Tests of electric properties of supply-control system of mining floor-loader

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Abstract. Tests of electric properties of the supply-control system designed for a floor-loader operated in underground mine workings, are presented in the article. The tests included functionality of the machine power electronics systems, consisting of the inverter controlling the induction motor and the charger of lithium-ion battery. The tests were concentrated on a verification of functional correctness of the system managing an operation of the battery (BMS) and its collaboration with the superordinated floor-loader control system. The obtained test results enabled to verify the accepted technical and functional assumptions of the supply-control system as well as to confirm a possibility of its safe operation in underground conditions (including the zones where an explosion hazard occurs). The supply-control system of the floor-loader is developed within the framework of the HYDKOM 75 project number POIR.04.01.02-00-0102/16, co-financed by the European Regional Development Fund.

1. Introduction
A floor-loader is a basic auxiliary machine, in most cases mounted on a caterpillar chassis, designed for a removal of waste rock and coal from roof and side walls (left after firing) [1, 2, 3]. An additional function of this type machines includes operations connected with pulling up of components being the mine infrastructure (e.g. pipes or rails).

In Figure 1 the floor-loader of BH3000 type produced by HYDROTECH J.S.C., is presented. At present the machines of this type are equipped with a wire electro-hydraulic drive. A concept of wire supply has a few disadvantages, among them the superordinated ones include: a limited mobility and a feeder cable susceptibility to mechanical damages. An attempt of eliminating the above-mentioned disadvantages consists in equipping the floor-loader with an autonomous source of supply, e.g. in a form of highly efficient battery. Such activities were undertaken within the framework of the project entitled “Innovative mobile machine with a universal electric drive system increasing the technical safety level“ HYDKOM 75, realized by the consortium consisting of the KOMAG Institute of Mining Technology and the industrial partner HYDROTECH J.S.C. within the framework of the Operational Programme Intelligent Development 2014 - 2020. The HYDKOM 75 project assumes designing, manufacture and testing of the battery-operated floor-loader to be used in underground mine workings, where potential hazards of methane or coal dust explosions occur [4]. The test of electric properties of the supply-control system of the designed floor-loader in the aspect of functional check-ups of power electronics systems and of the battery management system (BMS) are discussed in the article [5].
2. Object and scope of tests

The object of tests includes a prototype supply-control system of the floor-loader, which can be divided into four blocks:

- a battery together with the management system (BMS),
- an inverter controlling an induction motor,
- a DC charger,
- a system of control and protections.

The system was equipped with 3-phase induction motor of 55 kW power to meet the testing needs. Electrical parameters of the used motor complied with the parameters of the motor which will be finally installed in the floor-loader under designing. The motor was supplied from the lithium battery assembly via the power electronics inverter. The batteries were charged by means of a DC charger directly supplied from the 500 V AC grid. Similarly as in the case of the motor, the battery pack had the same parameters as the pack to be used in the final version of the floor-loader. The IGBT transistors of power electronics equipment (i.e. the inverter and the charger) were cooled with water.

The main objective of the conducted tests was a check-up of the described supply-control system from the verification point of view of the accepted design assumptions, functional properties and possibilities of operating in the zones, where explosion hazards occur. In relation to that the following scope of tests was accepted and it included as follows:

- a determination of the correctness of cells’ charging process,
- a determination of the proper realization of a driving operation (a process of discharging cells),
- a determination of the correctness of the cell battery management system,
- a determination of surface maximal temperatures,
- a determination of limit load for which a motor startup is correct.

The system under testing was installed on the motor test bench at KOMAG Institute of Mining Technology. The motor test stand of the power 223 kW enabled a free conditions’ shaping of the induction motor supply-control system. In the system of the drive transmission a torque transducer, enabling a measurement of the actual torque and of the actual rotational speed was installed. The parameters of the electric system were measured by means of power analyzer. In Figure 2 a block diagram of the supply-control system of the floor-loader together with the measurement apparatus is presented.

**Figure 1.** BH-3000 floor-loader made by HYDROTECH J.S.C.
Figure 2. Block diagram of supply-control system of floor-loader together with measurement instrumentation.

Such a measurement system enabled taking measurements and recording of the following parameters:
- voltage in the battery DC circuit $V_{DC}$,
- current in the battery DC circuit $I_{DC}$,
- power in the battery DC circuit $P_{DC}$,
- phase current on the output of the inverter (motor phase current) $I_M$,
- torque of the induction motor $M$,
- rotational speed of the induction motor $n$.

Simultaneously in the selected points of the system temperature measurements (among others: of the cassettes with battery and copper plates as well as of inverter and charger housings) were taken. In Figures 3 and 4 views of the supply-control system on the test stand are shown.

Figure 3. Supply-control system of the floor-loader on the test stand.
3. Test course and test results

The objective of the test programme required to perform battery charging cycles and drive cycles (discharging the battery) of the supply-control system of the mining floor-loader. In the same time correctness of the cells’ charging process, drive operation, operation of the BMS system were verified and the temperatures of selected system surfaces were measured.

3.1. Battery charging

The process of battery charging was realized by means of a charger supplied from a public distribution network 500 V AC. The charging current was 30 A. The charging process was controlled by the master control system, communicating with the loader by means of the CAN bus. A check-up of the charge level was realized by the management system (BMS) installed in the battery. Each charging cycle was started for the battery - discharged to the minimal level foreseen by the producer. Basing on the conducted tests minimal and maximal charging time which was about 2 to 3 hours [6] was determined. During the test some instantaneous charging breaks lasting about 4 seconds were observed. Their occurrence was caused by the breaks in the CAN communication between the superordinated control system and charger. The maximal battery voltage, after charging completion, was 766 V. The charging process ended automatically when the voltage on the battery single cell achieved the maximal value of 3.65 V. During the charging process maximal temperatures of the copper plate and of the charger housing were 35.2 °C and 37.4 °C respectively, however the temperature of the battery was 41.6 °C [6]. In Figure 5 exemplary time graphs of $V_{DC}$ voltage, $I_{DC}$ current and $P_{DC}$ power in the battery circuit, recorded during the charging process, are shown. In Figure 6 the thermogram of the charger, made during charging by means of a thermovision camera, is presented.
Figure 5. Exemplary time graphs of electrical parameters during the battery charging process.

Figure 6. Thermogram of the charger made during the charging process (current of 30 A).
3.2. Drive operation (battery discharging)

The drive operation was realized by the frequency converter supplied from the battery of cells. The frequency converter supplied a three-phase induction motor of 55 kW power. The motor test bench was used for controlling the motor load to force constant, rated phase current of the frequency converter in the intensity of ~75 A. During the tests a constant torque and a constant rotational speed resulting from the applied frequency converter operational frequency (50 Hz) were maintained. Each of the test started after earlier charging the battery to the maximal level foreseen by the producer of cells. Basing on the conducted tests minimal and maximal operational time, which varied form about 57 minutes to about 1 hour and 6 minutes [1], was determined. The drive was switched off automatically when the voltage on the battery individual cell reached the minimal value of 2.65 V. During the driving mode operation maximal temperatures of the copper plate and of the frequency converter housing reached 27.5 °C and 31.1 °C respectively. However, the temperature of the cell battery was 48.0 °C [6]. In Figure 7 exemplary time graphs of the $V_{DC}$ voltage, $I_{DC}$ current and $P_{DC}$ power in the battery circuit and the $I_{IM}$ phase current of the frequency converter are shown. In Figure 8 the frequency converter thermogram, made with use of a thermovision camera, is presented.

![Exemplary time graphs of electrical parameters during the drive operation.](image_url)
3.3. Motor startup tests

The tests aimed at a determination of the motor load value of the floor-loader supply-control system, for which a correct startup to the rated frequency (50 Hz) was possible. The motor load was established on the percentage value of the inverter rated current value (I_M), controlled by the motor test bench during its operation at the rated frequency. The tests were conducted for seven current values, i.e. 50%I_M, 60%I_M, 70%I_M, 80%I_M, 90%I_M, 95%I_M and 100%I_M. The load value, determined earlier by means of the motor test bench, was maintained during the drive startup. A condition of the correct startup consisted in starting the drive in such a way so that to “rotate” the motor to the rated speed. The tests were conducted on the charged battery. Basing on the obtained results, the load limit value, at which a correct motor startup was possible, reached 95%I_M. Above this value so called stall of the motor occurred,
resulting in failure conditions of the inverter. In Figure 10 exemplary time graphs of mechanical and electrical parameters during the startup in the case of 95% value of the rated current, are presented.

![Image](image_url)

**Figure 10.** Exemplary time graph of mechanical and electrical parameters during the drive startup for 95% of the inverter rated current.

4. Summary and discussion

The tests of electrical properties of the floor-loader supply and control system with the autonomous battery supply, developed within the HYDKOM 75 project, are described in the article. The obtained test results confirmed the accepted design and functional assumptions. The control-supply system correctly realized charging of the cells with the current of 30 A intensity. The maximal charging time was 3 hours and ended automatically when an individual cell reached the maximal voltage of 3.65 V. In the drive mode, the system supplied the rated phase current of 75 A intensity, at the voltage of 500 V AC. The maximal time of the drive operation for the rated load was 1 hour and 6 minutes. After having reached the minimal voltage by a battery individual cell, the system of control and protections switched off the drive automatically, thus protecting the battery against the excessive discharging.

An observation of the battery management system (BMS) forms the basis for meeting the requirements of PN-EN IEC 60079-0:2018-09 Standard in scope of using batteries in zones where explosion hazards occur [7]. Maximal temperatures of the selected system components, recorded during their operation in the charging mode and in the drive operation, do not cause any risk of gas or coal dust explosions in mine conditions. The startup properties of the applied drive enable a free motor startup for an initial load of 95% of inverter rated current.

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