a positive result.

The attempt to limit the drive torque by the inverter supplying the drive motor was aimed at checking the possibility of limiting the torque by the drive system during drilling in order to prevent the tool from jamming in the rock mass. The test was carried out with mains power supplied via the *P1* converter while increasing the load torque above the set limit torque. In addition, in this case, the limitation was effected through the *P2* converter supplying the motor. It is also one of the standard limitations in converters working as inverters and can be set in a wide range. The test was performed for the limit set at 50% rated torque. After exceeding the set torque limit, the speed of the drive motor began to drop rapidly. The result of the driving torque limitation test was positive.

Another attempt to limit the current by the inverter supplying the drive motor was undertaken to check the possibility of limiting the torque by the drive system during operation (drilling) in order to prevent the tool from jamming in the rock mass. The test was carried out with mains power supplied through the *P1* converter. Increasing the load torque causes the current of the drive motor to increase. When the limit current is reached, the load current stabilizes, and the rotational speed is reduced, which should prevent tool jamming. In addition, in this case, the limitation was effected through the *P2* converter supplying the motor. It is also one of the standard limitations in converters working as inverters and can be set at any level. The test was performed for the limitation set at 50% rated current. After exceeding the set current limit, the speed of the drive motor began to drop rapidly. The current limitation test was positive.

7. Conclusions

Wherever machines powered by internal combustion engines are used, attempts are undertaken to replace them with electric equipment. In the case of many working machines and vehicles, the mains supply does not allow them to be fully operational; hence, it is necessary to use a battery power supply. It is crucial for every working machine that its battery-powered version meets the same requirements as the one powered by the combustion engine. Therefore, the requirements in the target place of work in terms of

battery power must always be specified. Underground mining is characterized by difficult working conditions and requirements that do not allow implementing solutions applied in other industries. Conditions in underground mines are so diverse that it is not always possible to develop universal solutions and machines.

The aim of the works described in this article was to determine and describe the operating states of the machine as well as to develop power systems and control algorithms that enable work in all operating conditions occurring in the analyzed mine. After the basic operating states of the machine had been described, the algorithms for controlling the electric power system were determined. In simple words, it comes down to the states of charging and discharging the battery under various possible conditions. The above-discussed algorithms for switching on the main voltage, riding, and operation set control over the converters and other elements of the electrical system so as to enable work with electrical parameters corresponding to the rated data of the designed machine. Next, the algorithms were checked during simulation tests and in the real electrical system. The system was based on the currently available elements, but its configuration corresponded to the layout of the designed machines. The developed concept, taking into account the control method, was tested in a model system with properties similar to the actual power supply system of the target machines. Machine operating states, such as riding, braking during ride and operation, were checked and verified. The validation proved the correctness and effectiveness of the power systems and control algorithms, which were then implemented in the designed machines. The developed and tested self-propelled electric bolting rig Roof Master RM 1.8KE and the drilling rig Face Master FM 1.7LE are the best proof that the works were performed properly. These are the first fully electric and battery-powered machines in Poland that have been designed and manufactured for the conditions of KGHM S.A. Battery-powered machines are the inevitable future of mining, which is also being created by Polish research units and Polish companies.

The drilling and bolting rigs are based on the above-presented power systems and control algorithms, which makes them unique on a global scale. The applied power systems and control algorithms are universal enough to be implemented in two different types of machines. Both machines were specially designed to substitute diesel machines in the conditions of a Polish ore mine. They are the lowest underground battery-powered drilling and bolting rigs with onboard chargers. Additionally, the machines can also be charged using external fast battery chargers. Machines offered by other manufacturers are much higher, above 2 m, which is not a challenge. Despite the low height, the presented machines' operation time without charging is similar to that of competitor products. Their limitation lies in the fact that they can work successfully only in approximate conditions in terms of user requirements and underground power grid parameters. However, some modifications can be made to adapt the presented machines to different conditions.

The next step is to develop power systems and control algorithms. There are two major directions. The first is to increase the working time without charging, whereas the second is to enable charging not only in gaps between drilling or bolting but also at the time of machine operation. There are also some general problems to be solved, for example, how to reduce the consumption of energy needed for riding as well as drilling and bolting processes.

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