Simulation of operation of a sequential hybrid drive of a haul truck with a traction battery and a bilateral DC-to-DC converter

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Abstract. In this article we consider one of the possible options for organizing the traction drive of a haul truck. The used scheme of the drive organization is given, and its performance is estimated by means of the drive simulation. The consideration is given to DC-to-DC converters in drives of hybrid traction systems. The conclusion is made about their influence on the efficiency of the hybrid traction drive.

1. Introduction
There are three main schemes for organizing the traction system of vehicles with combined power plants [1–4]: sequential, parallel and mixed. The circuits may include an internal combustion engine (ICE), generator, batteries, capacitors, traction motor (TM), rectifiers and converters. The role of the internal combustion engine and generator can replace fuel cells.

All electrical devices in the sequential scheme are connected to a common direct current bus (DC bus). The internal combustion engine is not connected to the wheels mechanically and can be switched off while driving; in this case the vehicle is driven by battery power. The internal combustion engine operates at a constant speed corresponding to the most optimal mode. If the power required for movement is less than that developed by the generator, the excess is used to recharge the batteries. If there is a lack of power developed by the generator, the batteries come into operation. The advantages of a sequential scheme include greater freedom of layout, maximum energy efficiency of recovery, and the disadvantages – significant dimensions and weight relative to other schemes, energy losses during its transformations.
In a parallel scheme, the internal combustion engine and traction motor have a rigid mechanical connection with the wheels. In the vast majority of cases, the internal combustion engine operates in optimal mode for a significant part of the time. Traction motor is activated in situations when the engine does not provide the required power. If the internal combustion engine provides an excess of power, the traction motor is switched to generator mode. The advantages of this scheme are smaller sizes and weight compared to the sequential scheme and less energy loss; among the disadvantages there are the need to use complex mechanical transmissions (an electric car combined with a transmission element) and greater complexity of the layout compared to the sequential scheme.

The mixed scheme uses features of parallel and sequential schemes: the internal combustion engine is connected mechanically to two electrical machines by means of a transmission with two degrees of freedom. The transmission gearbox is excluded in this case. In terms of advantages and disadvantages, such a scheme is close to a parallel one and is sometimes considered a variation of it.

2. Modeling of a hybrid sequential traction drive

The sequential scheme is suitable for use in heavy machinery due to its simplicity and layout capabilities. In this article we consider the sequential scheme, presented in the figure 1.

![Conditional traction drive scheme](image)

Figure 1. Conditional traction drive scheme: a) without DC-to-DC converter; b) with DC-to-DC converter.

As previously noted, the generator, traction motor and batteries are connected to a common bus. This solution has the following limitations – when using a common bus with multiple devices connected in parallel, it is not possible to control the power flows between them. They are determined by the internal resistance of these devices, in general, depending on a variety of parameters. In order to provide the traction motor with energy in full, it is necessary to match the exact generator voltage and the batteries voltage, while the algorithms for controlling the generator voltage become more complex.

In all types of batteries, together with a decrease in the charge level, there is a decrease in voltage. In this regard, the generator voltage must also be reduced as the batteries are discharged to ensure that the generator and batteries work together on a common load. Together with a decrease in the voltage on the common DC bus, the power of the traction motor will fall, which may make it impossible to continue driving when working in difficult conditions.

This problem is overcome by using bilateral DC converters (DC-to-DC converters). Their use allows combining devices with different rated voltages and controlling the electrical power flow in the system [5].

There are many different implementations of DC-to-DC converters. The efficiency of existing schemes exceeds 90% [6–9]. For some converters, the efficiency can be 96–98% with a power of 100 kW [10].

2.1. Prototype

The appliance of the above scheme is planned for a promising haul truck truck with a 4x4 wheel arrangement, the total weight of the haul truck is 50 tons, the curb weight is 25 tons. The following requirements are applied to the truck traction drive based on the simulation of the working cycle [11–14]:

– nominal rating power, kW, not less than 220;
– peak output, kW, not less than 350;
– maximum traction motor rotations per minute, rpm 3335;
– peak frequency torque, N∙m 743.

Based on the requirements, the following devices are selected: traction motor – as part of the front and rear axles, internal combustion engine, generator and battery pack. EM-PMI540-T1500-2400-DUAL electric motors are used as traction motor. Table 1 shows the characteristics of electric motors. The LSM280A-HV electric motor is used as a generator, the characteristics of the generator are shown in table 2. Microvast 6C+2B lithium-titanate (LpTO) batteries are used as a battery pack, the battery characteristics are shown in table 3.

### Table 1. Traction motor characteristics.

| Continuous torque, N∙m | Long-standing power, kW | Rated current, A |
|------------------------|-------------------------|------------------|
| 1510                   | 380                     | 522              |

| Coolant temperature   |                           |                  |
|-----------------------|---------------------------|------------------|
| +40°C                 |                           |                  |
| Long-standing power   |                           |                  |
| +40°C/+65°C           |                           |                  |
| Rotation speed, rpm    | Maximum rotations per minute, rpm | Peak torque, N∙m |
| 2400                  | 4000                      | 2135             |

### Table 2. Generator characteristic.

| Parameters                     | Theoretical value (600 В DC, 45°C) | Theoretical values (750 В DC, 45°C) |
|--------------------------------|------------------------------------|-------------------------------------|
| Continuous mechanical power    | 225 kW                             | 281 kW                              |
| Continuous torque              | 1852 N∙m                           | 1852 N∙m                            |
| Rated rotation speed range     | 0–3400 rpm                         |                                     |
| Maximum sustained current      | 350 А DC                           |                                     |
| Highest efficiency             | 0.948                              |                                     |

### Table 3. Battery bank.

| Parameters                     | Quantity                                      |
|--------------------------------|-----------------------------------------------|
| Nominal voltage/Capacity       | 556,6 V/140 Ah (78 kWh)                       |
| Operating voltage              | 400 V ~ 677,6 V                               |
| Module configuration           | 7p66s/1C, 7p44s/1V                           |
| System configuration           | 264s14p                                      |
| Cell type                      | LpTO                                          |
| Charging at a temperature 25°C | Maximum DC 480 A                             |
| Discharging at a temperature 25°C | Maximum peak current 500 A < 10 sec          |
| Discharging at a temperature 25°C | Maximum DC 365A (20% ~ 100% SOC)           |
| Discharging at a temperature 25°C | Maximum peak current 500 A < 10 sec         |

2.2. Simulated mathematical model

The mathematical model of the described hybrid traction system, in versions without DC-to-DC converter and in combination with DC-to-DC converter, was obtained in the MATLAB Simulink programming environment. The block schematic diagram of the model is shown in the figure 2.
Figure 2. Block schematic diagram of the mathematical model of the traction system in the Simulink programming environment: a) without DC-to-DC converter; b) in combination with DC-to-DC converter.

The presented model consists of blocks: two traction motors, generator, DC-to-DC converter and battery. The subsystems are connected to a common DC bus.

The traction motor blocks contain mathematical models of an inverter, vector traction motor controller, and a model of a synchronous motor with permanent magnets. The generator block contains a mathematical model of a controlled DC power source. The battery block subsystem contains a mathematical model of a lithium-ion (LiIon) battery; the model takes into account the processes of the battery charging and discharging.

2.3. Modeling exercises
To assess the need for DC-to-DC converter in the scheme used, the following experiments are performed.

The performance of the traction drive is evaluated when the engines are running in constant power mode for 20 seconds. In the simulation, the generator recoil current is controlled at the level of no more than the allowed generator current in accordance with table 2. Modeling exercises are performed for cases where the drive operates without a battery, with a low battery level, and with a high battery level. As a result of the modeling exercises, power flows in the drive are estimated.

2.3.1. Battery-free operation. The first experiment involves running a generator on a traction drive without using a battery and a DC-to-DC converter. The graphical interpretation of the simulation results (figure 3) is: the generator current, the total current of the traction motor, the voltage on the common DC bus, and the mechanical power developed by the traction motor.

Figure 3. Test parameters when the drive is operated without a battery.
The load on the shafts of the electric motors is 1000 N∙m, the speed of the electric motors is 1000 rpm, and the power developed by the two engines is 210 kW.

2.3.2. Drive operation without using DC-to-DC converter. In these modeling exercises without a DC-to-DC converter, the operation of the drive is considered, in which the battery and generator voltages are equalized. In all experiments, the motor shaft speed is maintained at 1000 rpm.

In the current experiment, the load on the shafts of electric motors is 1550 N∙m, the power developed by two engines is 327.5 kW, the initial battery charge level is 90%, the voltage on the DC bus was maintained at 578 V in order to ensure long-term permissible recoil currents of the battery and generator.

A graphical interpretation of the experiment results is shown in figure 4.

![Graph](image1.png)

**Figure 4.** Drive parameters without DC-to-DC converter, battery charge level – 90%.

The third experiment started with a battery charge of 30%. At the same time, the overcome moment of resistance on each electric motor was 1460 N∙m, the power developed by the two engines was equal to 307.5 kW, and the voltage on the common DC bus decreased to about 550 V. The graphical interpretation of the experiment results is shown in figure 5.

In the next experiment, the generator voltage is controlled to maintain the battery charge current of no more than 30 A. The graphical interpretation of the experiment results is shown in figure 6.

![Graph](image2.png)

**Figure 5.** Drive parameters without DC-to-DC converter, battery charge level – 30%.
Figure 6. Experimental parameters when the drive is operating without voltage equalization, the initial battery charge level – 10%.

The load on the shafts of electric motors is 600 N·m, the power developed by two engines is 127.5 kW, the battery charge level at the initial time is 10%. In this case, the voltage on the common DC bus was 577 V.

2.3.3. Drive operation while using DC-to-DC converter. Figure 7 shows the simulation results when using a DC-to-DC converter running on a battery with an initial charge level of 10%. The battery charge current is controlled by a DC-to-DC converter and is 30 A regardless of the common DC bus voltage (700 V). At the same time, the overcome moment of resistance on each electric motor was 850 N·m, and the power developed by the two engines was equal to 180.2 kW.

Figure 7. Experimental parameters when the drive is operating with DC-to-DC converter in the mode of the battery charge, the initial battery charge level – 10%.

The last experiment involved the joint operation of a DC-to-DC converter and generator on a common load with a battery charge of 90%. The results are shown in figure 8. The voltage on the common DC bus was also 700 V, the resistance moment on each electric motor was 1730 N·m, and the developed total power was 365.8 kW.
3. Conclusion

Based on the results of previously conducted modeling exercises [15], the dependence of the torque of one of the drive engines on the driving time was formed for the vehicle in question (figure 9).

In the Pmax section, the engine speed was 78.9 radian per second. The total power of the two engines is 207.86 kW. Table 4 shows a comparison of the capacities that can be obtained under different modes of operation of onboard power sources of a hybrid vehicle, both with the use of a DC-to-DC converter and without the use of this device.

The following conclusions can be drawn from the presented data:

– using DC-to-DC converter allows to get more power at both high and low battery levels;
– this device allows to disconnect the discharged battery from the common DC bus without mechanical switches, while the generator will provide the necessary power for driving;
– when the battery is low, the DC-to-DC converter can provide a low current charge, while the generator can provide the power needed to move at a slightly lower speed compared to a typical driving cycle.
Table 4. Onboard power source capacities.

| Operation mode                                                                 | Maximum continuous power, kW |
|--------------------------------------------------------------------------------|-------------------------------|
| DC-to-DC converter and traction motor generator, battery charging – 90%        | 365.8                         |
| Generator and traction motor battery (initial battery charge level – 90 %)    | 327.5                         |
| Generator and traction motor battery (initial battery charge level – 30 %)    | 307.5                         |
| Traction motor generator (battery-free)                                       | 210                           |
| Standardized power                                                            | 207.86                        |
| DC-to-DC converter at the battery charge (charging rate – 30 A, initial battery charge level – 10%) and traction motor generator | 180.2                         |
| Traction motor generator and battery charge (charging rate – 30 A, initial battery charge level – 10%) | 127.5                         |

4. Confirmation

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