ENERGY RECUPERATION AS ONE OF THE FACTORS IMPROVING THE ENERGY EFFICIENCY OF MINING BATTERY LOCOMOTIVES

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Abstract:
Mining industry is currently one of the biggest industries in the world. All mines produce "indispensable" minerals, starting from fuels such as coal and ending with noble metals such as gold or copper. Mines in the world compete in the volumes of mined minerals what requires use of state-of-the-art, more efficient and, and what is more important, safer machines. Such trend favors development of technology and mobilize engineers to adapt the technologies that were used so far in easier environment to the needs of the mining industry.
The article presents the issue of energy recuperation in mining battery locomotives. Simulation tests of the power supply and control system of the Lea type battery locomotive are discussed. The results of tests on the electric energy consumption of the locomotive during the operational change in the mine were presented, which were referred to the simulation results. Factors influencing the efficiency of energy recovery and the risk resulting from hydrogen emission in the recuperation process have been indicated. Also discussed is the study of the concentration of hydrogen concentration emitted from the battery of lead-acid cells during their recharging in the process of electrical braking with energy recuperation.

Key words: battery supply, energy recuperation, hydrogen emission, mine locomotive unit, PMSM drive

INTRODUCTION

When it comes to hard coal mines in Poland 99% of all mining plants are the mines with methane or coal dust explosion hazard. Besides of basic coal dust sources there are many secondary coal dust sources, which extends the use of machines in difficult conditions [6, 23]. Working in that specifically conditions increase machine failures, which have destructive effects on continuity of operation and lead to production losses in long-wall mines [3]. The transport of people in underground mining excavations and the transport of materials and spoil in mines is one of the most important processes affecting the efficiency of raw material production. The means of transport used include floor locomotives and suspended tractors [10, 21]. There are three types of floor locomotives: diesel, traction and battery-operated. Due to the emission of harmful substances from diesel locomotives, efforts are being made to reduce them and replace them with electric drives. In the deepest seams of mines, when driving headings, combustion engines are practically not used. The extraction of ore and the transport of materials is carried out by means of electrically powered transport systems [4]. The accumulator locomotives used match the mobility

of diesel locomotives, outperforming them with efficiency and lower emissions of harmful gases. Higher energy efficiency of battery locomotives additionally reduces the heat emission to the mine atmosphere [4]. Traction locomotives give way to battery machines, mainly due to restrictions resulting from the possibility of conducting electric traction in selected areas of the mine. However The source of power for mining battery locomotives are lead-acid cells, which emit hydrogen during charging or recharging (e.g. during electric braking) [5]. The amount of hydrogen emitted from the cell depends, among others, on: charge level, charging current, charging duration, electrolyte temperature. The analysis shows that the effectiveness of battery ventilation during operation of the machine is not verified in any way, and the level of energy recuperation during the electrical breaking is extremely important for the hydrogen gas emission. For this reason, tests were carried out to check whether there was a need to monitor the concentration of hydrogen in order to ensure safety and maintain the efficiency of the electric braking process, with energy recovery.

LITERATURE REVIEW

The most popular, operated battery machine in Polish hard coal mining is the Lea locomotive (version BM-12 or 12P3) - Fig. 1, which has been in operation for almost fifty years.


Fig. 1 Lea 12P3A battery mine locomotive

This locomotive is powered by a LDs-245 DC (Lea BM-12) or LDs-327 (Lea 12P3) DC motor. Motors, due to the installed electric power, have different rotational speed (LDs-245 n_N = 2910 rpm, LDs-327 n_N motor = 1450 rpm). In the first solutions, resistors were used in the battery locomotive drive system to control the start-up and to regulate the speed of traction motors [4]. The machine speed control consisted of connecting series starting resistors and switching traction motors from serial to parallel connection. These systems had a number of disadvantages, such as: difficulty in adjusting the angular speed of motors, large power losses on starting resistors and the need to use a large number of contactors and adjusters switching high currents, which caused rapid wear of contact elements. However, the biggest disadvantage of this type of control system was the inability to return energy to the battery during the electric braking process. All energy recovered during braking was dissipated as heat. The disadvantages of the original control systems determined the low efficiency of the locomotive's propulsion system. Therefore, locomotive designers and manufacturers sought to develop a higher efficiency powertrain solution. Nowadays the series DC motor was eliminated to be replaced by one or two brushless permanent magnet synchronous motors (PMSM). The main advantages of IM over DC machine for the same performance are cost, robustness and reliability [1, 2, 14, 18, 19], also the permanent magnet synchronous motor has the advantages of large energy density, high efficiency, long service life and low complexity [8, 13, 15, 16, 17, 20, 22]. Supply and rotational speed control is based on DC thyristor switch, which is DC/DC converter of forced-commutation. Bidirectional DC/DC converter with isolated structure is most popular [7, 11, 12]. It can operate in a switch on or switch off position for any time interval. The power-electronic key allows for smooth step less motor startup and energy recuperation to the battery. The energy efficiency of locomotives equipped with this type of control system, compared to resistor control systems, is about 25% higher. In addition, as a result of the controlled flow of current in traction drives, the life of engines and mechanical gears of locomotives was extended.

SIMULATION TESTS OF THE POWER SUPPLY AND CONTROL SYSTEM OF THE MINING LOCOMOTIVE WITH ENERGY RECUPERATION

Simulation tests of the power supply and control system of the mining battery locomotive, intended for energy recovery, were conducted in the PSIM simulation environment. The scope of the simulation included the passage of the locomotive from the firehouse towards the loading point (driving on a slope without loading), and then the passage from the loading point to the place of unloading (driving after falling with loading). Simulated acceleration of the locomotive, coasting and braking with energy recovery. The model of the power supply and control system for the Lea Bm-12 locomotive is shown in Fig. 2. The study took into account the profile of the transport route previously identified in one of the mines as real, on which mining battery locomotives move. A route with unfavorable traction parameters was selected. The route length was about 3000 m (from the loading point to the unloading point) and the average slope 0.4% (towards the unloading station). The following parameters of the battery locomotive were assumed for simulation tests: maximum tractive force Fp_{max} = 30 kN, maximum speed V_{max} = 6 m/s, gear ratio with = 1:19.26, wheel diameter d = 560 mm, rated battery voltage U_n = 144 V, five-hour capacity of C5 batteries = 840 Ah.
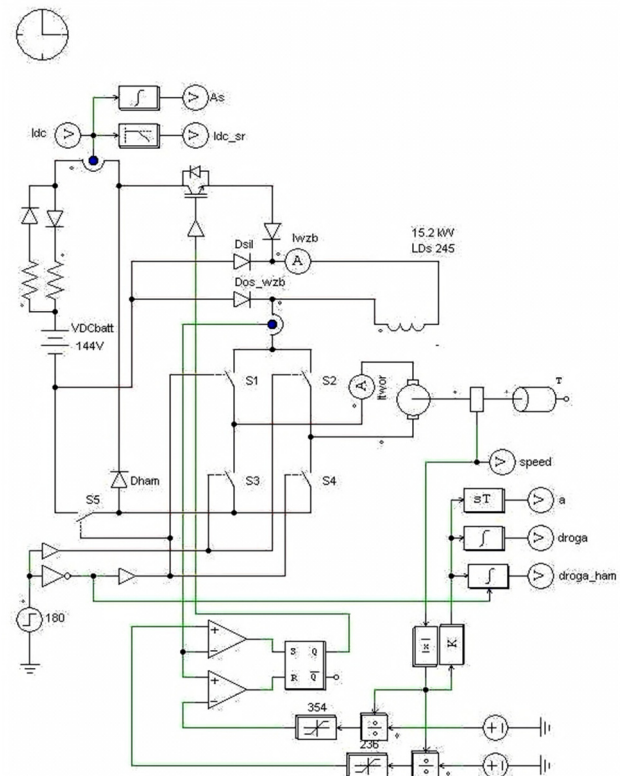
Fig. 2 Simulation model of the power supply and control system for the Lea BM-12 locomotive, powered by a DC motor type LDs-245

The most unfavorable conditions from the point of view of hydrogen emissions were simulated, i.e. acceleration of

the transport set (with loading), after a fall with a slope of 0.4%, in the speed range of 0-3.2 m/s. After reaching the steady speed, braking followed until the locomotive stopped. The following parameters were recorded during the simulation: locomotive speed, electromagnetic torque of the engine, motor armature current, average battery current, energy absorbed and transferred to the accumulator battery. Based on the recorded parameters, the mechanical power on the motor shaft was calculated. The simulation results are shown in Table 1.

Table 1
Simulation results

Series 15kW DC motor type LDs-245 driven on a 0.4% incline track with a load				
Speed [m/s]	Distance [m]	Energy [Wh]	Energy recuperated [Wh]	Electrical breaking road [m]
3.2	516	1224	168	33.6

In simulation studies, only two sections of the route were analyzed in which electric braking with energy recovery occurs. The route profile and load of the battery locomotive were unfavorable for the machine, which in relation to information obtained from the mine are very rare. Despite this, energy of 168 Wh was recovered. In typical operating conditions, the battery locomotive moves with lower loads, traveling on milder sections of transport routes, on which electric braking with energy recovery occurs much more often.

TESTS IN THE REAL CONDITIONS
The test object in real mine conditions was the power supply and control system of the Lea-type mining battery locomotive. This system consisted of a power supply battery, converter and drive motor. Technical parameters of individual components of the power supply and control system are presented in Table 2.

Table 2
Technical parameters of the tested power supply and control system

Type of locomotive	Power [kW]	Voltage [V]	Rotatory speed [rot/min]	Battery capacity [Ah]	Current [A]
Lea BM-12	15.2	144	2910	840	120
Lea 12P3A	18	144	1450	840	140

The tests was carried out on a single-track drift of one of the hard coal mines. The following parameters were recorded during the tests:
− the intensity and shape of the electric current flowing to the battery during braking with an electric motor, with energy recuperation,
− hydrogen concentration inside the accumulator battery (according to standard methodology).

The measurement of the intensity and shape of the electric current was recorded using an appropriate current probe (Fig. 3). Since hydrogen emission only took place during charging (recharging) of the battery, current waveforms were recorded only during braking with an electric motor, with energy recuperation. The guidelines set by National EV IWC, recommend a minimum total power factor of 95% and a maximum current THD of 20% [9].
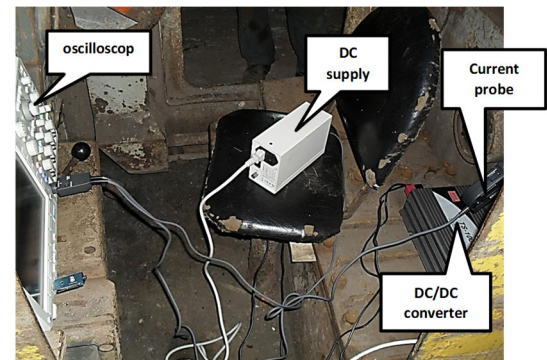
**Fig. 3 The measurement devices for measure and registration of the current and shape**

Hydrogen concentration measure methodology
The measure of the hydrogen concentration was made according to the standard methodology shown of Fig. 4.
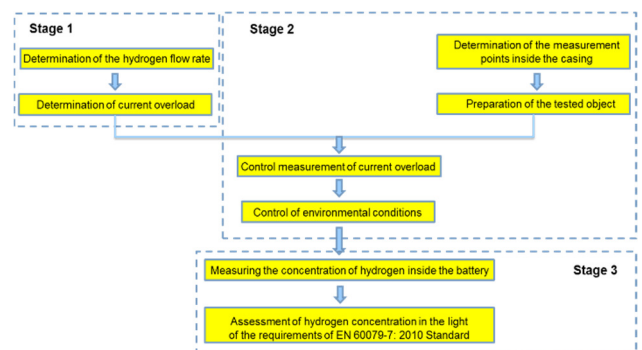
Fig. 4 Hydrogen concentration measure methodology
Source: [5].

The measurement of hydrogen concentration was carried out using two catalytic sensors located in the battery enclosure (Fig. 5).
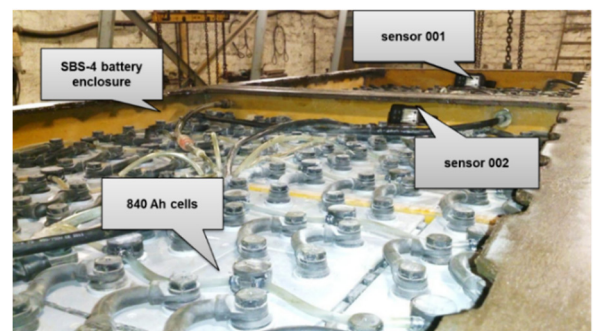
Fig. 5 Preparation of the tested object – arrangement of hydrogen concentration sensors

The location of the hydrogen concentration sensors resulted from the construction of the SBS-4 flameproof battery

enclosure and the direction of driving of the locomotive. Hydrogen concentration sensors placed inside a charged battery, recorded hydrogen concentrations during the operation of the mining locomotive until it was discharged. The measurement took approx. 4 working shifts (approx. 24 h). The percentage of LEL hydrogen concentration (Lower Explosion Limit) was recorded. The conversion from percentage to volume resulted from the need to determine the explosive concentration of hydrogen (hydrogen in air is an explosive gas at a concentration of 4 to 75% by volume). The value of 100% LEL was set to 4% by volume The % LEL reference to the entry in PN-EN 1889-2 + A1 (2010), regarding the ventilation of the battery box (so that the hydrogen concentration does not exceed 2% by volume), resulted in the measurement of hydrogen concentration below 50% LEL meant compliance security requirements. It should be emphasized that exceeding the level of hydrogen concentration above 50% LEL was not a threat, but only signaled the failure to meet the requirements of the standard. A real threat of hydrogen explosion occurs when its concentration level is exceeded by 90% LEL.

RESULTS AND DISCUSSION

As The analysis of the obtained test results was made in terms of the impact of current intensity and distortion on the intensity of hydrogen evolution. Fast Fourier Transform (FFT), used for periodic waveforms, was used to analyze current waveform deformation. The current waveforms recorded during the tests were periodic, however they were of a vanishing nature, which significantly hindered their analysis. Each mileage consisted of two parts: work and braking.

Fig. 6 presents examples of voltage and current curves for accumulator batteries recorded during actual mining operation of the Lea BM-12 battery locomotive. Color blue represented the voltage, color green is the current under the acceleration, color black is the current during the operation, color purple is the current under the electrical breaking and color red is the current under the electrical breaking with energy recuperation. During 800 seconds of operation of the locomotive transporting several tons of material, electric braking with energy recovery was registered. During braking, the average effective value of the current flowing to the battery was 100 A. The course of the battery current was cyclical. Each cycle is divided into three stages: acceleration, coasting and electric braking with energy recovery. The direct transition of the accelerated machine into electric braking mode with energy recovery, due to the generation of a current of about 400 A, can adversely affect the power electronics system. This situation, however, usually does not occur during normal machine operation. The exception is emergency braking. Currently, power supply and control systems are not equipped with a system limiting the current flowing to the battery during electric braking.
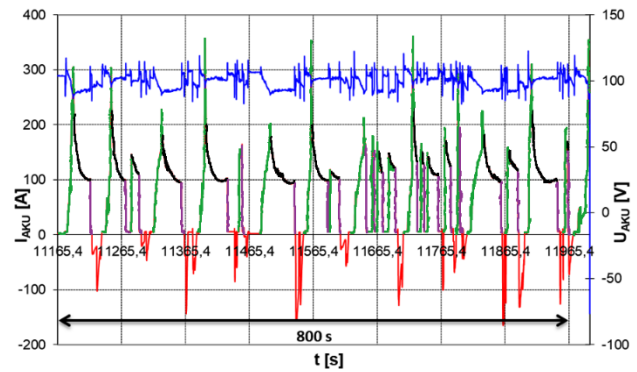
Fig. 6 *Variation of selected electric quantities in time during the real object testing*

Rapid transfer of high intensity electricity to batteries may cause an intensive emission of electrolytic gas – hydrogen, which in certain concentrations may become an explosive gas. The design of explosion-proof boxes allows, however, to vent accumulated hydrogen. Frequent skipping of the coasting stage and the rapid transition to electric braking with energy recovery may cause the accumulation of large amounts of hydrogen and require effective ventilation of the battery enclosure. The results of the hydrogen concentration recorded during the mine battery locomotive operation has shown in Table 3.

Table 3
Hydrogen concentration measured under the tests

Location of measurement points		Measurement 1	Measurement 2
		The maximum value of the concentration of hydrogen [% vol.] **The average value of hydrogen concentration [% vol.]** **The standard deviation of the mean value [% vol.]**	
Chamber 1	point 1A - half the distance between the upper surface of the cell and the cover	0.92	0.64
		0.73	0.47
		±0.16	±0.13
	point 1B - near the corks filling and ventilation	0.52	0.52
		0.46	0.48
		±0.05	±0.05
Chamber 2	point 2A - half the distance between the upper surface of the cell and the cover	0.76	0.40
		0.74	0.34
		±0.02	±0.05
	point 2B - near the corks filling and ventilation	0.44	0.64
		0.43	0.56
		±0.02	±0.09

The max. values of hydrogen concentration ranged from 0.20% to 0.92% by volume, the highest value of the hydrogen concentration was measured in chamber 1, at measuring point 1A, located halfway between the upper surface of the cells and the cover, the lowest value of the concentration of hydrogen was measured in chamber 2, at measuring point 2A, located also in the halfway between cells and the enclosure cover. Referring the discussed test results to the limit value given in the standard, no exceedances of the hydrogen concentration were found.

CONCLUSION

The analyzes and computer simulations of the power supply and control system in question using modern power electronics systems have shown that the energy efficiency of the battery locomotive has significantly improved. It can be further increased by energy recovery in the electric braking process. The amount of energy recovered depends on many factors, such as: locomotive load, efficiency of the power electronics system, propulsion engine efficiency, efficiency of accumulator batteries, transport route parameters. The efficiency of currently used DC motors is about 85%, assuming they are new machines. Taking into account the efficiency of the remaining power electronics system at the level of 90%, the total energy efficiency of the machine can be about 70%. In order to improve this condition, the control system is modified through the use of modern high efficiency inverters. The development of propulsion engines additionally enables the use of battery-operated synchronous motors with permanent magnets in mining drives, the efficiency of which is over 92%. However, it should be remembered that the risk of hydrogen emissions is associated with energy recuperation. The research shows that the amount of hydrogen released does not exceed LEL, but it should be noted that this applies to the selected case. It cannot be unequivocally stated that the currently used power supply and control systems fed from lead purse batteries do not emit hydrogen at concentrations exceeding LEL. In view of the above, it is reasonable that this type of power supply systems should be retrofitted with hydrogen concentration monitoring systems inside the battery boxes. Only this approach to the topic will allow you to safely increase the energy efficiency of these machines without the risk of a dangerous concentration of hydrogen. To sum up, the development of power electronics gives unlimited possibilities in the field of control systems. Along with it, the development of modern power sources is also observed. The time seems to be the question until the current lead-acid batteries are replaced by e.g. lithium cells.

REFERENCES

[1] A. Cifci, Y. Uyaroglu, S. Birbas "Direct Field Oriented Controller Applied to Observe Its Advantages over Scalar Control", *Electronics and Electrical Engineering*, vol. 3(119). pp. 15-15, 2012.

[2] A. Ejlali, D.A. Khaburi, J. Soleimani, "Sensorless Field Oriented Control Strategy for Single Phase Line-Start PMSM Drive", *Electrical Review*, vol. 10, pp. 229-232, 2012.

[3] A. Morshedlou, H. Dehghani, S.H. Hoseinie. "A data driven decision making approach for long-wall mining production enhancement", *Mining Science*, vol. 26, pp. 7-21, 2019.

[4] B. Polnik, Z. Budzyński, B. Miedziński. "Effective control of a battery supplied mine locomotive unit" – *Elektronika i Elektrotechnika*, vol 3, pp. 39-43, 2014.

[5] B. Polnik, B. Miedziński. "Hydrogen explosive risk in mining locomotive unit", *ECS Transaction*, vol. 63(1), pp. 159-166, 2014.

[6] D. Prostański, M. Vargová, "Installation optimization of air-and-water sprinklers at belt conveyor transfer points in the aspect of ventilation air dust reduction efficiency", *Acta Montanistica Slovaca*, vol. 23(4), pp. 422-432, 2018.

[7] D. Sha, D. Chen, J. Zhang, "A Bidirectional Three-Level DC-DC Converter With Reduced Circulating Loss and Fully ZVS Achievement for Battery Charging/Discharging", *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 6, pp. 2-2, 2018.

[8] E. Bayoumi, "Deadbeat Direct Torque Control for Permanent Magnet Synchronous Motors Using Particle Swarm Optimization", *International Journal of Power Electronics*, vol. 5(4), 2013.

[9] H. Jouybari-Moghaddam, A. Alimardani, S. Hosseinian. „Influence of electric vehicle charging rates on transformer derating in harmonic-rich battery charger applications", *Archives of Electrical Engineering*, vol. 61, pp. 483-497, 2012.

[10] J. Tokarczyk, "Method for identification of results of dynamic overloads in assessment of safety use of the mine auxiliary transportation system", *Arch. Min. Sci.*, vol. 61(4), pp. 765-777, 2016.

[11] L. Anbazhagan, J. Ramiah, V. Krishnaswamy, D.N. Jayachandran. "Comprehensive Review on Bidirectional Traction Converter for Electric Vehicles", *International Journal of Electronics and Telecommunications*, vol. 65(4), pp. 635-649, 2019.

[12] L. Schuch, C. Rech, H.L.Hey, H.A. Gru¨ndling, H. Pinheiro, J.R. Pinheiro, "Analysis and design of a new high-efficiency bidirectional integrated ZVT PWM converter for DC-bus and battery bank interface", *IEEE Transaction Industrial Application*, vol. 42(5), pp. 1321-1332, 2006.

[13] L. Qin, X. Zhou, P. Cao, "New Control Strategy for PMSM Driven Bucket Wheel Reclaimers using GA-RBF Neural Network and Sliding Mode Control", *Elektronika i Elektrotechnika*, vol. 6(122), pp. 113-113, 2012.

[14] M.S. Ahmed, N.A.A. Manap, M. Faeq, D. Ishak, "Improved torque in PM brushless motors with minimum difference in slot number and pole number", *Journal of Power and Energy Conversion*, vol. 3 (3/4). pp. 206-219, 2012.

[15] P. Vas, "*Vector Control of AC Machines*" Clarendon Press Oxford, 1990.

[16] R. Dolecek, O. Cerny, J. Novak, M. Bartłomiejczyk, "Interference in power system for traction drive with PMSM", *Electrical Review*, vol. 9. pp. 204-207, 2012.

[17] S. Geng, Y. Zhang, H. Qiu, C. Yang, R. Yi. "Influence of harmonic voltage coupling on torque ripple of permanent magnet synchronous motor", *Archives of Electrical Engineering*, vol. 66, pp. 399-410, 2019.

[18] S. Guo, J. He, "Sensorless control of PMSM based on adaptive sliding mode observer" *International Journal of Modelling*, "Identification and Control", Inderscience Enterprises Ltd, vol. 4, pp. 321-324, 2009.

[19] Y. Turygin, P. Bozek, I. Abramov, Y. Niíkitin. Reliability determination and diagnostics of a mechatronic system. *Advances in Science and Technology Research Journal*. Vol. 12, iss. 2, pp. 274-290, 2018.

[20] T. Biskup, "Initial rotor position estimation of permanent magnet synchronous machine", *Electrical Review*, vol. 4, pp. 157-162, 2012.

[21] T. Raffeinner, "Tailored transport", *World Coal*, No 9, pp. 99-100, 2005.

[22] Vanysek, P., Novak, V. Availability of Suitable Raw Materials Determining the Prospect for Energy Storage Systems Based on Redox Flow Batteries. *Acta Montanistica Slovaca*, Volume 23, Issue 1, 2018, pp. 90-99.

[23] M. Baranov, P. Bozek, V. Prajova, T. Ivanova, D. Novokshonov, A. Korshunov. Constructing and calculating of multistage sucker rod string according to reduced stress. *Acta Montanistica Slovaca*. Volume 22, Issue 2, 2017, pp. 107-115.

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