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Gentle accumulator drive (GAD) – new directions of development for the mining industry

Streszczenie. *Ciągnik górniczy GAD-1 wyposażony w nowoczesne baterie litowo-jonowe nowej generacji może stanowić korzystną alternatywę dla obecnie stosowanych maszyn transportowych. Jego zastosowanie może znacząco poprawić jakość powietrza oraz warunki pracy w podziemiach kopalń, gdzie wzrastająca liczba napędów spalinowych w ciągnikach podwieszanych oraz torowych naraża pracowników na wysoką koncentrację spalin, oraz generowanego ciepła i hałasu. GAD-1 jest wyposażony w napęd cierny oraz zębatkowy. Artykuł opisuje prototyp kolejki ciągnika, który został oparty o szereg nowych rozwiązań technicznych po raz pierwszy zastosowanych w przemyśle górniczym. (**Ciągnik górniczy GAD – nowe możliwości w rozwoju techniki górniczej**)*

Abstract. *GAD-1 mining drivetrain with state-of-the-art battery electric drive, equipped with the batteries of new generation can be advantageous alternative to currently applied transportation machines. It can significantly improve air quality and working conditions in underground mine, where in the result of increasing number of diesel drives in suspended monorails and floor-mounted railways the workers are exposed to high concentration of exhaust gases, generated heat and noise. The GAD-1 can also generate pulling force in rack-and-pinion and friction drive system. The article describes a prototype drivetrain GAD-1, which was based on a range of new technical solutions applied for the first time in the mining industry.*

Słowa kluczowe: napęd górniczy, silnik z magnesami trwałymi, bateria litowo-jonowa, napęd elektryczny.
Keywords: mining drive, permanent magnetic motor, lithium-ion battery, electric drive.

Introduction

An increasing number of diesel drives working in coal mine undergrounds creates significant discomfort associated with the concentration of exhaust gases, emitted heat and emitted noise. That has a direct impact on working conditions and safety of the mine crew. Additionally driving out more and more exhaust gases requires investing in ventilation systems used to discharge pollutants. Electrically driven - GAD-1 (*Gentle Accumulator Drive*) drivetrain of suspended monorail track, presented in the paper, is equipped with the state-of-the-art cells and it may be advantageous alternative to the diesel transportation equipment. The new drivetrain offers many innovative solutions, which are ideally suited for drives and devices from different industries. The main idea which has been adopted (for the first time in the mining industry!) in GAD-1 is the power source in the form of lithium - ion batteries. In terms of pulling power the GAD-1 is comparable to a diesel locomotive engine with a power of 80 kW. The prototype drivetrain was presented at the International Fair of Mining , Metallurgy And Energy in Katowice (Poland) in 2011. It was an opportunity not only to see the first prototype of this mine monorail but also a chance to take controls of GAD-1 and make a test ride. Gentle Accumulator Drive train was suspended on a specially assembled monorail for the purpose of exhibition (Fig.1).

Fig.1 The prototype drivetrain presented at the International Fair of Mining, Energy and Metallurgy in Katowice in 2011.

The word "Gentle" in this case can be understood as a quiet, due to the relatively silent operation in relation to diesel drive solutions. You could be convinced of this during the fair, comparing the operation of the discussed drive with the solutions presented by other companies. The innovative drive is designed to work in the areas threatened by dust and/or methane explosion hazard. GAD-1 during the fair attracted attention of the representatives of Polish and foreign companies involved in the mining industry. Interest in GAD-1 is still growing. The following institutes realize pioneering work on the new solution: KOMAG, BOBRME KOMEL and mine companies: NAFRA and VACAT. The project engaged few other companies involved in technology of lithium-ion batteries, electrical motors, control systems and state-of-the-art mining equipment.

BOBRME KOMEL Institute, which participates in the project, designed and built the state-of-the-art mining, permanent magnet motors designed to work in the areas threatened by dust and/or methane explosion hazard. Recovery of energy during braking process, what extends time between battery charging is one of the main advantages of the suggested solution. Possibility of generation of pulling force in the classical friction system as well as in rack and pinion system is a very important advantage of the solution. The transition from one system to another is dynamic and without a stop. Providing at least 8 hours of drivetrain operation without battery replacement, maintaining possibly minimal mass of the drivetrain, is the condition for the success in implementation of the battery drive system in mines. Due to the unfavorable ratio of energy density to mass in traditional acid battery cells, the only way to meet the above mentioned objectives is using the battery of new generation cells, energy recovery system during braking as well as permanent magnet motors characterized by high efficiencies both when working as an engine and as a generator. This paper presents the project of mine GAD-1 drivetrain together with its electrical system, control system, power supply system and the mechanics of changing driving modes.

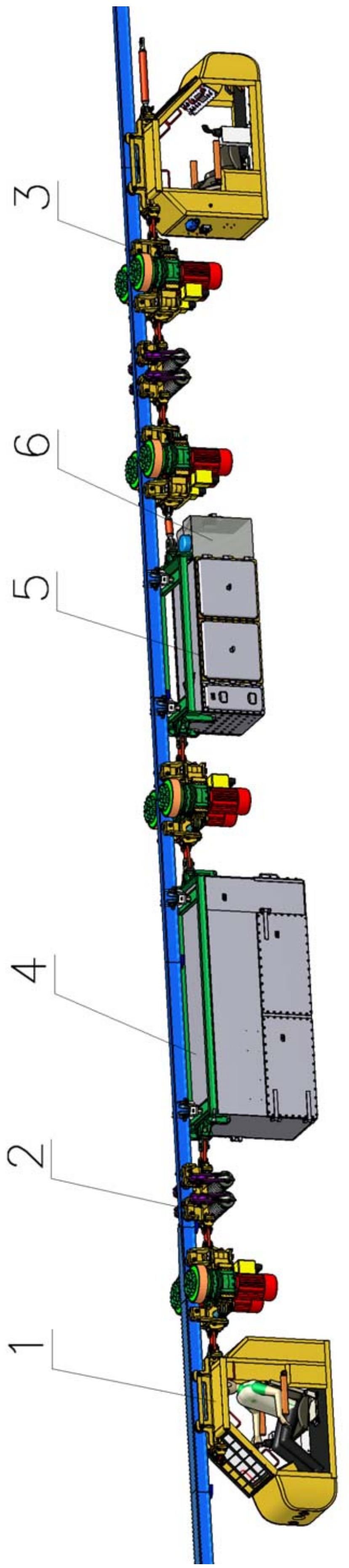

Fig.2. 3D Model GAD-1.

Power supply, control and protection systems.

GAD-1 drivetrain is shown in Figure 2. It consists of two driver's cabs (1), two double brakes (2), four drive trolleys(3) battery unit (4), power module, the electronics unit devices and the control system (5), the hydraulic unit to power trolleys braking and handling beam transport (6).Each of the four driving trolleys (fig.3) is equipped with two (identical) drive units consisting of motor (1), gear (2), the friction wheel (3) and toothed wheel (4). Depending on the railway track, which may be conventional, made only on the basis of parallel-flange beam 155, and additionally equipped with a toothed rack, integrated with the upper beam flange, the truck can operate in rack-and-pinion drive system or frictional drive system. During friction operation, the friction wheels are pressed against the track path (part of beam flange) with the actuator (5), whereas the gear rack wheels are not pressed at all. The change of the friction drive system to the rack system is used mainly in the area, where roadway inclination changes from smaller slope to larger one. For example, for slope less than 15 ° friction system is used and for the slope above 15 ° rack and pinion system is used.

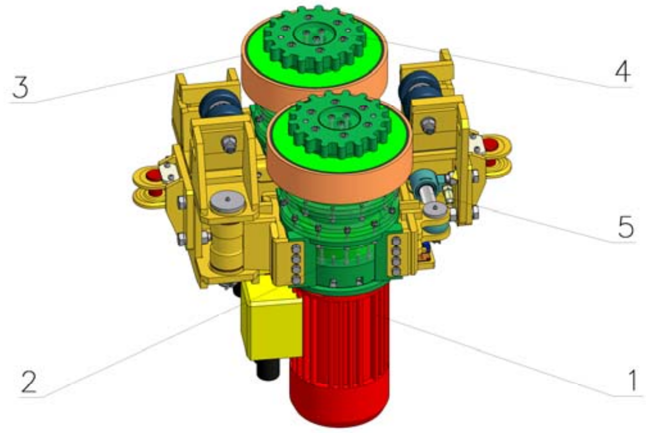

Fig.3. Design of the drive trolley.

Existing solutions of horizontal battery powered transportation equipment concern mainly floor-mounted railway drives, where heavy cells are in a sense the advantage, because of a need to ensure frictional contact between wheels and rails. In the case of a suspended drives heavy mass of cells is a disadvantage and it is not acceptable. Suspended GAD-1 drivetrain, was required for a more efficient cells with a higher energy density. To solve the problem, modern lithium cells were applied, which have not been used in the mining industry before, but are successfully used in the automotive industry worldwide. Examples include electric vehicle drives manufactured by BOBRME Komel like Re-Volt car, electric glider, electric quad, and a newly designed BLDC motor drive with changeable number of coils. Lithium - ion batteries have been successfully used in the GAD-1 drivetrain and they give a great prospective for development of this technology in the future. The use of cells with lithium can significantly improve electrical parameters of the cell (Table 1), while reducing the weight. Four battery units, consisting of a group of 68 cells which are connected together in series, forming a battery with a voltage of 250V DC are the power source for suspended GAD-1 drivetrain. Blocks of batteries of total energy 150 kWh are placed in one of the chambers, inside a special flame-proof box. Each of the four blocks of batteries is an independent power supply for a single drive trolley (consisting of two electric motors). In addition, one of the battery packs is used to supply the induction motor of hydraulic pump [1] and the control-measurement circuits of GAD-1.

Table 1. Parameters of power lithium cell battery

Capacity	150 Ah
Rated voltage	3.7 V
Discharge voltage	3 V
Max. charging voltage	4.15 V
Max. charging current	150 A
Max. discharging current	300 A
Weight	3.2 kg

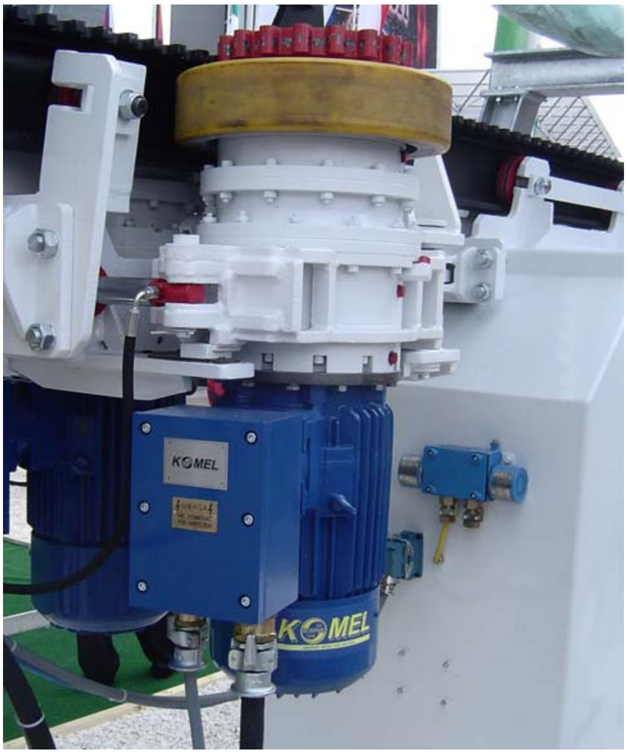

Fig.4. Electric mining motor SMwsPA132M6 type manufactured in BOBRME "Komel" , mounted in the GAD-1 drive

Energy from each of the battery packs, is supplied through a flameproof connector and conductors to the transmission apparatus (power module), which powers each of the eight drive motors via eight inverters with 3-phase voltage of adjustable frequency and amplitude.

Brushless synchronous motors with permanent magnets are used in the drive trolleys. The challenge for engineers was to develop an electric PM motor (*Permanent Magnets*), which would enable to meet the parameters required for the GAD-1 drive while keeping the smallest dimensions and meeting the mining standards for machines intended to be used in potentially explosive atmosphere of the mine. Electric, 10.8 kW permanent magnet synchronous motors with flameproof frame were mnufactured and designed in BOBRME KOMEL Institute (Fig. 4). The machine has IM2ExdIMb proof construction. The electrical parameters presented in Table 2.

Table 2. Parameters of SMwsPA132M6 motor.

Rated power	10,8 kW
Rated voltage	152 V
Rated current	45 A
Rated torque	114,6 Nm
Rotational speed	900 rpm
Efficiency	91 %

This type of engine, because of its advantages and opportunities to work as a generator that transmits energy to the battery offers new opportunities in the mining industry. Permanent magnet motors have high efficiency, compared to the induction motor and also the vector control of torque in eight drive motors is accurate. The electronic equipment is also equipped with the ninth inverter, which is used to supply the induction motor of hydraulic pump with a voltage of 188 V and a frequency of 50 Hz. The central unit, located in the electric apparatus box with security systems, is supplied through DC / D converter with auxiliary voltage o 24V DC while, all intrinsically safe devices such as LED lamps, control panels or electrohydraulic distributor are supplied with 12V DC. The whole control process is realized from the control panel located in one of the cabins (depending on drive direction), after its authorization by the machine operator. Master control system for GAD-1 drivetrain (Fig. 5) was designed on the basis of dispersed structure, which combines all the components of control system through the CAN bus. Due to sending the data in a form of low-voltage differential signal, digital CAN bus (connected in series) is of high resistance to disturbances coming from peripheral devices, and thus of high reliability. The CAN bus protocol was not commonly used in the mining industry so far. It has been used in cars, from which the concept of control was taken.

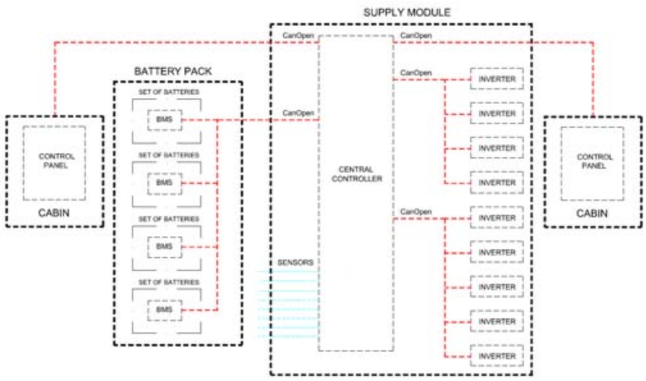

Fig. 5. Block diagram of master system for control of GAD-1 drivetrain

Versatility of used CanOpen protocol allows communication of sub-systems, made by different manufacturers, and switching between applications for diagnosis and configuration of CAN bus. Due to the use of vector control for multi-motor system, intelligent control enables precise management of power distribution, depending on present mode of machine operation A possibility of energy recovery to the pack of batteries during braking process is a big advantage of the GAD-1 drivetrain. During braking each motor operates as a generator. Generated current is transferred through the inverter to the power pack. Thus it is necessary to maintain some reserve of power packs capacity to store additional energy. Energy balance associated with a direction of transportation of loads on inclinations is associated with that problem. A situation, in which energy balance during transportation is positive, is rather unrealistic but possible. Such case can take place when heavy loads are transported on big inclination downwards and drivetrain without a load returns upwards. Intelligent Battery Management System (BMS) is responsible for the correctness of energy flow and not allowing for the situation described above (Fig. 6). BMS system is used for continuous monitoring of parameters of pack of batteries, as well as of each individual cell. The system decides about even distribution of energy to each cell during recovery braking.

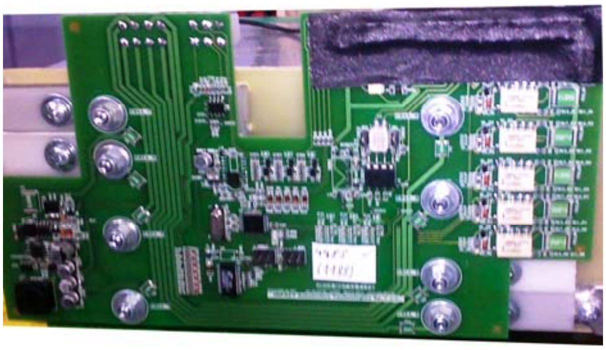

Fig. 6. Battery Management System (BMS) used in GAD-1 suspended drivetrain

Additionally, BMS plays the role of intelligent, protection against unwanted events such as e.g. overcharging or excessive discharge, both for software and hardware. Suitable selection of parameters of components cooperating with a system of batteries as well as development of safety algorithms significantly contributed to creation of mining machine for operation in conditions of combined hazards (methane explosion hazard and/or coal dust explosion hazard, fire hazard, water hazard). Solution of the problem associated with a sequential change of drive mode, i.e. from frictional drive to rack-and-pinion drive or from rack-and-pinion drive to frictional drive, by each car, is the main challenge, when it comes to the control system.

Problems associated with change of drive system

A part of drivetrain, which hypothetically moves from the right side to the left side, with a drive car that will be changing rack-and-pinion drive system to frictional drive system, i.e. in a sequence marked as Z→C, is presented in Fig. 7. The beginning of rack bar can be seen over the braking car. Control system has to react in a suitable way and to change rotary speed of electric motors to change the drive system. Signals from drive cars, informing about reaching the place of the route where drive will be changed for a given car, are sent to control system. Each drive car (Fig. 8) is equipped with IŁM connector (1), pusher (2) and articulated arm (3), through which the pusher can press the IŁM connector. The arm starts meeting the markers along the route.

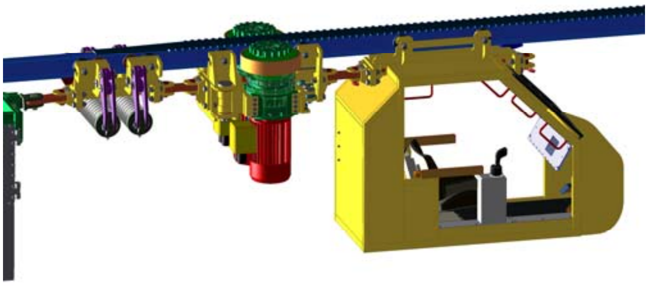

Fig.7. View of part of drivetrain with a drive car.

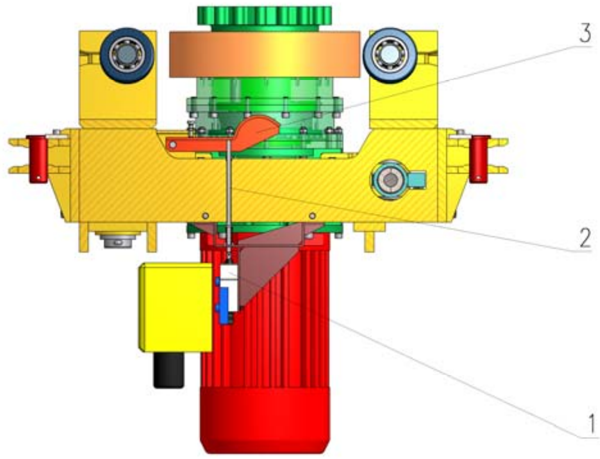

Fig.8. Location of IŁM connector with pusher and lever

View of the route at the place, where drive system is changed is presented in Fig. 9. Two-sided rack-and-pinion bar (1) and wedge bar (2) are on the upper shelf of I-bar. Lever of drive car starts when meeting the markers (4) located under the lower shelf of I-bar (3).

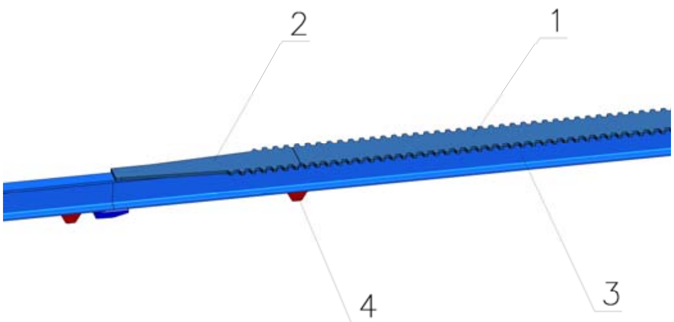

Fig.9. View of the route at the place where drive system is changed

Cooperation with toothed wheels during their positioning on the rack bar (1) as well as mitigation of the effect of sliding from the rack bar are the functions of wedge bar (2). During C→Z change of drive, depending on a degree of wear of friction wheel, the toothed wheel will contact the wedge bar at different places. In the case of worn wheel, that takes place at the beginning of the wedge bar, and in the case of a new wheel – in the middle of the wedge bar. During change of drive of each car the control system will receive two signals from the route markers. These signals will start proper procedures as regards power-electronic

system and hydraulic system. Control of overload of electric motors and adjustment of rotary speed to the value required at a given moment are the tasks of power-electronic system. Due to difference between the radius R_c of friction wheel and radius R_z of toothed wheel, in the case of C→Z change of drive the rotary speed of drive motors of car changing the drive should be increased by R_c/Rz before gearing, and in the case of Z→C change the rotary speed of the motors should be decreased by R_z/R_c.. Adjustment of rotary speed of the motors enables mitigating the dynamic phenomena during change of drive as well as smooth and effective change of driving method. It should also be remembered that friction wheels wear out during operation and their radius can decrease even by 10 mm. That is why precise control of rotary speed will not be fully possible without additional extension of algorithm and control system. In such a situation, impact of wear of friction wheels was not further taken into account because maximal difference between required rotary speed and speed obtained by control will be of only 5% and it will not have a significant impact on gearing. Control of motors overload results from the necessity of compensation of loss of pulling force during C→Z change of drive system. It should be remembered that such change will be realized during upward travel, e.g. when the route inclination changes from 15° to higher one. In such situation, the loss of pulling force can cause stop of the drivetrain. That is why it is necessary that the motors of the rest cars cover the loss of driving force and operate with 1.3 overload, while a possibility of overloading the motors is blocked in situations other than changing the drive system.
Applying pressure to the friction wheels during use of frictional drive and releasing the pressure during rack operation are the tasks of hydraulic system.

Summary

GAD-1 is an innovative drivetrain equipped with state-of-the-art drive supplied from battery cells of new generation. Drive system and intelligent control system enable operation of the system for energy recovery during braking. This solution conforms to ecological trends and enables many-hour operation of drivetrain without the need to charge the batteries from an external source. The monorail train has a possibility of frictional and rack-and-pinion drive, which was rare so far, even in conventional diesel driven solutions. It is a result of many signalized problems, which should be solved to make use of dual driving system possible. It is possible due to technically advanced control system of GAD-1 drivetrain. Due to zero emission operation, low level of generated heat and relatively quiet operation, the suggested solution will be very competitive in relation to diesel machines. Due to elimination of exhaust gases emission, work comfort of mining teams will increase. The use of lithium-and-ion batteries, modern control system, mine motors with permanent magnets, dual drive system (frictional and rack-and-pinion) and involvement of many companies, the design and then the prototype of mine drivetrain of a new type manufactured by Nafra and Vacat companies were developed. Innovative character of GAD-1 drivetrain and large interest during international mining fair suggests that this Polish mining drive will soon support the transportation operations in mines, both in Poland as well as in other parts of the world.

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