https://doi.org/10.32056/KOMAG2024.1.5

System for current collectors inertization for safe use in explosive atmosphere – nitrogen generator and SML locomotive

Received: 20.03.2024

Accepted: 25.03.2024

Published online: 28.03.2024

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Abstract:

R&D work regarding an innovative mine transportation system, planned to be powered by the three-phase busbar, developed within the RFCS project "Increase of mines efficiency and health protection through the innovative transport system based on BUSDUCT" is discussed. The issue regarding the nitrogen aggregate, the equipment of a suspended locomotive, intended for generating nitrogen from the air, to inject it into the working zone of the current collector brushes is presented. The research development process is presented chronologically, starting from the assumptions, designing, and presenting the prototype of the nitrogen generator. Also the visualization of the BUSDUCT target, the suspended locomotive SML is illustrated and discussed.

Keywords: monorail locomotive, current collectors, methane atmosphere, brush inertization, nitrogen generator

Publisher: **KOMAG Institute of Mining Technology, Poland**

1. Introduction

This paper refers to the article “System of current collectors inertization for safety use in explosive atmosphere-testing and results” [1] thus being a continuation related to the inertization of the current collector brushes of the suspended monorail locomotive, hereinafter referred to as SML. As mentioned in the previous article, R&D work based on the “Mid-Term Report” of the project “Increase of mines efficiency and health protection through the innovative transport system based on BUSDUCT” [2] is discussed. The project, coordinated by ITG KOMAG in 2019-2021, was realized in a consortium of 5 partners, three of them from Poland i.e. KOMAG, BECKER-Warkop and PGG, one from Germany i.e. RWTH Institute and BARTEC company from Slovenia. Completion was expected in 2022, but the project was terminated, as a result of doubts related to market demands for the proposed solution in the context of mine closures. Additionally, the experts supervising the project also had doubts about the safe use of the proposed solution in the conditions of methane mines.

The idea of the BUSDUCT project resulted mainly from the situation of the mining industry in Poland, where the transport routes are becoming longer in a result to reach the coal seams, which are more and more distant from the shaft, whereas building new shafts in terms of the policy of reducing the importance of coal as an energy source is unjustified. An efficient mine transportation system was perceived as very important for the effective functioning of currently operating mines. The commonly used, diesel powered locomotives are onerous due to exhaust gases and heat emission in confined space. Limited speed extends the exposure time of miners to exhaust gases and results in a significant shortening of their effective worktime. The development of the innovative mine transportation system based on a three-phase busbar, for powering the suspended locomotives, complies with the EU Directive [3] ATEX 2014/34/EU [4], standards [5, 6, 7] was the project objective.

According to the Polish legislation, mine workings are divided into three categories: “a”, “b” and “c” depending on expected methane concentration. The most unfavorable category is “c”, according to which in mine workings, despite active ventilation, the methane concentration may exceed 1%. The main goal of the proposed innovation was the possibility of using such a system in all mine workings even those with the highest risk of methane explosion. The planned transport system offers some important advantages, i.e. health protection of miners by elimination of diesel exhaust gases, higher mine profitability due to increased effective work time of miners, up to 65% energy savings and energy recuperation during downhill transportation, possibility of parallel operation in the same time of several locomotives with no danger of exceeding CO concentration in mine workings. The above mentioned advantages could have been achieved when the prototype, ready-to-be-produced for the transport system would have been launched, what was expected as the project result, however as mentioned before, the project was earlier terminated. Nevertheless, the developed prototype of the nitrogen generator, the SML concept, is innovative and technically interesting that the authors decided that it is worth presenting it in the article to share the acquired knowledge in the field of nitrogen separation from air and the method of current collector’s brushes inertization. The nitrogen generator was developed and manufactured and the article discusses step by step how this goal was achieved.

2. Development of a nitrogen generator for brushes inertization

At the initial stage of the project, it was assumed that the nitrogen generator would be a separate unit of the SML and due to the use of two current collectors, also two nitrogen generators were assumed to be used. Finally, as the inertization tests confirmed that the expected amount of nitrogen with 3 l/s would be sufficient for 8 brushes inertization [1], it was found as a more justified solution to use only one nitrogen generator. In addition, economic aspects and smaller dimensions of SML, which are always more advantageous in the case of not very extensive transportation routes in the underground mine, justifies the idea of using one nitrogen generator. Additionally, since it was assumed that a standard 4.5 m long supporting frame manufactured by BECKER would be used to install the nitrogen generator, it turned out that its dimensions could also place a hydraulic unit, which is a necessary component of suspended locomotives including planned SML machine.

It was decided to use the membrane gas separation technology to develop the nitrogen generator. That technology was chosen as the most advantageous due to necessity of meeting the requirements of the ATEX directive and the requirement of mobility. The ambient (atmospheric) air is compressed, carefully filtered, and then passes through a series of separation modules consisting of thousands of membrane fibres that separate nitrogen from air. The separation follows the principle of selective gas permeability through the membrane. Smaller gas molecules (water, carbon dioxide, oxygen and argon), which have high permeability, pass faster through the membrane fibres than the larger, less permeable molecules of gases such as nitrogen and methane. Purity of the nitrogen obtained by this method varies from 95 to 99.5%. As the separation of gases takes place at molecular level, air supplied to the separator must be specially treated. The requirements are related to the content of water, solid particles and oil aerosols got into the air during its compression. The residual oil content must be below 0.01 mg/m^3. Solid particles larger than 0.01 μm should be filtered out. The water vapor is not able to condense, so it is preferable that the pressure dew point is -20° C. In addition, the air should be free of solvents and hydrocarbons. To meet the above conditions, the nitrogen generator has been equipped with proper subassemblies and components.

The nitrogen generator visualization is shown in Fig. 1. It consists of three units: compressor, air treatment unit and nitrogen separation unit. Air compressed by compressor 1 flows to the treatment unit 2, where water is separated first, then solid particles and water and oil aerosols above 1 micron are removed in the initial coalescence filter and at the end particles above 0.01 micron are removed on another coalescing filter. Subsequently the air is directed to carbon filters 3 and nitrogen membranes 4 where separation process takes place. The oxygen as a by-product is discharged to the outside while the nitrogen is collected in buffer tanks 5 and 6 made of several pipes.

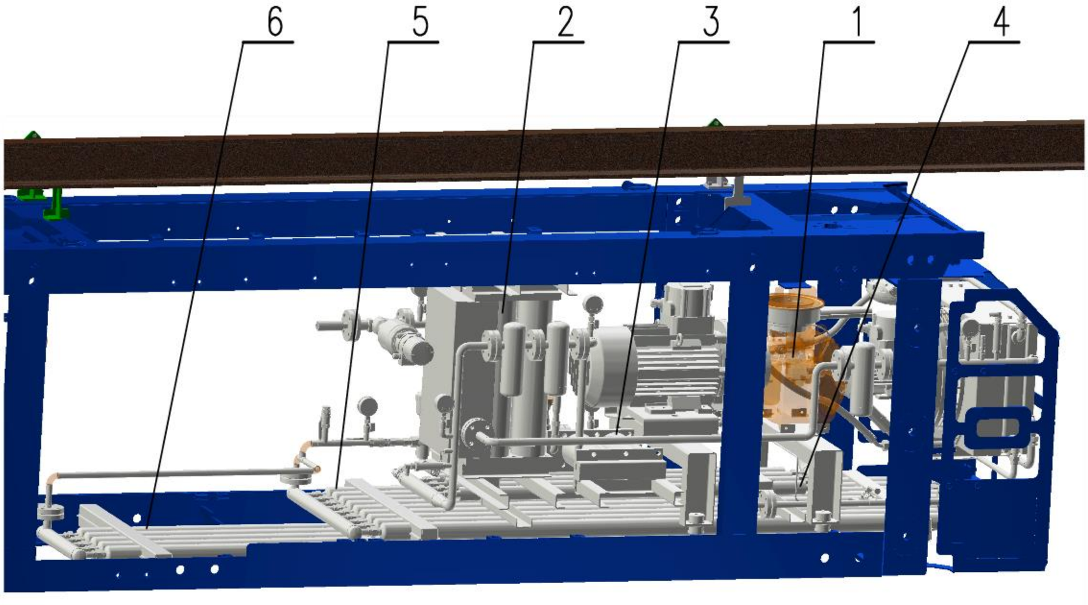

Fig. 1. Nitrogen generator visualization: (1) compressor, (2) air treatment unit, (3) carbon filters, (4) nitrogen membranes, (5, 6) two levels of tubular buffer nitrogen tanks

The required capacity of air to produce 3 l/s of nitrogen was determined to be not less than 48 m^3/h at overpressure of 10 bars. The motors used to drive the compressor and fan must have ATEX certification. The compressor unit (1), is the first unit for nitrogen separation designed to produce compressed air at the pressure and quantity required to produce nitrogen. Air sucked in from the environment i.e. mine workings, to the compressor through the filter, is constantly monitored for methane concentration using a methane sensor. The air suction unit is equipped with a control valve that adjusts the amount of sucked air to the current demand.

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It was assumed that the SML and the nitrogen generator will be stopped when methane concentration in the surrounding atmosphere is close to hazardous. For the above safety reasons, the intake air flows through a so-called flame arrester to prevent from flame penetration in the case of explosion of the air-methane mixture. Then the air is directed to the screw compressor, where additional oil is injected into it, which provides lubrication, sealing and cooling at this stage of compression. Oil and air mixture is compressed in two stages by screw rotors and then directed to the de-oiling tank, where the main part of the oil contained in the compressed air is precipitated. The oil from the tank is reused for injection in the screw compressor. The compressed air is directed to the cooler, where it is cooled to the temperature by 10°C higher than the ambient temperature. The pressure of the air leaving the compressor is checked by a pressure transducer. Compressed air at the outlet of the compressor contains solids, oil and water particles which negatively affect the air quality and air flow rate and therefore must be purified in the air treatment unit. Solids from the air are removed by cyclone separation and filtration on the filter inserts. The unwanted condensate, which is a mixture of water and oil particles, accumulating in the aftercooler or the buffer tank after the compressor, is drained from the system by the draining system and directed to the devices removing oil and water. The air treatment unit is equipped with two tanks filled with special granules. The principle of operation is a passage of air through the adsorbent, which are usually aluminium or silica gel granules, on which water particles (moisture) settle during the flow of compressed air through the adsorbent. Both tanks work in an alternating system, what means that when one absorbs moisture, the other one is in the regeneration process. To regenerate the adsorbent, part of the previously dried air passes through the tank in the opposite direction, which this time acts reversely collecting the moisture from the granulate. The moist air is discharged to the outside of the nitrogen generator system. The control system controls distribution of the air stream from air compressor and divides air to both tanks. The regeneration process requires about 15% of additional air stream to remove water (regenerate the absorbent), what was taken into account when planning the nitrogen generator output. Adsorption dryers operate with a dew point temperature of -25…-70°C. The main stream of dried air from the tanks passes through the valves to the dryer outlet. Pressure of the dried air is monitored by the pressure gauge installed on the dryer outlet. Excess air escapes through the control valve while the main air stream passes through the opened open-close valve. The compressed air temperature downstream of the treatment section is indicated by the temperature sensor.

The dried air is directed to the nitrogen separation unit. Its role is to separate nitrogen from treated compressed air. Fig. 2 shows the scheme of the unit. At the inlet, there is a shut-off valve (60), behind which the supply air is led to one end of the four parallel-connected MA nitrogen membranes (56), where the gas is separated into two gas streams: concentrate stream – retentate and filtrate stream – permeate. The permeate is directed to the discharge and the retentate to the nitrogen tank. Manometers with manometric valves (62) are installed on both outlets from the nitrogen membrane. A nitrogen guiding analyser system (64) controlling the nitrogen concentrate stream is composed of oxygen concentration (65), nitrogen pressure (66), nitrogen pressure supply (67) measuring units. The retentate flow is controlled on the pneumatic control valves (57), after which the nitrogen pressure is measured again on a pressure gauge with a pressure valve (62). Nitrogen goes to the three-way switching valve (58) pneumatically controlled, by compressed air, through the solenoid valve (61), where it is directed to the multi tube compressed nitrogen tank (68) via a check valve (59) or, when the tank is fully filled, directed to the discharge damper (69). The nitrogen pressure in the tank can be monitored by a pressure gauge with pressure valve (62) and is recorded by the pressure transducer (63). The nitrogen tank at inlet and outlet is fitted with shut-off ball valves and a drain valve (60). At the outlet of the nitrogen tank, behind the shut-off valve, there is a valve (59), shutting off the rest part of the unit. The compressed nitrogen is collected in the multi tube pressure tanks with a maximum pressure of 9 bars. These tanks make it possible to start brushes inertization process, ahead of the electric motors of the nitrogen generator, what is important for the safe use of the SML.

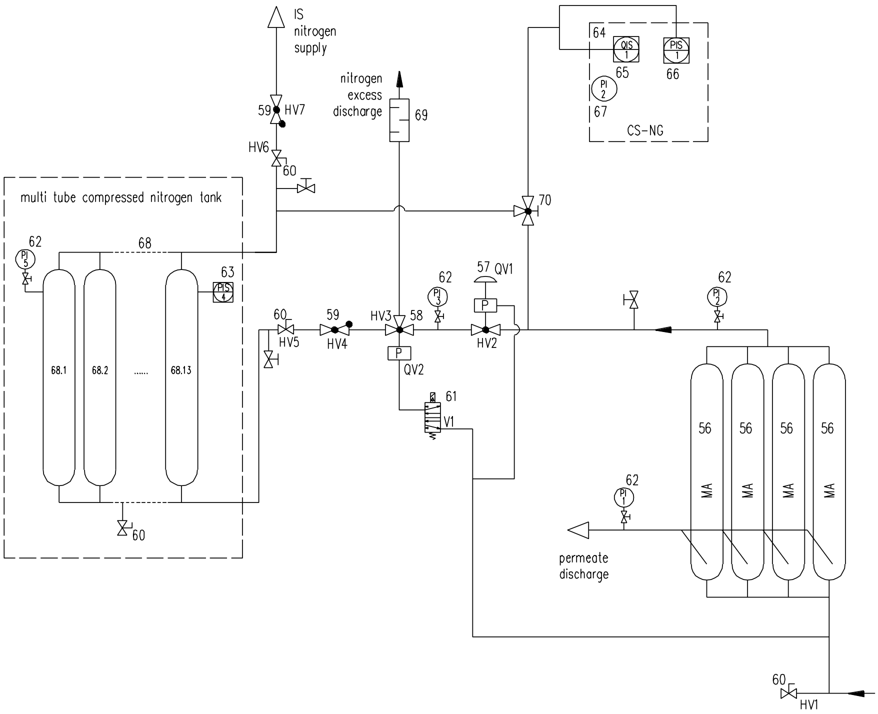

Fig. 2. Schematic diagram of the nitrogen separation unit

The diagram of the inertization system IS, responsible for controlling and monitoring the inertization process, is shown in Fig. 3. The inertization process is started by setting the solenoid valve located on the outlet stub of the pressure tank. Voltage applied to the valve coil opens the valve and directs nitrogen to the inerting system. It is split into two equal streams – one for each of the current collectors. First, nitrogen is directed to the reductors, where the pressure is reduced to a constant level (set at the start-up). Nitrogen of the reduced pressure is directed through the flow meter to the collector, where it is distributed to each receiver.

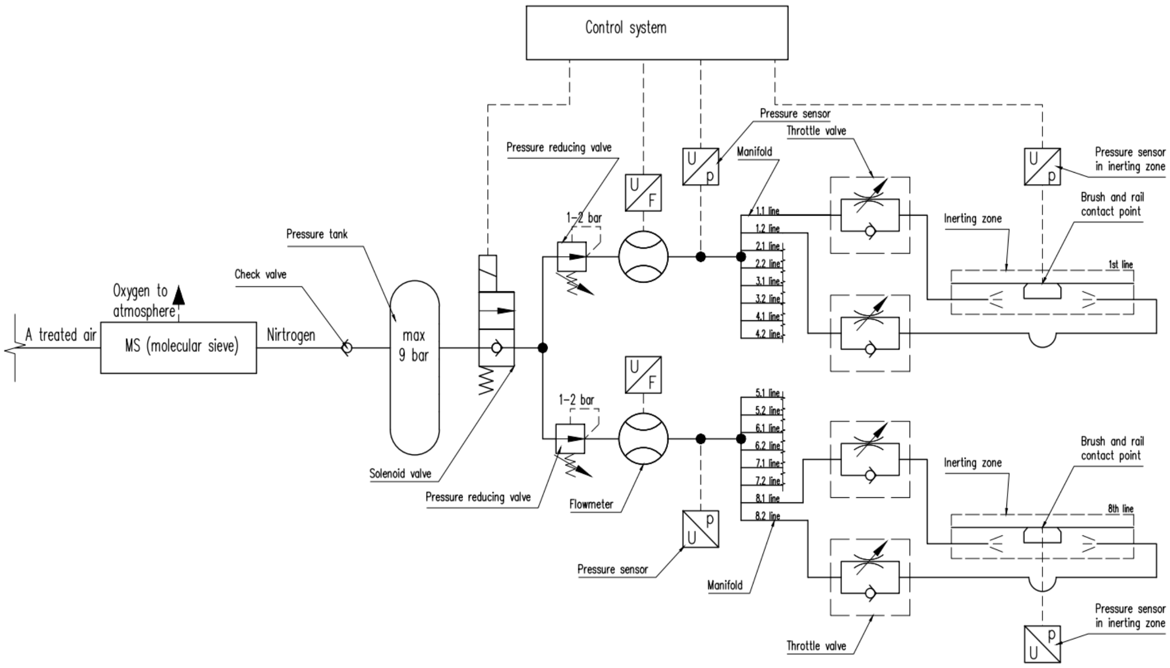

Fig. 3. Inertization system IS, arrangement scheme

The flow is controlled individually, through the throttle valves, for each hose supplying the nitrogen to the brushes. The flow of nitrogen for inerting the brushes of the current collectors (CC) is constantly monitored and maintained at a constant level by using the pressure transducer between the flow meter and the collector as well as by the fixed setting of the throttle valves on each hose. Two nitrogen hoses are directed to each brush. Each brush is equipped with its own pressure control system via a pressure transducer. Pressure control in the area of each brush and control of nitrogen flow to two CC is one of the components of the control and monitoring system of the machine operating in a potentially explosive atmosphere. These components are responsible for the nitrogen distribution on the way from the tank to each hose supplying the nitrogen to the brushes and responsible for monitoring and diagnostics of the inertization system operation. The nitrogen blowdown, and thus the inertization system, will be started by a Voith EV 2225 NC solenoid valve compliant with ATEX requirements adequate to IM2, installed directly on the nitrogen multi tube tank. It is a two-way, two-position solenoid valve designed to control neutral gaseous and liquid media in mine workings threatened by explosion hazard. The required voltage applied to the valve coil opens it and allows the flow to the further part of the system. The nitrogen after passing the solenoid valve is directed to the two nitrogen distribution units, also described in [1] and illustrated in Fig. 4. Each unit is responsible for supplying and distributing the nitrogen to one CC.

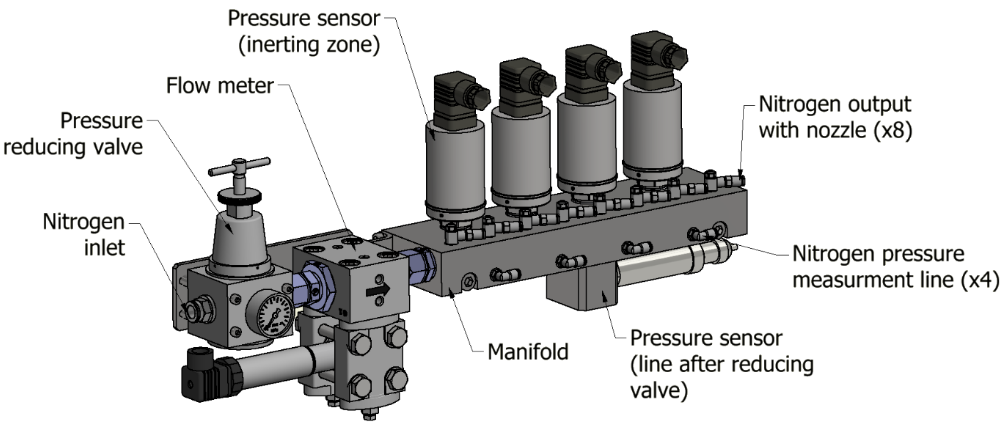

Fig. 4. Nitrogen distribution unit

The concept of the machine, powered by the busduct, with inertization system is described below.

3. Development of the suspended monorail locomotive SML

Due to the principle of safe power supply from the busbar, the main component of the SML is the nitrogen generator being discussed in the previous section. During the project implementation, it was decided that it would be placed in a common box frame with a hydraulic unit, necessary to power auxiliary devices. The initial arrangement of the mentioned units is shown in Fig. 5. The drawing shows the box frame (5) with nitrogen generator (1) and hydraulic unit (2) inside. The current collectors (3) sliding on the four-line busbar (4) are placed on top of the box frame. The carrying trolleys (6) are also positioned on top. The suspended route, equipped with rack and pinion segments, that BECKER has developed for the diesel and battery-powered locomotives is also visible above the box frame.

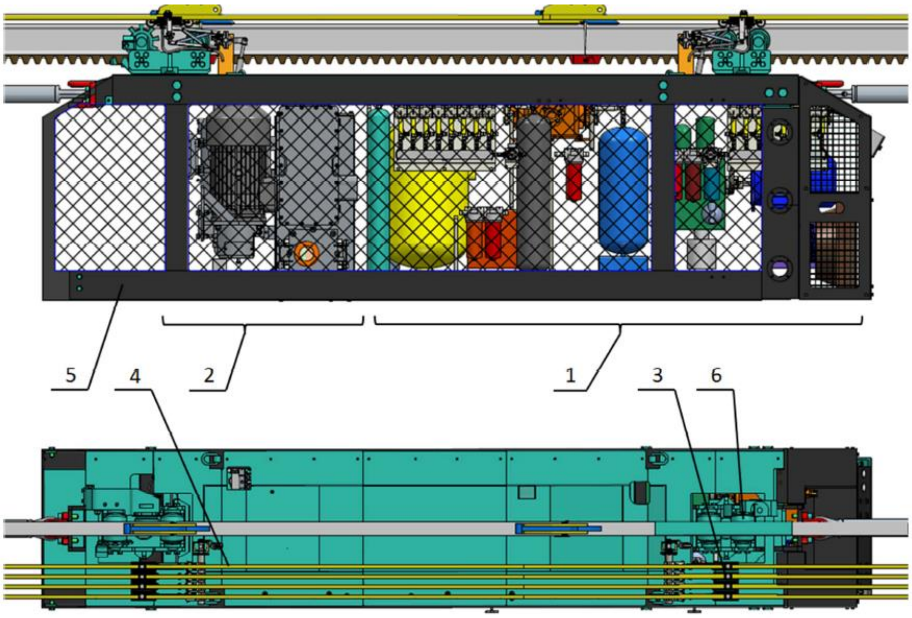

Fig. 5. View of the initial concept of the nitrogen generator (1) and hydraulic aggregate (2) two CC units (3) sliding on the 4 line busduct (4) in one supporting frame (5) with carrying trolleys (6)

The assumption is that at least one CC powers the machine. The analysis regarding CCs position at the top of the box frame, related to the issue of powering the machine, when up to 3 meters long power gap may occur in the busbar, mainly at a junction, led consortium to the conclusion, that the distance between CCs should be longer than the frame i.e. even up to 4.5 m. The previous idea presented in Fig. 5 was changed into the idea presented in Fig. 6. The CC is positioned on the boom arm and the second CC (not visible in Fig. 6) is similarly mounted on the opposite side.

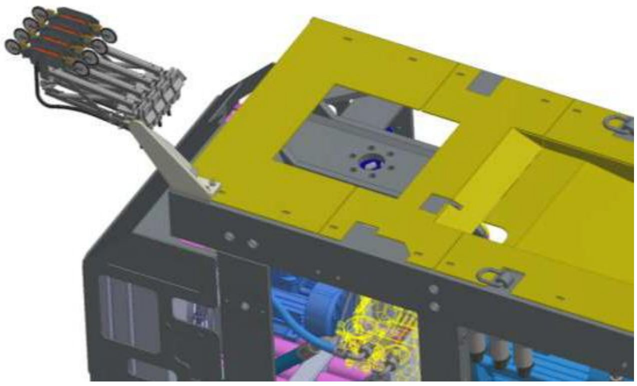

Fig. 6. The final location of CC at the top of the box frame

The consortium, mainly BECKER, worked in parallel on the SML drives. The company has experience in using a friction track integrated with a rack and pinion regarding their suspended, battery powered locomotives with such two options of drives. Based on this it was decided to develop two types of the drives for the SML prototype machine, one frictional drive, hereinafter called FRD and the second rack and pinion type, hereinafter called RPD. The drives are shown in Fig. 7.

The FRD drive (Fig. 7 on the left) consists of three main components: frame, drive system and braking system. It was developed to convert the rotational motion of the drive wheel to locomotive movement along the track. The drive is equipped with ϕ395 mm frictional wheels. Drive is transmitted by frictional coupling of the drive wheel using a drive wheel with a lining of the required friction factor resulting in proper clamping pressure of the wheel against the rail. The clamping pressure of the driving wheels is triggered by a hydraulic cylinder, which presses the swing arm towards the track axis. A gear connected to the electric drive system (electric motor with converter) and a frictional drive wheel are mounted to the swing arm. The driving wheels clamping pressure is constant and controlled by the locomotive control system. In accordance with the applicable regulations the braking system of the drive complies with the requirements for emergency braking equipment and can be used to secure the transportation set.

The designed drive should secure maximum speed of SML up to 4 m/s.

The RPD drive system is intended to change the rotational movement of the toothed wheel into the locomotive's movement along the track (Fig. 7 on the right) on the basis of toothed coupling between the drive wheel and the toothed bar of the route rails and the brake to immobilise the transport set by the brake system, which is an integral part of the drives. In accordance with applicable regulations, the braking system of the drive complies with the requirements for emergency braking equipment and can be used to secure the transportation set. The drive is transferred by toothed coupling of the drive wheel with the rack bar of the rail. The braking system is activated electrically. Due to safety operation, before supplying power to electric motors, the brake is mechanically activated.

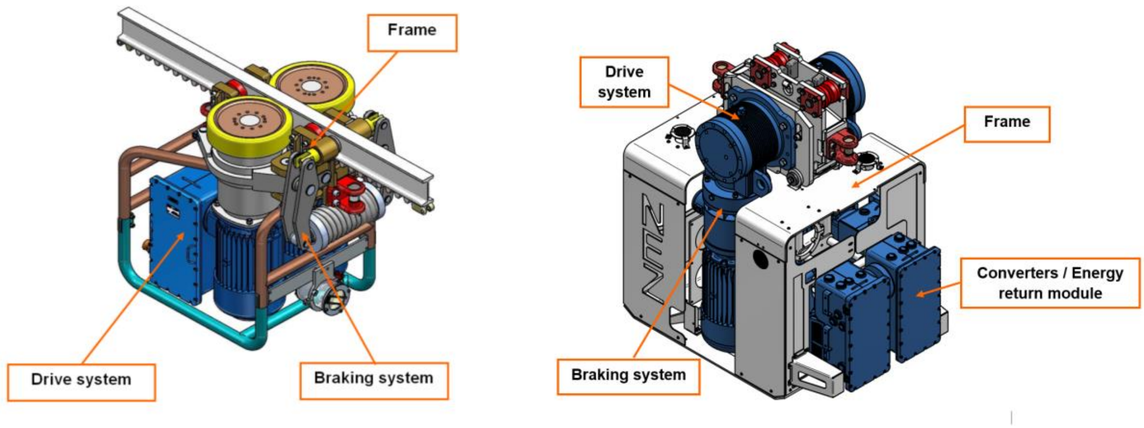

Fig. 7. Two types of SML drives: FRD on the left, RPD on the right

The next step regarding the SML development was to design the operator's cabin. BECKER based on their previous experience regarding the monorail locomotives, developed the cabin illustrated in Fig. 8.

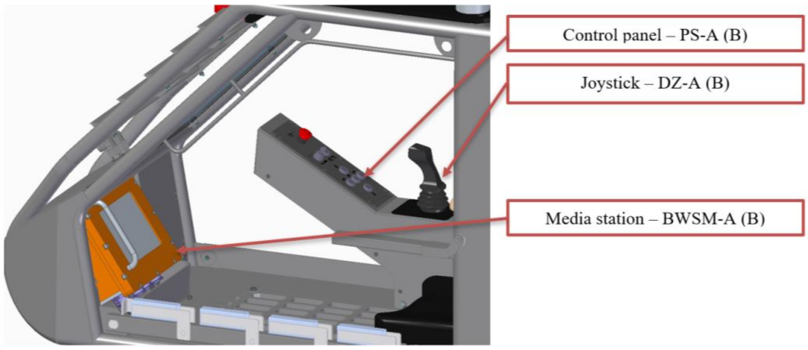

Fig. 8. Operator's cabin of the SML [2]

The operator has a set of control devices at his disposal, and the operating parameters are displayed on the monitor. After starting nitrogen inerting procedure, master PLC starts monitoring the locomotive operating parameters and provides the 24VDC auxiliary voltage for all SML's electric

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drives, Completion of the start-up process, depending on the locomotive configuration, is indicated by displaying the start parameters on the LCD display. If there are no disturbances in the control system, determined by input parameters, main voltage is supplied to all electric drives of the SML and to nitrogen generator. After supplying the electric drives of the SML, the motors protection circuits are checked. Next, the operating parameters of the drives converters are set. If no disturbances in the system are found, the drives indicate their readiness for operation, nitrogen generator unit starts nitrogen production, and "ready" status of components is displayed.

As a result of developed work it was possible to present the SML visualization (Fig. 9). In the central part of the machine there is a box frame encasing the nitrogen generator and hydraulic aggregate (1). Two current collectors are visible on the roof of the box frame. There are operator's cabins (2) at both ends of the machine, used depending on the travel direction. Positions (3) and (4) are FRD and RPD drives. All mentioned components are connected by the tubular spacers (5).

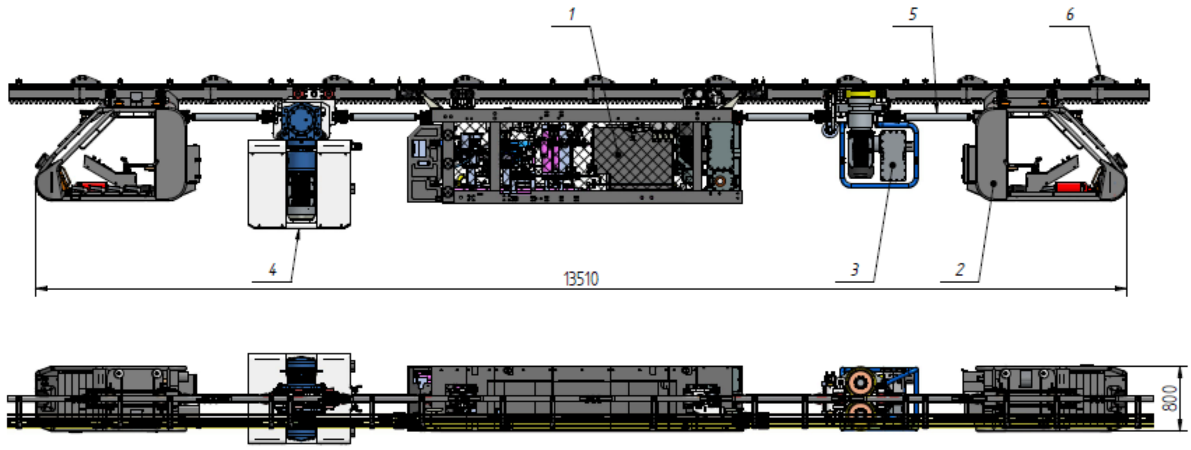

Fig. 9. SML visualization [2]

Unfortunately, at this stage of design, the work had to be stopped for the reasons indicated in the introduction.

4. Conclusions

The article shows the great effort of the BUSDUCT project consortium to create a new type of mine suspended transportation system. The main part, i.e. the nitrogen generator of the SML, had been completed and was ready to be used. The KOMAG and RWTH worked on the nitron generator. BARTEC manufactured electric motors for SML drives. BECKER tested a gear drive that draws power from a busbar. The project termination was a great disappointment for the consortium, however, we had to agree that the new railway system probably did not have time to be used due to the mine closures. Nevertheless, the authors' intention was to share knowledge on the possibilities of inerting sparking zones with nitrogen. The SML concept is innovative and technically interesting that the authors decided that it is worth presenting it in the article to share the acquired knowledge in the field of nitrogen separation from air and the whole SML concept.

Although the system has not been implemented due to the BUSDUCT project termination, the use of the inertization system in other solutions for devices operating in potentially explosive atmospheres cannot be ruled out.

References

[1] Drwiega A.: System of current collectors inertization for safety use in explosive atmosphere-testing and results. Mining Machines 2023, Vol. 41, Issue 4, pp. 274-284

[2] Mid-Term Report "Increase of mines efficiency and health protection through the innovative transport system based on BUSDUCT" Reporting period: 1st June, 2019 – 30th November, 2021 (unpublished)

[3] DIRECTIVE 2014/34/EU of the European Parliament and of the Council of 26 February 2014 on the harmonisation of the laws of the Member States relating to equipment and protective systems intended for use in potentially explosive atmospheres (recast) (Text with EEA relevance). (Official Journal of the European Union L 96, 29.3.2014, p. 309–356)

[4] Guidelines to Directive 2014/34 EU - ATEX 'Product' Directive. Fourth edition of the guide to the application of directive 2014/34 EU on the harmonisation of the law of the Member States relating to equipment and protective systems intended for use in potentially explosive atmospheres, published in November 2022

[5] Standard EN IEC 60079-0:2018 Explosive atmospheres – Part 0: Equipment – General requirements

[6] Standard EN 60079-2:2014 Explosive atmospheres – Part 2: Equipment protection by pressurized enclosure "p"

[7] Polish Standard PN-G-50090:1997 Work protection in mining industry - Electric network of wire traction - Requirements

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