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Resource-saving electromechanical transmission of the mining truck

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Abstract. The subject of the research is the electromechanical transmission of a mining truck, which provides all modes of movement of this type of mining equipment. The purpose of the work is to develop an electromechanical transmission of a mining truck that meets high requirements for unification and reliability, ensuring resource saving during its creation and exploitation. The main task is the optimal choice of the electromechanical transmission components, as well as the study of their influence on each other. Math methods and simulation modeling in the mathematical package of applied programs were used to perform the study of the developed electromechanical transmission. A complex simulation model has been created, it includes: a source of electricity; frequency converter (amounting to the active rectifier (energy converter and excitation device) and autonomous voltage inverters); asynchronous motors. The simulation model is equipped with blocks of oscillography and analysis of electrical variables of an electromechanical transmission. The study of the simulation model of an electromechanical transmission shows the strict correspondence of the speed characteristics of both drive engines and the mining truck. The vehicle accelerates to the rated speed at full load, braking on a slope, and turning. The electrical parameters of the electromechanical transmission correspond to the task, the control of variable drive engines in all modes of operation is provided at the proper level.

1. Introduction

Modern mining trucks (MT) are high-tech and reliable machines. Modern mining industry is placing higher demands on quarry machinery, which is due for the growth of mineral extraction volumes, and increasing of the depth of mining enterprises. In connection with this, the unit capacity, load-lifting capacity, and the speed of movement of vehicles are also growing. The growth of MT dimensions over the past decade has led to a gradual refusal of manufacturers from the "classic" version - hydro-mechanical transmission of a vehicle. MT with a load-carrying capacity of more than 100 tons (Figure 1) are equipped mainly with diesel-electric transmissions of alternating current [1-4], which provide the following modes of vehicle operation: movement on a horizontal surface, descent and ascent along an inclined road with an empty and loaded body; smooth start from a place, including on an inclined surface, with an empty and loaded body; turn of the MT, realization of electric differential; keeping the MT in a stationary state, including on an inclined surface, without mechanical brakes [5].

Severe working conditions of the MT require high reliability and maintainability, cost-effectiveness and ease of manufacture of electromechanical transmissions (EMT). Thus, the efficiency of the machine, the cost of its operation and maintenance depend on the choice of the structure and components of the EMT.

Figure 1. BelAZ-75710 at the mine

Today various electric machines and power distribution devices are used as parts of MT's EMT. Frequency converters (FC) which carry out the frequency isolation of electric generators and drive motors are mainly used as the latter [6-8]. Thus, the generators operate at nominal speeds, the inverters control the variables of drive motors: rotational speed, torque on the shaft.

This article presents the results of the development and research of resource-saving MT's EMT built on the basis of asynchronous electric machines, active rectifier (AR), autonomous voltage inverter (AVI).

In modern conditions, the most pressing issues for the engineering industry are: reducing material consumption and ensuring a high level of product unification, simplifying manufacturing and repairing. For the mining industry, the most important criterion is to increase the reliability and reduce the cost of mining equipment exploitation. These tasks can be solved by a rational choice of elements of the EMT design, as well as minimizing the number of functional units, combining the functions of various elements. Considering of existing solutions in the field of EMT is given below.

2. Materials and methods

EMT of modern MT are based on the general scheme: heat-engine (HE), electric generator, frequency converter, traction motors, mechanical transmission, wheels. Below we consider the most promising structures of EMT. Figure 2 presents the following composition of EMT of the MT BelAZ-75581: a dual-set synchronous generator (SG) with a brushless excitation system - a 12-pulse diode rectifier (DR) - a DC-bus - AVI - asynchronous motors (AM) [9-11].

Possible implementation of MT's EMT on the following element base. A synchronous generator (SGPM) and synchronous motors (SMPM) with permanent magnets on the rotor are used [5]. This structure has shown itself well in the composition of the drives of hybrid vehicles, as well as in ship rowing systems. The structure of EMT is illustrated in Figure 3.

The structure and capabilities of EMT based on switched-reluctance machines are considered in [12-13]. This type of machine is used both as a generator (SRG) and as a traction engine (SRM). The structure of EMT is described in more detail in Figure 4.

A comparison of the considered EMT types is given in table 1. The reason for the high cost of EMT on machines with permanent magnets lies in the price of rare-earth metals, and, besides, in the complex and time consuming technology of attaching magnets to the rotor and their cooling during operation. The relatively low resistance to accidents is due to the complexity of damping the synchronous machine rotor field in the case of stator windings fault, in addition, the destruction of the rotor magnets becomes a frequent cause of failure. Development and commissioning are similar as in EMT with SG and AM. The use of an autonomous current inverter (ACI) improves the quality of control of the SPDM torque,

but at the same time, the inertia of control increases. The high efficiency of synchronous machines and the wide possibilities of power part unification of the EMT are an advantage.

Despite the low cost of manufacturing of the EMT with switched-reluctance machines, it is inferior to competitors in the cost of development and commissioning, which is due to the high complexity of the control system (CS) algorithm. The cost of maintenance is minimal, requires regular maintenance of bearing assemblies. The relatively high resistance to accidents is due to the lack of connections between the stator windings of the machines, which allows us to maintain operability when a certain number of phases fail (n). A high degree of unification is an advantage. Despite this, the actual resource of EMT remains unknown, because of the MT on its basis is only being commissioned.

The confirmed high resource, low cost of implementation and operation are significant advantages of EMT with SG and AM. This EMT is distinguished from analogs by the low complexity of the CS algorithm, as well as the maximum use of SG power. The structure of EMT provides the necessary level of reliability and redundancy, but the issues are resilience to accidents. In comparing with analogs the EMT has a low level of unification and has a demanding for maintenance. Dimensions and weight of the SG are increased because of using two sets of stator windings.

According to the results of the analysis, the following requirements were formulated for the structure of the energy-efficient MT's EMT: a high degree of unification is ensured by using one type of electric machines; electrical machines must have a high reliability; an inverter rectifier combines the functions of an electrical energy converter and a generator excitation device; the simplicity and manufacturability of manufacturing ensured by the choice of the EMT elements.
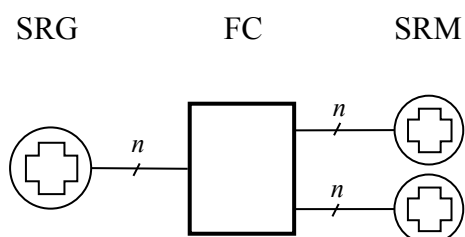
The developed scheme is presented in Figure 5. It contains: HE - asynchronous generator (AG) - AR - DC-bus - AVI - AM.
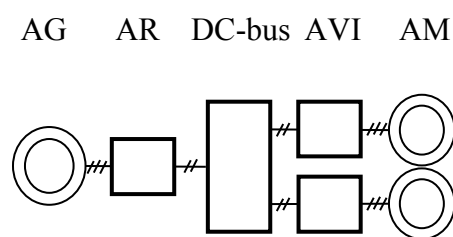

SG   DR   DC-bus AVI   AM
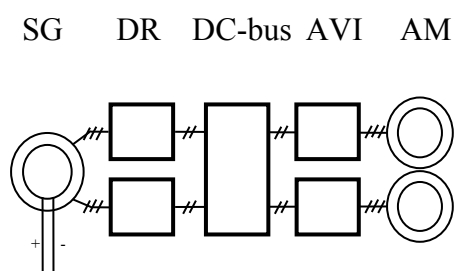
Figure 2. EMT of MT BelAZ

SGPM   DR   DC-bus ACI SMPM
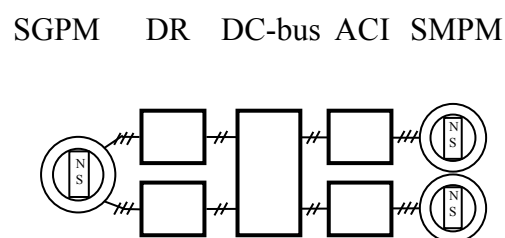
Figure 3. EMT with permanent magnets

SRG   FC   SRM

Figure 4. EMT with switched-reluctance machines

AG   AR   DC-bus AVI   AM

Figure 5. EMT project

3. Results and Discussion

The full complex of works on mathematical and simulation modeling was carried out at the development stage. The mathematical description of EMT is based on [7].

The EMT simulation model uses blocks that convert the measured currents and voltages from the three-phase static coordinate system ABC into rotating dq - system. To stabilize the AR output voltage, regulators (1) are introduced. To control the AR transistors, the inverse transformation into the *ABC* system was performed.

Table 1. The comparison of EMT structures

Parameters / EMT type	SG+AM	SGPM+SMPM	SRG+SRM
Coast of development	Low	Medium	High
Coast of manufacturing	Medium	High	Low
Coast of adjustment	Low	Medium	High
Coast of service	Medium	Medium	Low
Reserve	High	Medium	No data
Unification level	Low	Medium	High
Crash resistance	Medium	Low	High
Weight/dimensions	Large	Low/small	Medium

The AR CS is presented in Figure 6 and consists of the following elements: Udc set, Isq set – the sources of the voltage setting of the DC-bus and the reactive component of the current, respectively; Control U0 – regulator of the DC-bus voltage; Control Isd, Isq – the regulators of the active and reactive components of the generator current, respectively; Control Ud, Uq – the regulators of the active and reactive components of the AR output voltage, respectively. AM CS (Figure 7) is constructed similarly to the AR CS. For proper operation, the gain and time constant of the AVI (2) are calculated. The gain and time constant of PI-regulators of flux-forming and torque-forming current (4) as well as the flux linkage regulator (5), in addition, the rotational speed regulator (6) are calculated. The setting of the rotor flux linkage-control channel corresponds to the nominal flux linkage level.

The system consists of the following elements: wset, Fset – the sources of the setpoint of rotational frequency and flux linkage, respectively; Control speed – AM speed regulator; Control torque, flux – AM regulators of torque and flux linkage, respectively; Control current1,2 – AM regulators of flux linkage current and torque-forming current, respectively.
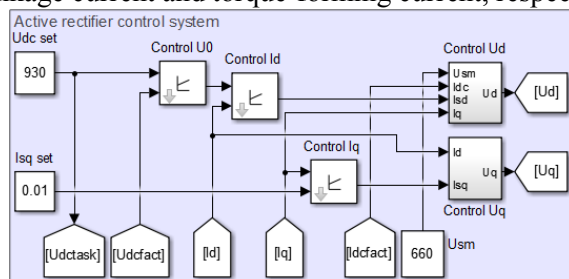

Figure 6. Active rectifier control system
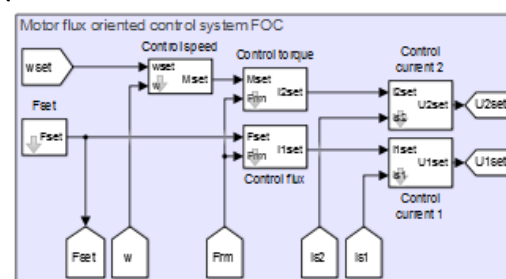
Figure 7. Asynchronous motors control system

The simulation model of EMT is presented in Figure 8. It contains the following blocks: Generator - model of electric power source (AG), Measurement 1,2,3 – block of voltage and current meters; Choke - three phase choke; Active rectifier – AR; DC-bus - direct current unit with a capacitor pre-charge device and a chopper; Autonomous inverter 1,2 – AVI 1 and 2 respectively; M1,2 – AM 1 and 2 respectively; Dump truck load 1,2 - load simulator; Oscilloscope – block of oscilloscopes.

Simulation modeling was performed in order to analyze the following modes of EMT during acceleration, ascent along the slope, moving to the dump and turning the MT under unloading.

From the oscillograms in Figure 9 (a) and (b) it is clearly seen that the actual speed of rotation of the AM and the MT speed are in full accordance with the specified values.

During the simulation, the linear voltages of the AG stator remained at the nominal level of 930 V (Figure 9 (a)). The phase currents of the AG are proportional to the load, the maximum value of 1000 A corresponds to the rated power. (Figure 9 (b)). The value of active power fluctuates in the nominal mode around the value of 700 kW, which corresponds to the nominal consumption of AM. At the same time, the value of reactive power is at the level of its AG consumption (60 kvar) (Figure 9 (c)).
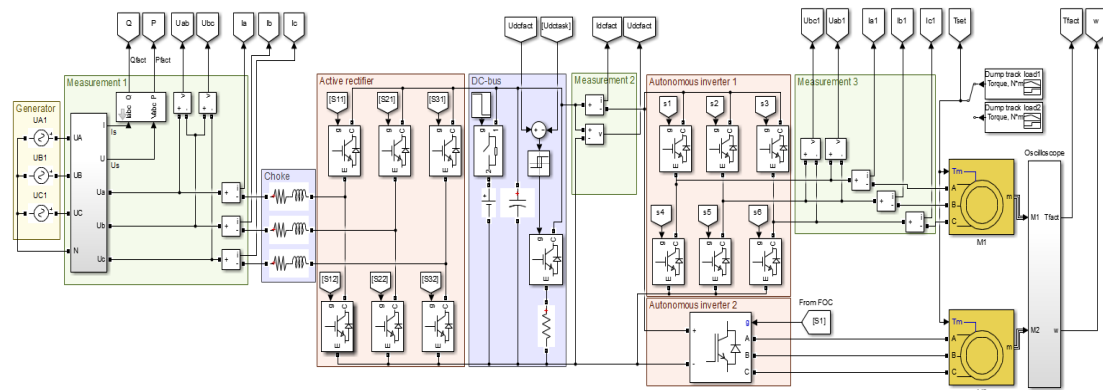
Figure 8. MT's EMT simulation model

The parameters of the DC-bus are also adequate to the mode of operation. The oscillogram in Figure 10 (a) shows the current in nominal mode is 700 A, which is slightly lower than expected. Figure 10 (b) shows that the voltage of the DC-bus is maintained by the AR at the required level of 930 V, the increase of the voltage at the DC-bus is due to the AM transition to the generator mode. The average power in the DC-bus is 700 kW, which corresponds to the nominal (Figure 10 (c)). The shape of the power curve is due to pulses of current in the DC-bus.
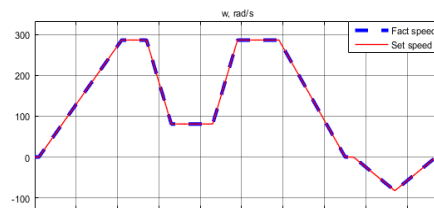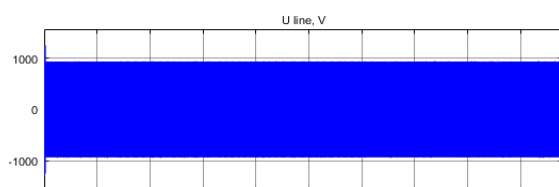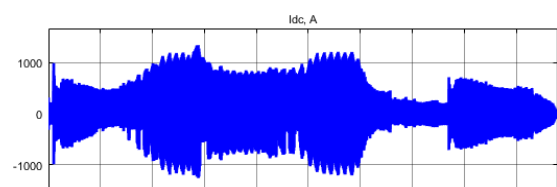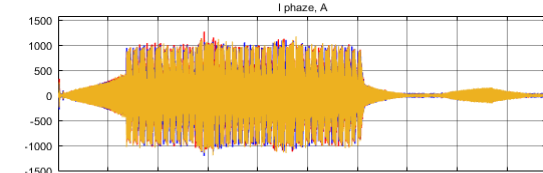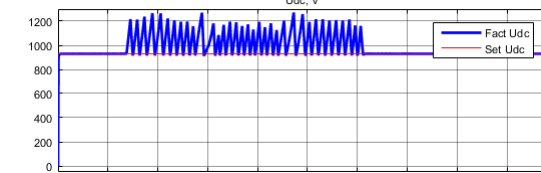

a
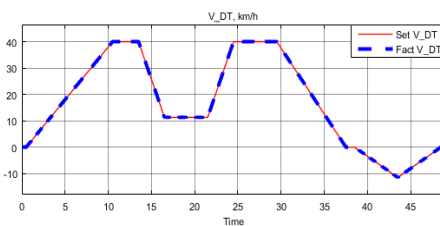
b

Figure 9. Speed characteristics
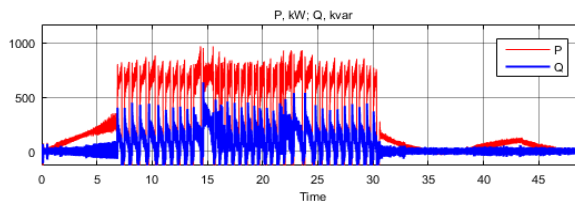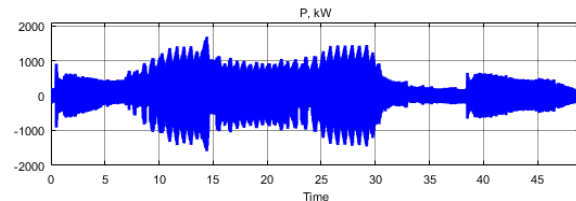

a

b

c

Figure 10. AG parameters

a

b

c

Figure 11. DC-bus parameters

4. Conclusion

EMT provides all working modes of career vehicles. Their performance and reliability fully determine the appropriateness of the application of the MT. The resource-saving MT's EMT has been developed; it meets the high requirements for unification and reliability. The study of the EMT simulation model shows the strict correspondence of the speed characteristics of both the drive engines and the MT as a whole. The advantages of the components of the developed EMT are used to the maximum: the possibility of energy isolation using AR, the minimum inertia in control due to the use of asynchronous machines. This ensures that the tasks assigned to the research are fulfilled.

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